Tim Law

The Future of Thermal Comfort in an Energy-Constrained World

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Tim Law

The Future of Thermal Comfort in an Energy-Constrained World

Doctoral Thesis accepted by the
University of Tasmania

🕎 Springer

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Law, T., Sargison, J., Fay, R., & Banbury, S. (2012). Ductless Task Air-Conditioning. ASHRAE Transactions, 118, 367–374.

*To my wife Juan and children, for whom
I pray my actions may leave a better world*

Supervisor's Foreword

The need to dramatically reduce the consumption of energy generated by the combustion of fossil fuels is becoming increasingly evident. Year by year, scientific evidence mounts and scientific consensus worldwide confirms the nexus between the burning of fossil fuels and climate change. Increasingly, the consequences of climate change are becoming more evident on the lives of people around the globe. The magnitude and frequency of extreme weather events are increasing and resulting in the displacement of millions of people together with massive infrastructure damage. Floods, droughts and insect infestations are affecting food production. Low-lying islands and cities and the people who live there are at increasing risk. Human health, particularly in developing countries is being affected adversely. The biodiversity on which humans depend is being eroded globally.

Tragically, the construction and operation of settlements and the buildings within them consumes a significant proportion of global fossil fuel generated energy. Even in benign climates the design of cities and buildings results in the unnecessary consumption of energy. However, in hot and cold climates the need to provide thermal comfort is difficult to argue with. Tim Law is a Singaporean. Singapore is hot and humid. It is also a highly developed country and its success is based on human rather than natural resources. Consequently, the provision of thermal comfort for knowledge workers is regarded in Singapore as non-negotiable. The productivity of these workers is based very significantly on the provision of thermal comfort by means of air conditioning.

Tim Law's research tackles this problem. How in a first world country like Singapore, he asks, could a knowledge-based economy be maintained in an energy-constrained world? His research started from a purely technical standpoint and he investigated a strategy in which a high rise building—common in Singapore—was designed to be a cooling instrument. This first stage was taken through to proof of concept. However, Dr. Law became increasingly aware that though theoretically feasible, the idea was unlikely to win favour in the real world of design and development. At this point Dr. Law's thinking changed. He hoped to develop solutions that would win favour in the marketplace. In other words, a very

efficient solution that is not taken up by industry is of little or no value while one that may be less efficient but has market acceptance is far better.

The approach taken by Dr. Law, with the benefit of hindsight, was that he worked from the macro, whole building solution to the micro, individual office worker solution. Consequently, the final stage of the research process led him to investigate the needs of the individual rather than the generic office worker. However, the research described in the following pages is of significance not only because it resulted in the development of a provisionally patented device that has the capacity to provide thermal comfort to an individual office worker but also because of the importance it places on the conversion of theory into invention, experimentation and commercialisation.

Launceston, April 2013   Prof. Roger Fay

Acknowledgments

> I didn't fail ten thousand times. I successfully eliminated, ten thousand times, materials and combinations which wouldn't work.
>
> Thomas Edison (1847–1931)

This work began under the label of *Novel Cooling Systems*. However, the term 'novel' in academia often carries a perjorative undertone, with a real likelihood that the entire candidature could be spent proving what could not possibly work, like Edison's ten thousand 'failed' attempts. In this high-risk, high-reward venture, it is of the Lord's mercies that I have emerged with some success, and a number of people need to be thankfully acknowledged for being blessings to me.

Professor Roger Fay, my primary supervisor (Architecture), for laying such a wager on me. He always had more confidence in my problem-solving abilities than I held in my own estimation, and many times it rubbed off on me and became self-fulfilling. His broad knowledge and endless curiosity made every supervisory meeting a brilliant exercise in lateral thinking.

Dr. Jane Sargison, who co-supervised this project (Engineering) was mechanical engineer extraordinaire, after all she was *Australian Professional Engineer of the Year 2011.* Her openness to inter-disciplinary work was exceptional and crucial to the validation of the innovations.

Mr. Steven Banbury, building mechanical engineering consultant, for many enlightening insights to the practice and for being my sounding board as a representative of industry.

Dr. Des Fitzgerald (Maths) for his valued statistical help. Dr. Catriona McLeod (Landscape Architecture), my esteemed non-technical reader, whose passion for clarity ensured that I communicated plainly.

Professor Michael Davis (Engineering), who stood in for Jane during her maternity leave, initiated me to key engineering concepts and gave a stern warning, 'If you try to violate the second law of thermodynamics, you can be sure it will resist you.' I have since steered clear of Maxwell's demon.

My fellow building technology geeks Justin Beall and Dr. Mark Dewsbury, for the generous sharing of their profound knowledge, and endlessly fruitful

Contents

Symbols

For ease of reference, nomenclature is included immediately after each equation in the *Equation Notes.* A selected list is included here where they appear in the text body.

Th	Hot side temperature, when used in DTAC refers to the temperature read from the underside of the PCM tank
T	Temperature
Tc	Cold side temperature, when used in DTAC refers to the temperature of the topmost cooling fin (nearest the TE modules)
S	Entropy
P	Pressure
H	Enthalpy
RH	Relative humidity
clo	Clothing insulation
met	Metabolic rate
MRT	Mean radiant temperature
H_{ss}	Enthalpy of supply air
H_{amb}	Enthalpy of ambient air
W_{TE}	Work (electrical) input to TE modules
Q_{TE}	Heat produced (on hot side) of TE module

Abbreviations and Acronyms

ABGR	Australian Building Greenhouse Rating
ACMV	Air-conditioning and mechanical ventilation
AHU	Air-handling unit
AIRAH	Australian Institute for Refrigeration, Air-conditioning and Heating
AMV	Actual Mean Vote
ASHRAE	American Society for Heating, Refrigeration and Air-conditioning Engineers
ATD	Air Terminal Devices
ATP	Adenosine triphosphate
BAU	Business as usual
BMR	Basal metabolic rate
BREEAM	BRE (formerly Building Research Establishment) Environmental Assessment Method
CAD	Computer-aided design
CAM	Computer-aided manufacturing
CC	Climate Chamber
CFE	Cooling fan efficiency
CIF	Corticotropin inhibiting factor
CO_2-e	CO_2 (carbon dioxide) equivalent
COP	Coefficient of performance, expressed as an equation, e.g., COP = 1. Typical abrreviataion used throughout thesis
COP	Conference of the parties, when referring to UN climate conferences, e.g., COP1. Used only in Chap. 2
CRH	Corticotropin releasing hormone
CST	Concentrated solar thermal
DTAC	Ductless Task Air-Conditioning
EHHF	Evelyn and Harold Hay Fund
EIT	Economies in transition
f-f	Floor to floor
GBCA	Green Building Council of Australia
GHG	Greenhouse gases
$GtCO_2$-e	Giga (billion) tons of CO_2 (carbon dioxide) equivalent
GWP	Global-warming potential

HR	Humidity ratio
HVAC	Heating, Ventilation and Air-conditioning
IDEAS	Innovation Development Early Assessment System
IP	Intellectual Property
LEED	Leadership in Energy and Environmental Design
M&E	Mechanical and electrical (used in conjunction with engineer/engineering)
MDF	Medium density fibreboard
mpg	Miles per gallon
MRT	Mean Radiant Temperature
NOAA	National Oceanic and Atmospheric Administration
NV	Naturally Ventilated
ODP	Ozone Depleting Potential
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
PCM	Phase change material
PEM	Personal Environmental Modules, a proprietary system of Johnson Controls
PMV	Predicted Mean Vote
ppm	Parts per million
PRC	Patent Review Committee
PSU	Power Supply Unit
PV	Personal Ventilation
PV	Photovoltaic
PVA	Polyvinyl acetate
RH	Relative humidity
SBC	Selective Brain Cooling
SEUI	System energy usage intensity
SOAD	School of Architecture and Design (University of Tasmania)
TAC	Task-Ambient Conditioning
tCO_2-e	Tons of CO_2 (carbon dioxide) equivalent
TE	Thermoelectric
TIM	Thermal Interface Material
TT	Technology Transfer
VAV	Variable air volume
WCI	Wind Chill Index

Chapter 1
Introduction

> … we need something like a 90 % reduction in national consumption. Nothing remotely like this is possible within a consumer-capitalist society committed to affluent lifestyles and limitless economic growth. *Renewable Energy Cannot Sustain a Consumer Society* (Trainer 2007, p. 117).

There is general recognition that the lifestyle in developed countries, typified by high levels of consumption and emissions, is not sustainable. In this multi-faceted problem, this thesis attempts to solve one part of the problem: the demand for thermal comfort in affluent tropical cities.

Admittedly, problem-solving is not a common approach for a doctoral thesis. Nevertheless we must recognise that academic research methods are integral to any viable solution, and keeps academia relevant to the challenges of our time. In the context of poverty, disease and global warming, Richard Levins, President of Yale University said, "The fate of the planet depends on our ability… to solve society's most pressing problems" (Gallagher 2011). For the core of these challenges to be properly understood, insights from other disciplines are always enriching, and often invaluable. Inter-disciplinary work is also necessary to validate any emergent solutions. Hence, whilst this thesis emerges from an architectural science platform with a primary interest in thermal comfort, it draws on a number of other disciplines to frame and resolve this complex problem:

1. Engineering: to validate the thermodynamic performance of innovations
2. Sociology: to describe behavioural attitudes to thermal comfort and predict future trends
3. Physiology: to understand the thermal regulation of the active brain under stressful conditions
4. Business: to identify market opportunities and business angles

Inventiveness, is however not a discipline in its own right, but more of an attitude to a problem, an attitude underpinning many chapters in this thesis. Innovation is not a linear process, though neither is it haphazard. Many times, the

innovation- critique process is run as thought experiments and I have restyled the writing as the first person, and at times as a dialectic with myself. 'Don't walk around the yard talking to yourself, the neighbour will think you're mad,' my wife often told me. Whilst this reflexive style is unconventional to a scientific thesis, it is the most honest account of the genesis of ideas, the self-dialoguing *madness* of the mad inventor. It is through these series of self-reflections that the research questions and hypotheses emerge as part of the narrative of this thesis, and are eventually encapsulated into a design brief.

To synthesise the disparate fields of study, a (Hegelian) dialectic approach has been found to be useful to discuss opinions and resolve contradictions. This will be presented as a series of catechetical reflections along the main narrative. For example:

Q   Why is there a need for Q&A?

A   The main thread of thought is carried in the narrative of the thesis. However there are many ancillary arguments, which when entered into detail will change the trajectory of the narrative. The arguments are nonetheless necessary to complete a complex picture by taking a short and distinct digression before returning to the narrative. By keeping the main arguments separate from augmented ones the train of thought can be clearer.

Q   How are the Q&As structured differently from the narrative?

A   The flow of logic in the Q&A's is such that each question relates to the next, whilst the answers can be drawn from diverse disciplines. In contradistinction, the main narrative is like a series of arguments that lead to each other.

Q   Why not use footnotes/endnotes?
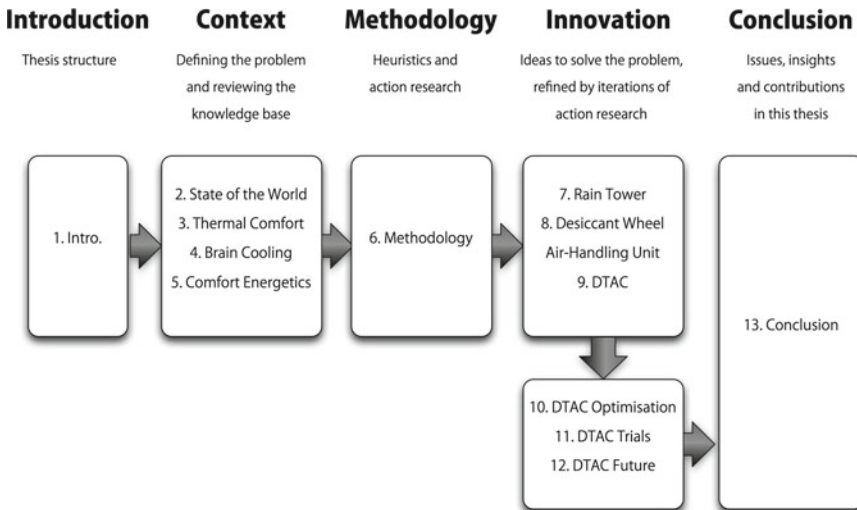
Fig. 1.1 Structure of chapters in this thesis

A   Whilst footnotes are useful in carrying supplementary information, some of
     these are vital to developing the argument and need to be read alongside the
     main text. By allowing a conversation as a Q&A forum, I can ensure these
     notes contribute to the fuller picture.

This thesis is broadly structured as *theory* (Chaps. 2 –5), *methodology* (Chap. 6),
innovation (Chaps. 7– 9) and *development* (Chaps. 10–12) as seen in Fig. 1.1.

Chapter 2 introduces the context of the problem: the majority consensus on
climate change and the role of buildings in mitigating CO_2 emissions. The role of
air-conditioning in this problem is identified in its energy demands amidst the
constraints of energy and environment.

Chapter 3 reviews the positions taken in deterministic and adaptive thermal
comfort and offers a way to synthesise the apparently conflicting findings of both
positions. The factors that impinge on perceptions of comfort are expanded beyond
the building sciences to involve marketing and sociology to explain the con-
tradictions in thermal comfort research and consumer behaviour. The definition of
thermal comfort is revisited and the premise and consequence of such a definition
is enjoined, giving an indication of where the future of thermal comfort will be
taken.

Chapter 4 discusses the physiology of stress and brain cooling. A convergence
is sought between thermal comfort, real-life work stress, sleep and other consid-
erations that affect mental performance in an office environment. The importance
of facial cooling is established here.

Chapter 5 introduces a new evaluation metric for comparing cooling efficacy
with energy demands. Called *comfort energetics,* multiple ways of improving a
thermal sensation vote are denominated by the energy required for improving
votes in each process. Dehumidification shows up poorly in its comfort energetics
and the need for controlling humidity is investigated at length, with a case made
for ignoring the recommended optimum relative humidity range.

Chapter 6 explains why this thesis is methodologically different from the
conventional. The role of heuristics, or *problem-solving approach*, is clarified.
Criteria are set for the evaluation of the innovations which follow.

Chapter 7 begins the problem solving process through a design brief iterated
through action research. The first innovation of the *Rain Tower* is explained and
modelled, the challenges to realising such a scheme are enumerated, and the need
for a solution that can be commercialised are established with case studies.

Chapter 8 introduces the business dimension into the innovation process and an
early warning appraisal to decisively curb potentially futile efforts. The signifi-
cance of intellectual property and its centrality to the innovation-investment
relationship is established with a case study.

Chapter 9 proposes the final innovation that met all the required criteria of
improved thermal comfort, energy savings and commercial potential. The Ductless
Task Air-Conditioning (DTAC) is built on the premise of task-ambient condi-
tioning (TAC) systems with an improvement in being implementable without

renovations. The key operating principles and proof-of-concept experiments are explained.

Chapter 10 explains the methodology of the DTAC field trials in both naturally ventilated and climate chamber work spaces, and discusses the results of the experiment.

Chapter 11 projects the planned future of DTAC, especially in the areas of indoor air-quality improvement, and recommendations for future thermal comfort research.

Chapter 12 concludes the thesis with a short recapitulation.

The main objectives of this present work are:

1. To study how the debate between deterministic and adaptive thermal comfort models can be resolved with insights from other disciplines, particularly sociology and physiology.
2. To study how cooling comfort can be quantified by the energy efficiency and cooling efficacy.
3. To develop technologies that can reduce the energy consumption of air-conditioning and be widely adopted in a consumer society.

One of the most inventive minds, Nikola Tesla, maintains in his autobiography that,

> The progressive development of man is vitally dependent on invention. It is the most important product of his creative brain. Its ultimate purpose is the complete mastery of mind over the material world, the harnessing of the forces of nature to human needs. This is the difficult task of the inventor who is often misunderstood and unrewarded. But he finds ample compensation in the pleasing exercises of his powers and in the knowledge of being one of that exceptionally privileged class without whom the race would have long ago perished in the bitter struggle against pitiless elements (Tesla 1919, p. 1).

It is the pursuit of human comfort in tropical indoor climates, accompanied by a sense of environmental stewardship, that underpins this undertaking.

I invite you to join me on my journey, and from hence, the term *we* will refer to you, my reader, and I.

References

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Chapter 2
The State of the World

In the fourth assessment report of the UN Intergovernmental Panel for Climate Change (IPCC), the *robust finding* [defined as that which 'holds under a variety of approaches, methods, models and assumptions, and is expected to be relatively unaffected by uncertainties' (IPCC, 2007, AR4 SYR—Topic 6)] was that 'warming of the climate system is unequivocal,' and that 'most of the global average warming over the past 50 years is *very likely* due to anthropogenic Green House Gases (GHG) increases' (IPCC, 2007, AR4, 6.1). The IPCC also identified the building industry as the one with the most climate mitigation potential (Table 2.1). When Time Magazine (Kluger 2007) ran a special feature called *The Global Warming Survival Guide,* buildings accounted for the largest share of U.S. emissions, noting that:

> While the power and auto industries get the bulk of the blame for the planet's carbon crisis, the business of operating office buildings and homes is responsible for 38 % of U.S. CO2 emissions. In the case of offices, mid-20th century technology worked against us, as the development of low-temperature fluorescent lights and high-powered air conditioning made it possible to design sealed structures that you could drop into any climate. "It gave architects the power to design anything, then hand it over to engineers and say, 'Here, you heat and cool it,'" says Gail Brager of the Center for the Built Environment at the University of California, Berkeley.

Politicians on the other hand have had little will to commit to the recommended CO_2 abatement measures. With the 20-year long history of UN Climate Change Conferences (Table 2.2), it has become clear that an environmental imperative was not enough to demand a political response when the immediate economic costs were too high.

Since preindustrial times, the CO_2 emissions have increased by 'about 36 %, with the rate of increase being about 2 ppm per year and still increasing' (Bolin 2007, p. 215). The lack of political will is even more stark when considered against the availability of technologies and plans for CO2 mitigation. Pacala and Socolow (2004) explained the need to stabilise carbon emissions at present levels, which require substituting the business as usual (BAU) industries with existing sustainable technologies. Their multi-faceted approach is construed as an aggregate of

Table 2.1 Economic mitigation potential in 2030 (IPCC 2007)

	Gt CO2-eq-year
Buildings	5.3–6.7
Agriculture	2.3–6.4
Industry	2.5–5.5
Energy supply	2.4–4.7
Forestry	1.3–4.2
Transport	1.6–2.5
Waste	0.4–1

wedges. Each wedge accounts for a reduction of 1 billion tons of carbon per year (Fig. 2.1 and Table 2.3). In 2004 when the paper was first published, it was anticipated seven wedges would be needed for stabilisation; and in 2011, it was increased to nine wedges, and would have resulted in ~ 0.5 °C higher stabilisation in temperature compared to 2004 (Socolow 2011). Further delays to act will only exacerbate an already monumental effort for transformation.

Table 2.2 History of climate change policy (Umashankar et al. 2009), mitigation outcomes (Lomborg 2010) and CO_2 ppm (NOAA 2012)

Year	Conference	Atmospheric CO2 concentration (ppm)	Mitigation outcomes
1992	Earth summit, Rio de Janeiro	356	to cut CO2 to 1990 levels by 2000
1995	'Conference of the parties' COP1, Berlin	361	
1996	COP2, Geneva	363	
1997	COP3, Kyoto	364	Kyoto Protocol: to cut CO2 to 5.2 % below 1990 levels by 2012
1998	COP4, Buenos aires	367	
1999	COP5, Bonn	368	
2000	COP6, The hague	370	
2001	COP6 (extraordinary conference), Bonn	371	
2001	COP7, Marrakesh	371	
2002	COP8, Delhi	373	
2003	COP9, Milan	376	
2004	COPIO, Buenos aires	377	
2005	COP11, Montreal	380	
2006	COP12, Nairobi	382	
2007	COP13, Bali	384	
2008	COP14, Poznan	386	
2009	COP15, Copenhagen	387	Copenhagen accord had no legally binding commitments
2010	COP16, Cancun	390	
2011	COP17, South Africa	392	
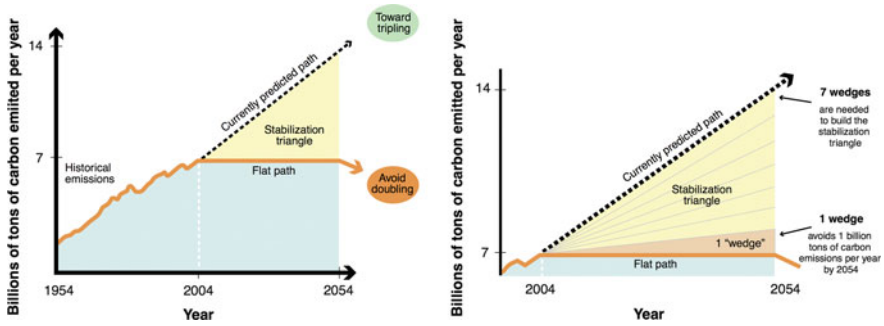
Fig. 2.1 Stabilisation wedges (Pacala and Socolow 2004)

By looking at the whole mosaic of stabilisation solutions we see that the energy problem is twofold: a lack of economically competitive renewable energy, and a lack of distribution capacity.

At its core, the global rise in living standards demand an increasing amount of energy to power modern conveniences. As long as renewables cost more than fossil-based energy, any measure to reduce carbon emission inevitably increases the affordability of a high standard of living. Developing economies are understandably resistant to any such commitment. However, even if renewables can be cost competitive it does not automatically ensure better living standards.

The problem of energy is not merely one of generation but of distribution as well. For example, the wholesale supply of nuclear electricity in the U.S. is 31 % of the meter price, with 69 % of the cost in transmission, distribution and management (Rosenfeld 1999). Rolling blackouts in developed economies illustrate both these problems combined: limited power generation capacity and inadequate transmission infrastructure.

In this regard, energy conservation solves both problems—it frees up capacity in both power generation and transmission. To be viable it also must be done in a way that does not compromise affluence. However it must be also noted that conservation has no media appeal, no star status, no poster boy. Thus Rosenfeld goes on to say:

> That makes it hard to convince most people that, for any given year in the foreseeable future, it will be cheaper and cleaner to improve efficiency by a few percent than to increase supply by the same amount. Give a congressman the choice of funding energy supply or energy efficiency, and he will go for supply almost every time (Rosenfeld 1999, p. 57).

2.1 Singapore as a Reference City

Singapore can be seen as the archetypal nation-city which transformed from third to first world status in a few decades. Without any natural resources for primary industries, Singapore's only recourse has been to rely on human resource.

Table 2.3 Examples of how to achieve a stabilisation wedge (Socolow and Pacala, in National Geographic Magazine, 2007)

Efficiency and conservation	Carbon capture and storage	Low-carbon fuels	Renewables and biostorage
Improve fuel economy of the two billion cars expected on the road by 2057 to 60 mpg from 30 mpg	Introduce systems to capture CO2 and store it underground at 800 large coal-fired plants or 1,600 natural-gas-fired plants	Replace 1,400 large coal-fired power plants with natural-gas-fired plants	Increase wind-generated power to 25 times current capacity
Reduce miles traveled annually per car from 10,000 to 5,000	Use capture systems at coal-derived hydrogen plants producing fuel for a billion cars	Displace coal by increasing production of nuclear power to three times today's capacity	Increase solar power to 700 times current capacity
Increase efficiency in heating, cooling, lighting, and appliances by 25 %	Use capture systems in coal-derived synthetic fuel plants producing 30 million barrels a day		Increase wind power to 50 times current capacity to make hydrogen for fuel-cell cars
Improve coal-fired power plant efficiency to 60 % from 40 %			Increase ethanol biofuel production to 50 times current capacity. About one-sixth of the world's cropland would be needed
			Stop all deforestation
			Expand conservation tillage to all cropland (normal plowing releases carbon by speeding decomposition of organic matter)

To capitalise on this resource, Singapore has always striven for a high education standard and a workforce that was industrious and productive. How did this happen in a hot and humid climate?

> Writing in the May 1929 inaugural issue of Heating, Piping & Air-Conditioning, Willis Carrier had been confident about air-conditioning's present and expressed buoyant optimism regarding its future. He imagined windowless office skyscrapers free of noise and dust and predicted air-conditioned comfort in the homes of average Americans as well as the wealthy. The air-conditioning industry could take credit, said Carrier, for the "present-day prosperity of the people of these United States." Its growth, he predicted, would be geometric (Ackerman 2002, p. 79).

This vision became reality in the knowledge-based economy of Singapore. The founding Prime Minister, Lee Kuan Yew, named the air-conditioner as the most significant innovation of the millennium, saying:

> The humble air conditioner has changed the lives of people in the tropical regions. Before air-con, mental concentration and with it the quality of work deteriorated as the day got hotter and more humid. After lunch, business in many tropical countries stopped until the cooler hours of the late afternoon. Historically, advanced civilizations have flourished in the cooler climates. Now lifestyles have become comparable to those in temperate zones and civilization in the tropical zones need no longer lag behind (Lee Kuan Yew, in Wall Street Journal, 1999).

Interestingly, Lee's style of governance created a climate that journalist Cherian (2000) described as politically stifling as an artificial climate, saying:

> So, think of Singapore instead as the Air-conditioned Nation—a society with a unique blend of comfort and central control, where people have mastered their environment, but at the cost of individual autonomy, and at the risk of unsustainability.

Over 70 % of the workforce is estimated to work in offices in Singapore (see Table 2.4 and over 80 % in the UK (CIBSE 1999).

For the purpose of this thesis the context for air-conditioning is confined to that for offices located in hot and humid climates.

2.1.1 Environmental Impact of Air-Conditioning

The environmental impacts of air-conditioners are two-fold: direct emissions via leakage of high global-warming potential (GWP) refrigerants, and indirect CO_2 emissions via the power needed to drive the air-conditioning and mechanical ventilation (ACMV) systems derived from fossil-fuel power stations.

2.1.2 Environmental Impact of Refrigerants

The refrigerants used in air-conditioning have tremendous global warming potential (GWP). Stated in terms of carbon dioxide's GWP, or CO_2-e, CFC

Table 2.4 Singapore resident employment in 2010 by occupation

Occupation	2010 employed (thousands)*	Office utilisation (lower)	Office utilisation (upper)
Legislators, senior officials and managers	335.2	335.2	335.2
Professionals	312.6	312.6	312.6
Technicians and associate professionals	373.4	373.4	373.4
Clerical workers	240.5	240.5	240.5
Service and sales workers	246.4	123.2	172.48
Production Craftsmen and related workers	86.5	8.65	17.3
Plant and machine operators and assemblers	154.2	15.42	30.84
Cleaners, labourers and related workers	145.5	14.55	29.1
Others	68.7	0	13.74
	1962.9	1423.52	1525.16
		72.52 %	77.70 %

"Office utilisation" are author's own estimates based on observation

Legislators, Senior Officials and Managers (100 %); Professionals (100 %); Technicians and Associate Professionals (100 %); Clerical Workers (100 %); Service & Sales Workers (50–70 %); Production Craftsmen and Related Workers (10–20 %); Plant and Machine Operators and Assemblers (10–20 %); Cleaners, Labourers and Related Workers (10–20 %); Others (0–20 %).

* Employment statistics from "Statistics Singapore—Yearbook of Statistics, 2011" (Singapore Department of Statistics 2011) (www.singstat.gov.sg/pubn/reference/yos11/statsT-labour.pdf)

(chloroflurocarbon) refrigerants have an extremely high GWP of 4,000–119,000 CO_2-e. Under the Montreal Protocol, ozone depleting CFC refrigerants have already been phased out, and the less active HCFC (hydrochlorofluorocarbons) will be phased out by 2030. However, even with refrigerants that have no ozone depleting potential (also referred to as Kyoto Protocol synthetic gases), the GWP ranges between 1300 (R134a) to 3900 (R507) (Australian Fluorocarbon Council 2001).

Globally, the various greenhouse gases responsible for radiative forcing in the atmosphere up to 2006 are (Australian Refrigeration Council 2011):

- CO_2: 61 %
- CH4: 22 %
- Montreal protocol gases (largely CFCs): 10 %
- N2O: 6 %
- Kyoto protocol synthetic gases (largely HFCs): <1 %

Refrigerants thus form a small but significant part of the global warming contribution. The successful phasing out of CFCs under the Montreal protocol bolsters a degree of confidence that the HCFCs will likely be well under control by the target dates. The remaining Kyoto protocol synthetic gases whilst insignificant
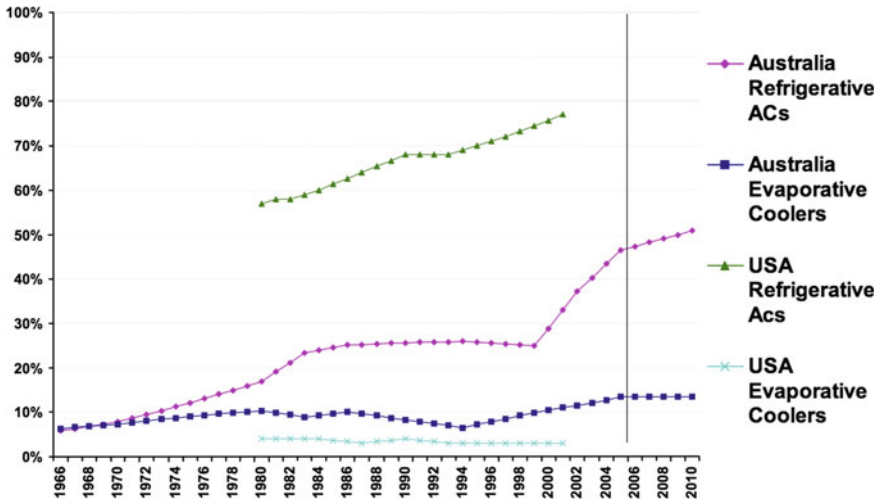
Fig. 2.2 Share of Australian households with air conditioning or evaporative cooling—historical and projected (Wilkenfeld 2006)

now will increasingly be an issue as these refrigerants replace those that have been phased out, and as the air-conditioning market continues to grow. Australia's growth in the decade 1995–2006 was by a factor of 2.5 times (see Fig. 2.2. Wilkenfeld 2006).

2.1.3 Environmental Impact of Air-Conditioning Power

Air-conditioning accounts for the largest share of building operational energy. In tropical cities like Singapore, it accounts for about 50 % of the system energy usage intensity in offices (Table 2.5). In the Australian commercial sector it typically accounts for 30–40 % of summer maximum energy demand (Wilkenfeld 2006).

Table 2.5 System energy usage intensity (SEUI, kWh/sqm/year) of offices in Singapore http://www.esu.com.sg

Percentile rating (%)	Class A 25th	Class B 50th	Class C 75th
Air-conditioning	82 (44 %)	132 (50 %)	144 (46 %)
Mechanical ventilation	23 (12 %)	36 (14 %)	51 (16 %)
Lighting	24 (13 %)	28 (11 %)	32 (10 %)
Lift and escalator	11 (6 %)	16 (6 %)	23 (7 %)
Others	47 (25 %)	53 (20 %)	61 (20 %)
Total (system) kWh/sqm/year	187	265	311
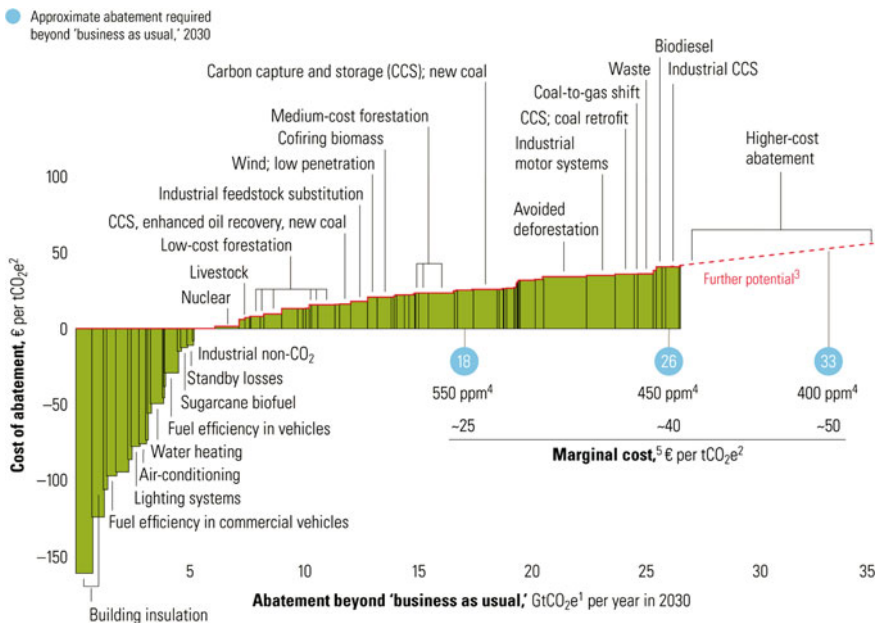
Fig. 2.3 McKinsey curve (McKinsey and associates 2007)

When the costs of abatement measures are compared to the tariffs on CO_2-e emissions, upgrading to more efficient air-conditioning becomes very attractive. As an abatement measure, more efficient air-conditioning gives one of the best returns for the capital outlay, coming behind building insulation, improved efficiency in commercial vehicles and more efficient lighting systems (Fig. 2.3).

2.2 The Role of Air-Conditioning in a Changed Climate

With global warming, the number of hot days associated with heat related injuries will be more frequent annually, together with more record highs (right end tail of Fig. 2.4). CSIRO projections of the number of days in excess of 35 °C (Table 2.6) show that heat waves are likely to be longer lasting. Nicholls et al. (2007) have discovered a trend in Melbourne's mortality rate anomaly which became substantially increased once mean temperatures exceeded 28 °C, and proposed a warning based on these criteria:

> If at any time during the forecast period the average of the predicted maximum temperature on one day and the predicted minimum temperature for the following morning exceeds 30 °C, a heat alert could be issued to the public and/or local authorities, ambulance services and other health and welfare organizations. The heat alert would indicate likely increases in mortality in the 24-h period following the high temperatures.

Fig. 2.4 Relationship
between means and extremes,
when extreme events are
defined as some fixed
threshold related to a
significant impact (e.g.,
heatwave leading to excess
deaths). (Australian
Department of Climate
Change and Energy
Efficiency 2011)
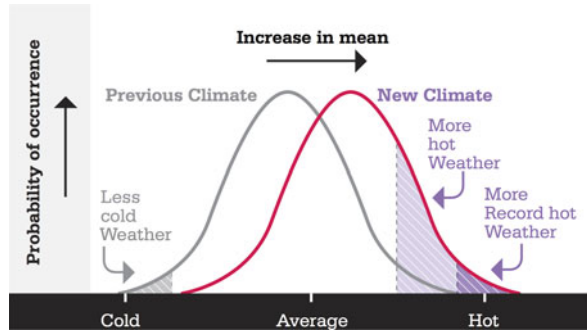
Table 2.6 Projected number of days over 35 °C in Australian capital cities

	2008	2030	2070	2100
Melbourne	9	12	21	27
Sydney	3.3	4.4	9	14
Brisbane	0.9	1.7	8	21
Adelaide	17	22	34	44
Perth	27	35	56	72
Canberra	5	8	21	32
Darwin	9	36	221	312
Hobart	1.4	1.7	2.5	3.4

Hughes and McMichael 2011

Where a warmer climate will have an impact on physical and mental health, the most vulnerable, according to Lesley Hughes, co-author of Australia's Climate Commission Report, are 'the elderly, those with existing heart and kidney disease, children, people in remote communities and… any outdoor workers' (ABC News 2011).

Or in other words, those who are not typically in an air-conditioned environment.

As a matter of health, or even life and death, there will be an increasing demand for air-conditioning. The heatwave in France in 2006 had lower mortality levels than the previous one in 2003. A meteorologist commented this was particularly due to one aspect of the government's *National Heat Wave Plan:*

> It is worth mentioning here, that air conditioning can allow people to continue to work effectively in hot weather and undoubtedly lessens heat stress, thus protecting susceptible sections of the population throughout a heat wave (Tan 2008).

Air-conditioning will remain both a cause and arbiter of the climate change problem for the immediate future. The logical step then is to see how air-conditioning can deliver cooling with minimal impact to the environment.

2.3 A New Paradigm of Thermal Comfort

> … the main antagonist of rooted culture is the ubiquitous air-conditioner.
>
> Wherever they occur, the fixed window and the air-conditioner are mutually indicative of domination by universal technique (Kenneth Frampton, in Foster 1983, p. 27).

If the only problem with air-conditioning was the mindless adoption of the international style, we would have little to fear in terms of its environmental consequences. There are a select few who would take issue with air-conditioning *per se,* like Prins (1992) who saw air-conditioning both as an evil in itself and as a tool for capitalistic domination. These are threads of research in and of themselves, and are not the focus of this thesis.

Rather, this work is concerned with the *energy intensity* of the over reliance on air-conditioning. Air-conditioning, as we will see, contributes to workplace productivity in a way that cannot be casually dismissed. It is the excessiveness of air-conditioning and the over-reliance on it that becomes problematic. More importantly, the crux of the matter is the intensiveness of energy demanded by air-conditioning in a world that is now struggling to resource it. If air-conditioning could be supplied affordably and sustainably, it would hardly attract contempt, with too few ills to outweigh its benefits.

Thermal comfort studies have long been established and underpin mandatory building construction, operation and maintenance standards. However, today the standards for temperature and humidity control need to be interrogated in the context of energy limitations. In returning to first principles we enquire if the understanding of *thermal comfort* is adequately covered with the use of a sensation scale. Particular attention is given to explain the difference between the deterministic and adaptive thermal comfort models. Does comfort in a naturally ventilated office with fans have the same quality as comfort in an air-conditioned one? How can these differences be reconciled without disregarding the validity of decades of rigorous studies? I will postulate an explanation from disciplines that have traditionally been outside architectural science. The experimental validation of this theory is however beyond the scope of this thesis.

Any proposed solutions will be evaluated in terms of their engineering efficiency, because the primary aim is to achieve the *efficiency and conservation* wedge for building operational energy savings. At the same time, the approach cannot be purely academic but needs to be tempered by market realities, because after all, the uptake of an innovation is predicated on there being an improvement to the standard of living.

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Chapter 3
Literature Review: Thermal Comfort and Air-Conditioning

3.1 Preamble

The cost of supplying energy to the office space has historically been insignificant compared to the cost of labour. A study on a typical American office (Holz et al. 1997) found the cost of salaries to be 100 times more than that of energy. In Singapore, the electrical consumption of offices accounts for 12 % of the overall non-manufacturing sector's usage, with an average annual energy efficiency of 231 kWh/m^2 (Lee 2001). In an ongoing study by the Energy Sustainability Unit in Singapore (esu.com.sg) the median office building uses 49 % of its energy on air-conditioning and a further 14 % on mechanical ventilation.

The common modern day office is predicated on an uninterrupted supply of affordable electrical energy. Ubiquitous deep-plan buildings with fixed windows and heat producing office equipment demand air-conditioning, artificial lighting and power. However, in a resource-constrained world where there is an increasing need to reduce our energy footprint, what levels of comfort could we forgo without sacrificing productivity?

It appears that thermal comfort is not a phenomenon that can be adequately defined in the science of temperatures, humidity, airflow, metabolism and clothing. It does not, for example, explain why in the tropics like Singapore, office workers do not adopt the climatically appropriate dress code. Winter clothes sometimes carry labels to indicate which conditions they are suited for. Most of the business clothes worn in tropical offices are hardly suited to prolonged wear within the 30–35 °C temperature range.

The need to go out for lunch in the hot afternoons, gives some respite to excessive air-conditioning in offices (see Figs. 3.1 and 3.2). During a poll in Singapore by the World Wide Fund For Nature (WWF 2011) it was found that 40 % of respondents found offices and schools too cold, stating:

> Almost half of them also compared the temperature in their office/school to "Autumn in Seoul", while one in four likened it to "Winter in Siberia".

Fig. 3.1 Office workers going for lunch in Singapore. Executives typically leave the air-conditioned offices for nearby eateries during the hour long lunch break. Image credit: Wolfgang Kaehler © 2008 (used with permission)

Fig. 3.2 Office clothing in typical eateries, known as hawker centres. Food and beverages served in naturally ventilated hawker centres typically cost half that of air-conditioned food courts. Image credit: anonymous sources on flickr.com under creative commons license

Whilst clearly tongue-in-cheek, the comparisons show a general dissatisfaction with indoor temperatures amongst the office workers, with a strong dissatisfaction from a significant minority. The situation of the excessively cold office is partly a result of routine over-sizing of air-conditioning plant equipment which will be discussed in detail later. The other contributor is the problem of overheated executives after walking under the blazing sun and dining in a warm and humid eatery, the whole time garbed in office clothing that is ill-suited for a tropical afternoon.

This phenomenon illustrates the complexity of the problem. The problem of overdependency on air-conditioning is intertwined with comfort, acclimatisation, marketing, social norms, workplace stress and personal preferences. Consequently, any resolution for the over-reliance on air-conditioning, and over-conditioning on top of that, needs to harmonise these disparate fields—a harmonisation that presents itself as a gap in our knowledge, and the most vital one in order to advance thermal comfort research.

A large amount of literature exists in the area of thermal comfort studies which can broadly divided into deterministic (Fanger 1970, 1986) and adaptive (Humphreys and Nicol 1998, 2000, 2004; de Dear and Leow 1990; de Dear et al. 1997; de Dear and Richard 1998). The problem with air-conditioning is however far more complex and a substantial part of this literature review will also cover the behavioural issues.

3.2 A Background to Thermal Comfort

The history of thermal comfort and thermoregulation has been exhaustively covered in a number of major texts like Nicol et al. (1995), McIntyre (1980) and Hensel (1981). A number of PhD theses also have extensive literature reviews on the topic from either a general overview (Andamon 2005), or specific interest, like the use of air-conditioning in Singapore (Kishnani 2002), comfort under non-uniform conditions (Zhang 2003) and personal ventilation (Yang 2009; Schiavon 2009). This present review is however more concerned with highlighting a number of salient threads in the research and finding a point of convergence.

Thermal comfort models relate the variables of environment and individuals to determine either how an occupant will feel under those circumstances or predict a preferred temperature. Whilst these models allow very precise predictions, the definition of comfort accommodates a far more subjective response.

> The Comfort Zone was first calculated in 1923 by research engineers F. C. Houghten and Constantin Yaglou at the Pittsburgh laboratory of the American Society of Heating and Ventilating Engineers (ASHVE). They created and used a new variable: effective temperature, which took both heat and humidity into account. It required measurements to be taken by two kinds of thermometers, dry-bulb and wet-bulb, and use of the psychrometric chart, developed by Willis Carrier in the teens, to calculate properly the indoor temperature and humidity. Comfort, they announced to their colleagues at a meeting in Chicago that May and in the chapter they published in September in the ASHVE Journal, was an effective indoor temperature between 61.8° [16.6 °C] and 68.8° [20.4 °C] with 64.5° [18.1 °C] the optimal temperature for most people. …The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) by 1966 was defining thermal comfort as "that state of mind which expresses satisfaction with the thermal environment." Compared to the carefully measured precision of the twenties' Comfort Zone calculation, it was an extraordinarily inexact and subjective definition. (Ackermann 2002, pp. 166–167)

Ackermann expands on this subjectiveness through architect Heschong (1979) who illustrates the range of subjectiveness as 14–21 °C in Britain, 21–27 °C in the United States and 23–30 °C in the tropics. The psychologist Rohles (in Ackermann 2002) observed that winter comfort recommendations have steadily risen from 18 °C (1923) to 20 °C (1941) to 25 °C (1960). Based on almost 40 years of research, Rohles (2007) made a few more observations like:

1. The *modal comfort envelope,* judged as comfortable by most subjects is 20–24 °C (inclusive)

2. The preferred temperature varied with age: 22 °C (for a mean age of 20 years), 23 °C (mean: 44 years) and 24 °C (mean: 75 years).
3. A group misinformed about the temperature being at 23 °C felt warmer at an actual temperature of 20 °C than groups with either the right information or no information.
4. A group in a climate chamber that had been welcomingly decorated felt 1.4 °C warmer at the same temperature than those in a bare meat locker.

These led Rohles to remark, 'Yes, comfort is a state of mind!' (Rohles 2007, p. 20).

Thread 1: Comfort temperature is defined not by a point but over a range.

3.3 Thermal Comfort Theories

Fanger's seminal work (Fanger 1970) underlies the standards used both by the International Organization for Standardisation (ISO 7730 2005) and the American Society for Heating, Refrigeration and Air-conditioning Engineers (ASHRAE 55 2010). His climate chamber experiments yielded the Predicted Mean Vote (PMV) formulation that has been widely adopted as the de facto standard for thermal comfort with air-conditioning. For typical office conditions (at RH: 50 %, v = 0.5 m/s, 1 met, 1 clo) the neutral temperature is 24.8 °C.

On the other hand, we have the adaptive model of defining thermal comfort (see Brager and de Dear 1998, for a primer) which can be attributed to Auliciems (1969) and extensive field studies by Humphreys and Nicol (Humphreys 1995; Humphreys and Nicol 2004; Nicol et al. 1995; Nicol and Pagliano 2007; Nicol and Humphreys 2009). They found that compound indices failed to predict accurately the comfort temperature for free-running buildings and a simple regression of outdoor temperatures was a far more reliable gauge. One of the earliest authoritative works comes from Humphreys (1975) who found strong statistical evidence to determine the neutral temperature from mean outdoor temperature:

$$T_{neutral} = 2.6 + 0.831 \times T_{daily\ mean\ outdoor} \qquad (3.1)$$

During a hot spell, the daily mean temperature in Singapore could average 30–32 °C and yield a resultant adaptive indoor comfort temperature of 27.5–29.2 °C. The difference between mean and comfort temperatures can be easily achieved by the cooling effect of indoor fans. For example, Szokolay (2000) proposes a function as a reasonable medium of eleven others as follows:

$$\Delta T = 6 \cdot v_e - 1.6 \cdot v_e^2 \qquad (3.2)$$

ΔT	Cooling effect of moving air
v	Wind velocity (0 – 2 m/s)
v_e	Effective velocity $v_e = v - 0.2$

So for the required cooling effect of about 2.5 °C, the wind velocity, required is only 5 m/s and easily achieved with a ceiling fan. Would the comfort delivered by a ceiling fan at 30 °C be equivalent to that from an air-conditioner at 24.8 °C? How could there be such a vast difference in comfort expectations between the two modes of cooling? An ASHRAE report (de Dear et al. 1997) sums up the debate concisely:

> The former [PMV model] permits only behavioural adjustments (personal/technological) to heat balance variables such as clothing or air velocity, whereas the original adaptive models were premised on changing physiological (i.e. acclimatization) and psychological (i.e. expectations/habituation) setpoints. While this may seem to be a fine distinction, failure to appreciate it has, in the opinion of the authors, been responsible for unnecessary controversy between the two sides of this debate.

The two camps have been irreconcilable and one of the problems has been the semantics of thermal comfort. The deterministic model comfort is predicated on the notion that comfort is the absence of discomfort. PMV is thus intended to discover the neutral zone in the thermal sensation scale, also referred to as the 7-point ASHRAE scale. Adaptive comfort is inclined to the body's acceptance of seasonal fluctuations and considers comfort levels with non-neutral thermal sensation to arrive at the optimum temperature on the Bedford scale, allowing an occupant to indicate one can be warm/cool and still comfortable. The debate has polarized thermal comfort studies into the following distinct identities:

> The proponents of laboratory-based comfort studies are concerned with presenting thermal comfort as an exact science. They consider that field studies are too vague a basis for any serious analysis, based as they are on statistical distributions which are often of high variance, depending on seemingly ill-defined physical or subjective measurements. The proponents of field studies, however point to the fact that the real world is a complex place physically, socially and culturally. They feel that laboratory studies deliberately miss out this complexity in their search for clean and reproducible results. (Nicol 1995, p. 22)

"Acceptability" also presents a different definition in both models. The general rule is that it refers to "combinations of indoor space environment and personal factors that will produce thermal environmental conditions acceptable to 80 % or more of the occupants within a space" (ASHRAE 55 1992). Acceptability varies depending on the nature of data collection. In the PMV standard, PMV = ±0.5 is acceptable even though that corresponds to PPD = 10 %. This allows for an additional average 10 % that may arise from local discomfort. In order to have a condition where 80 % of actual occupants are satisfied, the target conditions should meet the 90 % acceptability criteria of the lab-based model. In the ACS, "as a field-based method, the 80 % line of the ACS most accurately corresponded with 80 % acceptability in the field" (Brager 2001), though it is acknowledged that majority of the original dataset in the RP-884 database lacked direct measurements and researchers had to 'infer "acceptability" from the thermal sensation votes' (de Dear and Brager 2002, p. 553).

To summarise, the key differentiation between the two standards are shown in Table 3.1.

Table 3.1 Contrast in thermal comfort approaches, developed from Law and Fay (2009)

	Deterministic (PMV) comfort standard	Adaptive comfort standard (ACS)
Experiment context	Climate chambers	Field studies
Occupant feedback scale	Thermal sensation scale	Bedford scale
Premise and application	Air-conditioned buildings	Naturally ventilated buildings
Professional inclination	Equipment-oriented (Engineer)	Building-oriented (Architect)
Derivation	Combined index: air temperature, mean radiant temperature, relative humidity, wind velocity, clothing insulation and metabolic rate	Single indicator: mean outdoor air temperature
Scientific inclination	Physics of heat balance	Bio-physical correlation to natural patterns
Scope	Universal	Personal

Thread 2: The axis of debate between deterministic and adaptive comfort may lie in semantics.

In the course of reviewing the literature of both arguments the gap was quickly apparent: there were very few studies that attempted to bridge the arguments and research methods between the two. For the architect, this debate lies at the core of how we design: should it be a matter of freedom of form and plan with the confidence that the appropriate equipment can solve any comfort requirement, or should the building design resolve the climatic considerations, with low energy equipment like ceiling fans merely augmenting the comfort demands on particularly hot days.

One criticism of PMV is whether laboratory studies can be representative of real- world scenarios. Table 3.2 (Alfano and D'Ambrosio 1991) lists some of the parameters controlled in laboratory conditions that do not apply in real world.

Emmanuel (2005) has a further list of factors contributing to thermal comfort that are not captured in the PMV account:

- perceptible sweating
- vapour permeability of clothing, and not just insulation value
- natural ventilation
- "preferred" comfort, as opposed to PMV's "acceptable" comfort
- opportunities for adaptive behaviour
- seasonal acclimatisation effect
- expectancy factor

Despite its known shortcomings, these factors have not been substantial enough to detract from the popularity of PMV, which has been widely validated and found

Table 3.2 Comparison of Fanger's laboratory experiments and how the different parameters are not possible in the real world (Alfano and D'Ambrosio 1991)

Parameter	Fanger's lab experiment	Real world
Activity and garments	Identical	30 % statistical distribution of clo and met
Subjects	Paid, more tolerant to thermal environment	Adaptation to work and personal problems accentuate any discomfort felt
Physical condition	Only healthy subjects who are well-rested and fed (normal meal 1 h prior to experiment)	Varying states of physical distress, sleepiness and hunger lead to greater intolerance to environment
Scoring	Subjects kept for 3 h and score every 30 min	Steady state conditions not always achieved due to changes in activity, and movement in and out of conditioned spaces

to be an accurate index in Hong Kong (Tse et al. 2005), unaffected by basal metabolic rate or health status (Tse et al. 2005), valid for air-conditioning with medium to high humidity (Charles 2003), valid for high velocity distribution systems comparable to natural ventilation (Baskin and Vineyard 2003), and a useful model to reduce operating costs (Simmonds 1993; Calvino et al. 2004).

> Thread 3: The PMV model's strength is in predictive simulation, and when corrected for real-world applications, can be representative of the group. Its weakness is that it is assumes homogeneous conditions and behaviour.

Q   Why can't thermal comfort researchers come to a consensus on which model to use?

A   Each study is performed under particular conditions and they typically hold valid for those conditions. Fanger's research, which underpins the air-conditioning standards in the U.S. (ASHRAE 55 2010) and internationally ISO 7730 (2005), was based on observations from volunteer students in climate chambers responding to a thermal sensation questionnaire. Adaptive thermal comfort is based on actual field studies of a larger scale taken by office workers performing regular work all over the world (ASHRAE RP884, de Dear et al. 1997) or in Europe (EN15251) mainly in naturally ventilated buildings using either the ASHRAE thermal sensation scale or Bedford scale. In 2001, the adaptive comfort scale (ACS) was accepted in the ASHRAE 55 standard as an alternative standard for naturally ventilated buildings.

Q   Why is the ACS not more widely adopted?

A   Central to the ACS is adaptation: biological (acclimatisation) and mental (expectations for comfort). In developing cities, where outdoor air quality is generally poor, natural ventilation required for adaptive comfort is not viable. The other challenge in ACS is that of behavioural change. Many solutions to the climate problem exist that require behavioural change, the cheapest and yet also the most difficult to implement.

Q   How difficult is behavioural change?
A   Take for example lifestock farming being the greatest single contributor of
     anthropogenic greenhouse gases. The Food and Agriculture Organization of
     the United Nations (2006) estimates it generates 18 % of the planet's
     greenhouse gases. The combined total of all transport (cars, trains, planes and
     boats) accounts for 13 %. Theoretically, a global switch to a vegetarian diet
     can eliminate this problem and have the world produce more food than we can
     currently consume. However, even with prominent environmentalists like
     Lord Nicholas Stern and Nobel laureate Al Gore, the switch to a purely
     vegetarian diet has been recognised to be too much of a personal challenge.
     Further examples can be taken from the switch from driving to cycling,
     carbon-based energy to renewables, purchasing international produce to
     purchasing local produce, etc. The benefits of each switch are clear but the
     change in lifestyle is too onerous, and in many cases perceived as a regressive
     step. Similarly, until the mindset of society at large can be changed in both
     developed and emerging economies, the dominant view will persist that a high
     standard of living is marked by air-conditioning, a car, and a high protein diet.

> Thread 4: The adaptive model's strength is that within a temperature range, occupants can
> be expected to find their own preferred temperature. Its weakness is that substantial effort
> is required to design with it and to change attitudes towards behavioural adaptation.

3.4 A Critical Review of the Thermal Comfort Debate

A needful way to resolve this divide would be to compare thermal comfort against
thermal sensation conducted by field studies in air-conditioned offices: thus using
the tools of adaptive comfort to verify the occupant preference in a centrally
controlled environment.

Such a study was undertaken by Schiller who found that despite the universality
alluded to by PMV, office workers in air-conditioned offices had an optimum
temperature of 22.5 °C, significantly lower than PMV would have predicted at
24.8 °C (Schiller 1990). The need to distinguish between Schiller's optimum
temperature and Fanger's neutral temperature was because her surveys allowed
occupants to provide feedback not just on the neutral temperature (7-point
ASHRAE scale), but also on the level of comfort experienced (6-point general
comfort scale). The inclusion of a comfort scale not only adds another dimension
to the study, it distinguishes thermal sensation from satisfaction, a view that is
shared by Baker (1996). Since field studies have been conventionally accepted as
more representative of real-world climate control needs, Schiller's observation
could be further explained by the increased need for cooling caused by real-world
stress, as opposed to the climate chamber experiments where occupants were given
tasks that merely simulated work. I postulate that this is the same explanation for
the discrepancy found in a study of office occupants in Sydney (Rowe 2001) where

actual mean comfort vote was 0.30 higher than predicted, i.e. occupants would have voted as PMV predicted had operative temperature been 1.14 °C cooler. A classroom study in the tropics also showed a preference for cool sensations (Wong and Khoo 2003). Field studies in offices and shops undertaken by Kähkönen (1991, p. 446) found 'calculated PMV values were usually lower than PMV (self) estimations'. In this study, the actual mean vote for offices was 0.9 ± 0.5 higher than PMV. It can be deduced that occupants are most comfortable when they are slightly cool, not when they are neutral.

> Thread 5: Adaptation from simulated work to real work requires more cooling than predicted by PMV.

If the ideal temperature is likely to be cooler than neutral, seeing that field studies reveal a greater demand for cooling than climate chamber studies, one can argue that thermal comfort cannot be defined solely in terms of physical activity, but that mental work imposes cooling requirements which the rest of the body would not necessitate.

This would be particularly true for office workers, where the rigours of mental concentration can account for a preference for cooler environments. This mental load has not been accounted for in comfort studies, where metabolic load has been related to physical and not mental activity. The mental metabolic load could also explain why natural ventilation has never been attractive to offices in developed cities in hot and humid climates: the adaptation to warm (30–32 °C) and humid conditions (RH = 60–80 %) could come with a penalty in mental performance. Being comfortable in these conditions is not synonymous with being the most productive.

PMV is predicated on the definition of comfort being the absence of discomfort, and that the neutral temperature is the most comfortable because discomfort is most absent. Schiller's work indicates that this neutral point is not the same as the ideal, preferred or optimum temperature and that occupants know the difference between *comfortable* and being *very comfortable,* which is fundamentally different from the meaningless converse of discomfort being more or less absent.

3.5 The Missing Met

When describing how PMV could be extended to NV buildings in warm climates, Fanger notes:

> In many field studies in offices, the metabolic rate is estimated on the basis of a questionnaire identifying the percentage of time the person was sedentary, standing, or walking. This mechanistic approach does not acknowledge the fact that people, when feeling warm, unconsciously tend to slow down their activity. They adapt to the warm environment by decreasing their metabolic rate. The lower pace in warm environments should be acknowledged by inserting a reduced metabolic rate when calculating the PMV. (Fanger and Toftum 2002, p. 534)

Table 3.3 The missing met

Parameter	Input	Input	Input
Clothing (clo)	0.70	0.70	0.70
Air speed (m/s)	0.05	0.05	0.05
Relative humidity (%)	50.0	50.0	50.0
Effective temp. (°C)	24.8	22.4	22.4
Activity (met)	1.0	1.0	1.33
PMV	0.020	−0.780	0.019

Based on Schiller (1990), the field regression corresponding to the lowest dissatisfaction rate
would be 22.4 °C. The lowest dissatisfaction rate predicted by the PMV-PPD model would have
been at 24.8 °C. So for the field participants to be desiring the cooler ambient temperature, they
would have been expanding the equivalent of 0.33 met more energy than the laboratory-based
ones

There can be a large variation in metabolic rates (met) in different climates, even
when the physical exertion is similar. Fanger observer that what researchers might
rate as a "typical office task" of 1.2 met is in fact a "siesta" of 0.9 met in certain parts
of the world (Fanger in van Hoof 2008). de Dear and Brager dispute this "siesta
factor", pointing that this would amount to having occupants in cooler climates
expending 1.6 met against the 1.05 met of their tropical conterparts (de Dear and
Brager 2002). In field studies of air-conditioned offices, Brager (previously as
Schiller 1990) determined an optimum temperature of 22.4 °C instead of 24.8 °C
predicted under PMV. This difference equates to an additional 0.33 met (see
Table 3.3 for my derivation) from field trial participants over the predicted model
based on simulated work.

Is it possible that this difference could be accounted for by a different degree of
metabolism? Given that the typical office conditions are sedentary, this cannot be
accounted for by a difference in met rates which measure physical activity.
However, there is a higher mental demand in real work as opposed to simulated
tasks in climate chambers. These controlled experiments simply do not reflect the
stimulation, stress and complexity required in real life employment.

Could this be the missing met?

Thread 6: Real (productive) work could require a higher met than simulated work.

3.6 Mental Effort

This hypothetical mental effort for a task can be seen as a combination of several
factors, and can be illustrated conceptually as such:

$$Mental\ Effort\ =\ |MM - Q_c| \times \frac{f_s}{f_m} \tag{3.3}$$

MM	Mental metabolism
Q_c	Cooling power
f_s	Sleepiness factor
f_m	Motivation factor

The notion of taking the absolute value $|(MM-Q_c)|$ assumes that the degree of cooling should be just sufficient to balance the heat given from an exerted brain but without overcompensating. Above and below an ideal temperature (around 20 °C in the RP884 comparison, see Fig. 3.3), extra effort would be required to overcome discomfort in performing rigorous mental tasks. Sleepiness and motivation factors are self-evaluated, and can be based on the Karolinska Sleepiness Scale or Likert scale (Ali et al. 2011) respectively. Each scale has to be experimentally weighted, which will be beyond the scope of this thesis.

When different tasks were attempted under varying conditions, (Zhang et al. 2010) determined that for Sudoku (logical thinking), performance was better in warm conditions whereas Math (mental performance) and general performance was better in cool conditions. Many other tests have been done (see Table 3.4 and Figs. 3.4 and 3.5) and a range of results have emerged. A few trends can be deduced:

1. one ideal temperature does not exist for all the work conditions
2. many ideal temperatures are below the neutral temperature
3. there seems to be gender bias in the ideal temperature

Thread 7: Workplace productivity is affected by temperature.

How should one to integrate all this information? Theoretically it may be possible to use these studies to predict the preferred temperature, specific to the job
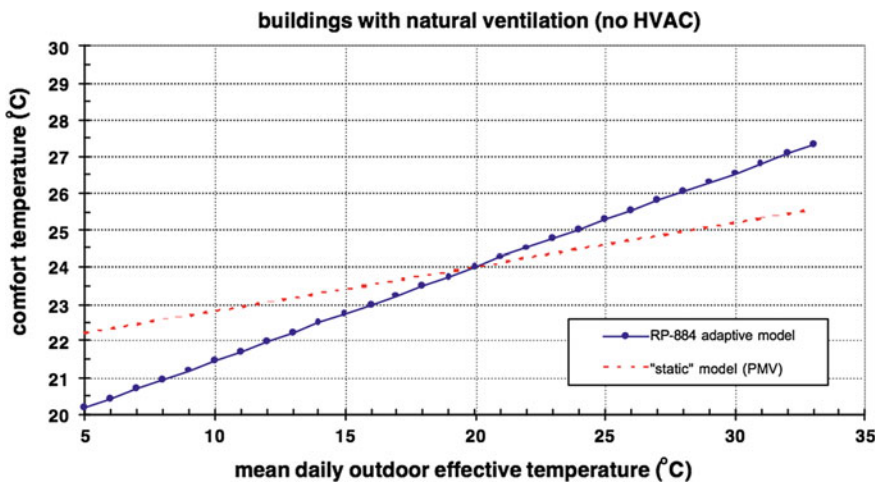
Fig. 3.3 Comparison of adaptive model and PMV model predictions on observed neutralities applied to naturally ventilated buildings (de Dear et al. 1997)

Table 3.4 The effect of thermal environments on productivity compiled from Fisk (1999), Kosonen and Tan (2004) and Seppänen et al. (2005). These researchers have observed task and gender bias in preferred temperature

Reference	Nature of work	T tested (°C)	Outcome	Preferred T (°C)
Wyon (1974)	Manual and mental	20, 24	18–49 % more typing, mental work not affected	20
Meese (1982)	Simulated factory work	18, 24	Faster performance	24
Wyon (1993)	Driving response time	21, 27	18 % faster response	27
Pepler (1968)	Academic memory	20–33.3	20 % lower error rates (but 5–10 % longer time)	26.7
Wyon (1976)	Reading	20, 27, 30	Better speed and comprehension	27
Wyon (1979)	Reading	23, 26, 29	20 % faster	23, 29
	Multiplication, male		20 % faster	>28 or <27
	Memory, male		20 % better	26
	Memory, female		Better	26, up to 29
Wyon (1996)	Thinking	20–30	Up to 42 % faster then at T > 27 °C	21
	Typing	20–30	Up to 42 % faster than T > 25 °C	21
Seppänen et al. (2005)		21–25	No loss in productivity	21–25
		25–33	Productivity ↓ 2 % for every +1 °C	25
Nimela (2001)	Call centre		Productivity ↓ 1.8 % for every +1 °C	<25
Nimela (2002)	Call centre		Productivity ↓ 2.2 % for every +1 °C	<25
Federspiel (2002)	Call centre	24.8, 26	Productivity ↑ 18 %	24.8
Link (1970)	Apparel factory	23.9, 32.2	Productivity ↑ 9 %	23.9
Johansson (1975)	Learning and arithmetics	24, 27, 30	11–16 % better	24
	Cue-utlisation and attention	24, 27, 30	u-shaped	27
Pepler (1968)		17–33	Lowest error rate	26.7
Meese (1984)	Manual dexterity	18, 24	5–18 % better	24

profile. So a job composition of 50 % typing (21 °C), 25 % memory (26 °C) and 25 % calling (24.8 °C) should give a T (job preferred) = 0.5 × 21 + 0.25 × 26 + 0.25 × 24.8 = 23.2 °C. However, 23.2 °C is the mean temperature weighted by job duration, and is not the right temperature for any single one of the tasks.

The problem is further complicated with the understanding of productivity.
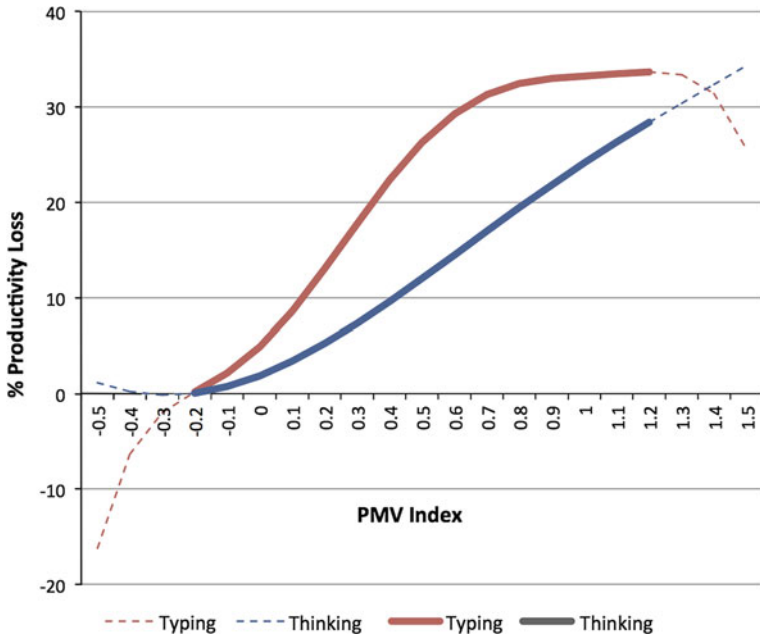
Fig. 3.4 Loss in productivity as a function of PMV and temperature, redrawn from formula proposed by Kosonen and Tan (2004) and Seppänen et al. (2005)
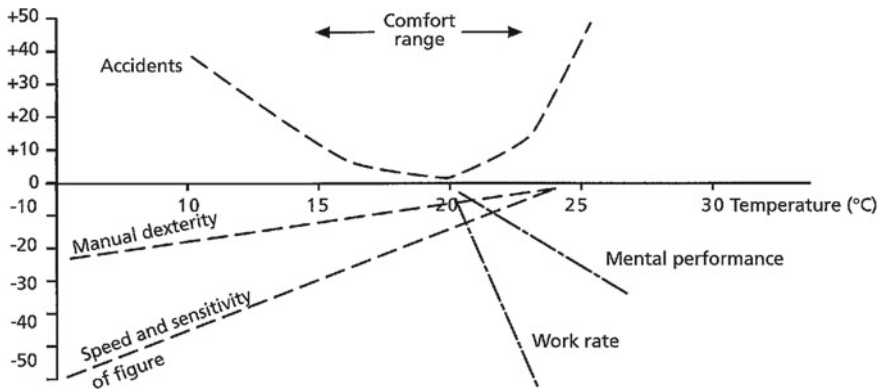
Fig. 3.5 The relationship between temperature and performance (Wyon 1986 in CIBSE 1999)

3.7 Studies on Comfort and Productivity

During the years of the great depression, air-conditioning became a symbol of an employer's commitment to workplace productivity.

By launching a massive expansion of air-conditioning throughout official Washington's vast marble halls, the Roosevelt administration—at least on the official level—shifted the rationale for air-conditioning from comfort, or even health, to efficiency and productivity. The federal government justified air-conditioning with arguments more closely aligned with the technology's early use in factories and manufacturing processes than with the appeals to middle-class comfort advanced by movies, department stores, hotels, and trains. If government buildings were the factories of democracy where bureaucrats worked long days and hours to rescue America from the Depression, then air-conditioning was not a palatial comfort but a stimulus to greater achievement. (Ackermann 2002, p. 72)

Humphreys and Nicol, earlier noted for their work in adaptive theory, undertook a field study to determine how comfort affected productivity (Humphreys and Nicol 2007). Unlike Hancock's approach to quantifying performance against thermal stress under controlled conditions, they used field surveys to compare perceived comfort against self-assessed productivity, establishing a strong correlation between the two and a weak one between perceived and predicted comfort (PMV and Standard Effective Temperature). They noted that 'perceived productivity fell slightly at temperatures above 25 °C or below 21 °C', a range in agreement with Schiller's observation that 'office workers' sensitivity to changes in temperature was relatively flat, or at least broadly curved, over 3 °C range near the optimum [of 22.5 °C]' (Schiller 1990). Similar studies have not been performed in the tropics and one wonders if these productive temperature ranges are not equally applicable to hot-humid regions.

In their field-studies in Pakistan, Humphreys and Nichol found that office workers in the tropics could tolerate much higher temperatures than those stipulated in ASHRAE standards (Humphreys and Nichol 1995). However, the comparison of interest would be to those workers who have worked in air-conditioned offices.

This would give a benchmark reference to ascertain if performance had been diminished by heat adaptation.

People intuitively know that the temperature of one's head has a correlation on one's ability to process information. It is common to use terms such as being *hotheaded* meaning 'having an impetuous or quick-tempered nature' or being *coolheaded* referring to one who is 'not easily worried or excited' (definitions from *New Oxford American Dictionary, 3rd ed.*). We will revisit this in greater depth to show how the brain accounts for a significant concentration of heat. On that premise, one can postulate that part of the thermoregulatory response would be to reduce the firing rates of neurons to prevent overheating. If an experiment similar to the aforementioned Humphreys and Nichol was conducted in Singapore today, the results might be very different from Pakistan.

…Carrier Corporation executive Logan Lewis had fretted over the "luxury" label that he himself tended to associate with his industry's products. In a continuing project of personal and corporate justification, Lewis labored until his death in 1965 to link the idea of indoor comfort to the more politically and morally persuasive claims of health and efficiency, and to answer the critics of environmental uniformity. "No, our ultimate objective is not comfort," Lewis declared characteristically at a 1943 industry panel discussion. "It

is to give man or woman a fair chance to apply the fundamental of creating wealth by producing up to the limit of his latent capacity." (Ackermann 2002, p. 144)

How can productivity be measured? A CIBSE report (1999) illustrates how complex this effort is. In early industrial fieldwork, productivity can be characterised by repetitive tasks in factories. In laboratory studies, participant are placed in unnatural environments, and given simple performance tasks. When productivity is studied by psychologists, the interest is cross-sectional, lacking intervention and control groups. In field surveys, with high variability in tasks, selfratings are the only viable means of capturing productivity, though it introduces subjectiveness.

Almost akin to the thermal comfort debate, there are also two schools of thought in productivity measurements: objective and subjective. The Federation of European Heating and Air-Conditioning Associations (REHVA), in their guide-book on *Indoor Climate and Productivity in Offices,* dismiss subjective measure-ments, stating:

> Although the literature shows that the temperature, indoor air quality and ventilation, noise and light, and the possibility to control them individually does affect human performance, only for the temperature and indoor air quality and ventilation was it possible in the present work to develop the quantitative relationships describing their effects on office work or sick leave. These quantitative relationships create the core of the present Guidebook. The literature provides much data by which qualitative relationships can also be established, but the Authors of the present Guidebook decided not to use them due to a very high level of uncertainty. The same applies to the data indicating that the indoor environmental quality affects office work as assessed by employees, so called self-esti-mated performance. (Wargocki et al. 2006, pp. vii–viii)

The review of literature on productivity could be an entirely separate research enterprise which this thesis will not address at length. A good starting point would be the reviews by Haynes (2007, 2008a, b). The following examples illustrate how difficult this endeavour is:

1. The *Hawthorne effect* which suggests that there is a temporary bias in the productivity and satisfaction of workers by their awareness of being studied. It is somewhat similar to the effect of just knowing one is being part of a medical trial, such that even when a patient is prescribed a glucose pill he feels posi-tively better. This placebo effect is well documented and hence the need to have a double-blind (both doctor and patient being uninformed) and placebo con-trolled experiment. Productivity studies, particularly those before and after a major retrofit, are simply too costly and complex to undertake with similar blind-control and Hawthorne-control groups. Thus, even though there appears little evidence for the original Hawthorne effect (Jones 1992), it has had a persistent legacy and is often addressed by way of opinion rather than accounted for with evidence (for example Romm and Browing 1994; Singh et al. 2010).
2. Seppänen et al. (2006) conducted field surveys on call centre customer service to suggest the highest productivity at 21–22 °C. The methodology has been

criticised by de Dear (2010) as being based on the quantity of transactions, which bears no relation to the quality of work.

3. Humphreys and Nicol (2007) undertook a large scale self-evaluated survey on five European countries, asserting that very few aspects of office work can be quantified. However, the difficulty in self-evaluation was evident from between-country differences with language and social background, 'most noticeably the Greek respondents had a more positive assessment of their productivity than did those of the other countries' (p. 609).

4. Absenteeism is one of the common quantitative measures of productivity. However, time spent away from work may not necessarily be unproductive. Google encourages creative staff to spend a day a week, on a weekly basis, on personal projects unrelated to their regular work (Postaer 2012).

Thread 8: Because productivity still cannot be reliably indexed, its relationship to temperature is still tentative.

Even the state-of-the-art in productivity measurements will be subject to numerous confounding factors. In the light of these challenges, I am suggesting that it may actually be easier to have a demanding task, suited to the experiment candidates' competence, with a large incentive. The aim here is not to measure productivity but to create the conditions so as to assume that it is one's personal highest, then measure what environmental interventions can best support the task. Revisiting the conceptual formula for mental effort (Eq. 3.3), it would be to maximise the *motivation factor,* minimise the *sleepiness factor,* and determine the temperature that minimises *mental effort.*

This is attempted in the experiment in Chap. 10.

3.8 The Case for 'Mental Metabolism'

One can be comfortable on a hot afternoon if one is relaxing on the beach in a hammock. Whilst the met rate for office occupants has often been presumed to be sedentary (1–1.2 met), their optimum temperatures are in no way comparable to the beach loafer even when differences in clo are accounted for. Met rates reflect the physical activity of a person and are based on muscle metabolism. The mental demands on the other hand are not properly accounted for in this metric. In the context of thermal comfort, most research is performed for and intended to apply in the fast-pace and productive office, not in an idyllic resort. Can an active and stimulated brain account for a difference of 0.3 met? This notion seems worth pursuing.

It is clear that even when the environmental variables are identical (T-air, MRT, RH, wind v), and the personal variables are similar (clo and met), the comfort requirements are highly dissimilar due to the mental demands of the task.

The brain represents an incredible concentration of heat, accounting for 20 % of the total energy measured at basal metabolic rate (BMR) concentrated in 2 % of

the total mass (Elia 1992, Table 3.5). BMR is based on a rested state after a 12 h fast, and under these conditions clinical physiologists (Kinney 1992) consider total energy expenditure (TEE) as:

$$TEE \ = \ BMR \ + \ TEF \ + \ ACT \tag{3.4}$$

where the thermic effect of food (TEF) and physical activity (ACT) each contribute to energy expenditure beyond the BMR.

For a male based on Table 3.5, the energy metabolised by the brain is 16 W. Amongst the many chemical processes in the brain, neurons in particular have been studied thermodynamically (Karbowski 2009) to ascertain that, on average, the heat generated was about 7 W. To deal with the heat from the brain, several processes are involved in cooling it:

1. The nose performs a vital humidifying function to increase the RH of air to assist proper lung operation (Proetz, in Burroughs and Hansen 2004)
2. The evaporation of water at the mucosal surfaces of the nasal turbinates makes the venous blood cooler (Irmak 2004)
3. The connections of the diploic veins with intracranial and extracranial venous channels allow the cooled blood spread from the scalp, through the skull to the meninges and the brain (Irmak 2004)
4. Heat is transferred to the blood for the deeper brain regions via conduction; and convection to the environment for regions near the scalp (Karbowski 2009)

The need for cooling computer hardware seems to parallel that of our brains, though less elegantly so. Computation requires electrical power with heat emitted as an invariable by-product. This heat has to be removed, typically by a fan-forced heat sink, or a water circuit. Overclocking CPUs (i.e. running them at higher clock

Table 3.5 Contribution of different organs and tissues to body weight and basal metabolic rate in the reference *M* male, *F* female and *C* a 6 month old child (Elia, in Kinney (1992), p. 63)

	Tissue weight			Tissue weight (% of body)			Organ Met	Met rate (% total)		
	M	F	C	M	F	C	kcal/kg/ day	M	F	C
Liver	1.8	1.4	0.3	2.6	2.4	3.5	200	21.0	21.0	14.0
Brain	1.4	1.2	0.7	2.0	2.1	9.5	240	20.0	21.0	44.0
Heart	0.3	0.2	0.0	0.5	0.4	0.5	440	9.0	8.0	4.0
Kidneys	0.3	0.3	0.1	0.4	0.5	0.7	440	8.0	9.0	6.0
Muscle	28.0	17.0	1.9	40.0	29.3	25.0	13	22.0	16.0	6.0
Adip. tissue	15.0	19.0	1.5	21.4	32.8	20.0	5	4.0	6.0	2.0
Misc.	23.2	18.9	3.1	33.1	32.6	40.7	12	16.0	19.0	24.0
Total	70.0	58.0	7.5	100.0	100.0	100.0		100.0	100.0	100.0
								1,680 kcal/ day	1,340 kcal/ day	390 kcal/ day

cycles than manufacture specified) is primarily limited to the availability of cooling. Chips cooled to within their specifications also last much longer.

On the effect of high core temperatures on neurodegenerative diseases, Salerian and Saleri (2007) theorise:

> The Arrhenius rate law (ARL) mandates that all chemical reactions go faster with higher temperatures and that the relationship between temperature and the speed of the action is exponential. Consistent with the ARL, the preponderance of empirical evidence points to temperature attenuation as a powerful weapon by itself or as an adjunct to others in fighting a large class of ailments, including diseases such as Alzheimer's disease. …because of the laws of thermodynamics expressed through the ARL, previously hypothesised and stated as Salerian-Saleri Thesis of Temperature that cooler biologically compatible core body temperatures may combat neurodegenerative disorders and prolong longevity in humans.

The heat-rejection requirements from mental exertion might well justify the need for additional cooling for the head beyond what the rest of the body needs. This is self-evident in the way we dress: a business suit for the body (1–1.2 clo) and an uncovered head (0 clo).

Although the head needs to be kept cool for longevity, does it necessarily mean that high temperatures will limit the brain's performance?

Coller and Maddock's study on peripheral vasonconstriction (Coller and Maddock 1934) also offers some useful support for consideration. They found that the temperature of the skin on the arms and legs accounted for the largest response to environmental and metabolic stimulus and so "a major shift of blood to the extremities is therefore to an area sufficiently large to care for wide normal variations." We thus surmise that a thermoregulatory response to heat is for the diversion of blood from the rest of the body, including the brain, to the extremities by dilating the peripheral vessels there, suggesting that heat adaptation could come with a downside to mental performance.

Studies on brain sizes give an indication of physiological consequences of climatic stressors: Eskimos have an average cranal volume over 1,450 cm^3 against that of under 1,300 cm^3 for Australian aborigines, though these volumes have no significant relation to mental functioning between populations (Irmak 2004). However, since a slightly overheated brain can bring on convulsions, fainting, and brain damage (Irmak 2004), it is possible that adaptation to warmer climates may be accompanied with depressed mental activity.

> Thread 9: The active brain needs to be kept cool to perform well.

We take up this thought in greater detail in the next chapter.

3.9   The 'Perfect' Temperature, a Matter of Personal Taste

A parallel might be drawn to the provision of our nutritional needs. Food is as basic to our survival as is our thermal environment. Just as thermal needs have been studied, so scientists have also studied the basic nutritional requirements of human beings. Our level

of understanding makes it theoretically possible to provide for all of our nutritional needs with a few pills and injections. However, while eating is a basic physiological necessity, no one would overlook the fact that it also plays a profound role in the cultural life of a people. …The thermal environment also has the potential for such sensuality, cultural roles, and symbolism that need not, indeed should not, be designed out of existence in the name of a thermally neutral world. (Heschong 1979)

Malcolm Gladwell (2004) recounted how soft drink giant Pepsi called on psychophysicist Howard Muskowitz to help the company improve its product by finding the perfect level of artificial sweetener for the diet Pepsi flavour. After some experimentation Muskowitz told them that they had been asking the wrong question. "There was no such thing as the perfect Diet Pepsi. They should have been looking for the perfect Diet Pepsis," Muskowitz said. Whilst Pepsi did not adopt his idea, Campbell did and subsequently produced the range of spaghetti sauces now enjoyed under the Prego label. According to Gladwell, Muskowitz 'democratised taste'.

If the amount of cooling was dependent on the mental metabolism accompanying a mental challenge, the solution might not be one of determining a right general temperature, since each task demands the right temperature for the specific job. In the area of thermal comfort it has been long recognised that there is no universally perfect temperature. The PMV model recognises at least 5 % PPD even under thermal neutrality in climate chambers. Field studies in air-conditioned buildings found a minimum dissatisfaction rate of 12 % (Schiller 1990) and van Hoof (2008) cites a few other studies with PPD as high as 47.5 % at PMV = 0. Not only does the perfect temperature vary across individuals, each individual seems to have a different perfect temperature throughout the day that fluctuates with the biological circadian rhythm (Attia et al. 1980; Fanger 1974a, b; Lan et al. 2009; Cook 2000) and task. To improve thermal comfort from a universal set-point, it seems futile to continue researching what temperature the thermostat should be set at. Instead there needs to be greater scope given to individual feedback and control.

There is also a fundamental limitation with determining the PPD of a temperature. Being one-dimensional it shows only the ratio between number of satisfied occupants versus dissatisfied ones. What is lacking is the degree of satisfaction and dissatisfaction for a given T. In the Pepsi experiments, had the method been simply to determine the highest percentage satisfied with a sweetness, one need only pick the sweetness that corresponded to the highest proportion within the population sample. Muskowitz however recognised that there were degrees of satisfaction and had the tasting panel rate on a 100-pt scale how much they liked it. Through this, he discovered that for foods like spaghetti sauce and coffee,

If I make one group happier, I piss off another group. …if you create only one product the best you can get across all the segments is a 60—if you're lucky. But if I do the sensory segmentation, I can get 70, 71, 72. Is that big? Ahhh. It's a very big difference. In coffee, a 71 is something you'll die for. (Muskowitz in Gladwell 2004, p. 131)

Looking at comfort as a matter of taste, it is clear that to vote on a single scale of, for example, 'tasteless' to 'tasty', cannot adequately capture the spectrum of flavours. Even when comfort is reduced to thermal comfort and the study of temperatures, voting on an ASHRAE scale of thermal sensation from very cold to very hot cannot represent the richness of thermal transience, thermal desire, thermal delight, thermal suitability and thermal stimulation. At its very least, an added dimension needs to be considered for comfort, because being thermally neutral does not invariably correspond to being very comfortable.

> Thread 10: The 'perfect' temperature is not so much determined by the sensation of warmth or coolness, but whether one is 'very comfortable' with it.

Adopting this approach there is an open-mindedness to the possibility that the temperature that rates as 'very comfortable' may not necessarily correspond with feeling thermally neutral. If comfort were simply the absence of discomfort than one could justifiable pursue the determination of thermal neutrality. However, if the intention is to discover the thermal conditions with which the occupant expresses satisfaction (a definition adopted by ASHRAE 55 2010) then we need to look beyond the sensory scale.

In this regard, the Bedford scale gives a finer resolution inside the comfort zone than the ASHRAE scale. With the choice of "comfortably cool", "comfortable and neither cool not warm" and "comfortably warm" it expands on the range of feedback an occupant can provide. For example after returning from lunch at a hot and humid eatery into a cold office, what would rate as a vote of "−2" on the ASHRAE sensation scale, might have been meant by the occupant to mean 'cold in a way I enjoy' but interpreted as a 'dissatisfied level of cold'. On the Bedford scale, the occupant can feedback 'comfortably cool' with no confusion.

The mean thermal vote (MTV) scale [(Nilsson 1997; Wyon 1989) in Nilsson 2004] is conceptually similar to the Bedford scale, though the wordings are slightly different, as seen in Table 3.6.

Table 3.6 Thermal sensation scales

Numeric value	MTV	Bedford	ASHRAE/PMV*
+3	Much too hot	Much too warm	Hot
+2	Too hot	Too warm	Warm
+1	Hot but comfortable	Comfortably warm	Slightly warm
0	Neutral	Comfortable (Fishman 1982; Auliciems 1981), or comfortable and neither cool not warm (McIntyre 1976)	Neutral
−1	Cold but comfortable	Comfortably cool	Slightly cool
−2	Too cold	Too cool	Cool
−3	Much too cold	Much too cool	Cold

*For the purposes of this International Standard, thermally dissatisfied people are those who will vote *hot, warm, cool* or *cold* on the 7-point thermal sensation scale IS0 7730 (2005, p. 4)

Between the scales, there is agreement between the wordings of MTV and Bedford with the interpretation of ASHRAE/PMV, on the premise that the scales from ± 2 to ± 3 represent dissatisfaction.

3.10   The Importance of Being "Very Comfortable"

> A glance at the contents of this Volume (Bligh and Voigt 1990) shows that terms like 'sensory', 'thermosensitive', and others are unavoidable. These are basic terms which are not defined explicitly. Everyone seems to understand them without definition. They somehow mark the entire field of research covered by this Volume; they seem to form a kind of keystone for the entire theory. After all, when once the field of perception is completely researched and known, when all details, all causal chains from events in the outer world to conscious perception are revealed, then the term 'perception' shall have found its final meaning. (Janich 1990, p. 155)

The perception of temperature is a complex process. Despite the remarkable physiological advancements by Hensel (1981) on thermoreception and thermoregulation, Janich makes a valid point that not enough attention has been given to the definition of terms. Warm and cold sensations are taken to be self- explanatory, but they are clearly affected by a state of health, age, sex and a host of factors. In the overwhelming majority of research it is assumed that terms like 'hot', 'cold' or 'comfortable' are self-evident. The definition of terms is not pedantic, and avoiding a detailed accounting of terms has led to the ambiguity of what comfort is, and whether we necessarily perceive it in the same way.

Let us revisit the definition of comfort.

> Thermal comfort is that condition of mind which expresses satisfaction with the thermal environment. (ASHRAE 55 1966–2010)

Thermal comfort, to fulfil the widely accepted ASHRAE definition that has been adopted since 1966, is not merely an experience, it is an *expression*. We can interpret this as requiring a three step process: detection, deliberation, declaration. Based on the mind's assessment of sensory stimulation a decision is made quasi-consciously if it qualifies as the state of mind of satisfaction *experienced*. I say quasi-conscious because there is a large part of *thermoreception* that is unconscious, and another part of *thermoregulation* that is autonomic (to be discussed at length in the next chapter). There is also a part of perception that is based on memory and expectation that falls within consciousness and semi-consciousness. Finally, for that state of mind to be *expressed* an intentional act of the will is required, a motivation to think or say, 'I actually feel *really comfortable*.' There is a mental threshold to pass before one even considers the comfortability of the thermal environment worth noticing and that threshold distinguishes between being 'comfortable' and 'very comfortable'. For within the thermal neutral zone one is cognisant of comfort only by the absence of discomfort (the negative), but to be *very comfortable* the environment needs to (positively) surpass the expectations.

It is in this light that even the Bedford scale is also too limited for it cannot capture the degree of comfort associated with the sensation. For us to confidently say we can achieve 'the condition of mind which expresses satisfaction with the thermal environment' requires us to go beyond the evaluation of sensation and PPD. We need to attain a vote of 'very comfortable'.

> Where does classic comfort theory (PMV) fit in all of this? Since it relies on the seven-point scale of sensation PMV is confined within the descriptive dimension, devoid of hedonic tone. By registering a PMV score of zero, a given combination of thermal environmental parameters is expected to evoke a neutral whole-body thermal sensation—neither warm nor cool. But this says nothing about whether the occupants are going to actually *like* it. Like or dislike falls within the hedonic (comfort) dimension. (de Dear 2009)

The desire for neutrality can be explained in the notion of alliesthesia, where a disruption to an organism's internal environment would make a stimulus welcome if it restored that balance (Cabanac 1995). The state of mind and body prior to the present reference point would have a direct impact and thus define if the stimulus was appreciated. Whilst this can explain the desire for thermal balance, it does not explain why extreme sensations are sought by some, such that a cold shower can be "reinvigorating", or a hot sauna be "relaxing" despite neither condition being near a neutral state.

> When the body is at a neutral temperature, it is not possible to produce positively pleasant conditions. (McIntyre 1980, p. 130)

Once again, an analogy from food may be helpful. The popular Japanese dish *sushi* is often accompanied with pickled ginger on the side. The ginger is provided as a 'palette cleanser' so that with the next serving of sushi, the subtle flavours of the raw fish are more discernible. If neutrality was key, then plain water would suffice as a palette cleanser. However, with the astringency of ginger, the fragrance and richness of sushi can be heightened. Consuming sushi continuously would thus be like having the same note repeated, whereas each cycle between water and sushi would alternate the two notes (alliesthesia). Better still, the diverging experience of ginger and sushi would constitute two notes with a higher (hedonic) climax. A similar logic applies for the pairing of food with wine.

Thermal transients, or the transitions between hot and cold, parallels this pairing experience. Let us begin by assuming a condition of dressing, metabolism and humidity where neutrality was 25 °C, but the occupant had instead spent 4 h at 18 °C (quite typical for overly conditioned offices). Having a subsequent lunch break in an air-conditioned restaurant at 25 °C would be an improvement but still not feel as comfortable as a naturally ventilated hawker centre at 32 °C. When the core temperature of the body has been disrupted from its balanced set point, a move towards neutrality can be perceived as 'comfortable', but only a move to slightly overcompensate can be 'very comfortable'.

> Thread 11: The 'perfect' temperature is not a static value.

3.11 Marketing and Mass Consumption of Air-Conditioning

Of particular usefulness to the understanding of the high penetration rate of air-conditioning in the past century is the work of Marsha Ackermann (2002) *America's Romance with Air-Conditioning.* Before 1920, air-conditioning had been used almost exclusively in factories to ensure manufacturing consistency. It subsequently became adopted for human comfort only in the 1920s with the definition of the comfort zone. In the 1930s and particularly with the great depression, wide scale adoption of air-conditioning in the Roosevelt administration offices associated air-conditioning as the enabler of long productive hours of work as a 'stimulus for greater achievement' (p. 72). In the 1950s air conditioning became marketed more as a consumer appliance rather than one which was specified by building professionals. This was also the period that it was more aggressively marketed as the means to empower productivity (see Fig. 3.6).

From thermal comfort research of the 1960s onwards, Elizabeth Shove (2003) provides an important sociological perspective to the ascendancy of air-conditioning through governing standards.

> The representation of comfort as an attribute, rather than as an achievement, has also dominated the history of thermal comfort research and the design of the built environment. One consequence is that what were 'wide, and in large part discretionary, social variations in consumption patterns regarding heating and lighting' (Crowley 2001: x), have

Fig. 3.6 Carrier air-conditioning advertisements, 1949–1950 (Ackermann 2002). Image credit: United Technologies Corporation

converged around a remarkably narrow specification of normal and appropriate conditions indoors. (Shove Shove 2003, p. 26)

Cooper puts it precisely: 'When it was shown that no natural climate could consistently deliver perfect comfort conditions, air-conditioning broke free of its geographic limits. When no town could deliver an ideal climate, all towns became potential markets for air-conditioning' (Cooper 1998). In short, the quantification and specification of an ideal and ideally consistent environment, defined in terms of temperature, humidity and so forth, constituted a really significant breakthrough in constructing comfort as a marketable concept and in the normalization of man-made weather. (p. 30)

As represented here, standards are good not just for regulating and controlling practice but for doing business, building mass markets and creating opportunities on a scale that would be difficult to generate in any other way (Krislov 1997). In short, universalizing types of science are especially well suited to the dissection and specification of human need and to the design and diffusion of standards and standardized commodities purporting to meet these requirements. (p. 42)

Reviewing the field in 1993, Nigel Oseland concludes that the knowledge produced by conventional thermal comfort studies is of a type that legitimizes air-conditioning and that relates to the needs of that industry. Research in this tradition is, he says, of little value to those designing buildings to make use of solar energy. Put simply, 'Passive design requires thermal comfort information of a quite different kind, since the interest no longer focuses on thermostat settings, control bands, and cycling times' (Oseland and Humphreys 1993: 35). This observation underlines the extent to which comfort research has revolved around the taken for granted agendas of those who manufacture and specify equipment and the degree to which questions and methodologies correspond. (p. 31)

Thread 12: Marketing both shapes and reveals societal values.

There is a marked difference in the way air-conditioning is marketed before and after the institutionalisation of thermal comfort. Prior to comfort standards, advertising focussed on the benefits of cooling: deliverance from the oppression of heat, improvements to productivity, recovery from hard labour, and so forth. After air-conditioning had become routinely specified in accordance to ventilation, temperature and humidity standards, advertising the benefit of a technology was irrelevant, and marketing centred on branding: the quality (like reliability and quietness) and uniqueness (like styling and additional features). Subjects featured in the advertisements have likewise changed from the anonymous Joneses to movie celebrities—when air-conditioners all look similar, companies need to associate their brand with a face. The switch marks a change in the mind set of society that air-conditioning is no longer a luxury that requires justification for purchase, but a necessity one has to get, with the only remaining question being, 'Which brand do I buy?'

Advertisements are seen as being produced by the dominant group for approval by the suppressed group, envisioning a process that is gratifying to the masses yet contributes to their enslavement. (O'Shaughnessy and O'Shaughnessy 2002, p. 526)

Advertising reflects and reinforces the mindset that comfort is a private concern. There is scant regard for the heat rejected from the condensing unit to the neighbours, or on a larger scale, the heat island effect in central business districts. Ohashi et al. (2007) modelled this effect and found 'the waste heat resulting from

Fig. 3.7 Screenshots of Herman Miller C$_2$ television advertisement with tag line *be warm, be cool, just be* (reproduced by permission of Herman Miller.)

air conditioners has increased the air temperature by 1–2 °C or more on weekdays in the office district in Tokyo' (p. 78). The pre-eminence of self is the distinctive feature of a consumer society, where 'the more people grow to love their freedom, so as to regard it as the defining feature of the life style, the more they come to view themselves as having no obligation to do other than self-indulge' (Kass and Kass, in O'Shaughnessy and O'Shaughnessy 2002, p. 545).

> Thread 13: Consumer society has adopted air-conditioning as a necessity.

In 2007, furniture manufacturer Herman Miller introduced the C2 personal heater and air-conditioner (Fig. 3.7). The advertising plays on the frustration of a common thermostat setting and the need for control of one's personal climate. It appears that air-conditioning has developed from being privatised (from the 1930s and onwards), to also being institutionalised (from the 1960s), to the future where it will be personalised.

3.12 Acclimatised Addiction

> We shape our buildings, and afterwards our buildings shape us.
>
> > Winston Churchill (address to the House of Commmons, 28 October 1943).

Students in Rio de Janerio (hot-humid climate) who spent 76 % of time in air-conditioned spaces were showing a comfort sensation similar to people in temperate climates, the average vote deviating a negligible 0.05 from the ASHRAE thermal comfort mean, leading Grimme et al. (2003) to observe that 'a clear loss of the proven climate adaptation can be quite clearly seen' (p. 11). This trend is universally observed in countries with increasing affluence. As people become wealthier they can be more selective about their climatic needs, typically preferring lower temperature and humidity than what naturally occurs in the tropics. Fanger and Toftum (2002) observed too that those who accepted warmer conditions than PMV predicted did so because

> They may believe that it is their "destiny" to live in environments where they feel warmer than neutral. If given a chance they may not on average prefer an environment that is different from that chosen by people who are used to air-conditioned buildings. But it is

likely that they would judge a given warm environment as less severe and less unacceptable than would people who are used to air-conditioning. (p. 534)

Whilst the research in adaptive thermal comfort is acknowledged, the consumption pattern towards greater levels of air-conditioning cannot be ignored. There is a glaring divide here, for if one is comfortable in adapting to the mean monthly outdoor temperature, why should one prefer air-conditioning as the trend in Singapore suggests? It appears the physical adaptation to a warm set-point comes at greater inconvenience than to have the climate adapted to one's preferred temperature. The notion of comfort is a broad and subjective quality. It could range from the notion that because one is not uncomfortable, one is therefore comfortable. Or it could be defined as the ultimate satisfaction of mind with the environment where any variation will make one less comfortable.

Prins, an anthropologist, in his polemic on air-conditioning (Prins 1992) describes air-conditioning as "addictive", "relentless" and "severe". Whilst we may not use such emotive descriptors, there is a sense in which air-conditioning does alter one's preferred temperature.

> As early as 1842, touring English novelist Charles Dickens complained of the American penchant for overheating. His Boston hotel, considered one of the nation's finest, was, he wrote a friend, "made so infernally hot (I use the expression advisedly) by means of a furnace with pipes running through the passages, that we can hardly bear it." (Ackermann 2002)

A survey of literary works (Meyer 2002) between British and Anglo-American writers found a change in preferred winter indoor temperatures from 14 °C during mid eighteenth century to 22–24 °C in the periods 1825–1840. These figures may need to be taken anecdotally (Meyer appears not to differentiate between radiant and air temperature). However, he makes a valid point that energy efficient innovations coupled with affordable and abundant energy would cause climatic taste to be more exacting, as occupants become less tolerant to compromise, a phenomenon well expressed by Baker's term 'the irritable occupant' (Baker 1996).

> Thread 14: Routine adoption of air-conditioning diminishes one's adaptive capacity.

The demand for cooling in the tropics parallels that for warmth in the cold, where increased affluence can drive optimum temperatures lower or higher respectively. This acclimatised addiction to air-conditioning parallels the effects of coffee: one does not realise the productivity boost until one has experienced it, after which there is no going back, and without which one gets highly irritable. For coffee devotees, life without coffee is unthinkable, much less work without it.

We see this playing out in the tropics where increased affluence has driven optimum temperatures lower. A 'self-fulfilling prophecy' (Humphreys 1995) occurs when enough buildings set to the same artificially low temperature lead a generation to become "socially and historically conditioned" to climates unnatural to a place.

The need to appreciate this social aspect is pivotal. Wilhite et al. (1996) observed that Japanese saw air-conditioning as a social indicator of status and well-being. He goes on to say, 'The strong social significance causes overheating and over lighting as insurance against social failure. Cosiness has become what we

call a cultural energy service, which we define as a set of energy use behaviour deeply rooted in the social, cultural and symbolic presentation of the home.' In a survey on the expectations for air-conditioning in young Singaporeans (Hitchings and Lee 2008), it was found:

> The demand for air conditioning had largely reached the point where it was an expectation. In the public sphere, with regard to the office and the school, air conditioning was seen as essential not only for enhancing productivity but also as a courtesy towards employees and students who themselves worked hard to ensure the collective organisational success.

After six decades, the marketing of air-conditioning has ingrained the luxury of air-conditioning as a social necessity.

> Thread 15: Air-conditioning has become so common that it is perceived as a disrespect when denied.

3.13 Comfort and Energy

How then are we to resolve the need for comfort with energy constraints? If the deterministic model were correct, the primary focus would be on increasing plant efficiency and reducing building thermal load. If the adaptive model were to be more widely adopted, considerable emphasis would be placed on education: to change the mindsets of governments, developers, building designers and building users that office workers can be comfortable without air-conditioning.

Sue Roaf et al. (2005) have documented four different approaches and their varying success in resolving the over reliance on air-conditioning.

> Market forces. The theory that environmentally friendly technologies will be increasingly used over more damaging ones does not seem to apply with air conditioning. Here, market forces appear to work in favour of 'prestige solutions'.
>
> Guidance. Guidance measures, however strong, appear to be useless. In the UK for the engineering and architectural professions strong guidance not to use air conditioning systems has had minimal effect on the standards of environmental design of typical office buildings or their energy consumption (British Standard BS 8207:1985 and RIBA 1989 Policy Guidelines) to promote the ethical practice of avoiding refrigeration where natural and mechanical ventilation was a feasible alternative. Negligible attention has been paid to such guidance in the UK.
>
> Legislation. This works well. In the Canton of Zurich, Switzerland, a law was introduced practically overnight in the late 1980s, banning the use of air conditioning in buildings unless it could be proven to be absolutely necessary. …The real problem here is that it is very easy to design an air-conditioned building that more or less works, but it takes great skill and expertise to design a good passive building, skill that, frankly, many modern architects simply do not have. The experience of Zurich has proved that they can learn fast, although even there architects and engineers are now finding ways around the pioneering regulations, showing that enforcement is as important as the legislation itself.
>
> Political management of the problem. A major drawback is that in most countries there is no single authority with jurisdiction over the control of energy use in, or CO_2 emissions from, buildings—neither the planning nor the building regulations departments—and hence there is no related authority to control the use and performance of air conditioning systems. With the increase in significance of CO_2 emissions from buildings, and their

commoditization as an internationally tradable unit and legally controllable substance under international law, legislation for the control of energy use in buildings, and by countries, will inevitably be considered and eventually implemented in most countries.

Broadly speaking these methods are essentially two: free-market or governance. The success in Switzerland's legislation is encouraging but in reality there are few governments in the world who can enjoy continued support after making unpopular decisions. The stalemate in the Kyoto Protocol in Chap. 2 reflects this fact. In the capitalistic mode, each business does what is right for themselves, which according to Adam Smith's *invisible hand,* should promote the greatest good for all. Robert Frank (1999) devotes an entire chapter to show many exceptions to this theory in which ambitions are *smart for one, dumb for all.* Air-conditioning, with the way it privatises comfort at the expense of others and the environment, would also fall in this category. Between thermal comfort models we find that industry would gravitate to deterministic comfort in its business interest. The big challenge is therefore to prompt a switch to lower energy air-conditioning without sacrificing this interest (Table 3.7).

> Thread 16: Air-conditioning is unlikely to be eliminated by legislation. Energy-efficient air-conditioning needs to appeal to the industry before it can be taken up.

Table 3.7 Threads in this chapter

Thread-1	Comfort temperature is defined not by a point but over a range
Thread-2	The axis of debate between deterministic and adaptive comfort may lie in semantics
Thread-3	The PMV model's strength is in predictive simulation, and when corrected for real-world applications, can be representative of the group. Its weakness is that it is assumes homogeneous conditions and behaviour
Thread-4	The adaptive model's strength is that within a temperature range, occupants can be expected to find their own preferred temperature. Its weakness is that substantial effort is required to design with it and to change attitudes towards behavioural adaptation
Thread-5	Adaptation from simulated work to real work requires more cooling than predicted by PMV
Thread-6	Real (productive) work could require a higher met than simulated work
Thread-7	Workplace productivity is affected by temperature
Thread-8	Because productivity still cannot be reliably indexed, its relationship to temperature is still tentative
Thread-9	The active brain needs to be kept cool to perform well
Thread-10	The 'perfect' temperature is not so much determined by the sensation of warmth or coolness, but whether one is 'very comfortable' with it
Thread-11	The 'perfect' temperature is not a static value
Thread-12	Marketing both shapes and reveals societal values
Thread-13	Consumer society has adopted air-conditioning as a necessity
Thread-14	Routine adoption of air-conditioning diminishes one's adaptive capacity
Thread-15	Air-conditioning has become so common that it is perceived as a disrespect when denied
Thread-16	Air-conditioning is unlikely to be eliminated by legislation
	Energy-efficient air-conditioning needs to appeal to the industry before it can be taken up

3.14 Ideas Worth Exploring

In the popular perception in Singapore, air-conditioning is here to stay. Increased affluence has turned a previous luxury to a present-day necessity. In many fast developing Asian cities, air-conditioning is even more imperative to cope with air pollution by providing a distinct indoor climate. Consequently, it may be difficult or unrealistic to deny air-conditioning to office workers, but instead of a single deterministic setting, a range should be provided that corresponds with the mental demands of each space: formal and personal areas being cooler to promote concentration, whereas informal, communal and creative spaces are allowed to approach warmer temperatures.

Such a non-uniform environment builds on the delight of sensory fluctuations (Heschong 1979), the satisfaction of a larger temperature band with time variance (Baker 1996) and the awareness of adaptive opportunity (Baker and Standeven 1996). Ample adaptive opportunities should be provided for the worker to have flexible working environments as personal taste dictates: trips to the cybercafe with warmer conditions and a hot cappuccino, and back to a personal cool space for full concentration on a specific task.

Air-conditioning efficiency need not lie solely in equipment improvements. The largest part of the chiller load is latent: to dehumidify external air. This load is decided by indoor air quality (IAQ) standards dictating relative humidity and air changes per hour. A notable innovation to cope with pollution has been adopted by the Paharpur Business Centre in New Delhi, India: all fresh air is collected at roof level, filtered, circulated through a rooftop greenhouse before entering the air-conditioning system and distributed to the seven-storey building. The plants reduce CO_2 concentration, enrich oxygen levels and remove volatile organic compounds (Apte and Apte 2010). However, the presence of plants further increases the latent load on the air-conditioning system through transpiration. This, and other dehumidification requirements, can be solved with solid adsorption desiccant systems. New generation zeolites which can be regenerated at 60–80 °C, temperatures achievable from flat-plate solar collectors (Mazzei et al. 2002, 2005), show great promise in tackling the latent load in a passive way. The option of removing moisture with heat (using desiccants) should be more actively adopted in the tropics where high insolation makes passive heating readily available, and the high enthalpy of air allows heat pumps to operate extremely efficiently (COP of 8–10).

Chilled beams could also play a larger role in tropical offices. Radiant cooling studies have demonstrated the efficacy of using chilled ceilings to achieve sensible cooling (Yellott 1989). The asymmetric heat load of the body, with the head requiring the most cooling, means that the exposed head would benefit most from a chilled ceiling. To cope with the high dew-point of tropical air, chilled beams need to be adopted in conjunction with desiccant systems or conventional chillers that can pre-condition the air and maintain its humidity at a dewpoint under 13 °C. Well designed active chilled beams should have no condensation problems (Alexander and O'Rourke 2008).

Finally, personal control over one's immediate climate should also be a greater feature for future offices. Minimal ambient cooling should be provided in the general areas with extra cooling available on-demand, individually controlled and directed mostly to the head: a strategy akin to ambient and task lighting.

> But what if people could adjust their own micro-environments according to their own fluctuating requirements? On this point, Humphreys and Nicol (Humphreys and Nicol 1998) and Fanger agree that 'the ultimate solution…is individual control' (Oseland and Humphreys 1993:11). The notion of providing 'personalized' air is the next logical step (Fanger 2001). This might indeed be the perfect design solution for it places responsibility for the specification of comfort as well as for sustainability and energy consumption firmly in the hands of the user. As usual, the designer's task would be to meet users' needs but this time it is the need for choice rather than for comfort or sustainability that must be met. (Shove 2003, p. 40)

There is an important limitation that both PMV and ACS models assume a hypothetical *average occupant.* The 'requirements for temperature and air movement in spaces…prescribed in the present standards (ISO 7730 1994; ASHRAE 55 2004)…are based on average values for a large group of occupants' (Melikov 2004, p. 157). The basis and occurrence of personal variation is discussed in later chapters on *Brain Cooling* (Chap. 4) and *Personal Air-conditioning* (Chap. 9).

> Threaded summary: The future of thermal comfort is personal air-conditioning.

3.15 Concluding Thoughts on Thermal Comfort Review

> Clearly system change is needed. The problems cannot be solved by more conservation effort on the part of individuals and firms within consumer-capitalist society. They are being caused by an overshoot that is far too big for that, and they are being caused by some of the fundamental structures of this society. Consequently much of what is said under the heading of "sustainability" is nonsense and much of the effort being made to "save the planet" is a waste of time. Most irritating are the "What you can do in your own home" campaigners. "Buy biodegradable wash up liquid, use a low-flow shower head, recycle your bottles, buy a smaller car, etc." Such efforts can make no more than a negligible difference to household impact, when we need something like a 90 % reduction in national consumption. Nothing remotely like this is possible within a consumer-capitalist society committed to affluent lifestyles and limitless economic growth. It is only possible through dramatically reducing the volume of production and consumption and therefore by changing from such a society to one that is about frugal but adequate "living standards", as little production and consumption as possible and a stable economy. (Trainer 2007, p. 117)

In this chapter we have seen how the low cost of energy and appliances has led to the proliferation of air-conditioning, which bears a high environmental cost, as discussed in Chap. 2. It is imperative that this environmental impact is resolved, but without compromising comfort and productivity. A consumer society marked by self-interest has precipitated this disconcerting state of climatic affairs. One solution is to totally transform society as Trainer suggests in what he terms *The*

Simple Way, simplicity in terms of lifestyle but exceedingly difficult to implement as it requires mindsets to be totally transformed. It requires that cities (now containing half the world's population) be made much smaller, decentralised to small subsistence economies with minimised trade. But, as the economist Richard McKenzie says of colleagues during the Californian energy crisis,

> Few people seemed to be truly concerned enough to make real sacrifices. But then why should they? Most people seemed to take the view, 'Anything I might do to conserve would be of no consequence.' The 'free rider problem,' which economists have spent careers talking about in their classes, was on full display. (McKenzie 2008, p. 21)

In this debate, my position is to opt for a technological solution. A solution that works on the same principles of capitalism, characterised by individual consumers acting in self-interests. Society has and will continue to demand for air-conditioning, and if researchers can be smart about it, it just might be possible for us to give them what they really want: personal cooling technology that does less environmental damage than current air-conditioning systems.

> Human history shows…that the same kind of knowledge that permits man to alter his environment for the purpose of minimizing effort, achieving comfort, and avoiding exposure to stress also gives him the power to change his environment and ways of life in a manner that often entails unpredictable dangers. …The state of adaptedness to the world of today may be incompatible with survival in the world of tomorrow. For better and for worse, our world of tomorrow will be air-conditioned. (Ackermann 2002, p. 184)

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Chapter 4
Brain Cooling

"In the sweat of thy face shalt thou eat bread…"
Genesis 3:19 (King James Version).

In Genesis, the first book of the Bible, the fall of man is recorded and the consequence of labour and death is pronounced. The insights into the facility for brain cooling from eighteenth and nineteenth century commentators is remarkable:

> In the sweat of thy face—Though the whole body may be thrown into a profuse sweat, if hard labor be long continued, yet the face or forehead is the first part whence this sweat begins to issue; this is occasioned by the blood being strongly propelled to the brain, partly through stooping, but principally by the strong action of the muscles; in consequence of this the blood vessels about the head become turgid through the great flux of blood, the fibres are relaxed, the pores enlarged, and the sweat or serum poured out. Thus then the very commencement of every man's labor may put him in mind of his sin and its consequences. (Adam Clarke, *Commentary on the Whole Bible,* 1832)
>
> …it may have regard to all methods and means by which men get their bread, and not without sweat; and even such exercises as depend upon the brain are not excused from such an expense: so that every man, let him be in what station of life he will, is not exempt, more or less, from this sentence, and so continues till he dies. (John Gill, *Exposition of the Bible,* 1763)

This chapter discusses the role of the brain in productive mental work, where one can expect a high degree of work-related stress and arousal. The diversity of responses and the futility of defining a fixed perfect temperature can only be properly understood with an appreciation of the roles of cranial metabolism, autonomous stress response and brain-cooling.

Zhang performed extensive tests on the cooling of particular body parts. In her Ph.D. thesis (Zhang 2003) she wrote:

> We have showed that in general people are happy with a slightly cool head. The cool head helps to keep a cool brain. The reason that people are happy with the breathing zone air cooling and don't like breath warming might be correlated with the fact that breathing zone air is related with selective brain cooling. Cabanac (1995, p.27) concluded from human subject tests that upper airway convective-evaporative heat loss does contribute to cooling the brain.

The need for a cool brain may be self-evident. This does not however explain why comfort, according to the ACS, can be achieved in temperatures much higher than the PMV model. We have earlier alluded to the possible mechanism of mental metabolism and the need for a cooled head to maintain efficient mental processes, and take a deeper look at the relationships between cognitive function, stress and temperature.

4.1 Heat Stress

In more extreme conditions, heat stress significantly impairs judgment and performance. Several military studies have been conducted to ascertain its relationship and limits (Manton and Hendy 1988, to name one). Hancock (1986); Hancock and Vasmatzidis (2003) demonstrated that shifts to deep body temperature had pronounced effects in the performance of complex tasks (vigilance, tracking and multi-tasking). However conditions that can cause perturbation to deep body temperature fall well beyond the comfort scales into thermally stressful regions not typically encountered in the office. Of interest is the region where there is sensible discomfort without disturbing deep body temperature: a region where Hancock found no performance deterioration in his laboratory-based subjects.

If in the normothermic realm (no perturbation to core temperature) there is no performance decrement, then there is good grounds to promote the ACS on the basis that it provides better energy economy for equivalent comfort as air-conditioning. On the other hand if the adaptation to warmth comes with a penalty to performance that cannot be captured in laboratory tests, than this might explain why the market continues to demand air-conditioning, and air-conditioning at a lower T setpoint then the PMV would suggest for optimal comfort.

However in thermal comfort research, the metabolism of occupants has always been based on physical activity. So the mentally active but sedentary office occupant under a mountain of work would be considered no different from a mentally inactive person watching a boring program on television. Is this really the case? Work stress exerts an influence on thermal response, regulation and expectation. The magnitude of this effect may be uncertain, but there appears to be a consistent effect on metabolism. We begin by considering the stress response on a person's physiology.

The term 'stress' will refer to emotional or mental strain for this chapter, unless indicated as 'thermal stress' or 'heat stress'.

4.2 The Neurophysiological Stress Response

The main difference in the occupants undergoing a climate chamber trial and the field trial will be the mental exertion between a simulated and a real-world task.

What happens when we think?

Neurons have an average firing rate of 1.7 Hz (Karbowski 2009) at rest and 20–30 Hz when stimulated (Siegfried 2001). The active neurons demand an increased consumption of oxygen and glucose utilisation rate. Karbowski (2009) developed a model to predict brain temperature by looking at the energy released in the consumption of adenosine triphosphate (ATP, the precursor to bio-energy).

$$T_{deep\ brain} \approx T_{bl} + \frac{P_{ATP}}{\rho_{bl}c_{bl}\ U_{br}CBF} \tag{4.1}$$

where

$$P_{ATP} \approx 31 F U_g (3V_{Na} - 2V_K - V_o) CMR_{glu} \tag{4.2}$$

$T_{deep\ brain}$	Deep brain temperature	Typically 0.1–0.2 °C higher than T_{bl}
T_{bl}	Blood temperature	309.8 K
ρ_{bl}	Blood density	$1.06 \cdot 10^{-3}$ kg/cm^3
c_{bl}	Blood specific heat capacity	$3.8 \cdot 10^3$ J/(kg K)
U_{br}	Brain volume	$U_{br} = U_g + U_w$
CBF	Cerebral blood flow	$0.018 U_{br}^{-0.10}$ l/sec
U_g	Grey matter volume	680.0 cm^3
U_w	White matter volume	$U_w = 0.166 U_g^{1.23}$ cm^3
$F(3V_{Na}-2V_K-V_O)$	Work done by one mole of ATP	
V_{Na}	Na$^+$ ion potential	0.068 V
V_K	K$^+$ ion potential	-0.100 V
V_o	Resting potential	-0.067 V
CMR_{glu}	Glucose cerebral metabolic rate	$5.7 \cdot 10^{-9}$ mol/(cm$^3 \cdot$sec)
P_{ATP}	Average power dissipated by neurons in the gray matter	5.5 W, and up to 7.8 W

A few key observations from Karbowski (2009) are that:

1. the brain is energy expensive and its total metabolic rate has larger scaling exponent than whole body metabolic rate (p. 3)
2. metabolic rate in white matter is 3–4 times lower than in grey matter and can be neglected (p. 11)
3. majority of metabolic energy in neurons goes to pumping out sodium ions (p. 31)
4. the boundary temperature (and scalp cooling) becomes unimportant in the limit of deep brain temperature (p. 26)
5. any local increase in the cerebral blood flow that exceeds an increase in glucose utilization rate leads to a lowering of brain temperature, and vice versa (p. 26)
6. in deep brain regions cerebral blood flow plays the role of a coolant, whereas in the superficial regions it serves as a strong brain heater (p. 27)

7. on the scalp, the heat transfer rate is dominated by convection/conduction, as it is twice the radiation rate (p. 28)

The firing rate of neurons does not have a linear relationship with the ATP consumption rate, and at an oxygen extraction fraction of 40 % (the practical limit for the brain), blood leaves the brain at 0.4 °C higher than it entered (Zhu 2006). This is in agreement with Cabanac (1995):

> …the human brain also is warmer in its center than in its peripheral layer and than core temperature, and the temperature within the circle of Willis is also cooler than brain temperature. There is a temperature gradient which facilitates the flow of heat from brain to arterial blood. In turn, the venous blood warms to about 0.2–0.5 °C above arterial blood and flushes this heat to the trunk. …The human brain is usually estimated to produce ca. 20 W of heat; the arterial blood flow with about 0.5 I/min can remove that heat with the actual arterial-venous temperature of only 0.5 °C.

The cranial metabolic rate thus does not produce any more heat than the body can cope with in homeostasis. However, to cope with the higher demand for blood oxygen and nutrients, an increase in cerebral blood flow (CBF) is required (Gisolfi and Mora 2000). This in turn is the primary cause for increased brain temperature (Zhu 2006). How does the brain indicate this requirement to the vascular system?

4.3 Stress and the Sympathetic Nervous System

Many stressors occur at the modern workplace that can range from looming deadlines, difficult co-workers, unreasonable demands from superiors and clients, and so forth. The body undergoes a physiological reaction to what the mind perceives as a stressor in an autonomic way, hence the reference to an autonomous nervous system.

The stress response and thermoregulation both reside in the hypothalamus. More specifically, stress and thermal regulation overlap the same areas as follows (Felten and Jozefowicz 2003, see locations in Fig. 4.1):

1. Preoptic-anterior hypothalamus (POAH): warmth sensitive neurons, initiate heat dissipation (parasympathetic)
2. Posterior hypothalamus area (PHA): cold sensitive neurons, initiates heat generation (sympathetic)

Since only either one will be active at one time, stress would initiate the regions associated with heat generation, and suppress the systems that regulate heat dissipation.

> The sympathetic nervous system kicks into action during emergencies, or what you think are emergencies. …Epinephrine is secreted as a result of the actions of the sympathetic nerve endings in your adrenal glands (located just above your kidneys); norepinephrine is secreted by all the other sympathetic nerve endings throughout the body. These are the chemical messengers that kick various organs into gear, within seconds. …The sympathetic
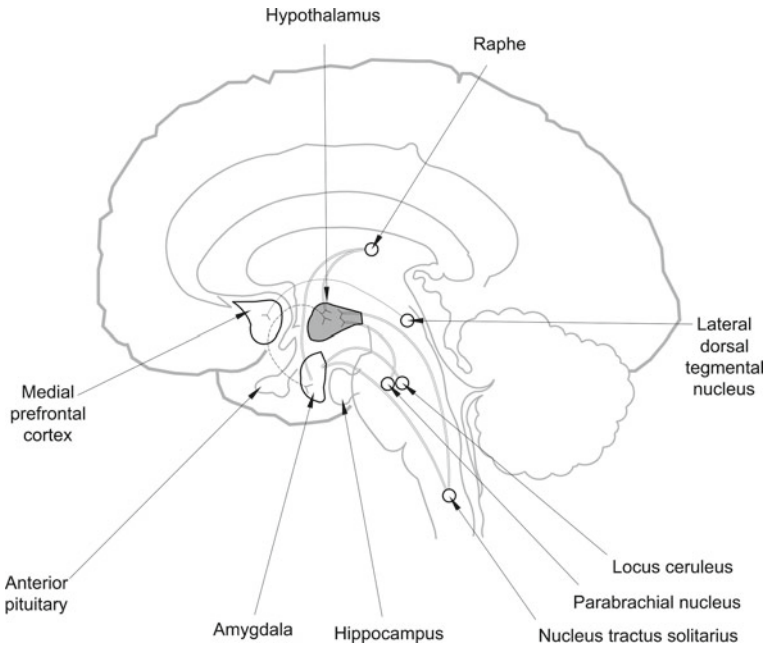
Fig. 4.1 Key areas linked to the expression of fear. Notice the primacy of the hypothalamus Redrawn from Schulkin (2003)

system speeds up the heart; the parasympathetic system slows it down. The sympathetic system diverts blood flow to your muscles; the parasympathetic does the opposite. It's no surprise that it would be a disaster if both branches were very active at the same time, kind of like putting your foot on the gas and brake simultaneously. Lots of safety features exist to make sure that does not happen. For example, the parts of the brain that activate one of the two branches typically inhibit the other. …Your body reverses all of the storage steps through the release of the stress hormones glucocorticoids, glucagon, epinephrine, and norepinephrine. These cause triglycerides to be broken down in the fat cells and, as a result, free fatty acids and glycerol pour into the circulatory system. The same hormones trigger the degradation of glycogen to glucose in cells throughout the body, and the glucose is then flushed into the bloodstream. (Sapolsky 1998, pp. 22–24, 56–57)

Insulin is a hormone that stores energy (Sapolsky 2004) and cortisol (a glucocorticoid associated with stress and fear) is the 'molecule of energy metabolism' (Schulkin 2003). The sympathetic response suppresses insulin and elevates cortisol levels. Together with epinephrine (adrenaline) and norepinephrine (noradrenaline) the typical response due to activating the sympathetic nervous system include (Seeley et al. 2006, p. 564):

1. Increased heart rate and force of contraction potentially increases blood flow through tissues. Vasoconstriction of blood vessels in tissues not involved in exercise, such as abdominopelvic organs, reduces blood flow through them, thus making more blood available for the exercising tissues.

2. Dilation of air passageways increases air flow into and out of the lungs.
3. The availability of energy sources increases. Skeletal muscle cells and liver cells (hepatocytes) are stimulated to break down glycogen to glucose. Skeletal muscle cells use the glucose and liver cells release it into the blood for use by other tissues. Fat cells (adipocytes) break down triglycerides and release fatty acids into the blood, which are used as an energy source by skeletal and cardiac muscle.
4. As exercising muscles generate heat, body temperature increases. Vasodilation of blood vessels in the skin brings warm blood close to the surface, where heat is lost to the environment. Sweat gland activity increases, resulting in increased sweat production, and evaporation of the sweat removes additional heat.

With an increased airflow in lungs more oxygen is absorbed and with the increased heart rate and force, more oxygen enriched blood circulates throughout the body. Sapolsky (2004) says, 'If you sit and think about a major deadline looming next week, driving yourself into a hyperventilating panic, you still alter cardiovascular function to divert more blood flow to your limb muscles'. Since in a sedentary office scenario the skeletal muscles are hardly exercised, the brain is the sole benefactor of increased circulation, oxygen and glucose levels—an excellent combination to fuel the processing power of an active brain.

> Glucocorticoids and the other hormones of the stress-response also act to block energy uptake into muscles and into fat tissue. Somehow the individual muscles that are exercising during the emergency have a means to override this blockade and to grab all the nutrients floating around in the circulation. No one knows what the local signal is, but the net result is that you shunt energy from fat and from non-exercising muscle to the exercising ones. (Sapolsky 1998, p. 57)

So during stress, blood pressure and overall circulation rises, but circulation to the limbs is limited unless they are exercised. This changes the thermoregulatory response of a stressed person. Extreme stress is associated with concepts like 'being paralysed with fear' or having 'cold feet'. The extremities of hands and feet are particularly effective at dissipating heat, so when their circulation is curtailed, blood does not cool the body as much.

In response to stress, the central nervous system is excited by vasoconstrictor agents increasing the metabolism of the liver for glycogenolysis (Cassidy et al. 1986). The brain derives its energy primarily from glucose but glycogen acts as an energy buffer for bursts of mental activity.

> In this role glycogen provides supplemental energy substrate in the form of glycogen-derived lactate to support function when normoglycaemic concentrations of glucose are insufficient to adequately meet immediate tissue energy demands, and leads to the intriguing possibility that glycogen may abet the energy transactions associated with such phenomena as learning and memory where intense bursts of synaptic activity induce synaptic plasticity. (Brown 2004, p. 548)

The brain and liver and respectively constitute 21 and 20 % of BMR (basal metabolic rate, Table 3.5 in Chap. 3). BMR is measured after a 12 h fast which would drastically reduce blood glucose and glycogen levels and thus impede

mental performance. Under ordinary conditions of office stress, the brain consumes glucose in copious amounts and the liver metabolises more glycogen for the brain under mental stimulation. The heart (9 % BMR) also works harder to cope with higher flow rates and blood pressure. The metabolism from these three organs, which alone constitute 50 % of BMR, would be significantly increased under work stress.

The lack of cooling from circulation to the extremities, together with increased metabolism of brain, heart and liver would force an increase in core temperature. This increased metabolism however comes with its own penalty. Cerebral blood flow is not simply delivered from the core to the brain. At rest the brain is in homeostasis at 20 W. Each increase of arterial temperatures by 1 °C pours 45–70 W of heat into the head (Cabanac 1995).

Whilst stress hormones are often associated with preparing the body for a *fight or flight* response, Taylor (in Sapolsky 2004) showed that there is also a gender bias, with females often demonstrating more of a *tend or befriend* response. We have seen that stress hormones can elevate body temperature, but can temperature affect hormone levels?

Anecdotally, in a discussion with a midwife at the Launceston General Hospital, I learned that cold water for drinking was given to women undergoing labour so as to intensify the contractions. Immediately after the child was born, the mother would be wrapped in a warm blanket to increase the oxytocin levels and aid the discharge of the placenta. Environmental temperature does appear to have an effect on hormones.

> …the fact that oxytocin is secreted during stress in females supports the idea that responding to stress may not just consist of preparing for a mad dash across the savanna, but may also involve feeling a pull toward sociality. (Sapolsky 2004)

4.4 The Perception of Temperature

There are thousands of thermoreceptors in the skin and other organs. Johnson (1966) demonstrated that a lowered core temperature caused shivering despite the skin being kept warm, allowing us to deduce that the brain integrates all the information from all the sensors and decides on the appropriate thermoregulatory response: one typically does not shiver and perspire at the same time. Much like the sympathetic and parasympathetic nervous systems, only one option is activated and these functions are autonomous (Johnson 1966; Attia 1980). How does the brain integrate that information and decide whether it is warm or cool? Is it the simple average of all values?

The body temperature, according to Gisolfi and Mora (2000) is taken to be as a combination of a core temperature and mean skin temperature according to environment such that:

In cold environments,

$$T_{body} = 0.6 \cdot T_{core} + 0.4 \cdot T_{skin} \tag{4.3}$$

In warm environments,

$$T_{body} = 0.8 \cdot T_{core} + 0.2 \cdot T_{skin} \tag{4.4}$$

The core temperature, being relatively stable and homogenous can be determined by one or a few measurements and assumed to be constant. Mean skin temperature on the other hand will have a large divergent range, and the integral has often been determined from weighting factors as recommended by Hardy et al. (1938), with measurement made at head, hands, trunk and feet; or Ramanathan (1964) measuring chest, arms, thighs, and legs. They are similar in methodology, which is to assign a coverage surface area coefficient of a segment (c, in percent of total skin) to the temperature of that segment (T) (Mitchell 1969), so that:

$$T_{mean\ skin} = c_1 T_1 + c_2 T_2 + \cdots + c_n T_n \tag{4.5}$$

However, the skin is not equally sensitive in all areas.

> Shell temperature is frequently measured by placing temperature-measuring devices on numerous skin locations and averaging the values. However, this mean skin temperature is potentially misleading if each individual temperature is not weighted according to the area and sensitivity (temperature-receptor density) of the site represented. (Gisolfi and Mora 2000, p. 100)

Considered this way, there is a need to differentiate between the conventional weighting by skin coverage versus weighting by skin sensitivity. The notion of weighting of each skin region makes perfect sense since the amount of heat lost is not only dependent on coverage area, but also by the proximity of the blood vessels to the surface and how widely they are distributed in the region. The neck is particularly sensitive to heat and cold with the carotid arteries located on either side of the neck carrying blood to the head. Thus wrapping a scarf on the neck will have profound effects on the retention of heat and the overall feeling of warmth, even though the area of the neck is small. We may further argue that covering the same skin area with a scarf, say in the lower leg, will hardly be as beneficial. Zhang (2003) measured regression of the sensitivity of body segments to overall sensation and proposed the weightings in Table 4.1. Zhang notes the following contributions to overall sensation (p. 316):

- back, chest and pelvis have dominant weights
- head, face and breathing show asymmetrical slopes, being more sensitive to warming
- hand and feet have little impact

The asymmetric sensation weighting of the head is consistent with our hypothesis that the brain is more sensitive to warming than to cooling. In this light, the formulation of *mental effort* in Chap. 3 (Eq. 3.3) of |(MM-Qc)||(MM-Qc)| should be separated into functions with different coefficients (slope) for cooling and warming.

Table 4.1 Overall sensation model obtained from single body part local cooling and heating tests, the larger the weight ('slope' in original article) the stronger the impact on overall sensation (Zhang 2003)

	Cooling weight	Warming weight
Breathing	−0.16	0.19
Head	−0.13	0.21
Neck	−0.13	0.23
Face	−0.15	0.3
Chest	−0.23	0.23
Back	−0.23	0.24
Pelvis	−0.17	0.15
Upper arm	−0.1	0.14
Lower arm	−0.1	0.14
Hand	−0.04	0.04
Thigh	−0.13	0.26
Lower leg	−0.13	0.26
Foot (2 feet)	−0.09	0.24
Foot (1 foot)	−0.09	0.14
Upper back	−0.16	0.26
Lower back	−0.21	0.35

de Dear (2009) proposes that the neurophysiological hypothesis explains why a transition to a temperature down-step is more significantly felt than an up-step due to the closer proximity of cold neurons to the surface; and proposes how a draft can be welcome alliesthesia in warmth and unpleasant in cold. This agrees with Gisolfi (2000) that in cold-skin the cold sensitive neurons are more innervated, and the cold response is "2–3 times more effective in activating heat production" than the heat response (see Fig. 4.2).

The neurophysiological approach to temperature sensing is methodologically different from isothermal heat balance approach, the latter being the premise for thermal manikins (see Ph.D. thesis by Nilsson 2004 for an excellent review on thermal manikins). Defining thermal perception in terms of warm-cold neuron firing rates (Ring and de Dear 1991) translated into a thermal sensation vote (Zolfaghari 2010) provides a more accurate accounting for fluctuating temperature transients, where the static heat-balance model offers no such latitude. However, is the perception of temperature necessarily the most reliable gauge for the required heat balance? Is there any danger of sending the wrong signal to the brain by cooling the most sensitive sensors, much like messing the thermostat by putting the thermistor in the supply vent?

Whilst heat-sensitive neurons are fairly equitably distributed across the skin surface, there is a prevalence of cold-sensitive neurons on the forehead (Fig. 4.3). If spot density determined sensitivity, then the head should not be particularly sensitive to heat, and very sensitive to cold. However experiments which showed that the head has a high sensitivity to either deviation from neutrality, led Cabanac (1995) to deduce that restoring the head to normothermia is highly effective in achieving thermal comfort not because of sensor density but due to assistance rendered to the selective brain cooling mechanism.
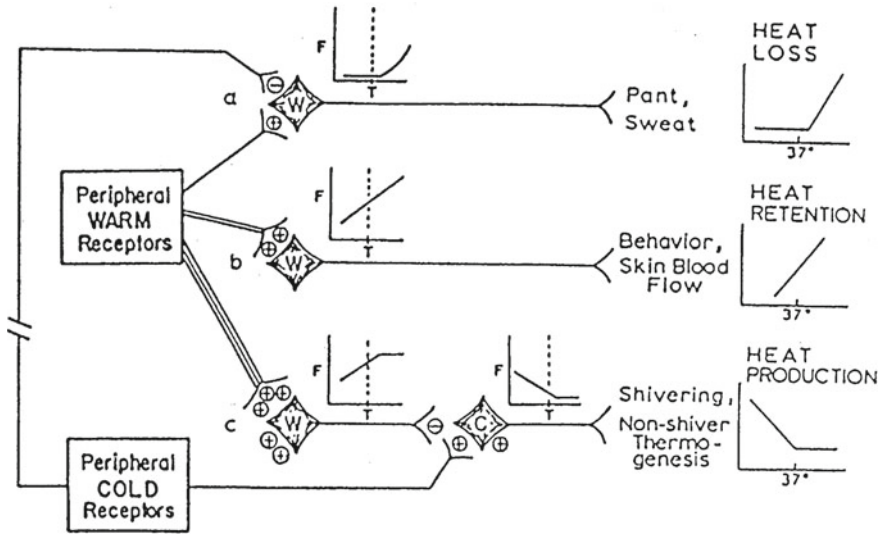
Fig. 4.2 Neuronal model proposed by Boulant (1996), in Gisolfi and Mora (2000) in which *four* types of thermosensitive neurons are warm (*W*) neurons (*a*, *b*, and *c*) and cold (*C*) neurons. The cold and warm inputs to these neurons are depicted as excitatory (+) and inhibitory (−). The frequency (*F*) of neuronal firing is plotted as a function of brain temperature (*T*)

An increase in hypothalamic temperature produces marked increases in sweating and skin blood flow. Likewise, a decrease in hypothalamic temperature produces shivering and intense cutaneous vasoconstriction. Thus, it seems that it is more specifically the temperature of the brain that is being protected from marked deviations in temperature, rather than the entire core, which includes the abdominal and thoracic cavities. In support of this notion, it is brain temperature that seems to drive sweating, shivering, and skin blood flow responses. (Gisolfi and Mora 2000, p. 102)

Fig. 4.3 Mean density of temperature spots obtained on eight adults, four males and four females, in the various skin areas stimulated. The stimuli were given with 1.1 mm^2 thermodes applied with a force of 5 g for is (cold, 0 °C) and 2 s (warm, 44 °C) duration, on a 4 cm^2 sample of each of the skin areas tested. *L* leg, *T* thigh, *Ab* abdomen, *Fa* forearm, *Ar* upper arm, *C* chest, *B* back, *Fh* forehead (Cabanac 1995)
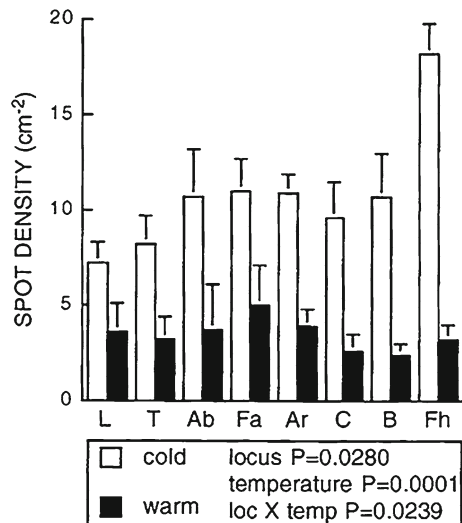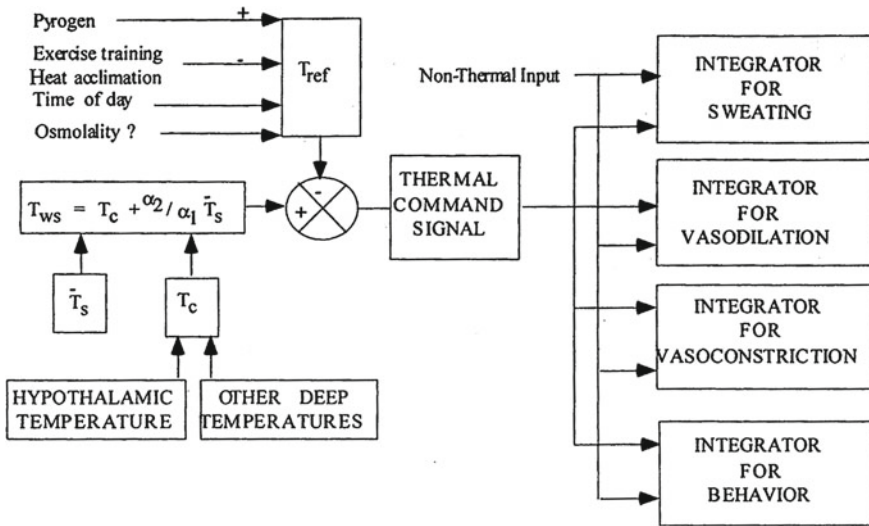
Fig. 4.4 Schematic diagram illustrating the elements that control the temperature regulatory effector responses. Basic thermal input is transmitted from skin (T_s) and core (T_c) thermoreceptors. This information is integrated and a "weighted sum" (T_{ws}) of this activity is then compared with basal neural activity (T_{ref}) within the regulatory circuiting to form a "command signal" that impinges on all integrators for regulating brain temperature. The ration of a1/a2 is 9/1. (Gisolfi and Wegner 1984 in Gisolfi and Mora 2000)

Thus considered, the hypothalamus is not merely an integrator of thermal sensations but is itself a key sensor. Corbit (1969), in Gisolfi and Mora (2000) found that rats would work to change their own hypothalamic temperature to relieve discomfort sensed from either the skin or hypothalamus. Why would the

Fig. 4.5 Sagittal (almost median) section of the head and neck, with a portion of the brain included (O'Rahilly et al. 2004). Note the close proximity between the hypothalamus (*marked red*) to the respiratory tract (*marked blue*)
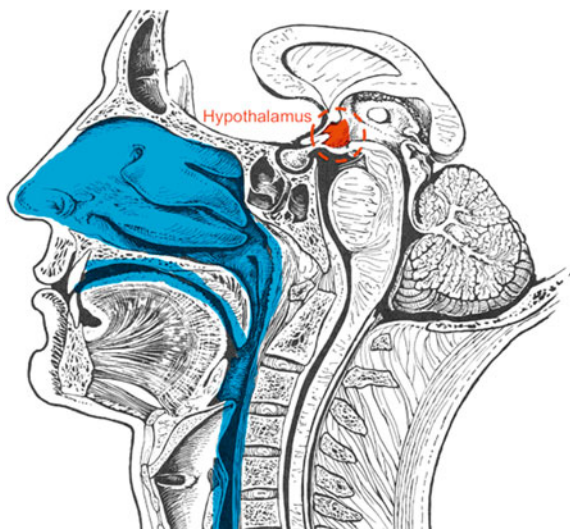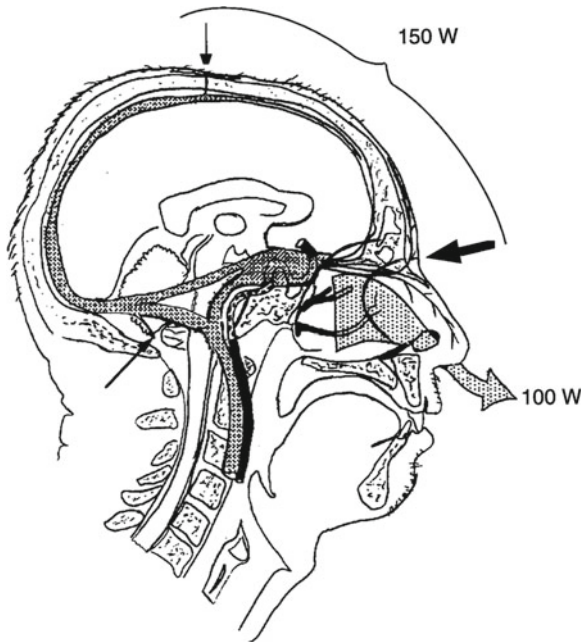
Fig. 4.6 Schematic representation of some of the heat exchange mechanisms of selective brain cooling in humans. Cabanac says, 'The important heat loss areas are shown on the figure: head skin and upper airways including the conchae. The blood of the carotid artery can exchange heat with the returning venous blood in the neck (internal jugular vein), in the cranial bone (carotid sinus, spotted area), and in the sinus cavernous. An important structure is not shown, the pterygoid sinus, an important network of veins in the cheek and pharynx communicating with the intracranial venous network. The *arrows* indicate the veins where blood was recorded as flowing inward during hyperthermia' (Cabanac 1995)

hypothalamus not only take inputs from the other parts of the body, but also from itself (see Fig. 4.4)? It seems crucial that the temperature of the brain is read, not by cutaneous or core sensors, but by the hypothalamus itself. The human body can be seen as a poikilothermic shell (lacking temperature regulation, like reptiles) around a homeothermic core (Gisolfi and Mora 2000). The core temperature is tightly regulated and operates within a much smaller margin than the shell which consists of skin, subcutaneous tissue and muscle. Within the core, consisting of abdominal, thoracic and cranial cavities, what is the priority of temperature regulation (in terms of sensitivity weighting)? It would appear that from the supremacy of the hypothalamus reading, that the cranial temperature is the most important.

If cooling the hypothalamus was like messing with the thermostat, this makes it all the more puzzling as to what advantage there could be in cooling the brain directly. It seems more logical to view the brain as the organ that would suffer the most from excessive heat gain, and thus the need to protect it from overheating. Figure 4.5 shows the proximity of the hypothalamus to the respiratory tract. It appears plausible that with the close proximity between the respiratory path and

the hypothalamus, that inhaling cold air could cool the hypothalamic sensors that regulate brain temperature (see Fig. 4.6).

4.5 Selective Brain Cooling

Selective brain cooling (SBC) is the mechanism to cool the brain directly through special venous arrangements. Though SBC is well accepted in some animals, the existence of such a phenomenon in humans is still debated (see *Journal of Applied Physiology,* 2011; 110 (2) for a point-counterpoint series of debates on *Humans do not demonstrate selective brain cooling during hyperthermia*).

The brain is particularly sensitive to temperature rises. The logic behind SBC is to protect the brain against the unabated rise in temperatures brought on by hyperthermia. Beyond 42 °C protein denatures and becomes insoluble, much like the process of boiling eggs. Partially denatured proteins are able to recover when normal temperatures are restored but the process is complicated by other enzymes that break down partially denatured proteins (Suvernev 2006). Thus the impact on a subject recovering from excessive heating is not just a threshold temperature but involves the exposure time (Table 4.2). Another reasoning for the need for brain cooling is the Salerian-Saleri Temperature Thesis which states, 'Cooler biologically compatible core body temperatures prolong lifespan and are of value to combat illness' (Salerian and Saleri 2006).

The temperature of the brain is typically higher than the trunk. The proponents of SBC therefore judge that the unequivocal criterion for demonstrating SBC is to prove brain temperature can be decreased below trunk temperature during hyperthermia. In many human SBC experiments, hyperthermia was generated though exercise (Cabanac 1995). When brain temperature is increased, a direct and immediate effect is seen on blood pressure (Rodbard 1948). Whilst it is clear that a heated brain will drive a thermoregulatory response, it is less obvious if a stressed brain will be heated. With no significant muscular metabolism in the sedentary office setting, one wonders if work stress alone can elicit a SBC response. This can be further analysed along the following considerations:

1. Can stress directly trigger SBC?
2. Does a stressed brain require SBC even before there is hyperthermia?
3. Can stress raise core temperature (hyperthermia) to illicit a SBC response?

Animals where SBC is not disputed possess a carotid rete (or *rete mirabile)* that channels blood across the stream of respired air. Maloney (1997) found evidence

Table 4.2 Tolerance as a function of dose rather than absolute temperature (Cabanac 1995)

Estimated brain temperature dose	
42–42.5 °C	60 min before irreversible brain damage
43 °C	10–20 min before irreversible brain damage

suggesting that in animals SBC could be adrenergically driven (responding to stress hormones), with SBC following a reduction of sympathetic activity, so that muscles which control the flow of arterial blood passively dilate the angularis oculi vein and constrict the facial vein. This means that after a stressful episode, blood flow is diverted from face to the back of nose, where the carotid rete cools the supply of blood to the brain (Fig. 4.7). So in animals with a carotid rete, SBC is initiated *after* a stressful episode.

Human facial veins are supplied with both α- and β-adrenoreceptors which respond to transmural nerve stimulation and noradrenaline (Table 4.3), these 'unusual characteristics for a vein are basically similar to the ones described for the rabbit facial vein' (Mellander et al. 1982, p. 393), a view also supported by Bevan (1983).

However, in humans there is no carotid rete as heat exchanger, so the blood should ideally be cooled before entering the sinus cavernous (a big lake in the endocranial space beneath the brain), not in it. The stress response which would have dilated facial vessels and consequently made SBC less effective in animals with a carotid rete is now an essential part of the human SBC response. So under
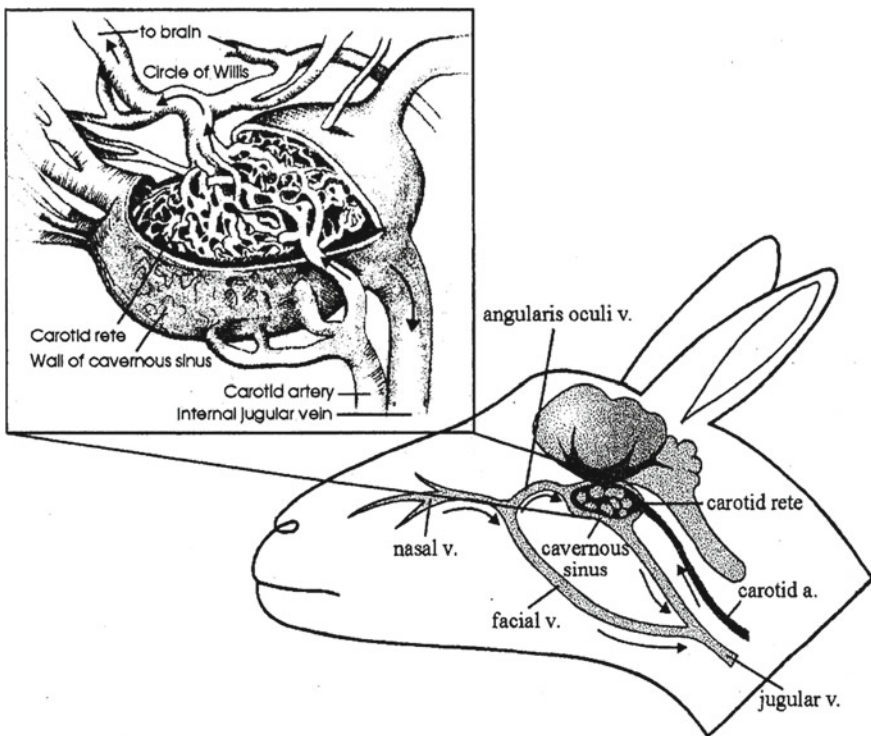
Fig. 4.7 Vasculature involved in selective brain cooling (SBC) in artiodactlys (Maloney 1997)

Table 4.3 Adrenoreception of facial and angularis oculi veins

Blood vessel	Predominant receptor (Maloney 1997)	Response to epinephrine	Level for predominance (Cassidy et al. 1986)
Facial vein	β-adrenergic smooth muscle	Vasodilation	Dominant at low levels of epinephrine
Angularis oculi vein	α-adrenergic smooth muscle	Vasoconstriction	Dominant at high levels of epinephrine

conditions of moderate stress the face flushes as the superficial facial veins carry more blood to the surface and cool it more effectively before delivering that to the brain. Under extreme stress however, vasoconstriction dominates and the face appears 'pale as a sheet'. The exact response varies across individuals depending on the 'abundance of "innervated" α- and β-adrenoceptors in the facial vein' of which age appears to be a factor (Mellander et al. 1982, p. 397).

Panting which facilitates heat loss from the carotid rete, is absent in both humans and horses which lack the carotid rete. Both mammals instead rely on sweating for heat loss, which is most profuse on the head (Cabanac 1995). Doppler ultrasound measurement show strong blood flow from face (forehead and upper face) → *angularis oculi* veins → brain (intracranial space) during hyperthermia (Cabanac 1995). Even in normothermia, the flow is similar (Cabanac and Caputa 1979). So heat is not merely lost by surface radiation of the heat in the head which was conducted though the skull and scalp, but the act of cooling the face cools the blood that supplies into the brain.

The skin on the head is also equipped with a higher density of sweat glands than that of the rest of the body. Does the mere act of perspiring cool the body, or does perspiration need to be evaporated for it to be effective?

> There are people born without sweat glands (anhidrotic ectodermal dysplasia). …A high school miler from Des Moines, Iowa, who was born with anhidrotic ectodermal dysplasia, illustrates an important physiological point. The mile typically runs on a quarter-mile track, and each competitor must complete four laps. This man was able to compete because his team mates formed a bucket brigade and doused him with a bucket of water every quarter-mile of the race, to produce evaporative heat loss. This anecdotal story is extraordinarily relevant because it emphasizes a biological fact: that heat is lost by evaporation and not by the process of sweating itself. In other words, it doesn't make any difference how water reaches the surface of the skin, by sweating or by bucket; it is the process of evaporation that cools the skin, not the process of sweating. An important question is whether these individuals have a high skin blood flow, even though they have no sweat glands. (Gisolfi and Mora 2000, pp. 104–105)

There appears to be evidence supporting the need for a cool face under times of stress. When dressed in a standard office garb of long-sleeve shirt and tie, little evaporative opportunity is provided to perspiring skin. The only viable and most effective mechanism for cooling is thus to cool the face. This explains why even when occupants are in conditions identical in thermal comfort parameters, the different levels of stress they experience account for drastically different different demands for cooling. Surgeons perspire more than nurses even though they have

the same physical activity (in muscular metabolic terms, Fig. 4.8a); cars now feature separate climate controls to both seats even though the environment is similar (Fig. 4.8b); and in stressful reality TV appearances (like Millionaire Hotseat and Dragons' Den), difficult questions posed to participants cause a number to break out in sweat. So under identical conditions (of T, MRT, RH %, vel, met and clo) different responses emerge as a direct consequence to stress, and this is evidenced most noticeably in facial perspiration.

Further support is found in Magilton et al. (1984) who in human experiments discovered that the temperature of blood flowing through the angularis oculi vein was lowered during mental challenges. They state:

> …the blood in the angularis oculi vein is acting as the coolant for arterial blood ascending to the brain. …The evidence presented here supports the concept that the rate of heat transfer from the superficial vessels in the face and nasal mucosa to the ambient air is regulated in responses to mental activity. Consequently, the temperature of the venous blood flowing towards the cavernous sinus via the angularis oculi vein is decreased during periods of increased heat production in the brain occasioned by an increase in the level of mental activity. (Magilton et al. 1984, pp. 3, 7)

4.6 Nasal Air-Conditioning

Besides facial perspiration, nasal air-conditioning also facilitates the brain cooling process. Irmak notes the impact of craniofacial features on the efficacy of cooling:

> The size of the nasal cavity is strongly affected by climate. In hot, moist climates, it is generally broad: in cold, dry climates it is narrow. In hot climates, a broad cavity permits maximum surface area of nasal turbinate's for cooling the inhaled air, while a restricted air intake under cold conditions would seem to be essential to lessen the danger of freezing

Fig. 4.8 Anecdotal evidence of **a** a perspiring surgeon and **b** separate climate control systems in modern cars, that even with identical environmental conditions, the personal response goes beyond clothing and physical metabolism (Stock photography)

the lungs. Individuals from hot climates have thick, everted lips, and those from cooler climates, have thin inverted lips. Thick, everted lips tend to radiate more heat and thus cool the brain by angular vein. Conversely, thin lips tend to conserve body heat and prevent their freezing in severely cold weather. (Irmak 2004, p. 977)

Whilst facial cooling of blood appears to be a primary means of cooling the brain with cooled blood, respiration also plays an important role. Mariak et al. (1999) showed that the human brain could be cooled, at its outer frontobasal aspects, through heat loss to the upper airways. It would follow that the higher the flow rate through the nose, the more heat is loss through this passage. Since a dilated nostril reduces nasal airflow resistance and increases maximum flow rate (Cabanac 1995), the efficacy of nasal cooling on brain temperature can be determined by nostril dilation vs temperature of ear tympana (T-ty), where White and Cabanac (1995) found a strong correlation between dilation and a reduced rate of T-ty increase.

The nose plays an important part in warming and humidifying the inspired air to alveolar conditions. Based on the measurements by Lindemann et al. (2001), under ambient conditions of 22 °C, 35 %RH; healthy candidates had nasopharynx conditions of 32–34 °C and 85–95 %RH at the end of inspiration. Elad et al. (2008) propose a psychrometric process of determining nasal air-conditioning based on a respiration rate of 15 breaths/min and tidal volume of 0.5 l. The nose can thus account for 1.5–1.8 W of sensible cooling and 6.7–9.0 W of latent cooling; in agreement with, but slightly less than, Elad et al. who assume alveolar conditions (37 °C, 100 %RH) in the nasal cavity.

The magnitude of respiratory heat loss in exercising, hyperthermic humans was demonstrated by Rasch et al. (1991) to be as high as 100 W. It is interesting to note that when therapeutic hyperthermia is employed in cancer treatment, the only cooling thermoregulation of the anaesthetised patient is that of high frequency artificial lung ventilation (Fig. 4.9).

4.7 Dehydration, Cognitive Function and Temperature

Excessive water consumption is often discouraged in thermal comfort studies in order to avoid trips to the toilets so as to maintain uniform conditions for both the environment and occupant. Where cognitive, and possibly thermoregulatory, functions are concerned, dehydration plays a larger role than acknowledged in thermal comfort studies. Batmanghelidj (2003), who researched into the effects of dehydration, explains:

When there is a gradually establishing chronic dehydration in the body, the brain has to depend more on glucose as a source of energy. The brain needs more glucose for its energy value and its metabolic conversion to water. Under the urgent circumstances produced by stress, up to 85 % of the supplemental energy requirement by the brain is provided by sugar alone. This is why stressed people resort to eating sweet food. While all the other cells need to be influenced by insulin to take up glucose through their cell walls,
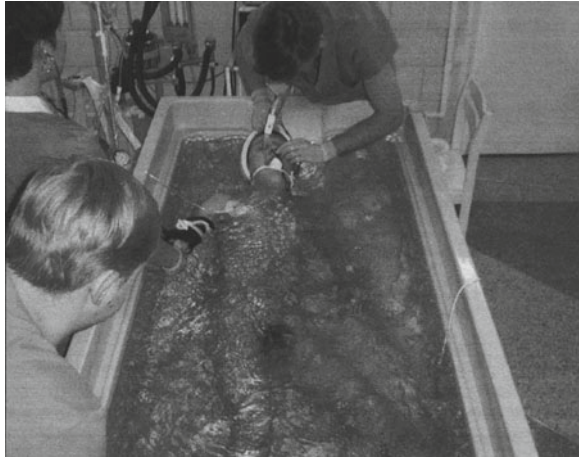
the brain does not depend on insulin to carry sugar across its cell membranes. (p. 110)
With dehydration, the level of energy generation in the brain is decreased. The ATP pool
of energy becomes gradually depleted, more at some sites of activity than others. Many
silent functions of the brain that depend on hydroelectric energy become inefficient. We
recognize this inadequacy of function and call it depression. To the human body, caffeine
is very much like the booster system in an engine. In the same way a booster system burns
fuel at a faster but inefficient rate to propel a car or plane at an exaggerated speed, so
caffeine forces an increase in consumption of ATP. (p. 200)

Dehydration has well established impediments to cognitive function. Whilst the
correlation is clear, the explanation behind this is still uncertain. Wilson (2003)
reviews the theories behind hormonal and cellular theories and finds the evidence
inconclusive. The most convincing, in Wilson's view is Barr's global workspace
theory (Baar 1993) which unifies physiological, psychological and philosophical
concepts.

This is based on the concept that cognition is of limited capacity. Thus, cognitive pro-
cesses perceived as working in parallel are actually functioning in competition with each
other. Selected activities are presumed to dominate cognitive awareness by harnessing
executive function more effectively than other competing processes. Utilizing Baar's
[global workspace] theory, Cohen attempts to explain the effect of dehydration on cog-
nitive function in a simplistic, albeit, rather plausible manner (Cohen 1983). Based on the
assumption that complex tasks require increased attention, Cohen proffers that acute
stressors such as dehydration compete for executive attention and awareness with parallel
processes occurring in other cognitive domains, thereby compromising overall cognitive
performance.

Since both the stress response of office work and thermoregulatory response of
the office environment will impose competing demands for attention from the
hypothalamus, Baar's global workspace theory would suggest that:

1. if the hypothalamus had sufficient capacity it could respond to both streams of
   inputs unconsciously; or else,

2. if the hypothalamus had inadequate capacity, the streams would compete for access to a broadcasting capability, i.e. to effect a conscious change in behaviour, disposing the occupant to reduce either the stress of work or thermal discomfort

The adequacy of *workspace capacity* would be highly subjective, and this explains why different individuals differ in their tolerance to thermal discomfort. The highly motivated individual will also be able to focus on the task more and ignore the insults of the thermal conditions. Even a well-rested individual will have more capacity, and thus be able to cope better under similar conditions of stress and thermal discomfort than a participant with inadequate rest.

Sleep plays a major role in cognition, and interestingly is also closely tied to metabolism and environmental temperatures.

4.8 Sleep, Cognitive Function and Temperature

Thermoneutrality for sleep is reached for at ET = 30–32 °C naked, or at 16–19 °C with pyjamas and at least one sheet (Onen 1994). The relatively stable temperature under a blanket of 30 °C is maintained at a preferred ambient temperature of 19 °C (Muzet 1984). During summer in Hong Kong, a survey found that the overwhelming majority would wear sleepwear (92 %), use blankets (90 %) and switch on the air-conditioning for most of the night (68 % use the air-conditioning for 5 h or more) (Lin 2006). In Singapore, there is a high level of residential air-conditioning ownership (see Table 4.4), primarily used for cooling through the night. This will be no surprise since Bach et al. (2002) found sleep to be less efficient at 35 °C than at 20 °C.

Sleeping typically proceeds from NREM (non-rapid eye motion) to REM (rapid eye motion) stages.

During NREM sleep the body still thermoregulates and perspiration is proportionate to the ambient thermal load, whereas during REM sleep, sweating is absent (Henane et al. 1977 in Gisolfi and Mora 2000). During the transition from NREM to REM sleep stages, the hypothalamic temperature rises independently of ambient temperatures. During REM sleep the body does not thermoregulate (Gisolfi and Mora 2000).

Table 4.4 Households with air-conditioning in Singapore by age group of main income earner (Singapore Department of States 2007)

Air-conditioner ownership										
Age	Below 25	25–29	30–34	35–39	40–44	45–49	50–54	55–59	60–64	65 and over
Percentage	60.1	73.9	81.3	82.6	79.8	79.4	74.6	72.1	59.9	48.1

Parmeggiani (2003) suggests that the poikilothermic state during REM sleep is produced by an inactivation of the hypothalamic thermostat. As the thermoregulatory response is switched off, sleeping outside of thermal neutrality elicits a conflict between maintenance of homeothermia and sleep pressure, where 'the probability of REM sleep onset depends on a successful down-regulation of core temperature' (Parmeggiani 2003, p. 564, see also Fig. 4.10). In a sense, the hypothalamus must be satisfied that thermoregulation is no longer needed before it can shut down.

Dreaming occurs during REM sleep where the increased neural activity is accompanied by higher metabolism, oxygen consumption and cerebral blood flow which cannot be attributed to muscular metabolism (Haskell 1981). 'Reduced metabolism in animals during REM sleep can be largely attributed to muscular atonia, whereas increased metabolism in humans may depend on their large brain' (Haskell 1981).
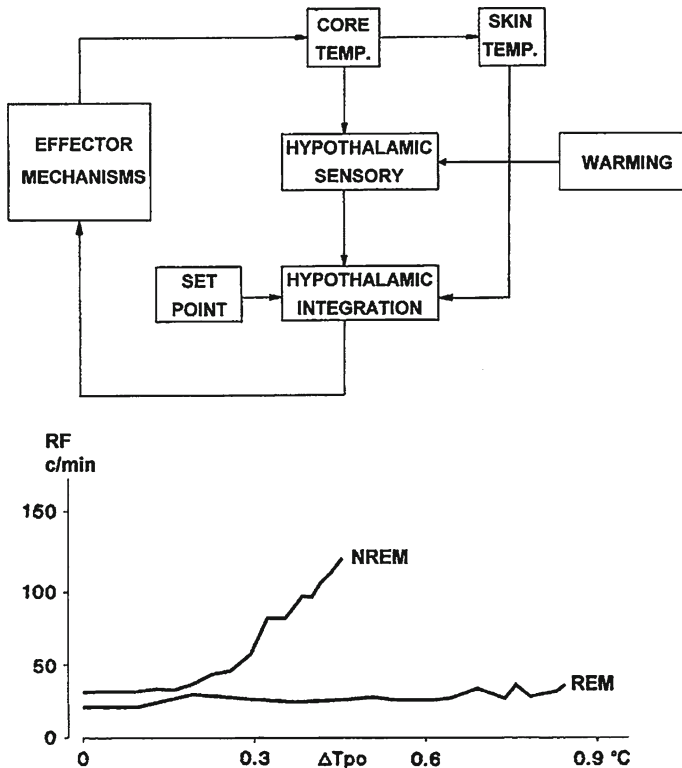
Fig. 4.10 Influence of preoptic-anterior hypothalamic diathermic warming on breathing rate during sleep (cat). The slope of breathing rate during NREM sleep shows a steep increase beyond the response threshold (about 0.2 °C), whereas there is no response during REM sleep. *RF* respiratory frequency; *Tpo* preoptic temperature (Parmeggiani 2011)

Gisolfi and Mora (2000) suggests that NREM sleep is necessary to provide a homeostatic balance for brain and body cooling. He finds support for his argument in the following:

1. Elevated waking temperature in mammals and birds could not be sustained without the brain cooling provided by sleep (McGinty and Szymusiak 1990).
2. In dolphins, which basically have two brains and show unihemispheric sleep, the sleeping brain cools (Kolval'Zon and Mukhametov 1982).
3. Hyperthermia induced by vigorous exercise in the day increases NREM sleep at night. Exercise in the presence of cooling, so that no hyperthermia is experienced, prevents the increase in NREM sleep. The brain appears to record how long brain temperatures have been elevated during the day and compensates for this "awake heat load" by sleep- related cooling (McGinty and Szymusiak 1990).

Deep sleep or slow wave sleep (SWS), which happens in the late stages of NREM sleep, is also the phase where energy restoration occurs, particularly stores of glycogen which is heavily consumed by an active brain or a sleep-deprived brain (Sapolsky 2004).

> …metabolically costly processes of respiration, heart rate, gut motility and muscle activity are reduced during sleep and some of the resulting energy saved may be redistributed to other metabolically costly processes that are proposed as sleep functions [e.g. sleep-dependent hormone synthesis and release, increases in immune function, replenishment of cerebral glycogen stores and synaptic plasticity]. Thus, based on our findings and findings from the existing literature, we propose that one of the functions of sleep in humans is to conserve energy and that some of the energy saved is redistributed to support other critical sleep-dependent physiological processes. (Jung 2011, p. 242)

SWS couId be stimulated by decreasing body temperature at sleep onset. The increase in SWS can be interpreted as being a thermal response which prevents hyperthermia and/or serves to down-regulate body temperature.

> Behavioural thermoregulation is negatively affected by sleep since the motility related to the search for thermal comfort can only precede the onset of sleep. However, specific postures elicited by positive and negative thermal loads are static behavioural thermoregulatory responses during NREMS to maintain the balance between heat production and heat loss. In contrast, the drop in postural muscle tonus during REMS, occurring in all studied species including humans, is unrelated to ambient temperature and impairs postural thermoregulatory responses. (Parmeggiani 2003)

Bringing this knowledge together, the picture during REM sleep gives a good parallel to the active brain in the day: high mental activity accompanied with increased blood flow, oxygen consumption and elevated temperature. Despite there being no muscular metabolism, the act of dreaming elevates body temperatures and gives an indication of the significance mental metabolism plays on the whole body.

The thermoregulation of NREM sleep on the other hand gives a valuable insight into why people in the tropics, or temperate summer, would sleep with blankets in an air-conditioned room instead of sleeping naked. Thermoregulation by

perspiration is available during NREM sleep but shivering only occurs during wakefulness and shallow sleep. Thus cold is more disruptive to sleep than warmth (Haskell 1981). The further temperatures depart from neutrality, the harder it is to fall asleep and maintain deep sleep. NREM sleep (and particularly the SWS stage of NREM sleep) is also the stage where brain and sympathetic activities slow down enough for brain cooling. If one of the functions of sleep is to cool the brain, then the exposure of the head to cooling will either give a better quality of sleep or supply the required brain cooling within fewer hours of rest. The aim is therefore to achieve a stable 30 °C under the sheets and 19 °C on the exposed face. Thermal neutrality may prove monotonous in the day but at night, it may actually have an important role to play for quality sleep (Libert et al. 1982).

> As we glide down into slow wave sleep, some obvious things occur to facets of the stress-response system. For starters, the sympathetic nervous system shuts down, in favour of that calm, vegetative parasympathetic nervous system. In addition, glucocorticoid levels go down. …Some of the hypothalamic control of pituitary hormone release consists of an accelerator and a brake—a releasing factor and an inhibiting factor. …Thus, sleep deeply, and you turn off glucocorticoid secretion. (Sapolsky 2004)

If sleeping in an air-conditioned room can allow one to sleep better, it will concurrently reduce the level of stress hormones circulating in the system, which will in turn better prepare the body for the challenges of the next day. And since sleep also has a profound impact on the level of mental performance following, resting temperature also has an indirect effect on thermal comfort expectations the next day.

> Take a normally rested subject, stick her in a brain imager, and ask her to solve some 'working memory' problems (holding on to some facts and manipulating them—like adding sequences of three-digit numbers). As a result, her frontal cortex lights up meta-bolically. Now, take someone who is sleep deprived and he's awful at the working memory task. And what's going on in his brain? What you might have guessed is that frontal metabolism would be inhibited, too groggy to get activated in response to the task. Instead, the opposite occurs—the frontal cortex is activated, but so are large parts of the rest of the cortex. It's as if sleep deprivation has reduced this gleaming computer of a frontal cortex to a bunch of unshaven gibbering neurons counting on their toes, having to ask the rest of their cortical buddies to help out with this tough math problem. (Sapolsky 2004)

Since sleep deprivation requires more of the cortex to be mobilised to solve a mental problem, more energy is expanded by the brain and more cooling is demanded. The attention resource availability theorem (earlier mentioned with regard to dehydration) would explain the need to activate other regions of the brain when the cortex is exhausted.

It follows that a participant in a thermal comfort experiment should not just be healthy (a fever would drastically alter metabolism rate) but be well rested. It can further be argued that in fast-paced cities where offices operate till late, the need for air-conditioning in offices is necessitated by the chronic sleep deprivation of many workers.

This is supported by a review of research by Gallup and Hack (2011) showing a positive relationship between brain temperature and yawning. They explain the thermoregulatory role of yawning as follows:

> First, yawning produces significant changes in circulation, including acceleration in heart rate and elevation of blood pressure. More specifically, powerful jaw stretching during yawning produces increases in neck, head and facial blood flow, and the deep inspiration during yawning produces significant downward flow in cerebrospinal fluid and an increase in blow flow in the internal jugular vein. Together, these processes may act like a radiator removing hyperthermic blood from brain while introducing cooler blood from the lungs and extremities, thereby cooling cortical surfaces through convection. Secondly, it is hypothesized that yawning also provides a direct heat exchange from deep inhalation of cooler ambient air. The air exchange during yawning could cool venous blood draining from the nasal and oral orifices into the cavernous sinus, which surrounds the internal carotid artery supplying blood to the rest of the brain. (Gallup 2011, p. 972)

4.9 Stress, Blood Pressure and Ambient Temperature

Stress is strongly linked to elevated blood pressure, but blood pressure on the other hand is significantly influenced by ambient temperatures with SBP (systolic, or maximum, blood pressure) lowered by 5 mmHg per 10 °C increase in ambient temperature (Kunutsor 2010). The stress response has been earlier showed to deliver more resources to the brain and warmer temperatures would negate this benefit by reducing blood pressure. This could explain why when Singaporeans are expected to perform productive mental tasks, it would be an insult to not provide air-conditioning (Hitchings and Lee 2008).

This further explains why during a break from the stress of work, that change for a warm environment becomes particularly appealing. Much as Singaporeans may gripe about the excessive air-conditioning of their offices, this condition makes *prandial thermophily* (selection of a warm environmental temperature for feeding) to be particularly rewarding in terms of alliesthesia, and the return to the chilly office refreshingly welcome.

Stress would limit the circulation of blood to the extremities and elevate core temperature. This paradoxical situation sheds light into why some people experience cold sweaty palms under stress: the cold is a result of blood being shunted from the hands, and the perspiration from the elevated core temperature. Evaporating the sweat on the palms cools the hands and further constricts the circulation, making a bad situation worse. Under such a scenario, taking a lunch stroll on a hot afternoon would actually have some therapeutic benefits.

The afternoon lunch break gives office workers a chance to recirculate blood flow to the limbs by strolling out for lunch. The warmth of the walk and eating destination reduces blood pressure and increases peripheral circulation. In preparation for the consumption of a meal, the parasympathetic system is activated, and encouraged by the calming effects of warmth. The previous stress response on the

sympathetic system in releasing energy is now replaced by the parasympathetic system in the uptake and storage of energy. This lasts well after lunch, commonly referred to as the post-prandial snooze; an effect easily dismissed with the onset of the next stressor. Once stressed again, the sympathetic nervous system kicks in, the digestive system shuts down and energy is mobilised to tackle the next mental challenge.

4.10 Stress Physiology and Psychology

The physiological response to stress can be seen as an action (the stressor) causing a cascade of reactions (in the sympathetic response), which generally tend to increase the temperature of the head. The mechanism behind this has been discussed, but it is inadequate to understand this process mechanistically. It is not as if the magnitude of a stressor could be turned like a dial and have the resulting temperature correspond. In the context of the workplace, we mentioned stressors like looming deadlines, difficult co-workers, unreasonable demands from superiors and clients, and so forth. None of these matters present physical dangers (like war and famine)—they are only as significant as one would make them out to be.

Take public speaking for example. To some it comes naturally, and to others it takes extreme coercion. In the latter, and speaking with first-hand experience, it can be accompanied with an elevated heart rate, increased blood pressure, perspiration on the forehead, sweaty palms, cold feet, hyperventilation, etc. The psychology of a person is integral to a stress response on two levels. Firstly an event has to be perceived as a stressor, and secondly the response is limited or amplified in the mind.

> An organism is subjected to a painful stimulus, and you are interested in how great a stress-response will be triggered. The bioengineers had been all over that one, mapping the relationship between the intensity and duration of the stimulus and the response. But this time, when the painful stimulus occurs, the organism under study can reach out for its Mommy and cry in her arms. And under these circumstances, this organism shows less of a stress-response. …A critical realization roared through the research community: the physiological stress-response can be modulated by psychological factors. Two identical stressors with the same extent of allostatic disruption can be perceived, can be appraised differently, and the whole show changes from there. Suddenly the stress-response could be made bigger or smaller, depending on psychological factors. (Sapolsky 1998, p. 213)
>
> As a physiologist who has studied stress for many years, I clearly see that the physiology of the system is often no more decisive than the psychology. (Sapolsky 1998, p. 339)

Emotional and mental states, whilst not quantifiable, take as much share as the biological and physical states. And since stress is as much physiological as it is psychological, there is a valid case to be made for the self-evaluation of stress: you are as stressed as you think you are.

The phenomenal power of the mind is clearly manifest in Wim Hof, the *Iceman* (Fig. 4.11), Guinness record holder for immersing himself almost naked in ice for

Fig. 4.11 Wim Hof, the 'Iceman', running a full marathon in northern Finland in temperatures close to −20 °C wearing only his shorts. He claims to have prepared for the event with no physical training, but only thermal conditioning in freezing canals and a meat freezer. *Daredevils: The Ice Man* ©2009 Firecracker Films, reproduced with permission

over an hour. Dr Ken Kamler who specialises in treating hypothermia believes that Hof's ability lies in the wiring of his brain. 'It's very easy to speculate that the same mind control that you use to control your heart when you're scared also can be called upon to control the other organs in the body. And maybe that's how Wim Hof does this,' said Kamler (ABC News 2008).

4.11 The Difficulty of an Index

Mental metabolism is missing in models, the existing ones largely cannot be applied to body segments like the head. For example, Gagge's ET* and SET* model (1986) is based on overall skin wettedness. Höppe's (1999) physiological equivalent temperature (PET) is based on the 'Munich energy-balance model for individuals' (MEMI), equations describing (1) the heat flows from body core to skin surface (2) blood flow from body core to skin and (3) heat resistance of the clothing (Hoppe 1999). Where the heat is concentrated in the brain and dissipation through the face and respiration, it is unlikely these models can be applied accurately.

The purpose of an index is to translate measurable data into controllable conditions. The neurophysiological stress response will result in large interpersonal variations and fluctuations dependent on the degree of stress and a response modulated by individual psychology.

There is inadequate data to model the heat generated by the brain in conjunction with mental demands. This is related to fluctuations in core temperature and varying heat flows to the brain, the role of smooth muscles on facial veins to different concentrations of stress hormones, the location of perspiration and their different rates, the breathing rate, and many other confounding factors. Even if the data was available to model the precise heat flows, the actual response will vary through the day, depending on stress, determined by psychology. Where the resultant temperature is correlated to productivity, the cognitive performance is affected by dehydration, sleep and other factors that demand attention from the cognitive workspace.

> If, say, a pianist plays a Bach fugue, I can listen to it and can watch him play and probably can adequately describe his playing. As critic, I might even be more competent to write about the concert than the pianist himself, but there remains something known only to the pianist. He plays, and he "erlebt", he experiences the playing of the fugue. To act is "unhinterfragbar", cannot be "questioned behind" or derived from something else. Any question about the quality of the experience of the pianist (1) is itself an act (and not a description of an act) and therefore presupposes that the questioner is able to act or at least "knows" what it means to act from his own experience, and (2) can finally be answered only by performing the actions of the pianist oneself, by doing something instead of talking about doing something. (Janich 1990, p. 154)

To borrow Janich's distinction between the unknown and the unknowable, the thermal response of humans under stress might be *unknown till now* but the complexity of an individual's thermal evaluation is, in my view, unknowable. The pianist in our study would be the office occupant, the performance would be the adaptive behaviour sought by an occupant. The pleasure he "erlebt" (or undergoes) is uniquely his own experience, and something that the thermal comfort researcher can observe, document and analyse. Yet the researcher will never attain the experience that underpins the expression of comfort. For the occupant, it is a *satisfaction of mind* known only to him.

In other words, only the occupant knows what his 'perfect' temperature is.

4.12 Concluding Thoughts on Brain Cooling

Stress arouses the sympathetic nervous system and many of these effects require a thermoregulatory response. A number of autonomic nervous responses also parallel those needed to thermoregulate, especially in the area of SBC. The global workspace theory explains why sleep and hydration also have indirect but strong influences on cognitive performance and temperature demands.

In the office environment the most effective cooling response for productive mental work will be from facial cooling and respiration. However whilst stress can be measured by the concentration of circulating stress hormones, the stress physiology is modulated by a person's psychology.

Work stress can explain why field studies reveal a desire for colder temperatures than the climate chamber studies would determine. The confounding factors and diversity of possible responses also reveal why a common temperature cannot universally satisfy.

The practical consequence of this literature survey suggests that air-conditioning is not only needed for productive mental work in a stressful environment, but more air-conditioning is needed than was predicted with the PMV model. Due to the efficacy of facially applied air-conditioning, there should be a special effort to deliver chilled air to both the face and breathing zone, instead of delivering ambient cooling. The variety of working demands require versatile and personal control: the air velocity affecting the facial skin cooling and the air temperature affecting the respiratory cooling.

Lee Kuan Yew, who made Singapore the *air-conditioned nation,* works in an office set at 22 °C and sleeps at 19 °C (McCarthy 1999). For a person with undisputed mental performance, he may have intuitively known the impact of air-conditioning on a developing knowledge-based economy.

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Chapter 5
Comfort Energetics: Thermal Comfort Under Energy Constraints

This chapter represents an energy-conscious approach to understanding thermal comfort. With the environmental variable of T, MRT, RH and wind v as its structure, it begins with a psychrometric analysis where the roles of temperature and humidity are denominated in PMV votes and the power needed to improve those votes. The role of humidity is critically reviewed with a case made for challenging the accepted norms an optimum RH range. Finally the efficacy of moving air is analysed in the different ways it can be employed.

5.1 Case-Study: The Windup Girl

The PMV is the most popular standard for air-conditioned buildings, underpinning the ISO 7730 and ASHRAE 55 standards. It is used as a tool to assist mechanical engineers in specifying the correct plant sizes to meet the anticipated space cooling requirements. It is common that the engineering tools and rules of thumbs already have a safety margin, in addition to which engineers typically load another margin (Houghton 1998). Assumed in this approach is that there will not be any energy constraints placed in the life of the building and its equipment. It assumes that it is acceptable to over-engineer the mechanical ventilation system for that worst case scenario with the consolation that it can always be operated at partial load, even if that requires far more power than running a correctly sized plant at full load.

In his award winning science-fiction novel *The Windup Girl*, Bacigalupi (2009) paints the world post global-warming, where the oil economy has collapsed and the primary sources of energy are from methane composters and food calories. Electricity is so scarce it only exists to run government-owned computers, and personal computers are pedal operated like an old-fashioned sewing machine. Energy is produced by the muscles of people or beasts of burden, then stored kinetically in either flywheels or springs to power factories, transport and weapons. What is realistic and sobering about Bacigalupi's future is the challenge he makes to many assumptions we take for granted: unlimited resource, continued global

collaboration, genetic diversity. What if the only energy available was what we could muster from our muscles in a world with limited food?

> Overhead, the towers of Bangkok's old Expansion loom, robed in vines and mold, windows long ago blown out, great bones picked clean. Without air conditioning or elevators to make them habitable, they stand and blister in the sun. (Bacigalupi 2009, p. 10).

The windup girl, the protagonist of the story, is a genetically modified woman with porcelain-perfect skin and greatly reduced pores, once a secretary for the rich who could afford air-conditioning, she has now been abandoned in hot-humid Bangkok (Fig. 5.1).

> Even with her augmented vision she barely spies the pores of her flesh. So small. So delicate. So optimal. But made for Nippon and a rich man's climate control, not for here. Here, she is too hot and sweats too little. She wonders if she were a different kind of animal, some mindless furry cheshire, say, if she would feel cooler. Not because her pores would be larger and more efficient and her skin not so painfully impermeable, but simply because she wouldn't have to think. She wouldn't have to know that she had been trapped in this suffocating perfect skin by some irritating scientist with his test tubes and DNA confetti mixes who made her flesh so so smooth, and her insides too too hot. (Bacigalupi 2009, p. 51)

5.2 PMV, Psychrometrically Analysed

If presented with the severe energy constraints of Bacigalupi's Bangkok, how would one reapply the principles underpinning the PMV model so that our windup girl does not overheat? For argument's sake, assume she votes on the comfort scale the same way normal people do. The aim here is to provide improvement to comfort with the smallest energy input. Starting with a reference condition (Table 5.1), one can determine the impact on PMV with each variable changed, and the corresponding energy needed to drive the change.

The windup girl, for this exercise, will be housed in a small and heavily insulated cubicle (1 × 1 × 2.4 m, see Fig. 5.2). Fresh air is supplied at low level by displacement ventilation at a rate of 10 l/s in a small space (c.f. Fanger 2000), the air change will be high at 15 ach (air-changes per hour). Under steady-state conditions, air is exhausted at the same rate as it is being supplied, and there is no recirculation. It is assumed that the supply air temperature will be the same as room air temperature and MRT.

The following calculations determine how much energy is required for each process, and the extent to which the PMV is improved. As the heat loads (external and internal) are independent of process, they have been omitted to simplify the calculations.

Four methods are plotted psychrometrically with about 7 steps in each process, in which the PMV is compared to the energy required for each step shown below and tabulated in Table 5.2.

Fig. 5.1 Book cover of *The Windup Girl* (Bacigalupi 2009) illustrated by Raphael Lacoste. Image credit: Night Shade Books © 2009, reproduced with permission

Table 5.1 Reference conditions for study in comfort energetics

Reference occupant		Notes
Ventilation rate	10 l/s/pax	Typical rate in practice (Melikov 2002)
T, outside	30 °c	
RH, outside	70 %	
Air speed	0.05 m/s	
Clothing	0.7 clo	Between 0.5 and 1.0 clo used to generate comfort envelope in ASHRAE 55 (2010) pp. 6, 24
Metabolic rate	1.1 met	As used to generate comfort envelope in ASHRAE 55 (2010) pp. 6, 24
PMV	+2.0	
Air-conditioning	C.O.P. = 3	One watt of electricity transporting 3 w of heating/cooling

Omitted items: envelope thermal load, internal heat load, fan power

1. Cooling without dehumidification: air is cooled at constant moisture ratio up to dew point (30 to 24 °C, 1 °C/step).
2. Cooling with dehumidification: air is cooled past dew point (70 to 40 %RH, 5 %RH/step).

Fig. 5.2 Climate booth to determine energy required to improve PMV by various cooling processes
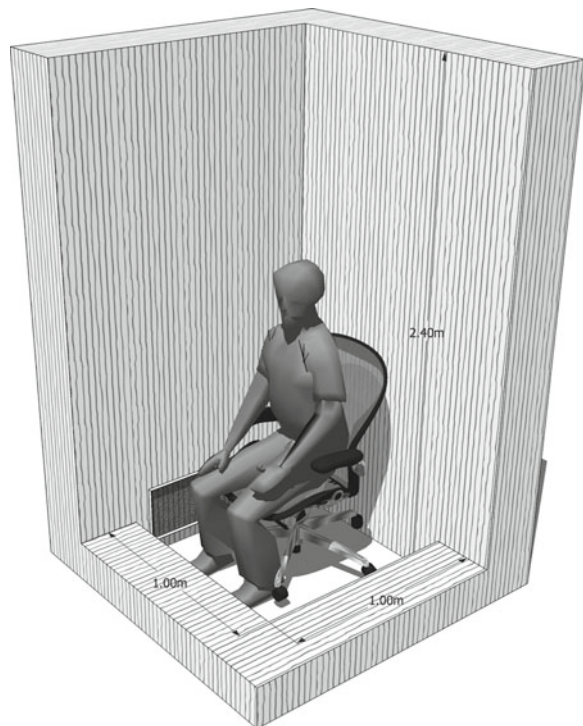
Table 5.2 Four methods analysed psychrometrically

Cooling, no dehumidification

T (°C)	RH (%)	PMV	H (kJ/kg)	dH (kJ/kg)	Spec vol (m³/kg)	Power (W)	Thermal W/vote	Electrical W/vote
30	70	1.994	78.37					
29	74	1.728	77.33	1.04	0.882	11.8	44.3	14.8
28	79	1.454	76.29	2.08	0.879	23.7	43.8	14.6
27	83	1.181	75.24	3.13	0.8761	35.7	43.9	14.6
26	88	0.907	74.2	4.17	0.8732	47.8	43.9	14.6
25	94	0.632	73.16	5.21	0.8703	59.9	44.0	14.7
24	100	0.356	72.12	6.25	0.8674	72.1	44.0	14.7

Cooling + dehumidification

RH equiv. (if at 30 °C) (%)	PMV @dp	Dew Pt	H- dp	dH (kJ/kg)	Spec vol (m³/kg)	Power (W)	Thermal W/vote	Electrical W/vote
70	0.327	23.93	72.04					
65	−0.056	22.7	67.22	11.15	0.862	136	66.5	22.2
60	−0.467	21.39	62.36	16.01	0.856	194	78.8	26.3
55	−0.908	19.98	57.41	20.96	0.850	254	87.4	29.1
50	−1.376	18.45	52.36	26.01	0.844	315	93.5	31.2
45	−1.903	16.78	47.19	31.18	0.837	379	97.4	32.5
40	−2.487	14.94	41.86	36.51	0.830	447	99.7	33.2

Direct evaporative cooling

RH (%)	T (°C)	PMV	HR (g/kg)	Vapour density (g/m³)	Humidification (g/sec)	Power (W)	Electrical W/vote
70	30	1.994	18.89	21.33			
75	29.17	1.796	19.23	21.76	0.0043	0.030	0.154
80	28.33	1.561	19.57	22.2	0.0087	0.062	0.142
85	27.56	1.385	19.89	22.6	0.0127	0.090	0.148
90	26.83	1.175	20.18	22.98	0.0165	0.117	0.143

(continued)

Table 5.2 (continued)

Direct evaporative cooling

RH (%)	T (°C)	PMV	HR (g/kg)	Vapour density (g/m³)	Humidification (g/sec)	Power (W)	Electrical W/vote
95	26.11	0.993	20.48	23.37	0.0204	0.145	0.145
100	25.5	0.84	20.73	23.69	0.0236	0.167	0.145

Desiccant dehumidification

| RH (%)	PMV	H (kJ/kg)	HR (g/kg)	dH (kJ/kg)	Spec vol (m³/kg)	Power (W)	Thermal W/vote	Electrical W/vote
70	1.994	78.37	18.88		0.8849		786.1	262.0
65	1.943	74.83	17.49	3.54	0.883	40.1	786.7	262.2
60	1.892	71.3	16.11	7.07	0.8811	80.2	786.5	262.2
55	1.841	67.79	14.74	10.58	0.8792	120.3	786.7	262.2
50	1.79	64.29	13.37	14.08	0.8773	160.5	784.0	261.3
45	1.738	60.8	12.01	17.57	0.8754	200.7	784.6	261.5
40	1.687	57.33	10.65	21.04	0.8735	240.9	784.8	261.6
35	1.636	53.88	9.3	24.49	0.8717	280.9	785.3	261.8
30	1.585	50.44	7.95	27.93	0.8696	321.2		

3. Direct evaporative cooling: air is humidified at constant enthalpy (70 to 100 %RH, 5 %RH/step). This process is actually passive so the only energy input has been the embodied energy of water (for sourcing, conveyance, treatment, distribution, end use and water treatment, Cohen et al. 2004).
4. Desiccant dehumidification: air is dehumidified by desiccant (constant enthalpy) and allowed to cool to ambient (constant T) (70 to 30 %RH, 5 %RH/step).

When the energy input for each step change is tallied with comfort outcome, it was observed that there is a good linear fit (with the exception of 'cooling with dehumidification') where each step change of equal magnitude in T or RH were matched by both 'comfort' and 'electrical W/vote'.

5.3 Comfort Energetics

In recognising that there can be multiple ways of achieving a better comfort vote, how do we determine which method has the most effective use of the energy input? A new unit for comfort energetics, watts per vote, is proposed to express this rating. By comparing different cooling techniques and expressing the energy needed to improve PMV by one vote we have an index to rate the efficacy of each approach to thermal comfort.

The comfort energetics, in watts/vote are summarised and the cooling technique ranked in terms of PMV efficacy (Table 5.3).
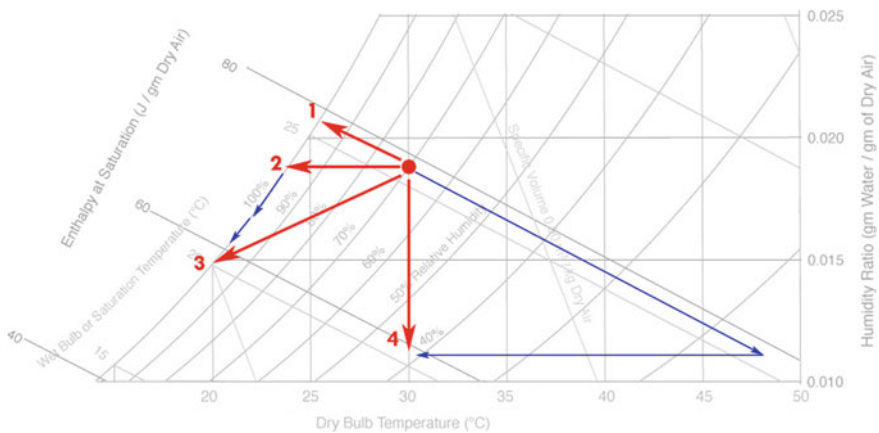
With the exception of "Refrigeration Past Dew Point" the comfort energetics described in watts/vote show good linearity and minimal deviation (s.d. < 3 %), indicative that the comfort energetics are constant and independent of the starting PMV. In other words, an improvement in comfort from +3 to +2 will require the same amount of energy as +2.5 to +1.5, +1 to 0 and so forth.

Table 5.3 Cooling methods analysed in terms of energetics

Rank	Comfort approach	Process	Comfort energetics (W/vote)	S.D. (%)
1	Direct evaporative cooling	Adiabatic humidification	0.15	2.9
2	Refrigeration up to dew point	Constant humidity ratio (isodrosothermic)	15	0.4
3	Refrigeration past dew point	Cooling with dehumidification	28	15.7
4	Desiccant dehumidification	Adiabatic + isothermic dehumidification	262	0.1

Whilst the linear fit was unexpected it is convenient that the ordinal scale of the comfort vote could relate so well with the numerical scale of the psychrometric chart.

5.3.1 Comfort in High Humidity

We can also see that a change in temperature has a far more profound impact on comfort than a change in humidity. This is not new, the ISO 7730 standard mentions that "typically a 10 % higher relative humidity is felt to be as warm as a 0.3 °C rise in the operative temperature." There is however little meaning to compare %RH to T°C unless it can be denominated in terms of the energy embodied to drive the change. Based on the psychrometric analysis of a PMV response, reducing air temperature will drive a response far more significant than the reduction in humidity. So in terms of comfort energetics we can say that reducing temperature (15 W/vote) is 17 times more effective than reducing relative humidity (262 W/vote), and that an evaporative cooler is 100 times more effective in achieving comfort than an air-conditioner, even if the air-conditioner does not perform any dehumidifying function.

This marginal impact of humidity is consistent with de Dear's findings that in climate chambers held at 35 and 70 %RH respectively there were no significant differences in preferred temperature (de Dear et al. 1991).

If energy was the only constraint, and thermal comfort the only consideration, then misting fans with their saturated supply air offer unmatched comfort energetics. These are used in outdoor and semi-outdoor settings with the common notion that they are unsuitable for indoor use because they increase the moisture ratio of indoor air. From the human thermal comfort point of view, this logic is flawed. If the indoors and outdoors were at the same temperature and the misting fans were merely saturating the air surrounding an occupant, then there is no psychrometric difference. If all environmental (T°C, RH%, MRT°C and v m/s) and personal variables (clo and met) were made equal to both indoor and outdoor conditions, the PMV will be identical. Likewise, the adaptive model will show that if the daily, or mean monthly T, were the same in both the in and outdoor, the ideal T will be the same. So strictly speaking, from the thermal comfort perspective,

there should be no objection that would prejudice against the indoor operation of misting fans, an example being provided by gadget blogger Christen Costa (2012).

Low humidity is associated with higher evaporation rates of the skin. The operative parameter should be that of absolute humidity rather than relative humidity. In the earlier calculation, air at 30 °C and 70 %RH had a dew point of 24 °C. It should not be assumed that skin cannot dry in air at 100 %RH as the saturated vapour pressure of moist skin of 5.3 kPa (at 34 °C) is still significantly higher than that of the air of 3.0 kPa (at 24 °C). The vapour pressure difference will drive moisture from perspiration to evaporate and re-condense in the saturated air as steam, a phenomena similar to breathing out mist in cold weather.

In an excellent review on the effect of high humidity levels on comfort (Fountain et al. 1999) research has consistently showed that the impact of humidity on comfort is minor (Table 5.4).

Dehumidification improves comfort very marginally and comes at considerable energetic cost. Dehumidification by cooling air past its dew point involved double the comfort energetics as compared to cooling without passing the dew point. In typical air-conditioning applications the dehumidified air is chilled so far below

Table 5.4 Literature on comfort in high RH (Fountain et al. 1999)

Years	First author	T range tested	RH range tested	Effects noted
1923	Houghten	26.7–69.4 °C	22.8–45 °C wet bulb	In comfort zone, comfort depends equally on wet- and dry-bulb temperature
1950	Glickman	Unspecified	20–80 %RH	ET* overemphasizes RH for long exposures
1960	Koch	20–34 °C	20–90 %RH	Small over entire range
1966	Nevins	18.9–27.8 °C	15–85 %RH	Increase of 0.3 °C temperature = decrease of 10 %RH for sensation
1967	McNall	15.6–40.6 °C	20–90 %RH	No effect at low met, some effect at higher met
1973	Anderson	23 °C	10–70 %RH	None
1987	Tanabe	27.8–31.3 °C	50–80 %RH	PMV predicts TS too high
1989	Berglund	21–27.2 °C	20–95 %RH	Temperature order of magnitude more important for determining comfort
1989	Hayakawa	30–35 °C	30–90 %RH	No effect on thermal sensation up to 70 %—discomfort increased significantly with elevated metabolism
1994	Tanabe	25–30 °C	30–70 %RH	SET* good relation with TS
1994	Tanabe	26–28 °C	35–75 %RH	TS vote at 1.2 met similar for all RH
1995	Berglund	Reanalysis of 1989 data		Increased discomfort above 18 °C WB
1996	Bauman	26.1–26.6 °C ET*/ 26.2–28.1 °C SET*	50–80 %RH	No change in TS, no difference in acceptability except under increased met
1999	Fountain	20–25 °C (ET*)	60–90 %RH (9-15 g/kg)	Acceptable humidity limit can be quite high when subjects are sedentary

comfort it has to be reheated. Though this can be done with passive devices (e.g. Dinh heat pipes) it is common for the reheat cycle to be performed by electrical heaters, bringing the comfort energetics to 3–4 times that of cooling without dehumidification.

High humidity is not contrary to thermal comfort. The ISO 7730 (2005) standard repeatedly states that whilst humidity affects comfort, its impact is minor.

> The influence of humidity on thermal sensation is small at moderate temperatures close to comfort and may usually be disregarded when determining the PMV value. (p. 4)
>
> If humidity limits are based on the maintenance of acceptable thermal conditions based solely on comfort considerations—including thermal sensation, skin wetness, skin dryness, and eye irritation—a wide range of humidity is acceptable. (p. 44)

Why then all this trouble to dehumidify?

5.3.2 Understanding Humidity

It is a common perception that humidity affects comfort and IAQ. In ASHRAE's "Top Ten Things Consumers Should Know About Air Conditioning" (http://www.ashrae.org/education/page/1455#10) it is mentioned:

> Humidity control was the problem that originally spurred the need for air conditioning. Lack of humidity control in hot, humid climates, in particular, can lead to mold growth and other moisture-related problems. High indoor humidities can lead to health and comfort problems. Modern air conditioners dehumidify as they cool; you can see that by the water that drains away, but this dehumidification is incidental to their main job of controlling temperature.

Humidity, to the technical minded, can often be used too loosely.

Humidity ratio (HR) expresses the masses of moisture to dry air, as a ratio in g/kg. Relative humidity (RH) expresses the vapour pressure in air as a percentage of the maximum it can potentially be at the same temperature. Until dew point is reached, HR is unaffected by temperature, whereas RH is always temperature-dependent.

Another common misconception is that when air is saturated it cannot contain more moisture. This is incorrect. At high altitudes and in the absence of condensing nuclei, air can be supersaturated to 'several hundred per cent' (Battan 2003, p. 8). Where condensing nuclei are present it will be correct to say that air cannot contain more moisture in the vapour state, yet still more moisture can still be accommodated as suspended droplets. For instance if one were to breathe outdoors on a cold morning when the air is saturated, one can observe a breath mist. In a similar condition if one were to go for a run, the profuse perspiration will evaporate, condense into suspended droplets, and appear as steam emerging from the hot skin. It is thus incorrect to think of saturated air being incapable of accommodating more moisture. The determining function is that as long as the
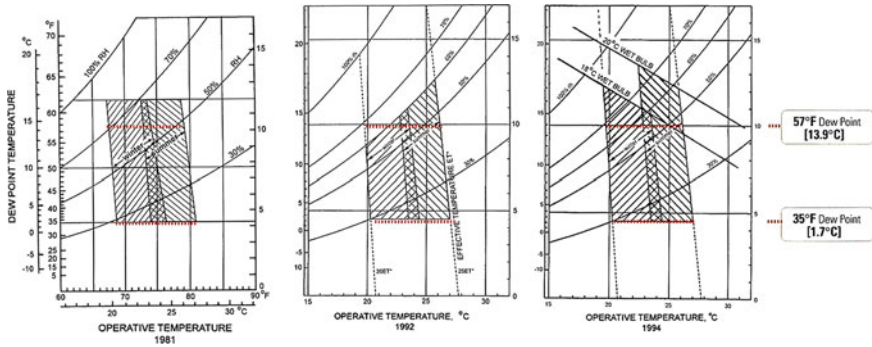
Fig. 5.3 Uncertainty in the RH stipulation in the ASHRAE 55 standard in years 1981, 1992 and 1994 (Harriman et al. 2008)

saturated vapour pressure of skin was higher than the vapour pressure of air, perspiration can still evaporate.

Currently the most complete treatise on this topic will be ASHRAE 90421 *Humidity Control Design Guide for Commercial and Institutional Buildings* (Harriman et al. 2008) which begins with a preface 'It appears to be the first time in the 101 year history of the Society that ASHRAE has focused a book on this topic.' The guide admits the uncertainty in defining a measure of RH and shows the variation over three editions of the same standard (Fig. 5.3). However there is a range of HR (corresponding to dew point temperature) that satisfies the three editions. The guide states, 'What does seem consistent is the sedentary people are likely to find comfort in all seasons when the dew points between 1.7 and 13.9 °C' (p. 73).

As this issue is of fundamental interest to the development of comfort energetics, we shall investigate it at length.

5.3.3 Optimum RH and ASHRAE 55 Misrepresented

The ASHRAE 55 (2004) revision maintained the upper 12 g/kg (17 °C dew point) limit and removed the lower limit. The 2010 revision maintains the 2004 limits for the graphical (i.e. psychrometric) approach but also allows the software (PMV) approach, for which the RH has no stated limit. With the PMV approach, as long as the range is within ±0.5 (corresponding to PPD < 10 %), the conditions are deemed to be within the comfort zone (ASHRAE 2010, p. 7).

When optimum RH values are recommended, the ASHRAE 55 and other standards have been serially misquoted by major references and texts (see Table 5.5). An example is:

> The earlier accepted relative humidity range, 20–80 %, was based primarily on comfort concerns; the narrower range today, 30–60 %, incorporates health considerations (Burroughs and Hansen 2011, p. 148).

Table 5.5 Recommended RH in common reference and textbooks

1st author, ref		Year	Recom. RH	Rationale, sources	Comments
Burroughs and Hansen	Managing IAQ (5th ed.)	2011	30–60 %RH	Health	ASHRAE, Proetz, Andrews, Ritzel, Sale, Gelperin and Green	Only ASHRAE and Green appear in bibliography. Still cites ASHRAE 55 (1992) though humidity standards have been superseded in 2004, and again in 2011
Nufert	Architect's data (3rd ed.)	2002	50–60 %RH 40–70 %RH	Comfort Health	–	
Adler	Metric handbook (2nd ed.)	1999	40–70 %RH	Comfort	–	
Avallone	Marks' standard handbook for mechanical engineers (11th ed.)	2007	Min. 0.0045 HR, max. 60 %RH	Comfort	ASHRAE handbook (1993)	
Kreith	Mechanical engineering handbook	1999	<30 % or >60 %RH	Energy economy	ASHRAE 90.1 (1989)	Standard for economy to not dehumidify below 60 %RH or humidity above 30 %RH
Stein	Mechanical and electrical equipment for buildings (10th ed.)	2006	None, inconclusive	Comfort	ASHRAE 55 (1995, 2004), ASHRAE handbook (1997, 2001), Egan (1975), Givoni (1998), Heschong (1979), Humphreys and Nicol (1998), Kwok (1998), Lechner (2001), Milne (1979), Olgyay (1963)	Recognises that ASHRAE 55 only stipulates control of HR, not %RH. Also recognises adaptive model has no RH recommendations
Bas	IAQ—a guide for facility managers	2003	30–60 %RH 50 %RH ideal	Comfort	ASHRAE 55 (1981)	

Once the erroneous referencing enters legislative controls, there are more serious implications. Under Australian Occupational Health and Safety (OH&S) guidelines (Jul 2011), the recommended range is 30–60 %RH. This range was adopted from the Canadian CSA Standard CAN/CSA Z412-00 (R2005)—"Office Ergonomics" which in turn has been sourced, it is claimed, from ASHRAE 55 (2010).

However, a review of the most current standards (Table 5.6) within my access indicate no stipulation for the control of RH.

Could it be possible that the ASHRAE 55 standard referred to have been those other than the 1981 and 2004 editions I have acquired? A summary of the standards preceding ASHRAE 55 (2004) has been documented (Fountain et al. 1999), from where we see that this humidity ratio of 0.012 has been specified since 1974 and is here updated with the 2010 edition (Table 5.7).

In my investigation, the only official ASHRAE document recommending an optimum RH range is to be found in the ASHRAE Handbook, *HVAC Systems and Equipment* (2008), with a lone reference to Sterling et al. (1985). The optimum RH chart shows a graphical indication of air quality concerns being directly correlated to RH and a sweet-spot of 40–60 %RH which can minimise all negative effects (Fig. 5.4).

Table 5.6 Humidity criteria from American and Australian standards

Standard	Years	Title	Humidity criteria
ASHRAE 55	2004	Thermal environmental conditions for human occupancy	$w(i)$ under 0.012
ASHRAE 55	1981	Thermal environmental conditions for human occupancy	$w(i)$ between 0.0045–0.012
ASHRAE 62	2010	Ventilation for acceptable indoor air quality	RH 65 % or less
ASHRAE 90.1	2004	Energy standard for buildings except low-rise residential buildings	Not stipulated
ASHRAE 160	2009	Criteria for moisture-control design analysis in buildings	$w(i) = 0.004 + 0.4\ w(o)$
ASHRAE 189	2009	Standard for the design of high-performance green buildings	RH under 60 % during post construction, pre-occupancy flush out
AIRAH DA20	2000	Humid tropical air conditioning	55–60 %RH, based on upper limit of Sterling et al. (1985)
AIRAH DA09	1998	Air conditioning load estimation	Not stipulated
AS 1668.2	1991	The use of mechanical ventilation and air-conditioning in buildings—mechanical ventilation for acceptable indoor-air quality	"Out of scope"
AS 4254	2002	Ductwork for air-handling systems in buildings	Not stipulated

$w(i)$ indoor design humidity ratio, $w(o)$ mean coincident design outdoor humidity ratio for cooling, 1 % annual basis

Table 5.7 Humidity control in ASHRAE 55 and preceding standards

Years	Issuer	Maximum humidity	Document
1915	ASHVE	50 % relative humidity (recommended)	Code of Minimum Requirements for Ventilation
1920	ASHVE	64 °F wet bulb (17.8 °C)	Synthetic Air Chart
1932	ASHVE	70 % relative humidity	ASHVE Ventilation Standard
1938	ASHVE	75 % relative humidity	Code of Minimum Requirements for Comfort
1950–1965	ASHRAE	No explicit limit	ASHRAE Comfort Chart
1966	ASHRAE	60 % relative humidity	Standard 55-66
1974	ASHRAE	14 mm Hg (12 g/kg humidity ratio)	Standard 55-74
1981	ASHRAE	12 g/kg humidity ratio	Standard 55-81
1992	ASHRAE	60 % relative humidity	Standard 55-92
1992a	ASHRAE	18 °C (64.5 °F) wet bulb, winter 20 °C (68 °F) wet bulb, summer	Addendum to Standard 55-92
2004	ASHRAE	12 g/kg humidity ratio	Standard 55-2004
2010	ASHRAE	12 g/kg humidity ratio, or software	Standard 55-2010

Over the years the chart has remained untouched in its basic form and is widely cited by manufacturers of humidity control equipment. This chart still underpins
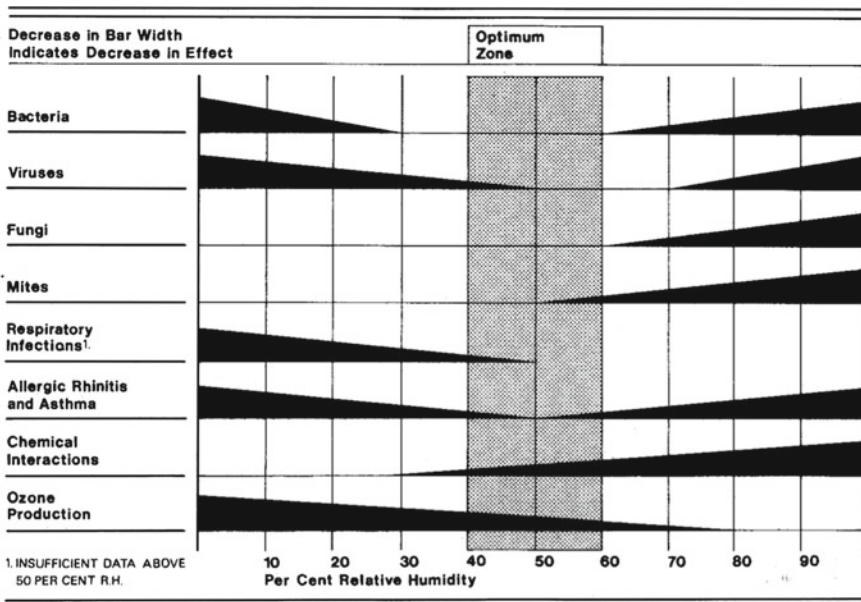
Fig. 5.4 The widely reproduced premise for recommending the optimum RH range, graphically presented (Sterling et al. 1985)

the section on "Humidifiers" in the current ASHRAE Handbook—HVAC Systems and Equipment (2009) ch 21.

> Extremes of humidity are the most detrimental to human comfort, productivity, and health. Figure 1 referring to Sterling et al. (1985)] shows that the range between 30 and 60 %RH (at normal room temperatures) provides the best conditions for human occupancy (Sterling et al. 1985). In this range, both the growth of bacteria and biological organisms and the speed at which chemical interactions occur are minimized.

In the most recent and extensive study commissioned by ASHRAE into humidity control, Brundrett [Chapter 9 in "Humidity Control Design Guide" (Harriman et al. 2008)] reviewed the behaviour of three viruses (*influenza A*, *Vaccinia*, *Poliomyelitis*) and ten bacteria (*Escherichia coli*, *Legionella pneumphilia*, *pneumococcus*, *Serratia marcescens*, *Staphylococcus aureus*, *streptococci*, *pseudomonas vulgaris*, *proteus morgani*, *Salmonella derby*, *Ps aeruginosa*), based on old papers, stating that such research was "rare and valuable". This literature reviewed averaged 1966 $\pm$ 12 y (s.d.), of which 5 of the 20 references could be found in Sterling et al. (1985). Brundett also recommends the same 30–60 %RH range even though 2 viruses and 5 bacteria in the review could be most limited by high RH.

After a half-century one wonders if new microbes have become more commonplace, or if these old strains of microbes have not long mutated to behave differently since they were tested. The dated research is also indicative that there is no modern evidence (in the last 20 years, based on the most recent of Brundrett's references) for RH as control mechanism for bacteria and viruses. It appears that the whole premise for the optimum RH range has not changed from trying to limit "the life span of the broadest variety of bacteria and viruses" (Brundrett 2008), an approach first proposed by Sterling.

This paper (Sterling et al. 1985) is here investigated in greater detail, not as a young researcher trying to be captious, but because it stands as such a significant document, and the only one offering a rationale behind the optimum RH range.

5.3.4 A Critique of Sterling

Sterling's et al. (1985) paper *"Criteria for Human Exposure to Humidity in Occupied Buildings"* was a starting point to recommend a narrower range of 40–60 %RH. The then current ASHRAE Standard 55 (1981) did not actually stipulate an acceptable range of 20–90 %RH as Sterling suggested, but a 4.25–12 g/kg ratio, which within the limits of acceptable operative temperature could potentially vary from 20 to 90 %RH (Fig. 5.5). Graphically, the acceptable range is bound by two (horizontal) limits in terms of *humidity ratio* lines of 4.25 and 12 g/kg, and so it is erroneous to interpret the standard as thinking the acceptable range is bound by (the curved) *relative humidity* lines of 20 and 90 %. The failure to distinguish the humidity units has, in my opinion, cascaded in a series of potentially flawed analyses.

Fig. 5.5 Acceptable T and
humidity range (ASHRAE 55
1981)
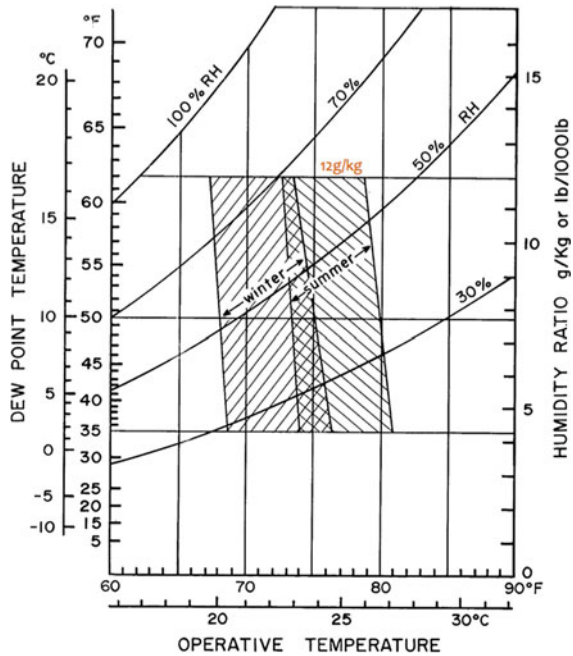
Sterling's paper is not based on original experiments but a "review of the
relevant health literature", a total of 75 separate studies, manuals and literature
reviews with a mean date 1975 ± 7.8 years (s.d.).

The paper looks at the premise for recommending 40–60 %RH as optimum "at
normal room temperature" (p. 615). However, instead of indoor temperatures, it
begins with the introduction:

> High relative humidity prevents effective evaporative cooling of the body during exposure
> to high temperatures and may lead to heat exhaustion or heat stroke and possible death.

Evaporation rate is affected by absolute humidity (or humidity ratio, HR) not
relative humidity (RH). To impede evaporative cooling takes the combination of
both high RH and, more importantly, high T, a T that well exceeds normal room
temperatures. We labour this point again because this paper presents a common
misconception: that high RH is a health hazard. The condition that causes heat
related injuries is primarily that of high temperatures. Whilst high RH can exac-
erbate the condition, it is not the primary cause of these injuries, and one can as
easily, if not more easily, succumb to heat stroke in the hot-arid desert as in a hot-
humid forest. It is temperature, radiant temperature in particular, that is the key
factor in "heat exhaustion or heat stroke and possible death" and not RH.

On closer inspection of Sterling's et al. (1985) graphical presentation, a number
of concerns can be raised:

1. The term "humidity" is used very loosely. Of interest to the issue of RH should be that of gaseous atmospheric humidity. However references are made to "humidifying equipment" where it is water in liquid state that becomes a breeding site for bacteria. Control of RH is immaterial to the subsequent delivery of these contaminants in the misting aerosol.

2. The literature review is based on work done with airborne pathogens but the selection does not necessarily reflect a representative sample of the most common variants in the indoor environment. Salmonella and rhinovirus are, respectively, the most striking bacterium and virus missing. Uncommon viruses like polio and cowpox are included in the mix and their relevance is somewhat stretched.

3. It is unclear what is meant by "effect" which for microbes could possibly refer to the increase in colony forming units per cubic metre of air (i.e. cfu/m^3). Alternatively, it could even refer to absenteeism, occupants who complain of at least two SBS symptoms, perceived air quality, and an unending list of criteria. Without understanding the actual mechanics of each parameter it is impossible to plot wedges to indicate linear relationships between effect and RH%.

4. In many instances the relationships are non-linear to RH%. Different species of viruses also behave differently: *influenza* and *vaccinia* decrease in viability at increasing RH whereas results for *poliomyelitis* and *Venezuelan equine encephalitis* showed the opposite tendency (Harper, 1961 in Kowalski 2005). One can as easily argue that 50 %RH is the ideal condition for limiting, as it is for promoting, respective strains of virus.

5. The graphical presentation gives the impression that at certain point in the RH scale, there are no deleterious effects. A casual observer will not realise that the author of the paper admits, '…there is probably no level of humidity at which some biological or chemical factor that affects health negatively does not flourish' (p. 615).

6. Many other parameters come into play to influence the 'effect'. For example the termination of microbes from desiccation is affected by "the initial moisture content, growth phase, rate of drying, relative humidity or composition of the surrounding medium, temperature, the coincident presence of sunlight, and other factors" (Kowalski 2005 p. 113). No mention has been made if these conditions have been kept constant to isolate RH % as the determining factor in the review of literature.

7. An impression is given that all the listed contaminants should be controlled for good IAQ. However, whilst 'viruses are almost exclusively communicable', fungal spores, on the other hand, 'are almost exclusively noncommunicable' and come 'mainly from the outdoor environment' (Kowalski 2005 p. 4).

Thus the optimum RH chart remains an oversimplified approach for controlling air contaminants by limiting RH to a range, though this is not to say RH does not have any effect on air quality.

What is needed is to ascertain firstly, if RH has a direct correlation to contaminant proliferation and human susceptibility; and secondly, if regulating RH is

the most effective way of controlling contamination. In a hot-humid context, the discussion is focussed on the following areas of concern:
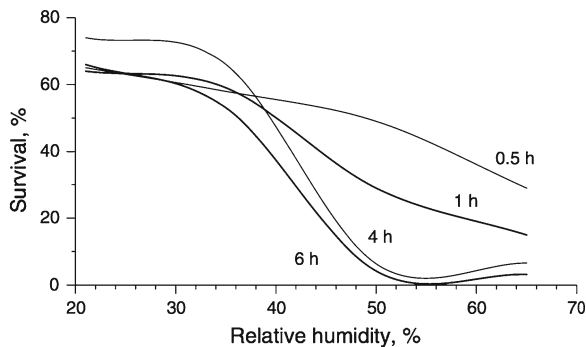
1. Bacteria
2. Viruses
3. Moulds
4. Mites

### 5.3.5 Effects of RH on Bacteria and Viruses

Airborne Legionella are capable of suriving "over greater distances when the relative humidity is 65 % or greater" (Kowalski 2005, p. 60). "Viruses may not behave the same as bacteria in terms of their susceptibility to variations in relative humidity. Low humidities appear to have a limited effect on virus viability while high humidities appear to decrease viability." (Kowalski 2005, p. 113). Figure 5.6 shows a graph where the survival of influenza is plotted against relative humidity at several sample times. "The pattern is clearly a decrease in viability at increasing relative humidity." (Kowalski 2005, p. 113)

Besides direct contact, the main mode of transmission of communicable diseases is through large droplets >10 μm and droplet nuclei <10 μm (ASHRAE 2009). 'The residue of the droplet after evaporation, which contains any organism originally present, is called a droplet nucleus. It is typically 5 μm or smaller in size' (Rural Infection Control Practice Group, 2008, Sect. 2.1). At 50 %RH, a droplet of distilled water of 3 μm can be reduced to a tenth of its original size in a fraction of a second (Dunklin and Puck 1948). Figure 5.7 shows that RH has an impact on the initial evaporation rates, with droplets evaporating about four times faster at 0 %RH than at 70 %RH. However, droplets which contain bacteria do not evaporate completely, and despite similar initial evaporation rates, droplets with bacteria retain the nuclei for much longer that those without. The authors of this graph observed:

Fig. 5.6 Influenza viability under different exposure of RH% and exposure (Clarke et al. 1999, in Kowalski 2005)

Fig. 5.7 Simulated water
evaporation from bacteria
containing 600 μm diameter
water droplets in an
atmosphere of 0 %RH or
70 %RH and 25 °C
(Lighthart and Kim 1989)
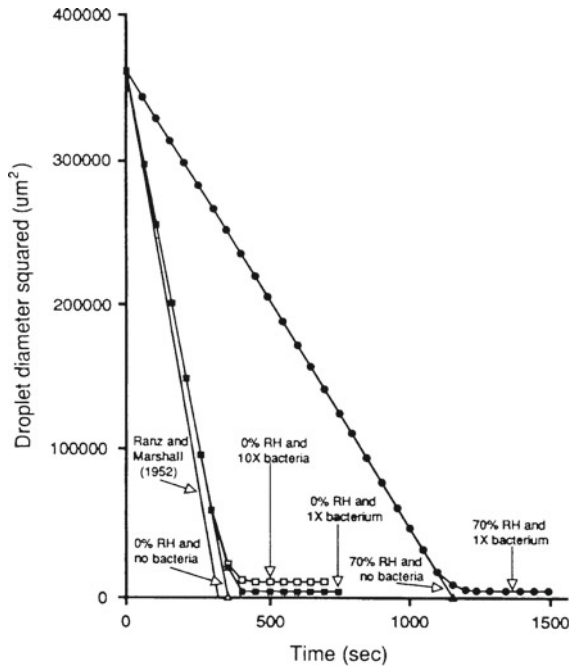
the graph shows how droplet-contained bacteria might not appreciably affect droplet
evaporation until almost all of the droplet water had evaporated and the agglomerated
bacteria or droplet nuclei were left. At this point the survival of the agglomerated bacteria
might depend on such unknowns as the water evaporation rate, the position in the
agglomerate, and the life-sustaining water content of the bacteria. (Lighthart and Kim
1989, p. 2351)

They suggest that the following mechanisms are involved with this phenomena:

…it is hypothesized that as droplet water evaporates, cells, which are thought to have a
lower water vapor pressure (e.g., due to lipid-containing cell membranes), may be present
in the droplet air–water film, lowering the overall droplet evaporation rate. Carrying the
argument further, it is hypothesized that as the cells agglomerate or form a protective shell
configuration during evaporation, the outermost cells would dry to a critical (life-sus-
taining) water content before those cells deeper in the agglomerate do. From this, it might
be expected that those relatively large droplets that originate with the most microbes
would contain at least one deeply embedded viable microorganism for the longest period
of transport time downwind. Thus, the larger droplet nuclei presumably will have more
surviving microbes over a longer time. (Lighthart and Kim 1989, p. 2354)

Evaporation of these agglomerated droplets under typical room conditions is
not immediate enough to control disease spread and the most effective way of
removing these droplets or droplet nuclei is by filtration. Filtration, however, is
significantly affected by RH. Below 80 %RH, air filters led to a marked reduction
of airborne bacteria concentrations by approximately 70 %. Above 80 %RH, a
proliferation of bacteria on air filters resulted in a subsequent release back into the

filtered air (Kowalski 2005, p. 225). Hence where air filters are used, care must be exercised to control the subsequent re-entry of bacteria into the air stream at >80 %RH.

For bacteria and viruses, air sanitisation has been the most reliable control. For instance, Langmuir (1948, in Fisk 1999) reported 23 % decrease in respiratory illness with UV irradiation during an epidemic in U.S. Army barracks.

## 5.3.6 *Effects of RH on Moulds*

Though moulds are non-communicable, the spores of some species, in high concentrations, can be toxic to humans. Mould growth occurs at the confluence of humidity, temperature and the availability of nutrients (Fig. 5.8). In referring to building enclosures, Kowalski (2005, pp. 175–177) notes,

> Evidence exists to suggest that many of the building materials like gypsum and wallpaper that favor the growth of fungi also influence the generation of potentially hazardous mycotoxins. Bacteria can influence the growth of fungi. Environmental bacteria can grow biofilms, and thereby provide fungal spores a nutrient base. Biofilms generally grow where there is excessive moisture or where water collects, such as drain pans, dehumidification cooling coils, and sump type humidifiers.

The indoor relative humidity itself is less an indicator of mould growth than is the water activity (Aw) of the building materials (Kowalski 2005, p. 174), determined as follows:

$$Aw = \frac{p}{p_o} \tag{5.1}$$

Fig. 5.8 Growth conditions for mould (Clark 1998, in Kowalski 2005, p. 176)
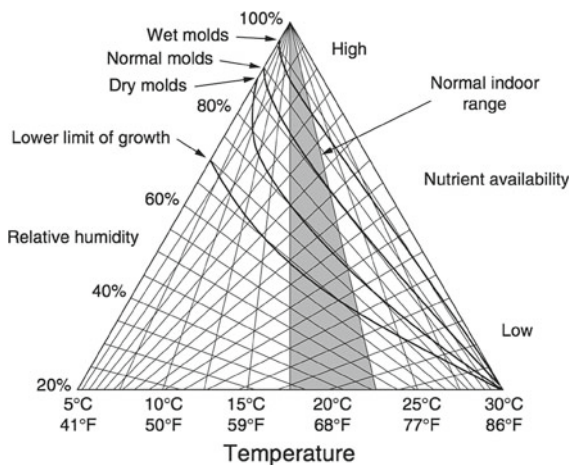
Equation notes	
P	Vapour pressure of water in the substance
P_o	Vapour pressure of pure water at the same temperature

Kowalski further observes, 'Fungal growth is likely if the water activity exceeds 0.76 to 0.96, depending on fungal species, temperature, time, and composition of the material (Pasanen et al. 1992, in Kowalski [2005]).'

Thus the way to control mould growth is thus by selecting the least hygroscopic materials and finishing them with hydrophilic paints. Alternatively, mould can be controlled by air filters, where it was found that the lack of available nutrients on clean filters generally precluded most mould growth even under high RH (Kowalski 2005, p. 223).

5.3.7 Effects of RH on Mites

In a review on 'Controlling Dust Mites Psychrometrically', M. J. Cunningham of the Building Research Association New Zealand (BRANZ) explains his rationale for using humidity control on mites management, 'Higher humidities provide conditions suitable for mite population survival and growth. It also results in greater faecal production per mite, resulting in higher allergen levels (Cunningham 1996).' However his research shows that low temperatures drastically impeded mite population growth rate, and at a rate far more significant than RH. He further notes that regulating the humidity in a room had little effect on the microclimate where mites were typically found (e.g. pillows, carpets).

It would thus be ineffective to regulate ambient T, and even less effective to regulate ambient RH, in order to control mite populations and their allergenic effects. To control mites it would be far more effective to deal with them in their habitats by vacuuming, chemical sanitisation, extreme heat or cold, or simply regular replacement of items like pillows.

5.3.8 Summary of Findings Compared to Sterling et al. (1985)

Sterling's work was for its time a significant contribution, and the optimum RH recommendation was based on tenable ideas. We must however recognise that this was a literature review and not basic research involving testing the contaminants, particularly the biological ones, with the specific intent of determining their viability under varying ambient RH conditions. After a quarter of a century, huge advancements have been made in microbiology, with potential epidemics like SARS and avian flu fuelling very active research into the area. It is needful that this work be

updated, if possible. As the sole reference in the ASHRAE Handbook and AIRAH Guide, and on which other standards and legal requirements are based, the limitations to our knowledge of such an optimum RH should be openly acknowledged.

The problem is that microbiologists themselves recognise that 'the effects of relative humidity on airborne microbes are complex and involve phase changes at the molecular level' (Kowalski 2005, p. 157). With so many aspects of aerobiological behaviour not fully understood it is no wonder that in the *ASHRAE Position Document on Airborne Infectious Diseases*, the only mention of humidity is that

> humidity affects survival of the infectious agent although not always in predictable ways. (ASHRAE 2009, p. 5)

Controlling RH% in today's context is, without doubt, a blunt and energetically costly way of controlling microbes, and for some viruses it is of questionable efficacy. There can be many other ways of controlling each factor that affects IAQ as tabulated in Table 5.8.

If indoor air quality (IAQ) were the real issue, than there are other approaches to improving IAQ without dehumidification. Instead of controlling humidity, designers could look at paints and finishes that inhibited microbial growth on walls and ceilings. They could also minimise the amount of soft finishes (carpets, drapery, fabric, etc.) used in interiors. The key is to look at materials with low water activity and low nutrient content for moulds. As an air quality issue, filtration and sanitisation devices could be employed to reduce, remove or destroy microscopic organisms. All these could be done, with less operational energy than to dehumidify air, an energy demand particularly strenuous in tropical cities.

However, when humidity is made a thermal comfort issue, the need for compliance does not leave designers any room to explore alternative solutions. In an energy-constrained world we need to evaluate the issues separately: lowering of temperatures for improved comfort which is distinct from removing of microbes for improved air quality—of which lowering humidity is but one of many viable strategies.

In as much as we can demonstrate energy efficient alternatives to improving IAQ, one reason why the control of indoor climates is so energetically inefficient is from the inclusion of humidity control as a comfort issue. Other than instances where air quality is crucial (like in hospitals), the inclusion of humidity control as a comfort consideration nullifies the need to adopt any of these alternative strategies.

Table 5.8 Alternatives to RH control in managing various microbes

Virus and Bacteria	Air filtration (Fisk 1999) and sanitisation (UV, ozone), control RH of filter (can be achieved by heating air passing through filter)
Mould	Select building materials with low water activity and low nutrient content, maintain clean filters, control bacteria biofilms
Mites	Control amount and type of soft finishes, reducing temperature, change pillows, steam cleaning, vacuuming with fine filter

5.3.9 Humidity and Disease

> I am New People. Your sicknesses do not frighten me. (Bacigalupi 2009, p. 488)

If microbes had no pathogenic effects on the windup girl, there would be no necessity for humidity control. Adopting a purist approach to thermal comfort, the most efficient route would be firstly by evaporative cooling and, if necessary, further refrigeration to reach thermal neutrality. There will be no need to dehumidify (to a humidity ratio of 12 g/kg) and reheat (till RH is at 65 %). Designing an energy efficient climate chamber for the windup girl has uncovered a new index for evaluating the effectiveness of climate control processes: comfort energetics. This hypothetical client, with her genetically engineered resistance to disease, also helps to distil the thermal comfort considerations from indoor air quality ones.

Nevertheless, we are not "New People", and high RH is a potential sick building syndrome (SBS) problem. Besides SBS, there are also other ways in which RH affects perceived air quality, odours and eye irritation, though these are not covered here as they have not been cited in the standards as reasons for controlling humidity. Recognising that the standards cannot be easily amended, compliance will still be obligatory for the immediate future. If we intended to improve thermal comfort with less energy and without increasing the RH of a space, what viable options remain?

5.4 Energetics of Fans

> Yellow card coolies crank at wide-bore fans, driving air through the club. Sweat drips from their faces and runs in gleaming rivulets down their backs. They burn calories as quickly as they consume them and yet still the club bakes with the memory of the afternoon sun. (Bacigalupi 2009, pp. 55–56)

The cooling effect of moving air can be analysed in three methods:

1. Altering the wind speed parameter in the PMV
2. Determining the effective dT of moving air and adjusting the operative T in PMV to account for this effect.
3. Determining the wind chill index (WCI) through wind velocity and air temperature ASHRAE Handbook: Fundamentals (ASHRAE 2005, 8.21). The methods discussed for methods 1 and 2 could also be applied to WCI, using the energy required to increase v to evaluate the lower vote from *WCI*. However, as the wind chill index has been developed for outdoor use, it is not considered in our discussion on comfort energetics.

Table 5.9 Comfort energetics of increasing ventilation rates

Increased ventilation				
Ventilation (l/s)	Velocity (m/s)	PMV	Power (W)	W/vote
10	0.05	1.994	5	
20	0.1	1.937	10	175.4
30	0.15	1.873	15	124.0
40	0.2	1.835	20	125.8
50	0.25	1.804	25	131.6
60	0.3	1.778	30	138.9
70	0.35	1.755	35	146.4
80	0.4	1.735	40	154.4
90	0.45	1.718	45	163.0
100	0.5	1.702	50	171.2

5.4.1 Wind Velocity in the PMV Model

Under this setup, the flow rate can be assumed to have a linear relationship with power consumption: a ventilation fan is installed in the ceiling with a fixed maximum power (5 W) and exhaust rate (10 l/s). Additional fans are installed, up to 10 units, all running at the same speed and power, giving a linear relationship between power and exhaust rates. The fan-only cooling under this calculation averages 148 W/vote (s.d. = 11 %, refer to Table 5.9) and does not improve comfort by much.

5.4.2 dT as a Result of Increased Cooling with Higher Wind Speed

Instead of looking at the fans as performing exhaust ventilation, we can see them as circulating the air, as in the case of ceiling fans. In this scenario it is assumed that the occupants will sit in the region where the fan speed is about 1 m/s (Rohles 1983, figure). The moving air across a lightly clothed occupant will cause a difference in temperature (dT) from the forced convection. Various models exist (Emmanuel 2005, p. 69) to determine the magnitude of the dT. At 1 m/s the average of these eight models is dT = −3.89 °C (s.d. = 1.69 m/s) in agreement with the difference in equivalent temperature of 3.3 °C when ceiling fans are compared to still air (Rohles 1983). This difference is applied to determine the operative T for the PMV model (ASHRAE 55-2004).

$$T_{operative} = A \cdot T_{air} + (1 - A) \cdot MRT \qquad (5.2)$$

Equation notes		
A	Ratio of air temperature	0.7 (at vel = 1 m/s)
T air	Air temperature, corrected for wind at 1 m/s	(30–3.89) °C
MRT	Mean Radiant Temperature	30 °C

Table 5.10 Comfort energetics of a ceiling fan

Ceiling fan reference	
Motor power (Martec 1.3 m)	69 W
Free air displacement	3,770 l/s
Assumed wind velocity	1.0 m/s
T (operative)	27.28 °C
Reference PMV	1.994
PMV with wind cooling	1.159
Comfort energetics for 1 pax	83 W/vote
Comfort energetics for 4 pax	21 W/vote

Based on a 69 W ceiling fan (Table 5.10), the comfort energetics works out as 83 W/vote for a single occupant. However, recognising that a ceiling fan can support a whole room (see Fig. 5.9), the comfort energetics could be as low as 21 W/vote if 4 occupants could be positioned within the 1 m/s range of the ceiling fan.

In the ASHRAE standards, draft rates (DR) are used to predict the percentage of people dissatisfied with a draft condition based on the work of Fanger and Christensen (1986) and Fanger et al. (1988) with the following expression:

$$DR = (34 - T_a \times [v - 0.05]^{0.62}) \times (0.37 \cdot v \cdot Tu + 3.14) \qquad (5.3)$$

| Equation notes	
v	Mean velocity
t	Air temperature
Tu	Turbulence intensity

The turbulence intensity (Tu) for ceiling fans were measured to be 7.1 % under the middle of blades and 3.5 % at 300 mm from the outer edge of blades (Chiang et al. 2007). Based on a DR <20 % stipulated under ASHRAE 55, the air speed cannot exceed 0.9 m/s. However other researchers (Zhang et al. 2007) present a case to raise the draft limit. It was found that even when the draft standard had been exceeded, 41 % of occupants feeling neutral and 68 % for occupants feeling warm still wanted more air motion.

5.4.3 How Much Air Movement is Considered a Draft?

The maximum permissible air speed has varied at different times between researchers:

1. '0.2 m/s is the de facto draft limit in the current ASHRAE and ISO thermal environment standards' (Zhang et al. 2007, when referring to ASHRAE 55-2004).

Fig. 5.9 Wind speeds under
a ceiling fan (Cook 1989,
p.46)
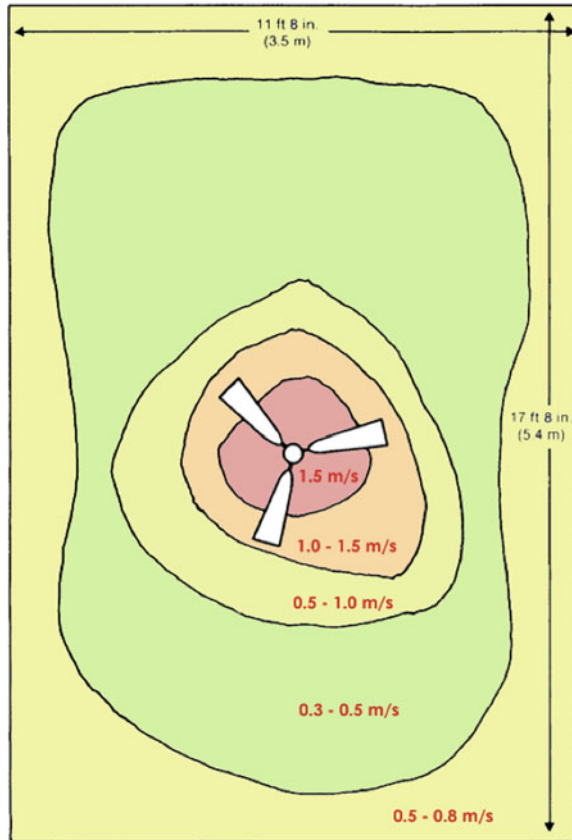
2. The ASHRAE Standard also states that 'loose paper, hair and other light objects
   may start to be blown about at air movements of 160 fpm (0.8 m/s).' (Rohles
   1983 when referring to ASHRAE 55-1981)

> It should be emphasized that the 1.0 m/s (200 ft/min) air speed was not demonstrated to be
> a maximum allowed speed. ASHRAE defines 0.8 m/s (160 ft/min) as an upper limit on
> uniform air speed in occupied spaces based on motion of hair, paper, and other light
> objects. Such annoyance was not observed at 1.0 m/s (200 ft/min) in the Kansas State
> experiments. In an earlier experiment with ceiling fans mounted above a flow straight-
> ening louver, McIntyre concluded that 2 m/s (400 ft/min) was the upper limit on
> acceptable air speed (McIntyre 1976). …However, because the rate of convective heat
> removal increases as only the square root of the air speed, higher air speeds provide
> diminishing comfort returns at increased power requirements (McIntyre 1976). Clark,
> *"Passive Cooling Systems "*in Cook (1989), p. 366.

High air velocities of up to 1.6 m/s were preferred by Japanese subjects
exposed to a modified temperature of 31 °C (Tanabe et al. 1987). Modified tem-
perature was defined as the ambient temperature connected to the equivalent
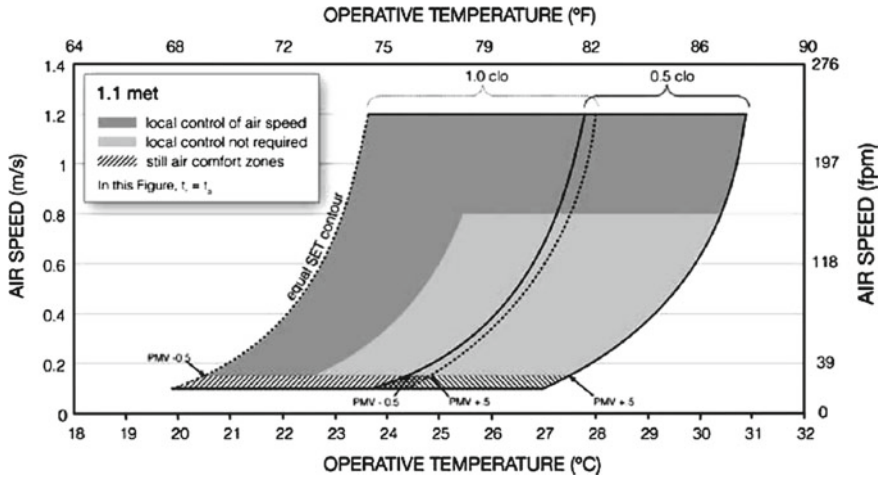
Fig. 5.10 Acceptable operative temperature and air speeds for the comfort zone at humidity ratio of 0.010 (ASHRAE 55, 2010, in Turner 2011)

condition at 50 %RH and 0.1 m/s air velocity, according to the PMV-model, that would be felt equally warm by a subject wearing 0.6 clo.

Toftum (2004) when referring to the highest category (in terms of measuring instrumentation and rigour) in the ASHRAE RP884 Project *"The World Database of Thermal Comfort Field Experiments"* commented:

> The distribution of air velocities measured during these field studies was skewed towards rather low values. Thus, out of a total number of 5653 observations, only 8 % resulted in air velocities higher than 0.2 m/s, 3 % higher than 0.25 m/s and 2 % higher than 0.3 m/s. This alone may explain why occupants under warm conditions frequently expressed a desire for more air movement rather than complained of draught.

The latest ASHRAE 55 (2010) standard recognises this research and has increased the maximum permissible operative temperatures dramatically from traditional still-air comfort zones (Turner 2011) as seen in Fig. 5.10.

5.4.4 Air Movement Summarised

Relating air movement to PMV is heavily dependent on the method in which airflow is generated. In an air-conditioned office, the increased air speed is achieved by increased supply-air flow rate, and in a naturally ventilated office by the recirculation with a ceiling fan. With the acceptance of higher air velocities in the ASHRAE 55 standard, it might even be possible to have a hybrid system of fans within an air-conditioned office space. These methods are concerned with general flow rates across an occupant and do not consider the different sensitivities of body parts to air movement. To understand this, we turn our discussion to a specialised form of air movement known as personalised ventilation.

5.5 Personalised Ventilation

An alternative approach to air movement would be to apply personalised ventilation (PV). PV works on the principle each occupant should have direct control over the immediate thermal environment in order to adjust it to their personal preference. PV is delivered locally at each workstation through air terminal devices (ATDs) that typically cool the upper part of a seated occupant.

10 l/s is negligible flow rate under PMV model. In the reference climate booth the air speed would average 0.01 m/s and could potentially reach 0.05 m/s in the constricted areas where the body is close to the wall. In a 120 mm diameter fan this same flow rate will produce a face velocity of 0.7 m/s. When applied frontally to the face, air speeds of up to 0.9 m/s (Gong et al. 2006) were found to be acceptable to 96 % of occupants at an ambient and task air supply temperature of 26 °C. This gives another indicator of the energetics of personal ventilation. The PMV at the experiment conditions would be +0.596 without air movement, and the actual vote is assumed as 0 with air flow directed to the face (96 % satisfaction will surpass the 5 % PPD at PMV = 0).

To achieve 0.9 m/s air speed, a flow rate exceeding 23 l/s (49 cfm) is required and this be easily achieved by a 120 mm axial fan (used in computer cases, see Fig. 5.11 for a sample specification) running at 7 W, yielding 11.7 W/vote in comfort energetics.

Schiavon (2009) developed a cooling fan efficiency (CFE) index comparing the AT equivalent of whole body cooling effect with the power input for the fan, expressed in °C/W. He determined that the most effective cooling device was the desk fan (16–20 W) with an efficiency of 0.123 °C/W. We also see from Fig. 5.12 the AT has a practical limit of −3 °C. Within this range, personal ventilation

Fig. 5.11 Flow rate of 120 mm diameter fan at 3,000 rpm (Specifications from manufacturer: Commonwealth Industrial Corporation)
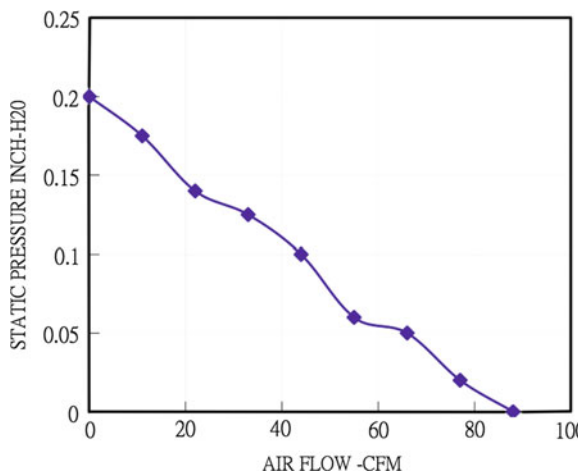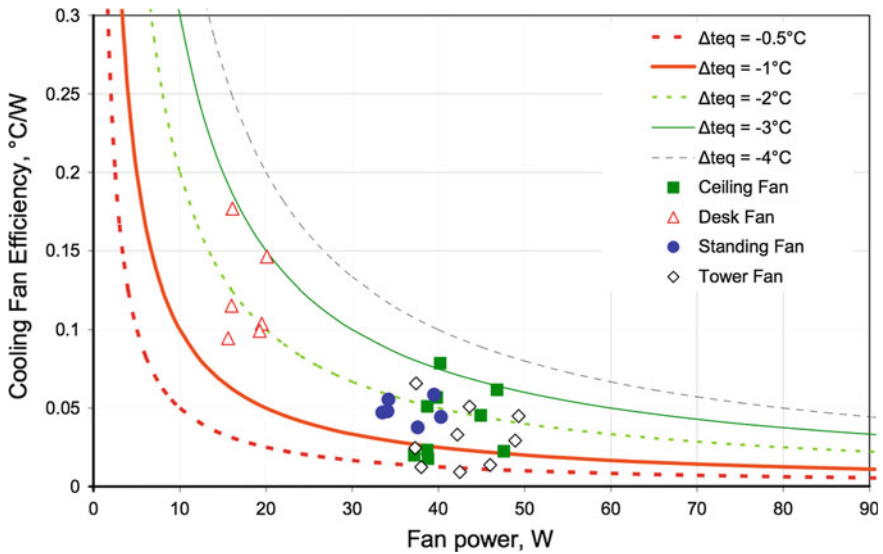
Fig. 5.12 Fan power versus cooling fan efficiency index for the ceiling fan (*CF*) the desk fan (*DF*), the standing fan (*SF*), and the tower fan (*TF*). Lines with constant cooling effect (ΔT >eq) are plotted (Schiavon 2009)

yields 26.3 W/vote (Table 5.11). Most significant to the difference between the comfort energetics of desk fans (26 W/vote) and computer fans (12 W/vote) is the power input. At a fan power of 10 W, the CFE is double that at 20 W and places the earlier estimation in the same ball-park as Schiavon's detailed model.

> …the required power input of the fan is a critical factor for achieving energy saving at elevated room temperature… The power of a fan used to cool people by increasing air movement should be in general less than 20 W. …Computer fans can be used as cooling fans because their power input is extremely low while the generated flow rate is quite high. (Schiavon 2009, pp. 43–45)

Table 5.11 Comfort energetics of a desk fan based on Schiavon's CFE index

Cooling fan efficiency				
T	Fan power (W) CFE = 0.123 °C/W	PMV	dPMV	Elect W/vote
30.0		1.994		
29.5	4.1	1.840	−0.154	26.4
29.0	8.1	1.685	−0.309	26.3
28.5	12.2	1.530	−0.464	26.3
28.0	16.3	1.375	−0.619	26.3
27.5	20.3	1.221	−0.773	26.3
27.0	24.4	1.066	−0.928	26.3

Table 5.12 Summary of comfort energetics for cooling

	Comfort approach	Process	Comfort energetics (W/vote)
1	Computer fan	Wind directed only on face	12
2	Direct evaporative cooling	Adiabatic humidification	14
3	Refrigeration up to dew point	Constant humidity ratio (isodrosothermic)	18
4	Ceiling fan	Recirculation (shared 4 pax)	21
5	Desk fan	Wind directed to upper body	26
6	Refrigeration past dew point	Cooling with dehumidification	29
7	Ceiling fan	Recirculation (1 pax)	83
8	Refrigeration past dew point	To ASHRAE standards	76–124 (depending on reheat efficiency)
9	Extraction fan	Exhaust ventilation	148
10	Desiccant dehumidification	Adiabatic + isothermic dehumidification	277

5.6 Comfort Energetics, in Summary

In summary, the various processes can be ranked in the power each process consumes to effect an improvement of one vote. A fan power consumption of 7 W is here added to the computation where it had been earlier omitted to give a common baseline against fan-based cooling and tabulated in (Table 5.12).

5.7 The Limit of Comfort Energetics

Comfort energetics offers a basis to compare the efficiency of different approaches to comfort. As a theoretical exercise it separates peripheral issues like RH, which is more an air quality issue, from the central components of thermal comfort: air temperature and air movement. Whilst the human sensitivity to MRT is acknowledged, it is often not significantly different from air temperature for office occupants sitting away from the windows.

It needs to be noted that these tabulations are based on PMV scenarios. Even for processes that show linearity it may not be feasible to use one process alone to improve comfort by 2 to 3 votes. Based on the science of thermal comfort, for the best comfort energetics in a hot-humid climate, it is noted that:

1. PMV is most effectively improved by reducing temperature
2. increased air movement is generally welcome
3. high RH not a comfort issue, and arguably not even an IAQ issue
4. IAQ is better improved with filtration and sanitisation than with dehumidification

5.8 Conclusion to Comfort Energetics

> With the wet season, Emiko's life becomes bearable. The flooded metropolis means that
> there is always water nearby, even if it is a stagnant bathtub stinking with the refuse of
> millions. ...She eats well and sleeps easily, and with water all around, she does not so
> greatly fear the heat that burns within her. If it is not the place for New People that she
> once imagined, it is still a niche. (Bacigalupi 2009, p. 501)

In the tropics the options for cooling are greatly limited with high humidity.
The difficulty with cooling in the tropics is that the air is already near saturation,
limiting the options for evaporative cooling. The high humidity and cloud cover
also limit the availability of radiant cooling to the night sky. Passive cooling in the
tropics is often limited simply to increased cross-ventilation, which requires
adequate spacing between blocks to encourage airflow.

In developing tropical cities confronted with poor air quality, massive demand
for prime commercial real estate and the need for a productive workforce, the
ubiquity of offices that are fully-glazed, deep-planned and air-conditioned is
inevitable. Where increasing the humidity ratio is not an option, the best
improvements in terms of comfort energetics will be, in order:

1. Low-power computer fan blowing at the face
2. Refrigeration of air, up to and not below dew point
3. Ceiling fan covering multiple occupants

However, the long-term acceptance of air-conditioning marketing, the accli-
matised addiction to air-conditioning standards and the social expectations for air-
conditioning all indicate that there will be massive resistance from the general
public to accept the proposition that moving air will give them just as much
comfort as air-conditioning. Whilst low-power fans can use far less energy than
air-conditioning to ASHRAE standards, it is unlikely, at this stage, to provide an
acceptable solution in Singaporean office buildings. It is acknowledged that this
may be a disheartening conclusion unless there are mechanisms to change
behaviour, an endeavour not within the scope of this thesis.

It would appear that to solve the problem of over reliance on energy-intensive
air-conditioning, the solution is not to avoid air-conditioning altogether, but rather
to make it less energy-intensive. To do this we ask the following questions:

1. Without resorting to evaporative cooling, increased air movement or radiant
   sky cooling, can cooling still be achieved passively?
2. If it cannot be done passively, what are the limits to which the energy inputs for
   cooling can be minimised?

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Chapter 6
Research Methodology

This is not a conventional research thesis.

The thesis is concerned with solving a problem (hereafter referred to as *The Problem)* thus stated:

> How can we solve the problem of over-reliance on energy-intensive air-conditioning in knowledge-based economies located in tropical climates?

If *methodology* serves to appraise 'already formulated pieces of knowledge, such as theories or steps in a research program' (Kiss 2006, p. 315), this chapter is, strictly speaking, not about methodology in the deductivist sense.

> [The] deductivist style tears the proof-generated definitions off their 'proof- ancestors', presents them out of the blue, in an artificial and authoritarian way. It hides the global counterexamples which led to their discovery.
>   Heuristic style on the contrary highlights these factors. It emphasises the problem-situation: it emphasises the 'logic' which gave birth to the new concept. (Lakatos et al. 1976, p. 144)

In this chapter, which also serves as an interlude between *Context* and *Innovation* (see Fig. 1.1, at start of thesis), I will explain why the *rules for proof* (methodology) do not apply as the *rules for improvement* (heuristics). I must also emphasise that the methods derived for innovation have not been shaped by the ideas covered in this chapter. Instead, this chapter has been written retrospectively, a guide produced after the adventure into innovation had been completed. Thus I am not suggesting that innovations proceed from this chapter in an a priori sense.

Whilst the method of inventing and improving inventions are my original work, it is not to say the methods developed are all-together novel. I have found the work of Imre Lakatos (Lakatos et al. 1976; 1980; Lakatos 1980) particularly helpful in elucidating the thoughts I have struggled to articulate. The format for *emancipatory action research* (Zuber-Skerritt 1996) has also been a useful framework to structure the reflexive process. Lakatos' philosophical papers and the theory behind action-research were not an influence in the innovation process, though they greatly influenced how I now *describe* the process. Like allies for a common

cause, arrived at from different angles, they explain my reasons for breaking from the conventional thesis structure, such as the one described by Evans and Gruba (2003) in their book *How to Write a Better Thesis.* Instead I have opted for the system of Lakatos:

> In writing a historical case study, one should, I think, adopt the following procedure: (1) one gives a rational reconstruction; (2) one tries to compare this rational reconstruction with actual history and to criticize both one's rational reconstruction for lack of historicity and the actual history for lack of rationality. Thus any historical study must be preceded by a heuristic study: history of science without philosophy of science is blind. (Lakatos et al. 1980, pp. 52–53)

Before proceeding to the history of innovations, it is precisely for the important role of heuristics, rather than of methodology, that this chapter has been written.

6.1 Apologetics Against a Falsifiable Hypothesis

In a scientific thesis it is common to state a hypothesis that endeavours 'to explain, predict, and explore the phenomenon of interest' (Marczyk et al. 2010, p. 37). In an academic argument, the rejection of a hypothesis (or its null hypothesis) features as a central endeavour.

> First, all hypotheses must be falsifiable. That is, hypotheses must be capable of being refuted based on the results of the study. This point cannot be emphasized enough. Put simply, if a researcher's hypothesis cannot be refuted, then the researcher is not conducting a scientific investigation. Articulating hypotheses that are not falsifiable is one sure way to ruin what could have otherwise been a well-conducted and important research study. (Marczyk et al. 2010, p. 37)

In the earlier chapters (Chaps. 3–5, see Table 6.1) the key concepts, for instance, can each be loosely constructed as a hypothesis. Here, the causal connection postulated and a 'null hypothesis rejected' have have based on the literature reviewed. Accordingly, to be 'dogmatic' the null hypothesis should only be properly rejected with experimental data.

Table 6.1 Examples on the use of 'hypothesis' and 'null-hypothesis rejected' in the earlier chapters of this thesis

Chapter titles	Hypothesis	Null-hypothesis rejected
Chapter 3: Thermal comfort and air-conditioning	Thermal comfort will become more personal in the future	Thermal comfort will continue to be achieved by whole body cooling at a shared thermostat setting
Chapter 4: Brain cooling	Stress can affect the brain in such a way as to affect preferred temperature	Stress has no effect on preferred temperature
Chapter 5: Comfort energetics	For a particular cooling technique, comfort can be correlated to energy consumption	Comfort is independent of the energy needed to drive it

However, as we proceed to the innovation chapters, any hypothesis of this nature fails to account for the near-unlimited number of variables in the real world, nor does it have the flexibility to accommodate the development of lateral-thought. The scientific method of a falsifiable hypothesis ensures accuracy and consistency in *inquiry,* but offers little help, and can even be counter-productive, to *discovery.* This brand of justificationism is termed *dogmatic falsificationism* by Lakatos (1980):

> The hallmark of dogmatic falsificationism is then the recognition that all theories are equally conjectural. Science cannot *prove any* theory. But although science cannot *prove,* it can *disprove*: it 'can perform with complete logical certainty [the act of] repudiation of what is false', (Medawar 1967, p. 144) that is, there is an absolutely firm empirical basis of facts which can be used to disprove theories. (p. 12)

Lakatos then proceeds to show how this approach is untenable because it assumes a demarcation between theory and observation. Using arguments from psychology, logic and methodological judgment, Lakatos rejects this demarcation as non-existent and undefinable (pp. 14–16). This approach, which he also terms *naive falsificationism,* should be superseded with *sophisticated falsificationism* (also referred to as Popper's *methodological falsificationism*), with a defining feature being the distinction between false and 'false' (to be elaborated in a later section).

Besides the problematic rationale behind falsifiabiility (in the dogmatic sense), a further problem with the conventional approach is its singularity: *a* hypothesis. Since this thesis is concerned with *The Problem,* it cannot be constructed in a (singular) hypothetical statement on which the *modus tollens* is directed. Instead with heuristics 'we must use our ingenuity to articulate or even invent 'auxiliary hypotheses', which form a *protective belt* around this core, and we must redirect the *modus tollens to these'* (Lakatos 1980, p. 48).

Where *The Problem* is concerned, this thesis therefore cannot be presented as a hypothesis that can be tested and, if successful, not rejected. It is rather a program based on a *core* about the theory of comfort and a *belt* of theories about brain cooling and comfort energetics. I proposed that on this structure we build additional layers of engineering innovation. The criterion for success is a demonstration of a progressive *problemshift.* Lakatos (1980) explains the role of heuristics in a program as such:

> First, I claim that the typical descriptive unit of great scientific achievements is not an isolated hypothesis but rather a research programme. Science is not simply trial and error, a series of conjectures and refutations. … Newtonian science, for instance, is not simply a set of four conjectures—the three laws of mechanics and the law of gravitation. These four laws constitute only the 'hard core' of the Newtonian programme. But this hard core is tenaciously protected from refutation by a vast 'protective belt' of auxiliary hypotheses. And, even more importantly, the research programme also has a 'heuristic', that is, a powerful problem-solving machinery, which, with the help of sophisticated mathematical techniques, digests anomalies and even turns them into positive evidence. (p. 4)

From the earlier background, how can we construct this core? I may say:

> There exists a non-static perfect temperature for which an individual will express as 'very comfortable' the state of mind being satisfied with the thermal environment.

Around this core I can build auxiliary hypotheses, for example:

This perfect temperature (1) varies across individuals, and (2) varies within an individual at different times. This perfect temperature can be (3) perturbed in an office occupant significantly by the (4) autonomic response to stress, and insignificantly by (5) the level of relative humidity.

In the dogmatic falsificationist position, a hypothesis can process facts until it encounters an anomaly. Since a hypothesis has been made falsifiable (the conditions for its refutation), an anomaly destroys the hypothesis. The methodological falsification differs in that it adopts a 'problem-solving machinery' to process both facts and anomalies.

In heuristics, the research program, 'this product of human activity, "alienates itself" from the human activity which has been producing it. It becomes a living, growing organism, that acquires a certain autonomy from the activity which has produced it; it develops its own autonomous laws of growth, its own dialectic' (Lakatos et al. 1976, p. 145). I may further this analogy in a pathological sense. The research program (organism) periodically encounters criticisms (viruses) which reveals a lack of response (no immunity), it is *ill* (pun intended) -equipped to deflect the anomaly. But the program does not die: an *antithesis* is not its *nemesis.* The program accepts the challenge and adapts over a period (illness) with a synthesis (metabolising an antibody) of its original thesis and the challenging anti-thesis. It is this process of internalising the criticism that the program acquires limited protection (limited immunity) from similar future attacks (infection). I say *limited* because 'even the most rapidly and consistently progressive research programmes can digest their "counter-evidence" only piecemeal: anomalies are never completely exhausted' (Lakatos 1980, p. 49).

Lakatos' description of 'digesting anomalies' which he elsewhere refers to as 'monstrous counterexamples' (Lakatos et al. 1976, p. 22) has inspired me to illustrate both falsificationists' positions in Fig. 6.1; trusting that my humour is not entirely incongruous to the wit of his *Proofs and Refutations: The Logic of Mathematical Discovery* (Lakatos et al. 1976).

Thus, insofar as we are concerned with *The Problem,* it is the heuristics of a research program that offer the more appropriate framework to make and evaluate progress, rather than the methodology of a falsifiable hypothesis.

6.2   Appreciating the Difference Between False and 'False'

Lakatos (1980) asserted,

Methodological 'falsification' is very different from dogmatic falsification. If a theory is falsified, it is proven false; if it is 'falsified', it may still be true. If we follow up this sort of 'falsification' by the actual 'elimination' of a theory, we may well end up by eliminating a true, and accepting a false, theory (a possibility which is thoroughly abhorrent to the old-fashioned justificationist). (p. 24)
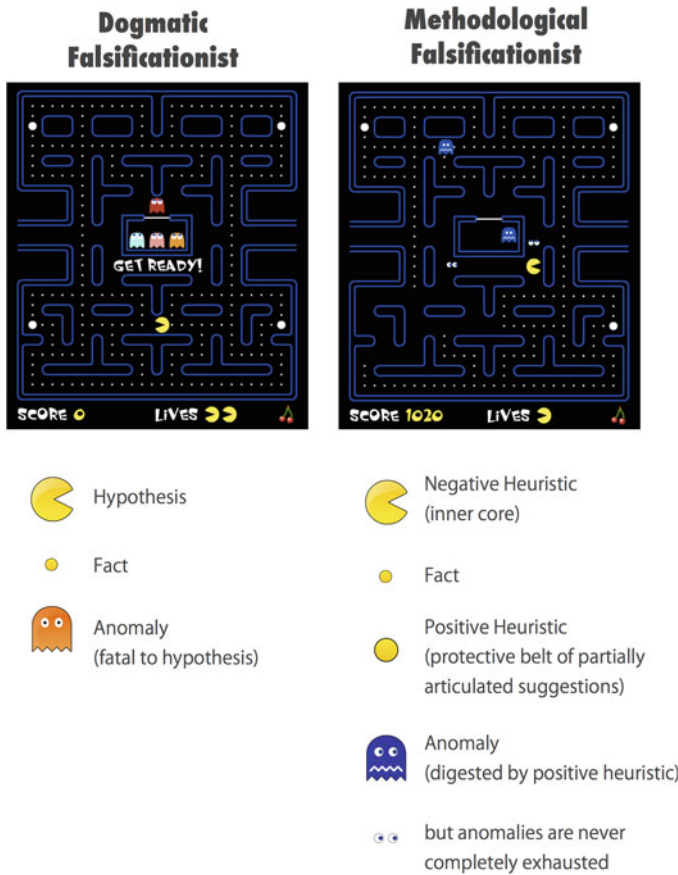
Fig. 6.1 Illustrating the dogmatic and methodological falsificationist reaction to anomalies. Screenshot of PACMAN game from www.thepcmanwebsite.com/media/pacman_flash/, characters from www.softicons.com

Particular to the debate between deterministic and adaptive thermal comfort, I have strenuously avoided making a judgment as to whether there was a true and false theory. My starting point has been one of respecting both arguments, and seeking to understand if there existed assumptions and limits (spatio-temporal) to which the theorems could be applied (*ceteris paribus*) and under what conditions the theorem failed to explain or predict (*anomalies*). This was not difficult to uncover, for there were distinct methods for acquiring the data on which the two models were developed (previously discussed in Table 3.1). The challenge was to harmonise the two theorems, and then with a third hybrid: the field studies (adaptive approach) in air-conditioned offices (deterministic approach) by Schiller (1990).

The problem is then shifted from the old problem of replacing a theory refuted by 'facts' to the new problem of how to resolve inconsistencies between closely associated theories. Which of the mutually inconsistent theories should be eliminated? The sophisticated falsificationist can answer that question easily: one has to try to replace first one, then the other, then possibly both, and opt for that new set-up which provides the biggest increase in corroborated content, which provides the most progressive problemshift. (Lakatos 1980, p. 45)

In Chap. 3, I attempted to frame the issue of over-reliance on energy-intensive air-conditioning usage from sociology, marketing psychology and the various positions taken by thermal comfort researchers, who in turn emerge from a myriad of disciplines including architecture, mechanical engineering, physics and anthropology, to name just a few. The plurality of opinions shed crucial insight and allow the problem to be framed more comprehensively. Similar to the Indian fable of *The Blind Men and an Elephant* (Fig. 6.2), each opinion is valid within a specified context, and the challenge is to integrate the information that is, seemingly, both accurate and contradictory.

It was six men of Indostan
    To learning much inclined,
Who went to see the Elephant
    (Though all of them were blind.)
That each by observation
    Might satisfy his mind.

——————

The First (side) "Is very like a wall!"

——————

The Second (tusk) "Is very like a spear!"

——————

The Third (trunk) "Is very like a snake!"

——————

The Fourth (knee) "Is very like a tree!"

——————

The Fifth (ear) "Is mighty like a fan!"

——————

The Sixth (tail) "Is very like a rope!"

——————

And so these men of Indostan
    Disputed loud and long,
Each in his own opinion
    Exceeding stiff and strong
Though each was partly in the right,
    And all were in the wrong!

From John Godfrey Saxe. "The Blind Men and the Elephant", *Clever Stories of Many Nations Rendered in Rhime*, 1865.

Fig. 6.2 The blind men and an elephant (Saxe 1865)

So oft in theologic wars,
The disputants, I ween,
Rail on in utter ignorance
Of what each other mean,
And prate about an elephant
Not one of them has seen

> The hermeneutic world view recognises multiple interpretations … Each individual has their own construction of the world and creates their own reality and their own learning pathway through it. There is no objectively 'correct answer' to any educational research question and it is therefore not necessary, or even desirable, to begin with a definite hypothesis about an educational situation. (Zuber-Skerritt 1996, pp. 50–51)

Whilst written from the perspective of one from the discipline of Education, Zuber- Skerritt's comment is wholly valid for research-based innovations. Like a lens, each academic discipline brings about a unique set of hermeneutics, procedures and criteria to analyse a given problem, but each lens focusses on particular aspects in such a way it becomes myopic to other ways of viewing it. These lenses can only deliver a consistent picture if an underlying theory can unite them: the theory is tested on how consistent it can hold up to scrutiny. As Lakatos explains, 'It is not that we propose a theory and Nature may shout NO; rather, we propose a maze of theories, and Nature may shout INCONSISTENT.' (1980, p. 45)

How do I propose my theories of *personalised comfort*, *brain cooling* and *comfort energetics* be evaluated? I think the criteria will be an 'increased corroborated content' and 'progressive problemshift' that is consistent from a multidisciplinary angle. I propose that this would be more appropriate than a binary judgment of false or not false based on dogmatic falsificationism.

Q   **What is the nature of a theoretically progressive problemshift?**
A   Lakatos (1980, p. 34): Progress is measured by the degree to which a problemshift is progressive, by the degree to which the series of theories leads us to the discovery of novel facts.
Q   **How is a theory 'falsified'?**
A   Lakatos (1980, p. 34): We regard a theory in the series 'falsified' when it is superseded by a theory with higher corroborated content.
Q   **What is the difference between rejection and disproof?**
A   To the dogmatic falsificationist, the two are conflated (Lakatos 1980, p. 25) in that a falsifiable hypothesis can be disproven and thus rejected. To the methodological falsificationist, theories have to be distinguished between the 'critical stance' and any number of 'non-observational propositions' (p. 25). Elsewhere Lakatos refers to them respectively as the negative and positive heuristics. He explains, 'The negative heuristic specifies the "hard core" of the programme which is "irrefutable" by the methodological decision of its proponents; the positive heuristic consists of a partially articulated set of suggestions or hints on how to change, develop the "refutable variants" of the

research-programme, how to modify, sophisticate, the "refutable" protective belt' (p. 50). On these definitions, the positive heuristic can be repeatedly rejected without the negative heuristic disproven.

6.2.1 The Role of Criticism

In *Proofs and Refutations*, Lakatos uses the dialogue between a maths teacher and his students (named after Greek letters) as a scene to debate theories and their proof. Here, 'students do not represent particular mathematicians, but rather customs and typical behaviours of scientists faced with the coexistence of alternative proofs and refutations to the same theorem: Which one is wrong, and what is the problem with it?' (Kiss 2006, p. 303).

In this lively scene where students hurl objections in the most unrestrained way, Epsilon proceeds to give his proof with special attention to definitions, when Kappa launches an oblique attack. Keen to return to the main argument, the teacher intervenes:

> TEACHER: Epsilon, do not listen to Kappa. Refutations, inconsistencies, criticism in general are very important, but only if they lead to improvement.
> A mere refutation is no victory. If mere criticism, even though correct, had authority, Berkeley would have stopped the development of mathematics and Dirac could not have found an editor for his papers (Lakatos et al. 1976, p. 112).

In the same spirit, Nathan Myhrvold (in Timoner 2010) describes his response to criticism for his work in geoengineering, for example delivering sulphur dioxide to the upper atmosphere:

> There are some folks who will say, 'Look, this technology got us here [global warming] in the first place. You guys are only going to screw things up worse.' And I think the appropriate answer is to say, 'Okay… what's your solution? *[pause] Don't* stop me if you don't have a solution of your own.'

No theory is irrefutable, no discovery is ultimate, no effort is final, no construction of truth is guaranteed. Consequently all theories are subject to criticism, but it is the heuristic attitude to sweep aside criticism that offers no improvement. A theory is never abandoned because of criticism, it can only be superseded by a superior theory.

> Contrary to naive falsificationism, no experiment, experimental report, observation statement or well-corroborated low-level falsifying hypothesis alone can lead to falsification. There is no falsification before the emergence of a better theory. But then the distinctively negative character of naive falsificationism vanishes; criticism becomes more difficult, and also positive, constructive. (p. 35)

I now make a short digression from *criticism of theories* in the academic realm to *criticism of ideas* (in the widest possible sense to include all creative output, intellectual and material) in the real world. In contradistinction from theories,

ideas are not merely produced but are also consumed, and many consumers have no involvement in the production of ideas, and are hence unable to offer any improvements. Should their opinion matter?

To illustrate this, the chef and connoisseur play distinct roles: one to create food and one to critique it (often in a deprecatory sense). Say the critic offers no (constructive) basis for her conclusion, 'I will not dine here again.' Should the connoisseur's opinion matter, seeing she cannot reproduce the food, let alone improve it? Should the critic defer to the technically superior knowledge of other chefs, for only they can *improve* the food by replacing it with a better version?

Here I make a qualified departure from the safety of Lakatos' shadow. *Firstly, the critics' opinions do matter.* Whilst criticisms of an unconstructive nature do not improve an idea, they can diminish its popularity. A scientific statement retains its validity whoever says it. Yet even in academia, the weight of a scientific statement differs with the esteem given to the one declaring it. In the broad context of society, differences in opinions are resolved, to an extent, on the popularity of the opinion. Hence we do not find scientists to be the ones endorsing air-conditioners but media celebrities appearing beside them in advertisements, providing the illusion of endorsement (Fig. 6.3).

Secondly, a mere opinion is still a real opinion. In the context of a scientific research program, evaluations are made though intellectual rigour. To a consumer, evaluation is based on personal gratification, with a large emotional component. It is pointless to convince a consumer that a critic's scathing review was irrational—opinions do not have to be rationally made or rationally accepted. Consumers can likewise make (scientifically) irrational statements like 'I feel more comfortable in high heels,' or, 'I feel important by putting on a designer jacket.' There is no empirical value in these statements, yet they are no less factual to the ones believing so.

Thirdly, an unconstructive criticism is not a useless criticism. In Lakatos' heuristic, unconstructive criticisms are not given consideration. However if a large portion of the consumer market agrees with the criticism, however unconstructive,

Fig. 6.3 Movie celebrities as air-conditioning ambassadors: **a** Hong Kong action star Jackie Chan and **b** Singaporean comedian Jack Neo. Screenshots from advertisements produced by manufacturers Gree Electric and Mitsubishi Electric respectively. Retrieved from YouTube

it should still be considered. Again, it is the creative force of an inventive mind that provides the positive heuristic to assimilate these opinions and invent a new solution. Thus the Hegelian dialectic needs to accept an antithesis even in the form of mere opinion on account of its popularity, not its validity.

I propose therefore, that criticisms have to be distinguished by their sources. Academic criticism of the rational sort will be subject to Lakatos' heuristic process. Market criticisms (from business, industry and consumer) need not fulfil any criteria of (scientific) rationality, but are considered in priority of their *representativeness:* a function of (l) the *weightage* of the opinion-giver and (2) the *frequency* to which the opinion is commonly held. These irrational criticisms have no bearing on the theory on the inner core, only affecting the invention at the outermost layer. The assimilation of these criticisms, more commonly called *critiques* in the design circle, is by way of integration into the design brief. I will explain this using the structure from Lakatos.

Under the heuristic model, there are two concentric circles with the non-negotiable negative heuristic as the inner, and the responsive positive heuristic on the outer. I suggest that with *research innovation,* the positive heuristic have two further coats: a double-layer atmosphere that distinguishes between the conditions for an innovation (foundational layer) and the innovation itself (superstructural layer)—or, the brief and the design respectively. Thus we have four concentric circles: the core is heuristically unresponsive; the belt is responsive only to rational debate; and the creative atmosphere (comprising layers of foundation and superstructure) are responsive to opinions, even irrational ones. This demarcation is necessary because there is no direct causal relationship between theory and invention, and thus no clear criteria on which to judge an invention. A design is deemed successful if it fulfils the brief, but fulfilling a brief does not equate to problem-solving. *The Problem* may remain unchanged, but with new understanding of its complexities, more conditions are introduced into the brief, making existing designs irrelevant and inadequate. The condition of acceptance should therefore be *consistency* on two terms: the design must be consistent with the brief; and the brief must be consistent with *The Problem.*

The design critique is crucial to the incremental complexity of the brief. Lakatos explains a similar process of proof as *lemma incorporation.*

6.3 Lemma Incorporation

The heuristic, or *problem-solving*, approach, made conjectures more rigorous by *proving*. In *Proofs and Reputations* the term 'proof' was more commonly used in the sense of *to demonstrate by argument,* rather than *to demonstrate to be true.* The proving process thus subjected conjectures to the debate of counterexamples and criticisms—or more commonly expressed, 'the theory must be made to stick its neck out' (Lakatos 1980, p. 26). The heuristic method 'improves by proving'. This

intrinsic unity between the "logic of discovery" and the "logic of justification" is the most important aspect of the method of lemma-incorporation' (1976, p. 37).

> According to Lakatos the human problem-solving process happens in three distinct stages, which he called monster barring, exception-barring and lemma-incorporation. In the first stage, monster barring, one attempts to negate a new problem by treating it as a monster, insoluble. If the problem persists, we reach the second stage, in which the problem is acknowledged, but incorporated into our knowledge as an exception to the established rule. Only in the third stage, the lemma-incorporation, will we accept the problem as such and modify our knowledge to incorporate a solution. (Mayer-Schönberger, 2000, p. 2)

In the subsequent innovation chapters it is not necessary to distinguish which of these three stages each improvement represented. There are, however, three major innovations that were developed by the gradual expansion of the invention brief, incorporating the lemmas that the previous invention could no longer accommodate. How did one innovation lead to another? I am tempted to say I gained new insights through cycles of action research. But Lakatos puts it better:

> TEACHER: I abhor your pretentious 'insight'. I respect conscious *guessing,* because it comes from the best human qualities: courage and modesty. (1976, p. 30)

The innovation process in Table 6.2 shows the horizontal sequence from innovation $I_1 \rightarrow I_2 \rightarrow I_3$ being Rain Tower $\rightarrow$ Desiccant Wheel Air Handling Unit $\rightarrow$ Ductless Task Air-Conditioning. The chronology of this sequence reveals no logic, each invention was, well and truly, guesswork. However, the rationalisation of the process, also true to the history, is in the expanding lemma incorporation in the vertical sequence of the table. I_1 fulfilled the criteria of L_1, L_2 that

Table 6.2 Lemma incorporation in the innovation process

Lemmas	Innovation, in response to lemma		
	I_1 Rain tower	I_2 Desiccant wheel AHU	I_3 Ductless task AC
L_1 Energy consumption (compared to conventional systems)	More efficient	More efficient	More efficient
L_2 Impact on global warming potential	No synthetic refrigerants	Reduced synthetic refrigerants	No refrigerants
L_3 Commercialisability 1: selling advantage to property developer		Reduced AHU room size	Reduced AHU room size
L_4 Commercialisability 2: selling advantage to customer			Direct individual control
L_5 Commercialisability 3: applicability within existing building stock			No installation

was initially thought requisite to solve The Problem. Further research uncovered criteria from outside the scientific process, starting with L_3. If accepted, both the idea and premise of I_1 were conjunctively rejected: it was 'proven' to not solve The Problem. Similarly, with the realisation of L_4 and L_5, I_2 had to, in turn, be superseded by I_3.

Will we discover yet more monsters in the future? Certainly! Thus I do not promise finality, only more (lemma incorporating) depth with each innovation (rephrased, Lakatos et al. 1976, p. 120).

The integration of lemmas into the design brief can be a trying process, because each additional lemma restarts the design process. When the foundation is redefined, the superstructure is demolished and rebuilt. It is here that the innovator must remember that a problem that has long persisted is not solved easily. Thus the conventional thinking:

> Except under special circumstances, we think it ill-advised to try to get university researchers to work on specific practical problems of industry, or on particular product or process development efforts. In general, university researchers are poorly equipped for judging what is likely to be an acceptable solution to a problem and what is not. University researchers are almost always insufficiently versed in the particulars of specific product markets to make good decisions about appropriate tradeoffs. Equally important, such work provides few results that are respected or rewarded in academic circles, unlike research that pushes forward conceptual knowledge in an applied science or engineering discipline. (Rosenberg and Nelson 1994, pp. 346–347)

I would thus recommend care in selecting what problem the heuristic researcher decides to solve. The problem should be so worthy it provides the inspiration to persist solving with tenacity and creativity, for if either virtue is depleted, so is the heuristic momentum. Daniel Koshland (in Schiavon 2009) puts it aptly, 'It's probably equally difficult to solve an unimportant problem as it is to solve an important problem, so you might as well pick an important problem.'

6.4 The Commercialisation Test

Lakatos viewed research programs as degenerative 'when the positive heuristic ran out of steam' (1980, p. 52), where *heuristic power* is 'a technical term to characterise the power of a research programme to anticipate theoretically novel facts in its growth' (p. 69). The innovation must therefore both be novel, and a source for novel findings. In this aspect, heuristics and patenting have some similarities shown in Table 6.3.

It is not requisite for research-based innovations to have a patent, and in fact there are dangerous pitfalls going down the commercialisation path (Nicholls et al. 2011). Nevertheless the commercialisation pathway has a method for *proving* on two key criteria: novelty (patent test) and marketability (pitch test).

The process of filing a patent through the university is very different from doing it privately and the two need to be distinguished. In a private submission, no

Table 6.3 Similarities in schema between the heuristic and patent processes

	Heuristic Process	Patent Process
Progressive problemshift	Discovery of novel facts	Invention of novel product or process
Time to ascertain factual novelty	'The novelty of a factual proposition can frequently be seen only after a long period has elapsed.' (Lakatos, 1980, p.69)	Open to challenges throughout the patent lifespan (typically 20 years)
Corroboration	'Acceptability' evaluated by anyone with relevant technique	Understood and confirmed by 'one skilled in the art'

checks are undertaken by the patent office at the time of filing a provisional patent. One need only pay a relatively small administration fee to submit the application. The application, not reviewed at this stage, is deposited in the patent office for safe keeping. Only upon a subsequent filing of the full patent (typically within a year) is the invention reviewed by a patent officer. Thus it is possible for one to hold a provisional patent for an invention that was entirely precedented on prior art—an unthinkable disregard for novelty.

Q **What is 'prior art'?**

A 'Prior art is any body of knowledge relating to your research that exists prior to the completion of the research or the filing of a patent application. It may include patents filed in Australia or overseas; printed publications such as books, theses, journals and technical reports; public discussions; or public use of the research anywhere in the world.' (www.ipaustralia.gov.au)

The technology transfer (TT) office of universities have a more onerous system to ensure prior art cannot exist in their submissions. The TT front office (usually located on campus) requires a background to the invention, akin to a literature review. This forms the premise on which the invention is seen to have taken the *inventive step* beyond the knowledge-base. Satisfied, the TT officer submits the invention to the back office, typically off-campus. Here a patent researcher does a search to confirm that no *prior art* exists. Following which a patent review committee is convened by the TT office comprising entrepreneurs, patent attorneys, and, when necessary, field experts. The inventor is typically not present, and the invention has to 'sell itself'. Only after the committee deems the invention *commercialiseable* is a recommendation made to the university to pursue a patent. Even though the patent office does not require patents to be drafted by attorneys, universities routinely engage them to ensure all documents will hold up to scrutiny if the patent is disputed in court. The attorneys double-check that the invention fulfils the legal criteria for inventiveness and novelty before lodging the application.

'In general, the process of commercializing intellectual property is very complex, highly risky, takes a long time, costs much more than you think it will, and usually fails. (US Congress, Committee on Science and Technology in Bozeman

2000). It is against these risks that the university patent process imposes such rigorous tests for novelty and commercial value.

One peculiar challenge is that the invention should need to 'sell itself'. This imposes another criteria on the innovation cycle. Besides increased lemma incorporation, successive inventions had to be increasingly elegant in their solution to *The Problem*. To the patent review committee, even though the decision is made *prima facie,* the more unknowns they had to accept tentatively, the less likely they were to recommend it for a provisional patent. But how can one make an invention simple in its novelty, or if you like, novel in its simplicity? The autonomy of the human product from human activity (Lakatos et al. 1976, p. 145), requires that the invention, by design, be imbued with enough meaning to justify its purpose. Products should be 'so strong and convincing in their own right, that they so to say carry the validation with them, such as a strong piece of art' (Kvale 1994, p.12). An invention receives the best review if it can convey the 'classical ideal of a unity of truth, good[ness] and beauty' (Kvale 1994, p. 12), or—to borrow the maxim from a science-fiction utopian city—'Functional simplicity, structural complexity: the best life for all.' (*Appleseed*, Shirow 1985)

In commercialiseable innovations, the recommendation of the TT office to proceed is *proof* of an invention's novelty. The converse need not necessarily be taken to be a *refutation* of novelty, as there can be many other reasons to decline commercialisation, particularly when there is no clear path to market. It is here that the inventor is at the mercy of the *intuition* of the reviewers.

> Entrepreneurs with strong entrepreneurial cognition may be more likely to quickly develop new hunches about how a new piece of information such as that relating to a technological breakthrough will impact a specific project idea long before it can be methodically and rationally explained. … The creation of significant scientific breakthroughs by university researchers may require leaps of intuition rather than deterministic logic. (Wright et al. 2004, p. 241)

I will explain my position on intuition and its role in marketability concurrently, which can also be understood heuristically.

6.5   The Role of Intuition

In *Proofs and Refutations*, Epsilon describes his intuitions as the 'nondubious apprehensions of a pure and attentive mind which are born in the sole light of reason'. (p. 107) He further explains,

> EPSILON: I get my definitions. just as I get my axioms, by intuition. They are really of equal standing: you can take my definitions as additional axioms or you can take my axioms as implicit definitions. They give the essence of the terms in questions.
>   TEACHER: Enough of philosophy! Let us see the proof. I do not like your philosophy, but I still may like your proof. (Lakatos et al. 1976, p. 108–109)

Intuition has two uses: it may be used to justify knowledge epistemologically, or used to account for a decision that canot be rationalised. In the former it is the master of knowledge, in the latter the servant of heuristics. Hegel and Lakatos reject intuition of the first kind.

> As a kind of philosophical knowledge given to those fortunate to be born with it, it is, for Hegel, entirely unrelated to ordinary modes of knowing, a special kind of cognition altogether. Consequently, certain types of knowledge are effectively unlearnable. Another result is that the world becomes divided between those who have the inarticulate feeling or intuition to grasp the absolute and those who inexplicably lack that capacity. Schelling, as Lukacs remarks, created in Hegel's eyes an "aristocratic theory of knowledge" in which authentic knowledge may be accessible only by a chosen few. In his lectures, Hegel made this aristocratism clear: 'As the science of reason, philosophy is of its very nature … available for all. Not all can attain to it, but that is not in question, any more than that few people become princes. That some men are placed higher than others is a scandal only if it is claimed that they are creatures of another kind and that nature had created them so.' (*Imre Lakatos and the Guises of Reason*, Kadvany 2001, p. 41)

Intuition of the second nature has its particular use, as we can see again from Epsilon's acknowledgement after being alerted to an inconsistency. He says, 'I was wrong. That "definition" was a stupid anticipation. I jumped to my judgment in a silly rush. True intuition, true interpretation, ripens slowly, and purging one's soul of conjectures takes time' (p. 109). Thus understood, this intuition is *fallible,* in contrast to the the earlier form. For example, Tversky and Kahneman (1974, p. 1130) show how even though 'the statistically sophisticated avoid elementary errors, such as the gambler's fallacy, their intuitive judgments are liable to similar fallacies in more intricate and less transparent problems.' It is for this precise weakness that intuition should not be used when a problem can be better solved rationally. However intuition is often relied upon when a complex situation requires a snap decision, a situation commonly encountered in the business world.

Businessmen hone their intuition by doing business. It is the product of apprenticeship, self-teaching, experimentation and reflection. In this sense, the *proof pedagogy* of business can be described as a Lakatosian heuristic process. How can an academic acquire business acumen without doing business? I suggest that the next best alternative is to role play the business encounter of a pitch. I have watched almost every episode of Dragons Den (UK), Dragons Den (Canada) and Shark Tank (U.S.). This was not intended for entertainment, for at the back of my mind was the action research format: plan → act → observe → reflect. I imagined myself in the role of the pitcher and attempted to understand the product or concept to be pitched (plan). I would then draft an elevator-style pitch, articulating in 90 s the unique selling points and market opportunities (act). Then I compared my approach with the pitcher's (observe) and rationalised the reaction of the investors (reflect). I accept that this approach is non-academic in that it cannot be theorised and its results cannot be peer validated; although it is an experimental technique which can be used by anyone.

The aim here is to develop sufficient business intuition so that a stage reminiscent of *Proofs and Refutations* can be recreated in the mind. I have composed a

short specimen, casting an innovator with investors, who are designated after currencies.

INNOVATOR: Air-conditioning accounts for the majority of the energy used in tropical cities. I have invented a new way of delivering cooling with lower power consumption than that used by conventional systems, and which uses no synthetic refrigerants. I call this the Rain Tower. It uses a column of water as a piston to compress and condense vapour in a single stroke, thereby achieving better thermodynamic efficiency…

YEN: Show me your prototype.

INNOVATOR: At this stage I have only calculated the thermodynamic properties

YEN: What? You haven't built anything yet?

INNOVATOR: No, not yet. I am here to ask for funding to prove that the engineering concept is viable and

POUND: [*interruptshim*]*You* have twenty seconds to explain, in plain English, how this thing works

INNOVATOR: [*perspiring and speaking quickly*] The engine of air-conditioning is the compressor. All compressors need to have a clearance because you can't have the piston striking against the walls. But like pumping a bicycle, if you don't squeeze it to the end you lose the valuable part of compression. I've eliminated that with my invention using a falling column of water to regenerate steam. No clearance equals better efficiency. [*breathes*]

DOLLAR: Cut out the science, I'm not interested. How do we make money?

INNOVATOR: We haven't got there yet. At this stage we need to confirm the technology is viable

DOLLAR: [*irritated*] Let's assume that the science works, how do we turn a profit?

INNOVATOR: Electricity will continue to get more costly and the carbon price introduces an additional charge for refrigerant leakage, which has a high global warming potential

DOLLAR: Is there a dollar value in there somewhere?

INNOVATOR: Yes at the proposed carbon price, the total emissions from refrigerant leakage and refilling in Australia will be about $96 million

DOLLAR: And how much is this Rain Tower going to cost?

INNOVATOR: I'm afraid I don't

DOLLAR: [*throws his hands up*]*You* don't know? How can you not know? That is the only number that matters! I am an investor, you want my money and you have no clue what it will cost, what it will sell for and if I'll ever see my money again?

INNOVATOR: I'm very sorry

DOLLAR: You should be! You're wasting my time. I'm out

EURO: [*aside to Doiiar*]*Cut* the poor fella some slack. [*turning to Innovator*]*I'*m intrigued, I think with the carbon price the market is ready for some innovation. How long before we can roll out a manufactured version?

INNOVATOR: We will need about three months to build a test rig, about as long to test and tune. Then we should, ideally, build it to full scale and that will take about nine months, and about as long to collect data. We will then be able to approach industry to manufacture to our specifications

YEN: By which time my children will have received their inheritance. [*shaking his head*] You should have built a prototype before asking for a share of my children's inheritance. I'm out

EURO: Why do you need so much time? How big is it?

INNOVATOR: For a 40-storey office block of average size, it would be a continuous section with a cross-section of four parking lots on the side of a building

EURO: Did you say *on the side of a building?*

INNOVATOR: Yes, it has to be in thermal communication with the ambient. So the side of a building is best

EURO: That's a bad idea. Not the water thing, the side of building thing. Don't like that. And it can't be installed in existing buildings?

INNOVATOR: I'm afraid not, the building has to be designed around the cooling apparatus

POUND I haven't said much but I've heard enough. You obviously don't have a clue how things work in the *real* world. Get out of university and get a *real* job selling something. Until then I'm not trusting you with my money. I'm out.

EURO I like you but I don't like your idea. Work on something else, this idea isn't going to be the one. And for that reason, I'm out.

DOLLAR *[to Euro]It's* a bad idea. Why are you still encouraging him? *[turning to Innovator]You* are dead to me. Now get off my carpet.

If an innovation cannot meet marketability criteria, regardless of novelty, it will not be funded, manufactured, distributed and retailed. The ability to role-play the pitch in the mind allows research ideas—this embodiment of academic knowledge—to be tested against business intuition. It is the fastest and cheapest way to refute an idea. It is also far easier to be self-deprecating than to be ripped apart and scorched by a panel of impatient investors: there is a reason why they are called *dragons* and *sharks.*

6.6   Concluding Thoughts on Heuristics

> The significant problems we face cannot be solved at the same level of thinking we were at when we created them. Albert Einstein (1879–1955)

The conventions of a methodology chapter and a falsifiable hypothesis do not offer the appropriate structure to solve problems. Being concerned with *The Problem*, this chapter has shown a better way in the heuristic style of Imre Lakatos. However his approach was intended for the academic realm and I have proposed modifications to extend the heuristic method so that research can be realised in the world of commerce. For this particular *Problem* the commercialisation route was chosen and served well to validate novelty and marketability. Recognising my own inadequacy to intuit business, I have devised a method to simulate a pitch, analogous to Lakatos' classroom scene.

Having explained why I made a break with convention, we may proceed, *tabula rasa,* to solve *The Problem.*

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Chapter 7
The Rain Tower

Rather than tinkering with small incremental improvements in the efficiency of air conditioning systems, we need a step change to new paradigms for cooling buildings. Just as with the cars, we need super-low-consumption, dual fuel, eco-buildings that are naturally ventilated in spring, winter and autumn, and in summer are run on solar air conditioning when the sun is out topped up by small amounts of grid electricity when it is not. This is the way forward. (Roaf 2005, p. 233)

The problem of energy-intensive air-conditioning has been very persistent. Incremental steps in improving energy economy may be too modest an approach to tackle the imminent risk of anthropological climate change. To accommodate the need for non-linear creative thinking, the following approach was taken as an adapted model for action research:

1. Framing the research problem as a design brief
2. Disruptive creativity: proposing solutions through lateral thinking, a process that is not necessarily linear or sequential
3. Action research: evaluating the solutions against its intents and ascertaining its implementability.

The inventive process is often non-linear, with the most significant breakthroughs often having little resemblance to earlier ideas. The valuable insights gained in the earlier stages however, frame the issues with greater clarity and facilitate reprioritisation so that the brief can be revisited with more knowledge and detail.

7.1 The Brief

In 9 April 2007, TIME magazine (2007) ran a special article on global warming. In that article, buildings were highlighted as key contributors to warming, with offices and homes said to account for 38 % of U.S. CO_2 emissions. All the green buildings mentioned in the article featured novel approaches to thermal control, such as the Federal Building (San Francisco), Bank of America Building (New York) and

Pearl River Tower (Guanzhou, China). In Singapore 34 % of the nation's annual 35.9 GWh energy consumption is attributed to buildings (both commercial and residential), of which 33 % is for air-conditioning and another 25 % for refrigeration (NCCC 2006).

Office workers are responsible for approximately 50 % of the US annual gross national product (Traynor, 1993 in Fisk 1999). In the foreseeable future, offices will continue to be the central power house for the economy. Until there is a large critical mass of lessees who will pay higher premiums for energy efficient buildings, these offices will continue to be developed as deep plan, fully-glazed offices. In areas with poor air quality or noisy external environments, in both cases necessitating closed windows, the reliance on air-conditioning is understandable, but even when air does not have to be filtered or conditioned there are prestige factors (Tselepidaki and Santamouris 1991), social norms (Wilhite et al. 1996) and building standards (Shove 2003) that lead us to predict that air-conditioning is here to stay—at least until circumstances force change.

For buildings to be sustainable, it is becoming increasingly important that they have high performance while consuming minimal resources. The area of research innovation here can be constructed as a brief:

> Design a system that can provide air-conditioning to high-rise offices in the tropics with little or no demand on grid power.

Being in the tropics the enthalpy of air is already high (hot-humid), and has limited capacity as a heat sink by further evaporative cooling. Being equatorial, the solar angles are high and limit the prospect for photovoltaics or solar-thermal collection to only the roof. Being multi-storey, the one roof needs to supply enough converted solar power for all floors. Being in a densely populated city, there is minimal availability for cross-ventilation due to the tight urban planning and deep office plans.

To tackle the issue of climate change at its root, incremental steps are not adequate. So instead of looking at marginal improvements to efficiency, the theoretical limits are considered. Similarly whilst the use of high global-warming potential (GWP) refrigerants is discouraged, the ultimate intent is to avoid these refrigerants altogether, and this intent is assumed in the brief.

The properties of natural refrigerants are in Table 7.1 and show the challenges of working with these refrigerants. Studied thermodynamically, Kilicarslan and Muller (2004) found that at a temperature lift (ΔT, or TD in Fig. 7.1) of 30 K, water is equivalent in COP to R134a at an evaporator temperature, $Te = 12$ °C and superior to all the other refrigerants modelled (R12, R22, R134A, R290, R152A and R717) at $Te = 34$ °C.

With a high COP (coefficient of performance), no ODP (ozone depleting potential) and neutral GWP, water appeared a *natural* choice around which to design a cooling system.

Table 7.1 Characteristics of natural refrigerants (Tanaka and Kotoh 2007)

Refrigerant		CO_2	Hydrocarbon	Ammonia	Water	Air
Chemical properties	Toxicity/flammability	O	Δ	Δ	O	O
	Material deterioration	O	O	Δ	O	O
	Chemical stability	O	O	Δ	O	O
Thermophysical properties	Moderate boiling point	Δ	O	O	Δ/O**	Δ
	Capacity per unit volume	O	O	O	Δ/O**	O
	Theoretical COP	Δ/O*	O	O	O	Δ
	Moderate discharge temperature	O	O	O	O	O
Global environmental property	Ozone layer	O	O	O	O	O
	Warming	O	O	O	O	O

* Evaluated with air-conditioners/water heaters.   O: Acceptable
** Evaluated for source-of-heat temperature at low/high   Δ: Unacceptable (shadowed)
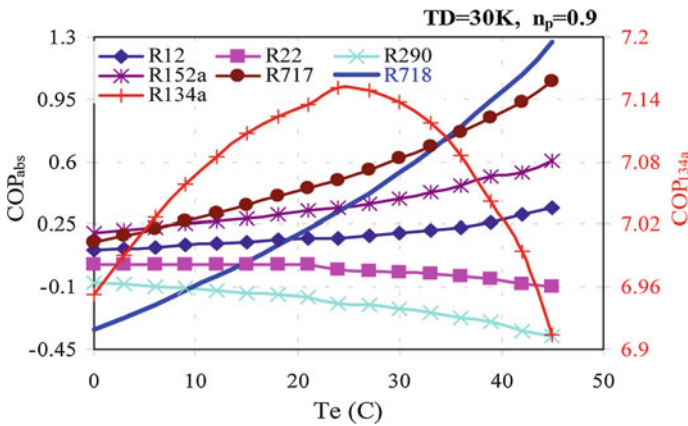
Fig. 7.1 Water (R718) compared to natural refrigerant ammonia (R717) and other synthetic refrigerants (Kilicarslan and Muller 2004)

7.2 Innovation 1: Water as Refrigerant

Conventional air-conditioning systems use mechanical compression to restore a refrigerant from gaseous to liquid state, a process that invariably generates more heat through inherent inefficiencies of the machinery. The proposed alternative to the air-conditioning system begins by rethinking how a gaseous refrigerant could be readily recondensed, and perhaps the passive cooling solution might be in selecting a refrigerant that was less volatile.

7.2.1 Cloud Seeding

The inspiration came from the notion of cloud seeding (Fig. 7.2). When suspended cloud droplets and supersaturated water vapour were sprayed with a suitable seed (dry ice or silver iodide), the ice crystal would grow till it became sufficiently heavy to fall, and passed through the warmer lower atmosphere as raindrops (Ball 2002; Battan 2003). What if we could have a tower filled with saturated vapour and seed it from the top? Or better, what if the top of the tower was so high that it was cold enough for the vapour to condense?

7.2.2 Adiabatic Lapse Rate

The higher we go, the thinner the atmosphere gets, and correspondingly, the colder it becomes. The phenomenon is known as the adiabatic lapse rate (see Fig. 7.3a)
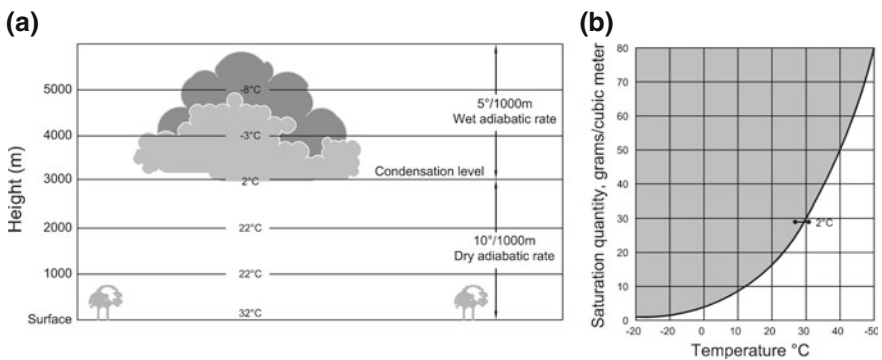
Fig. 7.3 a Adiabatic lapse rates, redrawn from Lutgens and Tarbuck (1995). **b** Water vapour saturation curve, redrawn from Loubere (2012)

and meteorologists have computed a range of values corresponding to dry and moist air of 10 and 5 °C/km respectively (Lutgens and Tarbuck 1995; Allaby 1992). Water vapour condenses naturally into clouds at about 3 km. If we could increase the humidity inside a column, could a tower 200 m tall have sufficient coolness to drive condensation with a 2 °C drop in temperature, for example in Fig. 7.3b?

If a column of air could be saturated to a humidity of 28 g/m^3 then a 2 °C drop in temperature between base of this tower and its summit (Fig. 7.4) would be sufficient to cause vapour to condense.

Operating on premise similar to evacuated heat pipes, the rain tower essentially uses the temperature differential from altitude to drive an evaporation-condensation cycle, and, through the processes of evaporating the water at low altitudes and condensing at high ones, allows ground level spaces to approach the temperature of high altitudes.

However, a 2 °C temperature drop would hardly be adequate for the tropics. With an ambient temperature of 30–35 °C in the tropics, a drop of about ∼10 °C was needed for comfort, and a further 10 °C necessary for dehumidification. For buildings that were already tall (Burj Khalifa, AC Towers), the adiabatic lapse rate could be a means of supplementing the cooling load. However, for the majority of buildings, simply building taller was clearly not the solution.

Some form of energy input is therefore essential to supplement the cooling with altitude.

7.2.3 Solar-Thermal Absorption Chiller

Pairing the power supply to the chiller to a solar source has the advantage of delivering more power when the outdoor radiant heat was high, and thus demand for air-conditioning was also at its highest. There are two passive ways of driving chillers, both with comparable efficiencies:

1. Photovoltaics (10–15 % solar-electric efficiency) to drive a vapour compressor (COP = 3–4)
2. Concentrated solar on evacuated heat pipes (80–90 % solar-thermal efficiency) to drive absorption chillers (COP = 0.5–0.7)

Once again, to avoid synthetic refrigerants, the use of vapour compression chillers is not considered. Instead water is heated by evacuated tubes or concentrated parabolic troughs, then passed through an absorption chiller (e.g. lithium bromide–water). The chiller condenses some of the vapour into liquid state and sprays a chilled mist into the tower where the rest of the water vapour is fed (see Fig. 7.5). The mist acts as condensing nuclei, causing the vapour to coalesce and precipitate to the base. The system would now be able to achieve more cooling without having to build higher, though height will still be an advantage, allowing droplets more growth time.

AT 200M OR APPROX. 70 STOREYS HIGH
TOP OF TOWER IS 2° C COLDER THAN FOOT

CONDENSATION

ADIABATIC LAPSE RATE OF SATURATED COLD AIR IS
9.8° C/KM OR APPROX. 1° C/ 00M

200M

EVAPORATION

COOLED AIR DESCENDS TO OCCUPIED STREET LEVEL
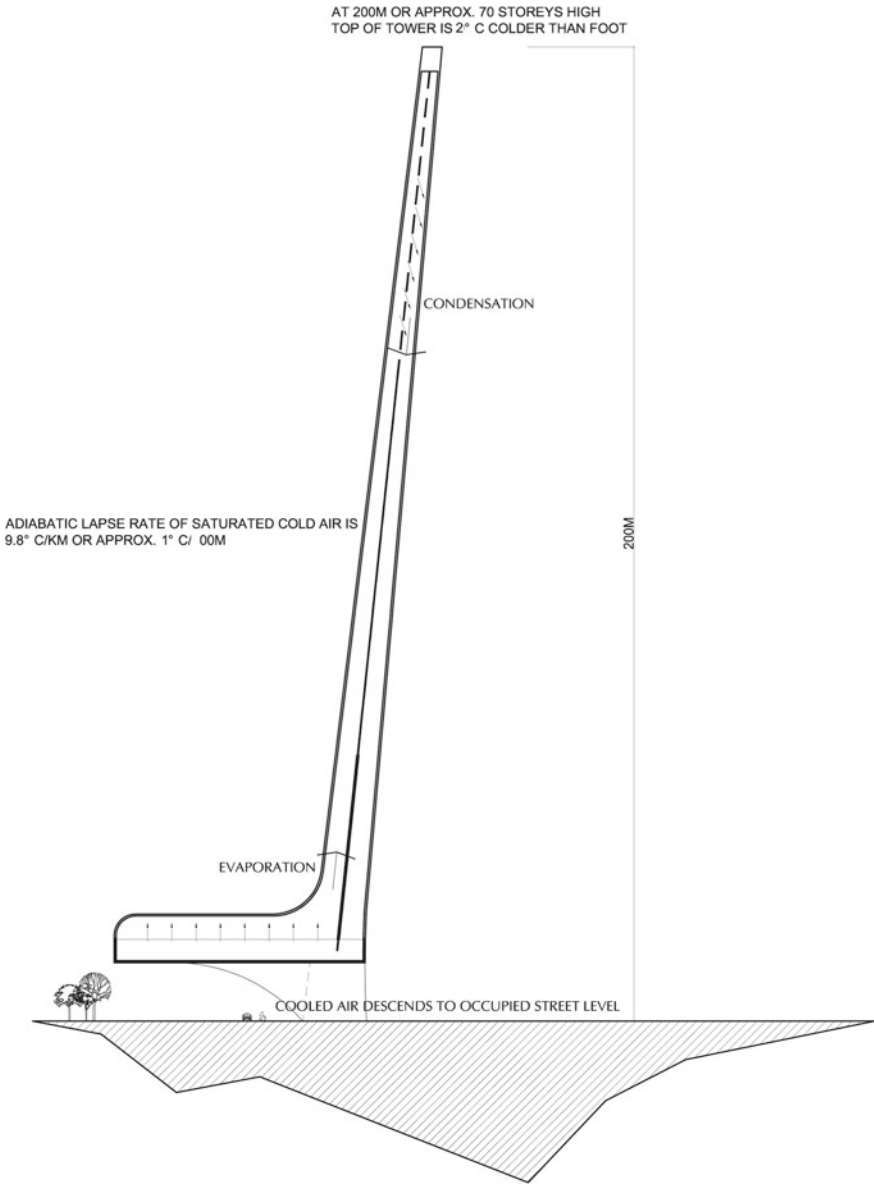
Fig. 7.4 Rain tower using altitude cooling
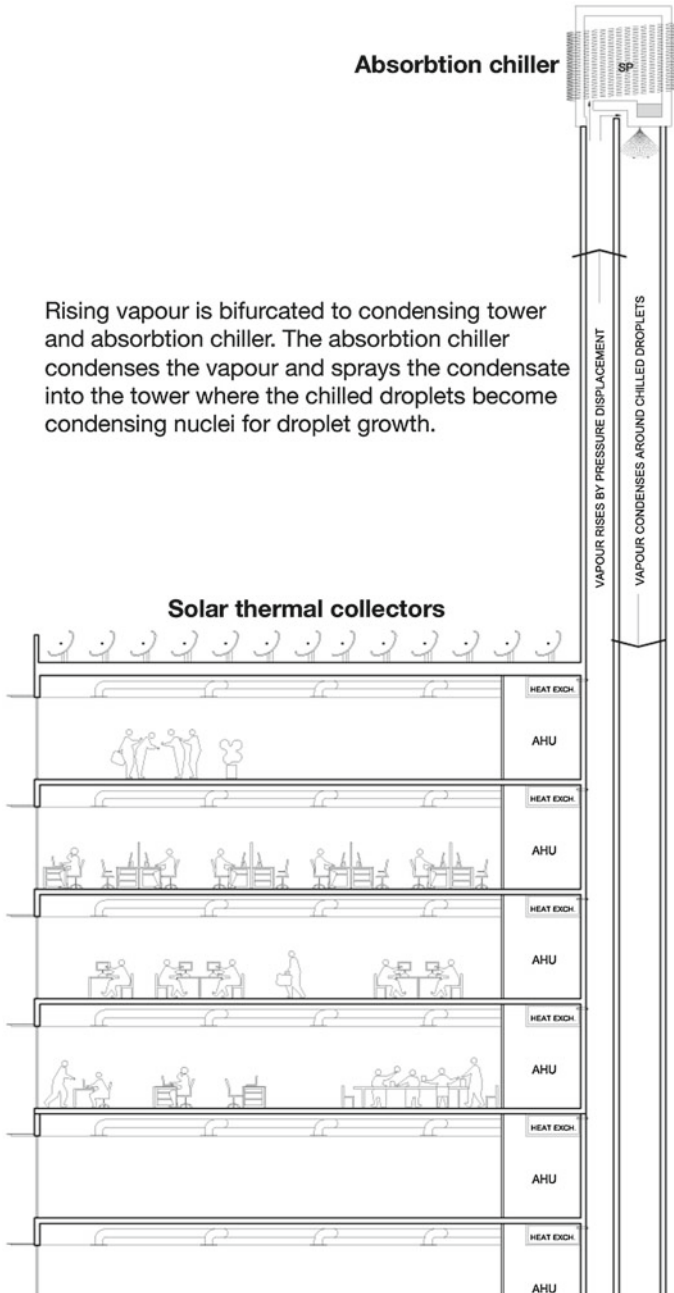
Fig. 7.5 Rain tower using solar thermal driven absorption chiller

7.2.4 Reflections

The early attempt to create an artificial water cycle utilising the height of a tower gave limited cooling of 2 °C. This was the limit to a passive mode of cooling. Further cooling required the use of a chiller, which could be run with solar power. To avoid the use of synthetic refrigerants, an absorption chiller coupled with concentrated solar-power can provide further cooling. However, the chiller capacity is limited to the size of the rooftop collectors, and cannot scale up for a large number of floors. When there are too many storeys to cool, each floor may not receive adequate cooling.

The limits to passive cooling were clear. Without the heat sinks of dry air and the night sky in the tropics, the only option of heat rejection to the upper atmosphere was not adequate for a 200 m high tower. At the same time, a multi-storey building had a very small roof-floor ratio and limited the possibility of using the roof as a solar collector.

If cooling could not be achieved passively, what was the theoretical minimum energy needed?

7.3 Innovation 2: Water as a Plug to Compress R718

There are technical difficulties working with water in conventional compressors which include:

- the need to work and maintain very low pressures to evaporate water
- when compared to synthetic refrigerants, water has a higher chance of condensing in the compressor (leading to compressor malfunction), thus requiring that the vapour be superheated. However, every degrees celsius of superheat decreases COP by approximately 0.05 (Lachner 2007).

Whereas the previous idea dealt with using chilled droplets to condense water vapour and coalesce suspended droplets to fall as rain, this idea deals with using water as a piston to compress vapour to liquid.

7.3.1 System Concept

The Rain Tower uses water as a natural refrigerant in a hermetically sealed cycle to create cooling from an ambient condition of 30 °C to an indoor one of 19 °C. Its mode of operation is similar to a vapour-compression air-conditioning cycle with the main exception being that the compressor is replaced by a falling column of water acting by gravity to compress and condense steam in one stroke (Fig. 7.6).
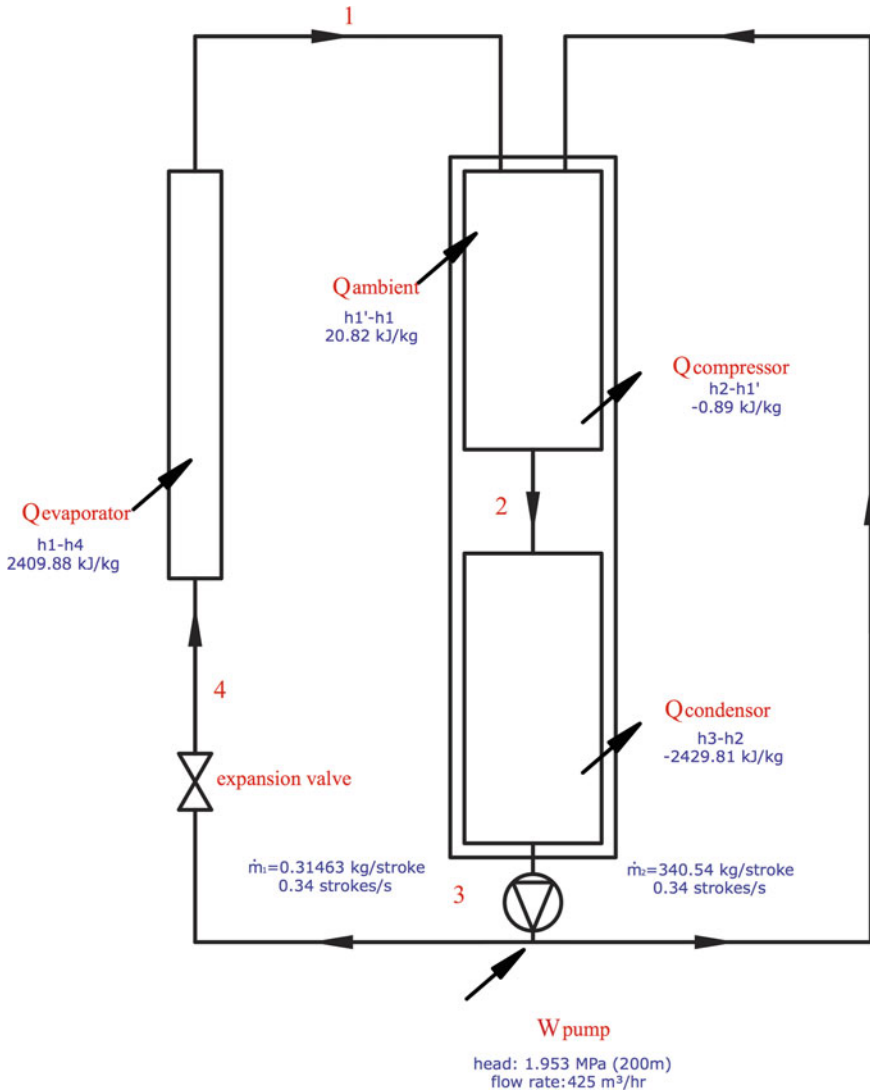
Fig. 7.6 System diagram for the rain tower

Water is passed across an expansion valve (3–4) to a mean pressure of 0.022 bar. The vapour is passed to the condensing tower, a 20 m high (variable as needed) thin-walled aluminium cylinder where it is allowed to warm to ambient conditions (30 °C, stage 1–1′).

A column of water exerting 0.034 bars is released on the steam and the falling column, acting as a plug, compresses the vapour adiabatically up to 35 °C. Assuming the cylinder walls are thin enough to maintain the T of steam (mixture

Table 7.2 Summary of compression cycle with a falling column of water

1–1′	Warming of steam (constant-volume) from evaporator to ambient temperature	
1′–2	Isothermal compression	
2–3	Isothermal condensation	
3–4	Isenthalpic expansion	

1

0.022bar

1′

0.022bar

0.022bar

0.34m | 0.034bar

0.022bar

0.022bar

0.022bar

19°C

0.33kg steam

30°C

0.31kg steam

20m

64m³/kg

100% steam

>0.022bar
>30°C
<64m³/kg

100% steam

2

0.042bar

25m³/kg

99% steam

7.8m

3

0.056bar
0.001m³/kg
100% liquid

Qambient   Qcomp   Qcond
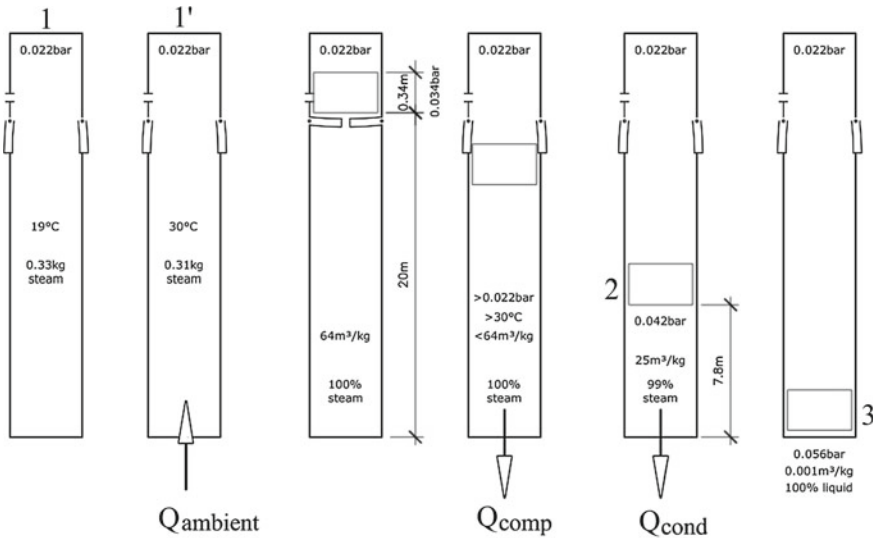
Fig. 7.7 Compression sequence

of vapour and droplets) close to 30 °C, the compression can be taken to occur isothermally (1′–2). The internal pressure of the steam eventually reaches equilibrium with the net pressure exerted (0.022 + 0.034 = 0.056 bar). As the steam fraction decreases, the volume corresponds and the steam is condensed isothermally (2–3). Table 7.2 and Figs. 7.7, 7.8 and 7.9 give further details to the thermodynamic process.

Considering one stroke of the cycle:

$$W_{pump} = (\dot{m}_1 + \dot{m}_2) \cdot \Delta PE = 67.93 \, \text{kJ} \tag{7.1}$$

$$Q_{evaporator} = \dot{m}_1 \cdot (h_1 - h_4) = 758.22 \, \text{kJ} \tag{7.2}$$

$$COP_{theoretical} = \frac{758.22}{67.93} = 11.16 \tag{7.3}$$

W_{pump}	Mechanical work of pump
$\dot{m}_1$	Mass flow rate through evaporator
$\dot{m}_2$	Mass flow rate to create water plug
ΔPE	Potential energy difference
$Q_{evaporator}$	Energy absorbed in evaporator
$\dot{m}_1$	Mass flow rate through evaporator
$h_1 - h_4$	Enthalpy of evaporation
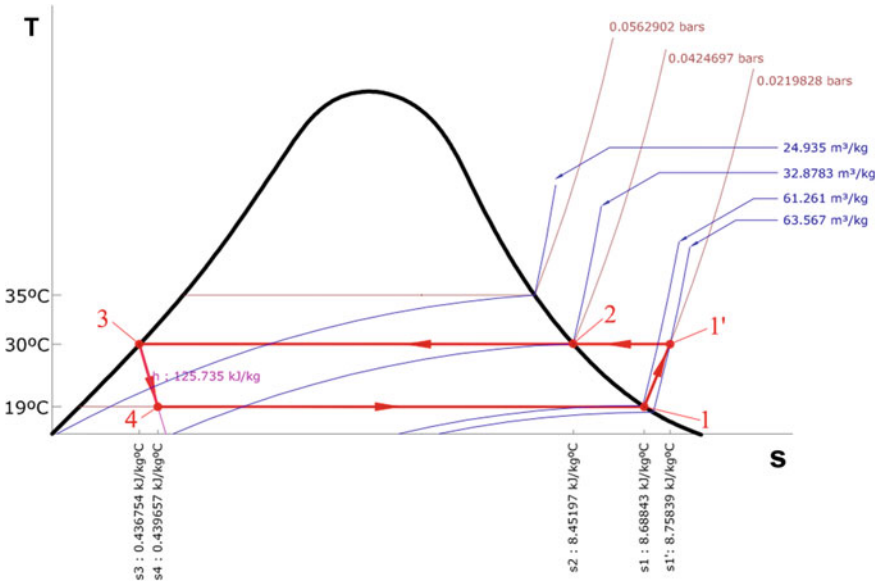
Fig. 7.8 Temperature-entropy diagram

In order to determine the pump efficiency, the flow rate had to be determined. This in turn is determined from the heat load of the building and covered in greater detail in the next section. From the flow rate, it can be estimated that:

$$COP_{net} = \eta_{pump} \cdot \eta_{fhl} \cdot \eta_{AHU} \cdot C.O.P. \tag{7.4}$$

η_{pump}	0.84	From pump efficiency table (www.lightmypump.com) at flow rate of 946 m³/h
η_{fhl}	0.9888	Frictional head loss, from pipe table (DN400), at 12.22 m/km
η_{AHU}	0.94	Highest typical fan efficiency, Nilsson (1995)
COP	11.16	
COP_{net}	8.7	
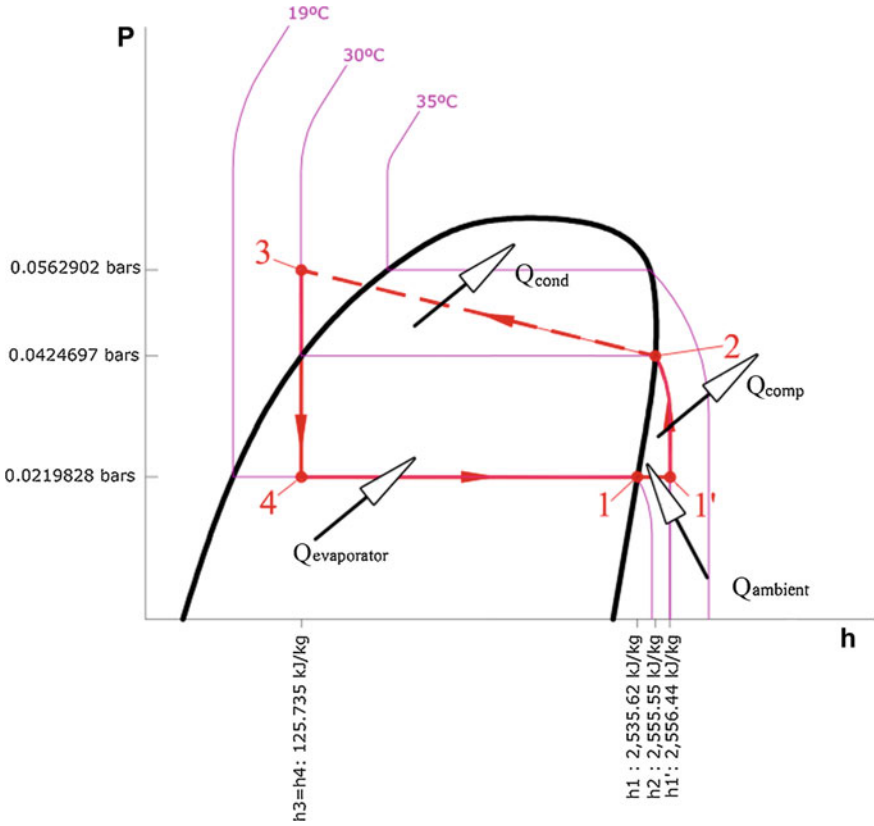
Fig. 7.9 Pressure-enthalpy diagram

Even with the foreseeable penalties on perfect efficiency considered, the net coefficient of performance (C.O.P.) is still high, at 8.7. Whilst this is still far below the maximum theoretical limit of a Carnot cycle (26.6 for the equivalent temperature difference), this is a marked increase in the C.O.P. of residential systems (3–3.5) and commercial (4–5). The central innovation is the use of a liquid plug to drive the isobaric compression, a technique that can also be extended to other natural refrigerants operating in low pressure (like ammonia and CO_2).

7.3.2 Calculations

To size the Rain Tower, a reference building was based on an office tower of 40 storeys (5 m f–f height) with a floor plate of 30.5 × 30.5 m^2 and a non-AC space of 9.1 × 9.1 m^2. Three different methods (Ansari et al. 2005; Bobenhausen 1994; Ding et al. 1983) were used to determine the cooling requirement and the highest

value was used. This was confirmed to also be higher than empirical values (Sekhar et al. 2003).

From the calculations shown in Table 7.3, a total of 9 ducts, each 1 m^2 in cross-section, will be required to continuously operate the Rain Tower.

7.3.3 Testing the Water Plug, the Rain Rod

Water as a refrigerant, R718, could be an alternative to synthetic refrigerants if the falling water plug could be realised as an alternative to the compression piston. The water plug needs no lubrication and requires no piston-wall clearance. With a liquid plug, the work input was through the pump, which typically had higher efficiencies than compressors. The presence of droplets in the compressor also poses no threat to a fluid piston and obviates the requirement for superheating, thus maintaining the high C.O.P.

But does a column of water retain its integrity as a body, or does it break up into droplets?

To empirically determine if a falling column of water can be used as a plug to compress steam, a rig was designed (Fig. 7.10). Sealed and evacuated, the tower (right) would be fed water from the mains. On reaching the requisite volume, the valve will release a column of water, causing a drop in pressure in its wake. The lower pressure causes the water in the evaporator (left) to boil and balance the pressure.

Quotations returned at $3,000 for fabrication and deemed as too costly. A low cost version had to be contrived. Consisting of three segments of copper pipe and two stop-valves, a column of water was retained whilst the rod was evacuated. To create a vacuum, the rod was filled with water, heated to steam to displace the water and allowed to cool. The condensed steam was expected to create a near-vacuum in its wake corresponding to its saturated pressure at ambient temperature. Setup and preparation is illustrated in Figs. 7.11 and 7.12.

When the column of water was allowed to fall it was expected that as it fell, the column of vapour above would be expanded adiabatically to show cooling, while the vapour below was compressed and eventually condensed to show some heat rejection. The saturated pressure of steam (0.032 bar @ 25 °C) with the pressure from the plug (0.035 bar from 350 mm water: 997 kg/m^3 @ 25 °C) would, upon release, compress the steam and condense it to water as long as the temperature did not exceed 38 °C. With this it was expected that the piston should demonstrate discernible temperature difference between the top and bottom. A thermal imaging camera was used to measure the difference and showed an average 4 °C difference in the 2 temperatures (Fig. 7.13).

Aware that the disparity could be a consequence of reading the background thermal radiation, and to avoid the likelihood of reading a reflection on a metallic surface, the surface of the copper pipes had already been painted matte black

Table 7.3 Determination of pump flow rate for the rain tower

	Parameters	Notes		Units	Value
1	Height of rain tower	A		m	200
2	Cross sectional area of duct	A		m^2	1
3	Height of piston	=	(34)	m	0.341
4	Specific mass	S		kg/m^3	999.34
5	Mass of piston	=	(2) × (3) × (4)	kg	340.90
6	Gravitational P.E. of piston at roof	=	(5) × (1) × 9.80665	kJ	668.62
7	External temp.	A		°C	38.50
		=		°F	101.30
8	Target temp.	L		°C	19.00
		=		°F	66.20
9	External humidity ratio	A		lb H20/lb air	0.020
10	Target humidity ratio	L		lb H20/lb air	0.009
11	Total floor plate	A	30.5 × 30.5	m^2	930.25
12	Non-airconditioned core	A	9.1 × 9.1	m^2	82.81
13	Air conditioned space	=	(11)–(12)	m^2	847.44
14	Number of floors	A		Storeys	40
15	Total a/c office space	=	(13) × (14)	m^2	33,898
				sq ft	364,871
16	Cooling load factor	R1		cfm/sq ft	1.2
17	Cooling load	=	(15) × (16)	cfm	437,845
		=	(17)/400	ton	1,094.61
18	Occupancy	A		pax/floor	90
19	Ventilation factor	R1		cfm/pax	20
20	Ventilation load	=	(14) × (18) × (19)	cfm	72,000
21	Required cfm	=	(17) + (20)	cfm	509,845
22	Q (sensible)	=	1.10 × (21) × [(7)–(8) °F]	btu/h	2,779,920
23	Q (latent)	=	4,840 × (21) × (9)–(10)	btu/h	3,833,280
24	Q (total ventilation)	=	(22) + (23)	btu/h	6,613,200
			(24)/12,000	ton	551.10
25	Total cooling load	=	(17) + (24) ton	ton	1,645.71
		=	(25) × 3.517	kW	5,787.97
26	Energy (heat) to be extracted in 1 h	=	(25) × 3,600	kJ/h	20,836,691
27	Mean pressure of duct	S	(steam prop. at 19 °C)	bars	0.0219828
28	Density of steam	S		kg/m^3	0.0163249
29	Mass of water vapour in duct	=	200 × (28) @19 °C	kg	3.2650
30		=	(29) × (292.15/303.15) @30 °C	kg	3.1465
31	Specific volume of steam	=	200/(30)	m^3/kg	63.5625
32	Requisite specific volume for condensation to occur	S	(steam prop. at 35 °C)	m^3/kg	25.2053

(continued)

Table 7.3 (continued)

	Parameters	Notes		Units	Value
33	Compression factor required	=	(31)/(32)	Dimensionless	2.5218
34	Pressure from piston required to deliver compression	=	[(33) × (27)]–(27)	Bars	0.0335
		=	(34) × 10.197162	m H20	0.3411
35	Δ Specific enthalpy of vapourisation in flash chamber	S	H-steam(19 °C)–H-water(30 °C)	kJ/kg	2,409.89
36	Δ Enthalpy of vapour in duct	=	(30) × (35)	kJ	7,582.73
37	Strokes of piston to achieve required a/c load	=	(26)/(36)	Strokes/hr	2,748
38	Energy to pump to roof for one hour	=	(37) × [(6) + (30) × 9.80665]	kJ/h	1,922,112
39	C.O.P	=	(26)/(38)		10.84
40	Number of ducts required	=	3 + 7 × (37)/3,600 7 s for piston to free fall down 200 m 3 s to refill		8.3
41	Pump flow rate	=	(37) × (5) + (30)/(4)	m^3/h	946

Notes
A assumed
S steam table
L locked parameter
= calculated
*R*1 Bobenhausen (1994)

(2 coats Fig. 7.14). Despite that it might still be possible that the emissivity of the surface was low enough to catch reflections (Fig. 7.15).

To complete the experiment the valves were released to atmosphere to see if the vacuum had been contained. It was ascertained that the procedure/apparatus did not successfully create or contain a vacuum. To exclude the possibility of off-gassing of non-water gases into the vacuum, the preparation was repeated with water filtered through a domestic filter (to remove chlorine) and double-boiled (to remove oxygen and other gases). Within 30 min of removing from flame, the valves were open to atmosphere. The creation of a vacuum had again been unsuccessful.

A few possibilities could explain the leakage:

1. Valve seals may have melted in extreme heat as steam T approach LPG flame T ≈ 2,000 °C
2. Rubber washers (2 no.s) deteriorated with extreme heat
3. Water fixtures may not be suitable for vacuum operations; though this is unlikely since plumbing fixtures are rated to 10 bars.

Due to the difficulty in achieving a vacuum without a vacuum pump, the
integrity of a falling column of water was inconclusive. Can a column of falling
water retain enough integrity to be a pressure plug? The plumbing practice to
ventilate waste stacks suggest that when water fall under gravity it does not break
up into droplets. 'The introduction of air near the fixture… breaks the possible
siphonage of water out of the trap.' (Stein et al. 2006, p. 989) When water is
flushed down a waste stack it can potentially fall as a plug, capable of suction,
otherwise there is no risk of siphonage. On hindsight the experiment was unnec-
essary though it provided insight into the challenges in creating and maintaining a
near vacuum of 0.02 bar.

SEGMENT 1
350mm

SEGMENT 2
350mm

SEGMENT 3
1630mm

plug (top)

½" copper pipe

quarter turn stopcock
(valve #1)

½" copper pipe

quarter turn stopcock
(valve #2)

½" copper pipe

Rod Assembly
Copper pipe painted matte
black to increase
emmissivity, then inverted
and filled with water through
valve #3. Rod is knocked to
release trapped air bubbles
before valve #3 is shut.

quarter turn stopcock
(valve #3)

plug (bottom)

P = 0.032 bar   P < 0.032 bar

Experiment Stage 1
Rod is rotated at 45° to allow
water to accumulate in segment
3. Valve 1 shut and rod inverted
to let water collect in segment 2.
Valve 2 shut. Rod restored to
upright position. At equilibrum
water and steam will coexist at a
pressure of 0.032 bar (ambient T
of 25°C).

Experiment Stage 2
The 350mm column of water is
released and its weight exerts an
additional 0.035bar on the
column of steam below (total
0.067 bars) causing it to
condense. As the column moves
downward the steam in segment 1
is expanded and presure drops
below the initial 0.032 bars. Being
no longer in equilibrium the top of
the water column should
evaporate into segment 1, whilst
condensing segment 3.

It is expected that with an infrared
camera there should be an
appreciable T difference between
the top and bottom of rod.

P = 0.032 bar   P = 0.067 bar

Fig. 7.11 The premise for using a rod to ascertain the plug integrity

Vacuum Preparation

Segment 1 is sealed whilst the pipe is heated by a butane torch. Valve 3 is opened at 30 sec intervals to release the pressure build-up. Bubbles were noticed in initial release, likely from air trapped below valve 3.

Rod is raised vertically and knocked at 2 min intervals after 15 min to avoid water being trapped at the top end. total preparation time 20+ min before no noticeable warm water ejected. thermal imager show generally high temperatures (60ºC - 120ºC) in segment 2-3, and 25ºC in segment 1.

Bottom plug is fastened whilst rod is immersed in basin of water.

Apparatus is left to cool, during which time steam is assumed to reach ambient temperature of 25ºC at a pressure of 0.032 bar

Fig. 7.12 Extraction of air and creating of an exclusive water-steam internal condition

Fig. 7.13 Thermal imagery of *top* and *bottom* of rod

Fig. 7.14 Non-uniformity in IR temperature of chrome valve as contrasted to *black pipe*

7.4 Reflections on the Rain Tower

This Rain Tower system should surpass the typical vapour-compression system adopted for most air-conditioning systems for the following reasons:

- Superior thermal transport properties of steam over synthetic refrigerants (Kilicarslan and Muller 2004)
- Use of water as a natural refrigerant avoids problems of ozone depletion and greenhouse gas emissions confronting synthetic refrigerants (Tanaka and Kotoh 2007)
- Non-reciprocating nature of piston (no need for clearance) avoids technical limitation of reciprocating compressors
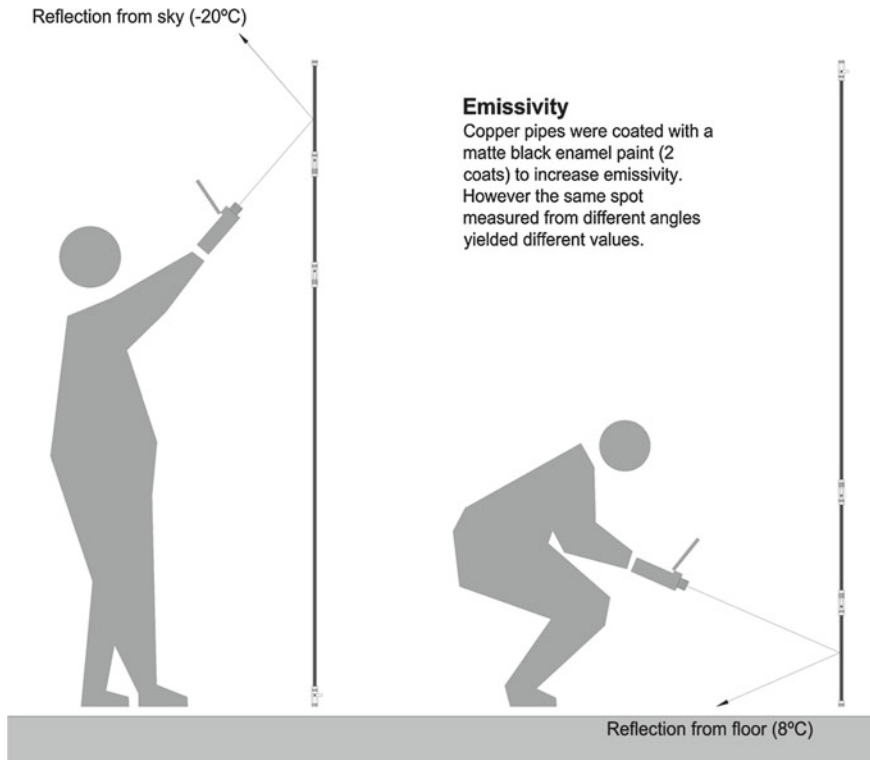
Fig. 7.15 How the geometry of the rod and its reflectance affected thermal imaging accuracy

- Ability of compression cycle to handle liquid droplets results in better matching of work input without fear of compressor malfunction
- Work input for compression is via the pump, with higher efficiency than reciprocating/centrifugal compressors
- Heat rejection is passive over large surface, without use of cooling tower or fans

   The known issues to implementing such a system are:

- Technical difficulties creating and maintaining a vacuum.
- The water column can lose effective height (and hence pressure) as wall resistance causes it to shape into a vortex.
- The cylinder walls must be highly conductive yet be able to resist atmospheric pressure against a vacuum.
- Refrigerant-grade water is an aggressive solvent.
- Due to the narrow optimum temperature lift, the air needs to be dehumidified by a separate process.

   The issues can be resolved with existing technology and do not pose insurmountable obstacles. For example, thin-walled detector tubes in particle

accelerators are made from self-organising vault structures in aluminium pipes 'designed to be as thin as possible. These tubes are maintained under high internal vacuum. The thin-walled tubes must be very rigid to avoid collapsing under atmospheric pressure' (Altan 2006). With the correct pipe geometry (like having a honeycomb inside the main pipe), the vortex effect can also be minimised. Dehumidification, on the other hand, would need to be tackled with desiccants.

Technical proof in hand, it appears all that was needed was to find the right investor. Assuming I could miniaturise the proof of concept to a tenth of the scale, where can I install a 20 m high aluminium structure on to the side of a building? It seems that this was the defining issue, not so much the technicalities of some novel energy-saving air-conditioning system.

> Most people innovate backward. They develop a product to solve a problem that bothers them personally without first confirming that it bothers the market universally. They dream up a product without first identifying who will use it, how, and why. They conjure up a clever idea-thinking, Man, this is going to be mind-blowing! Nothing like it out there! Then they build a prototype, file a patent, and start making and marketing it—without first identifying the market, qualifying the market, or even knowing whether there is a market for it. Not surprisingly, most of those ideas fail. In fact, most patents never make more money than the cost of the patent itself. Why?
>
> Primarily because the designer innovated for the sake of innovation rather than for the benefit of the market. (Key 2011, p. 37)

Consequently, the angle of approach from the technical, and not from the market viewpoint, described the Rain Tower innovation as a *backward innovation*. In fact it can also explain why good ideas, technically speaking, were excruciatingly slow to be implemented. Two of these ideas are here briefly studied to discover where the crux of the matter lies: the *Solar Tower* and *Zero Carbon Australia Stationary Energy Plan*.

7.5 Lessons from the Solar Tower

The Solar Tower (Figs. 7.16, 7.17), alternatively and originally referred to as the *Solar Chimney* (Schlaich 1995), was designed in 1980 as a renewable energy plant using sunlight to warm air under a canopy (glass or polyester), channelled to a tall stack where the rising convection currents turn wind turbines. A prototype was constructed in Spain starting in 1981 and commissioned in 1982.

The Solar Tower could supply renewable energy from the sun and overcome the major obstacles of photovoltaic technologies in cost and night time production (using the heated thermal mass of the earth below the canopy). Moreover, it offered a use for unproductive desert land. It had been built as a proof-of-concept and proven its ability to deliver renewable energy as claimed. Numerous studies have been performed around this technology (Petela 2009; more references in
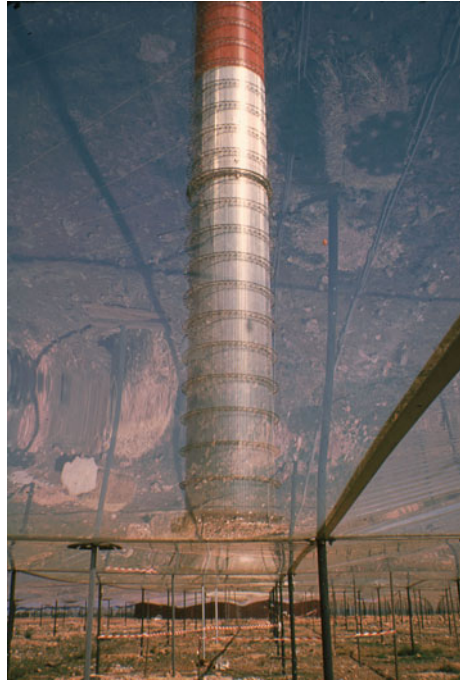
Thirugnanasambandam 2010) with the consensus that it was an elegant source of clean energy economically competitive to fossil-based electricity.

The Australian firm EnviroMissions acquired the technology in 1998. Since 2001 it has championed this technology with no success in Australia, and has only in 2011 secured investment to develop it in Arizona, ready to go online in 2015 (Blain 2011). Roger Davey, the CEO of EnviroMissions attributes this to the contrasting support for renewable technology between the two governments. Speaking of the incentives in the U.S., he says,

> There's input tax credits, there's an amount of money you can recoup on the capital cost once it's built and that comes to somewhere around 30 per cent so that reduces your capital costs which obviously therefore would increase your internal rate of return and perhaps provide some equity base and provide greater surety for those investors. Roger Davey, CEO, EnviroMissions (McDonald 2011)

With these incentives the proposed $750 million plant, designed to operate for 80 years, can have a pay-back within 11 years (Blain 2011). Assuming no future delays, it would have taken a total 35 years for the concept to eventually reach commercial reality. During this period it was the investment climate, rather than the science, that proved the decisive obstacle.
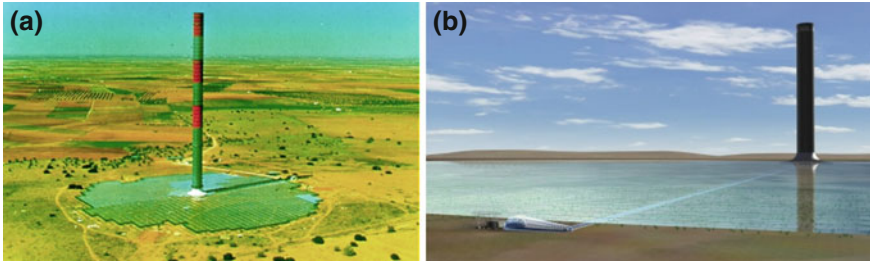
Fig. 7.17 a The Manzanares 50 kW Solar Tower, 195 m high (Thomas and Davey 2004), **b** Solar tower power station conceptualisation, 1,000 m high (Thomas and Davey 2004)

7.6 Lessons from Zero Carbon Australia 2020 Stationary Energy Plan

In 2010, the Melbourne Energy Institute of the University of Melbourne, published the 'Australian Sustainable Energy Zero Carbon Australia (ZCA) Stationary Energy Plan', a 'ten-year roadmap for 100 % renewable energy' using only existent and proven renewable generation technologies, primarily, concentrated solar thermal (CST) towers (Fig. 7.18). A sea of heliostats (mirrors) receive and concentrate solar radiation to the top of a tower which heats molten salt. The salt is passed between 'hot' and 'cold' tanks through a heat exchanger that flashes water into steam through a conventional turbine similar to those found in coal stations. This arrangement allows electrical generation through the night and ensures transferability of jobs from coal power to the clean alternative.

Fig. 7.18 CST plant (Redondo, in ZCA Stationary Energy Plan, 2010)

The ZCA plan expresses its environmental and political imperatives for the 10-year time frame:

> … to have a two-in-three chance of keeping global warming to less than 2 °C above pre-industrial temperatures, developed nations with the highest per capita rates of emissions, such as the United States and Australia, would need to decarbonise their economies by 2020…. Ten years is a meaningful timeframe for planning purposes, as it requires immediate action, whereas longer and less ambitious goals lead to half-responses and delay. (Wright and Hearps 2010, p. xvi)

Long delays are evidence to the lack of political will to implement the actions proposed by the IPCC in Chap. 2. Lomborg, the *skeptical environmentalist* (with a book of the same title first published in 1998), says, 'Kyoto was negotiated in 1997, but the restrictions will first hit between 2008 and 2012. The politicians who could claim victory in 1997 will generally not be the same ones to bear the costs of abiding by the restrictions.' (Lomborg 2007, p. 146)

The ZCA blueprint showed how an ambitious target could be achieved in a relatively short time. With mature CST and wind turbine technology, there were no technological barriers. With detailed economic modelling, the cost of mitigation was not high, and could be more than compensated for with increased energy security. The whole plan was viable, but contingent on the force of political will. The transition required bold leadership to make hard decisions that terminated existing technologies and reintroduced new ones. This potential backlash in making such a definitive move could not be measured. Adger et al. (2008) proposes that 'individual and social characteristics, in particular risk perception, interact with underlying values to form subjective and mutable limits to adaptation that currently hinder society's ability to act.' (p. 339) Hence, instead of aiming for the bold 100 % carbon reduction by 2020, the Australian government has only committed to a 5 % reduction by this date (Department of Climate Change and Energy Efficiency 2012).

Once again it is not the scientific premise of ZCA that was called in question. Two years into the 10-year plan, still no CST plant construction of the kind proposed under ZCA has been envisioned. The main obstacle is that the ZCA is entirely reliant on government initiative, which in a complex society marked by divergent values and an intricate landscape of governance (Adger et al. 2008), is predominantly risk-averse.

7.7 Power Conservation is far More Important than Power Generation

The carbon output from power generation can be mitigated by demand-side management and supply-side transformation, each with intricate socio-economical implications described by Biggart and Lutzenhiser (2007). Rosenfeld argues that even if energy could be produced for free, there is still the distribution requirement which poses the more significant cost.

… for end-use efficiency (versus additional central power plants) is that an efficient appliance saves electricity at your meter, priced at $0.08/kWh, whereas 1 kWh of new wholesale supply is worth only $0.02–$0.03 at the bus-bar. Thus even if electricity from some future wonderful new central power plant is "too cheap to meter," it still must be transmitted, distributed, and managed, for $0.05–$0.06/kWh. (Rosenfeld 1999, p. 49)

This cost is particularly significant in Australia, where outside the few major cities, the population is characterised by low density suburbs. The magnitude of this cost was evident in an episode of a popular Australian television forum ABC Q&A:

BARNABY JOYCE: It is something wrong that the people in Singapore deliver cheaper power to their people–30 per cent cheaper to their people with our coal than what we [Australians] can deliver to our people with our coal…. As you know, Premier, they actually have to move the coal 6,300 kilometres before it gets to the power station…. That is kind of a bit of a journey as opposed to the power station which is actually in the coal field.
   ANNA BLIGH: You know as well as I do it's the distribution network that costs the money. It's pumping it out there to people's homes. ABC Q&A (21 February, 2011, 51:15 of clip) http://www.abc.net.au/tv/qanda/txt/s3138582.htm

Put in another way, if energy conservation could halve the average household's electricity demands, it would both halve their power bills and double the capacity of the grid. If on the other hand, assuming there were no improvements in efficiency, and the grid was supplemented by renewables to double the output, the average cost of every household would be drastically increased (assuming present costs for renewables). Concurrently, existing infrastructure would also have to be upgraded, and further cost passed on to consumers.

Eventually it is cost that determines the price signal which affects behaviour. Thus, Rosenfeld ends his monograph with this thought:

In conclusion, energy efficiency is an enduring challenge. Inefficient use of energy and hence waste of money and resources will merit our attention for the foreseeable future, and I believe the same can be said of the threat of climate change. Energy efficiency has been a rewarding discipline because it simultaneously saves money and protects the environment. I'm proud to be working in this field. (Rosenfeld 1999, p. 80)

7.8 Lessons for the Future

There are many promising ideas, like the ZCA 2020 *Stationary Energy Plan* and the *Solar Tower*, which could do tremendous social and environmental good. These can be termed as *good ideas* that are based on detailed simulations, experimental proof-of-concepts and economic modelling. These ideas have been researched by academics with no conflict of interest, published in international peer-reviewed journals, and widely accepted as sound, robust and tenable. If good scientific ideas were all that were needed to drive a change, they do already exist. Yet the resistance to taking up these ideas has been disconcerting, leading one to

be doubtful if purely technocratic measures were practicable. Even when armed with a 'good idea', one still needed to navigate the lack of government funding, the social fears of the unexpected, and the unexciting appearance of energy-efficiency.

The Rain Tower was theoretically feasible. And if a massless, frictionless disc could be conceived one might even argue that it was technically possible to use a liquid plug to replace the chiller compressor for better efficiency. But how was one to avoid the fate of potentially good ideas not being implemented?

Nikola Tesla (1856–1943), inventor, mechanical and electrical engineer, would be the archetype of the learned inventor. He gave the world (literally, with minimal royalties) multiphase alternating current, the induction motor, the fluorescent light, radio wave technology and a myriad of modern conveniences. When describing Thomas Edison's approach to inventing, Tesla said:

> His method was inefficient in the extreme, for an immense ground had to be covered to get anything at all unless blind chance intervened and, at first, I was almost a sorry witness of his doings, knowing that just a little theory and calculation would have saved him 90 percent of the labor. But he had a veritable contempt for book learning and mathematical knowledge, trusting himself entirely to his inventor's instinct and practical American sense. Nikola Tesla, referring to Thomas Edison in his obituary (New York Times 1931, in Morgan 1939)

However, Tesla had a difficult career and died in poverty (Cheney 1989). The Rain Tower seemed destined to take its inventor on a similar route. It was hard for an inventor to sustain continuous innovation without commercial backing. Inventors need their patrons, and good ideas need investment. It appeared that ideas cannot merely be technically good, they need to be commercialisable and made attractive to investors seeking a monetary return.

In this regard, Edison puts it most compellingly,

> Anything that won't sell, I don't want to invent. Its sale is proof of utility, and utility is success. Thomas Edison (1847–1931)

For ideas to initiate socially beneficial market transformations, they have to be transferred from the inventor's mind to the consumer's hand using investor dollars. In a capitalistic society, problem resolution is dependent to a great extent on product acquisition.

Enter the world of research, innovation and commercialisation.

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Chapter 8
Finding a Market-Oriented Solution

In Chap. 7, a design methodology had emerged for the innovation process:

- Using a design brief instead of an academic research question.
- Adopting an action research cycle to improve the ideas: plan → act → observe → reflect → plan…
- Utilising the architectural studio model of *the critique* as reflection, which involved:

  - self-critique, and
  - supervisors' critique.

A technical approach alone might succeed in a technocracy, but in an economy more typified by capitalism, the brief needed to be expanded to accommodate a *value-proposition.* It was understood that an idea had to be implemented in order for it to be successful, and that many ideas, despite being technologically sound, did not impel a consumer across the purchasing threshold. The *reflection* stage in action research needed an additional business dimension of feedback from an *investment pitch.* There is little academic reference to the contents of a business pitch.

However, based on a video review of reality shows on venture-capitalism comprising Dragons' Den UK (8 series, British Broadcasting Corporation), Dragons' Den Canada (6 series, Canadian Broadcasting Corporation) and Shark Tank (3 series, American Broadcasting Corporation), the key aspects of a pitch are:

- establishing the value proposition
- presenting a business model
- declare the unique selling point
- describe the care taken with intellectual property
- immediacy of understanding the new concept
- virulence in transferring the concept behind the innovation

Intellectual Ventures is an innovation firm that is a 'hybrid of think tank, private equity firm, venture-capitalist investor, research and development lab and law firm' (Watts 2011 p. 110). Founded by former Microsoft executives Nathan Myhrvold and Edward Jung, the firm manages $5 billion in investments (Watts 2011) and files five hundred patents a year (Gladwell 2008).

> "The challenge isn't necessarily to find the golden nugget. The challenge is: don't spend too much money on the ones that aren't. You want to take the mentality of the venture capitalist: fail fast and fail cheap." Geoff Deane (VP Engineering, Intellectual Ventures), in Watts (2011 p. 114)

We see in this chapter how another idea was developed with a business slant, and how, through a quick evaluation process, the decision was made to proceed no further.

> Mumford did see real dangers in the heedless application of powerful machinery to human problems and processes. Technology, he argued, tends to overpower common sense and undercut traditional practices, actually encouraging social inefficiency. New tools like telephones supplant equally effective if somewhat slower methods of communication. Commercially canned foods make eating fresh produce in the country in the summertime seem provincial and outmoded. "One is faced here with a magnified form of danger common to all inventions: a tendency to use them whether or not the occasion demands," Mumford wrote.
>
> The habit of dependence on new technologies and the machines that implement them, Mumford argued, loosens the contingencies of time and season, ultimately causing the atrophy of the human function. A "purposeless materialism" develops, placing a "disproportionate emphasis on the physical means of living." Comfort seems to be modern man's greatest achievement, but it multiplies his desire for goods and dangerously increases his reliance on living conditions that are no longer produced by his own exertions. (Ackerman 2002, p. 142–143)

The over-reliance on air-conditioning is symptomatic of the processes described by Mumford. But how did this problem arise in systemic terms for the business players and their interaction? How can we move from energy efficiency being its own goal, and seeing inefficiency as endemic to the 'business as usual' (BAU) scenario? Who is the key decision maker that drives and defines the process? What motivates each profession, and how did each party acting in its self-interest contribute to the current problem?

To gain useful insights, the drivers of business investment, particularly in relation to property development, are investigated.

8.1 Property Developers

> The emphasis is now on selfishness and separation rather than contact and community. In the new kinds of urban development, the activities that traditionally overlapped are organised for the purpose of maximising profit for developers or retailers. (Richard Rogers, in Heng and Law 2002).

Real estate imperatives are predominantly determined by property developers. The professional consultants (architect, civil engineer, mechanical and electrical engineers, quantity surveyors, among others), being engaged by the developer, fulfil their roles according to the brief. In countries (like Singapore) where a handful of major developers dominate the real estate scene, even the planning authorities very much take into consideration the feedback from developers, understanding that without the support of private property developers, urban planning cannot come to fruition.

In short, property developers exert executive control on the professionals under them, and considerable influence on the authorities over them.

As a private business entity, the priority of property development is singular: profit. Robert Vale (2009, p. 10) states categorically, 'Developers nearly always prefer to make personal profit rather than to do good for the community.' The motive of maximising revenue has led to the down-town office typology of tight urban blocks, high-rise offices, deep floor plans and fully glazed facades. Where the typical business model is arranged such that developers absorb capital cost and tenants the operational costs, there is little incentive for developers to adopt energy saving mechanisms beyond what is required by code.

This is all the more apparent when we consider that the most efficient office buildings, in Australia for example, have typically been built and occupied by either a property developer or an owner-occupier, as seen in Table 8.1.

> Take 5 star Green Star as the base, the incremental cost increase to achieving the carbon neutrality outcome at Pixel is in the order of 14 per cent. David Waldren, GM Carlton Brewery project, Grocon (McGowan 2010)

In the competitive property market, a 14 % increase in construction cost is a very hard case for any project manager to propose to the owner. On top of this construction cost are the higher premiums charged by the architects and engineers for the extra work needed to design with sustainability which requires specific skills in modelling and resolving very site-specific issues. Unless the developers drive this process, or unless there is an anchor tenant who is committed to supporting it, there is very little likelihood that new multi-tenanted offices can meet or exceed the highest national or international energy standards.

Table 8.1 Office buildings in Australia that have received high accolades for sustainability

Building	Year completed	Accreditation	Developer/Owner
Bond	2004	First in Australia, GBCA 5 star—office as built	Lend lease
CH2	2006	First in Australia, GBCA 6 star—office design	Melbourne city council
The gauge	2008	First in Australia, GBCA 6 star—office as built	Lend lease
ANZ HQ	2009	GBCA 6-star office design	ANZ banking group
Pixel	2010	100 % Green star score	Grocon

The reduction in air-conditioning energy consumption is not a quest that can be driven by building professionals. It can only happen if there are attractive incentives to property developers, in accordance with their value metrics. This does not however absolve architects and engineers from any responsibility since these professionals are also contributors to the BAU scenario.

> A symposium on "Thermal Discomfort in the Name of Energy Conservation" was held during ASHRAE's 1979 annual meeting in Detroit. "From all sides we are told that we can no longer enjoy the luxury of being comfortable…. Must we sacrifice comfort to conserve energy? No!" declared Michigan architect Joseph B. Olivieri. He went on to recommend that glass be used less and insulation more, and that sections of houses, such as bedrooms, be placed underground because "we don't need large windows when we're asleep". Stressing winter comfort needs, Olivieri considered but seemed to reject such options as changing thermostat settings or wearing more or heavier clothing indoors. Such low-tech solutions would not require the expertise of an engineer or architect. (Ackerman 2002, p. 167b)

8.2 Architects and Engineers

Extensive glazing has however been a major culprit in the need for heating and air-conditioning, increasing the heat loss when heating is required, and heat gain when cooling is required.

> You want to save serious energy and serious money? Easy, use less glass. Windows and curtain walls are the most expensive component in a building and provide the worst energy performance. The more you use the more energy and money you burn. Limit the glazing area to approximately 30 percent—and use really good glass and frames. (Lstiburek 2008, p. 2)

Since offices with a view fetch better premiums than those without, the typical office is designed with a central service core and offices around the periphery. The need for glazing is evident from the financial point, but there is also a strong aesthetic consideration: a modern office needs to look *streamlined*.

> As Jeffrey Meikle explains, streamlining, acclaimed by the thirties public as "modernistic," was the visual representation of "frictionlessness," the achievement of social and physical control sought by leading designers and industrialists with a Depression-driven sense of urgency. "Streamlined" was short hand for unimpeded progress and smooth forward movement. It connoted control of air movement in the same way that air-conditioning signified control of air temperature. Both air-conditioning and streamlining obligated the very atmosphere to conform to a human plan. (Ackerman 2002, p. 81)

Furthermore the energy performance of buildings has been a recognised area of weakness amongst architects and purposeful neglect amongst engineers. Lstiburek, when referring to the myths of superior performance of a double-skin facade, says, 'If we taught architects more physics and less philosophy they wouldn't fall for this garbage—and while I'm at it shame on you engineers for using bad physics to deceive gullible architects.' (Lstiburek 2008, p. 7)

Bay and Ong (2006) identify two approaches in which tropical architects apply building science to respond to the environment: the thermal comfort checklist to

design typified by Fanger, and the bioclimatic response typified by Olgyay. Both approaches result from the common need for simplified tools for architects to solve the environmental responses concurrently with a broad range of design and legislative issues. They further observe:

> Architects tend to avoid applying building science directly in their design process, preferring where feasible to work with a building scientist as a consultant. … The typical architect prefers to work with broad principles and strategies. A survey on the use of environmental design software among architects showed that almost none of the architects surveyed employed such tools in their practice, and that consultations with building scientists are rare. (Bay & Ong 2006, p.6)

This behaviour is confirmed in the following personal discussions. Dr Mark Dewsbury (University of Tasmania) observed that architects are becoming increasingly reliant on energy accessors to advise them on how their buildings can be improved. The environmental impact of architecture has been treated as a matter of personal rather than professional ethic. 'An architect could be taken to court for leaking rain (of which Frank Gehry's *Stata Centre* at MIT comes to mind) but rarely for leaking heat,' said De Detlev Geard (University of Tasmania), 'because the regulations only control the submission of building plans, not the actual thermal performance.' Most poignant is this quote, 'Engineers interested in hyper-efficiency are a lonely bunch. There are so few of us in the world we probably all know each other,' said Mr David Wilton, an engineer who works with a chiller OEM.

Engineers, whilst in a position to optimise M&E systems, are presented with two perverse motivators: a professional penalty for undersizing air-conditioners, and a financial incentive for oversizing them.

Houghton (1998) has observed compounded safety factors resulting in cooling systems 'over designed by 100 % or more.' Lee Eng Lock, an engineer known for notably improving building energy efficiency says:

> In engineering, you have to do things elegantly, which sometimes conflicts with doing it for the fees. In a fee, you are driven to jack up capital costs. If you make it elegant and cheap and better, you're working against your own financial interests. (Berger 1998 p. 262)

Lee's experience with increasing air-conditioning efficiency is not for the lack of technological advancements, but that 'most of the problems in going to factor two or factor four reduction in energy are institutional barriers, consultants and architects and project managers and owner's representatives stick to the tried and true (truly wasteful and inefficient) and resist any kind of change' (Lee 2009). There is a systemic problem with the way professional fees are pegged as a percentage of project costs. Amory Lovins says it well (Berger 1998):

> As long as we reward design professionals for what they spend, not what they save, we can expect to get nutty results.

8.3 Consumers

How can one describe consumer society?

> The silly marketing that America falls for has resulted in this: we buy things we don't need
> with money we don't have in order to impress people we don't like. (Ramsey 2003, p. 31)

Consumerism is a large and complex field in socio-economics. This short
section is an acknowledgedly inadequate treatise, and the reader is referred to the
the BBC (2002) documentary 'The Century of the Self' for a primer and the
critical works of nobel laureate (Economics) Joseph Stiglitz (for example *Toward
a General Theory of Consumerism,* in Pecchi and Piga 2008).

Over the last hundred years, the two most significant economic catastrophes,
the Great Depression and the Global Financial Crisis, were preceded by the
Hoover and Bush Administrations respectively. Both administrations were
(amongst other factors) strong advocates for deregulation, free-market and con-
sumerism as the central motto of American life. And both, in Stiglitz's view
(2007), were contenders for 'worst president' due to their poor stewardship of the
American economy. Lynd (1934) remarked of commerce policy under Hoover,
'Never before had the Nation's business been so completely the business of the
National Government.' (p. 3) A month after the September-11 terrorist attack,
President Bush gave a press conference which was particularly revealing of his
view—that the good consumer was the good citizen:

> Now, the American people have got to go about their business. We cannot let the terrorists
> achieve the objective of frightening our nation to the point where we don't—where we
> don't conduct business, where people don't shop. That's their intention. (11 October 2001,
> http://www.johnstonsarchive.net/terrorism/ bush911e.html)

The engineering of consumer society originates from Freudian theory of the
unconscious mind being the dominant force that directs behaviour. His theories
were further developed by his nephew, Edward Bernays the 'Father of Public
Relations' (New York Times 1995) who 'showed corporations how to make
people want things they didn't need by linking mass-produced goods to their
unconscious desires' (BBC 2002). Whilst the prognosis of consumerism was
unclear in the early days of mass advertising, Lynd (1934) expressed this concern:

> It seems probable that under the pressures of modern business development, the consumer
> is becoming confused and illiterate as a buyer more rapidly than the combined positive
> factors of education, standardization, and so on are succeeding in making him literate as a
> buyer. (p. 4)

In the consumerist culture, purchasing is motivated not by the rational but the
emotive. Similarly, the choice to consume air-conditioning was rarely made on the
premise of informed rationalism. As early as in the 1930s, it had been understood
that air-conditioning should not be marketed in technical terms, but under abstract
concepts. It was not intended to address the rational and conscious intellect, but the

irrational and unconscious emotions. A 1939 article *Selling Seats with Modern Air- Conditioning* was categorical:

> Never, never, never refer to air-conditioning in the terms of refrigeration and coldness. Adherence to the "comfort zone" devised in 1923 by professional engineers would satisfy 97–98 percent of the audience. (in Ackermann 2002, p. 49)

The overconsumption of air-conditioning can thus be linked to general over-consumption in society, which stems from successful corporate marketing to manipulate society into becoming become docile consumers. We saw in Chap. 3 examples of the lifestyle marketing that transformed air-conditioning from a luxury to a present day necessity: indispensable and routinely expected. Consumer society is neither environmentally nor economically sustainable, marked by a 'strong value orientation that puts unrestrained freedom to the forefront' (O'Shaughnessy and O'Shaughnessy 2002, p. 544).

More than any other single factor, consumeristic behaviour has resulted in the status quo of big business and entrenched political interest that the BAU scenario epitomises.

8.4 The Angle of the Pitch

> Businesses will increasingly be judged on their 'triple bottom line' which takes into account their economic, social and environmental performance. There is huge interest in issues such as *intergenerational equity,* which means we try to leave the planet for future generations in as good or better shape than it is today, *sustainable development,* which is economic development that is in harmony with the natural environment, and *eco- footprinting,* which means we use only our fair share of limited. resources. The growing concern about these issues is driving new environmental legislation and regulation. (English and Moate 2009, p. 89)

Solving the energy demands of air-conditioning was an academic interest, and the benefit of it seemed obvious enough to myself as the inventor, but was inadequate in itself to prompt society to switch technology. To convince an investor that the innovation was worth pursuing, one had to demonstrate how a proposal was not only *on trend* for the near and medium future, it needed to be lucrative.

When evaluating the selection of air-conditioning systems, I found the following to be decisive in my professional experience as architectural project manager:

1. The key decision maker is the property developer(s), and his/their interest was in generating revenue. A more energy efficient airconditioning and mechanical ventilation (ACMV) system was only worth installing if the lease charge could be increased.

2. ACMV systems were selected primarily on a cost basis as long as the system met specifications from the mechanical engineer.
3. Specifications typically state refrigeration and ventilation rate requirements, and rarely stipulate the COP of the system.
4. Minimum COP of chillers (not the entire ACMV system) is controlled by regulatory standards (e.g. SS530:2006 in Singapore; ASNZ3823 in Australia). Unless pursuing an energy certification (e.g. Green Star, LEED, BREEAM, etc.) there was no incentive for developers to exceed the minimum requirement.

Based on preliminary sizing rules of thumb (Allen and Iano 2002, p. 190) the plant room size for an air-handling unit (AHU) occupies about 5 % of the gross floor area in a typical office block. Freeing up this area into tenable space would pose an attractive proposition to developers. A business case could thus be made to the developer:

1. There is a way to reduce the size of the AHU plant room.
2. This will increase the net leasable area and pay for itself within the short term and generate extra revenue in the medium-long term.
3. The efficiency of the system will be improved and cost the tenants less in power bills, giving the developer a competitive advantage.
4. The higher efficiency can complement other green initiatives to get publicity from energy certification.

For the benefits to be real to a developer, the following values needed to be quantified:

1. Area saved (m^2) and revenue generated (dollars per m^2 per year)
2. Energy saved (kWh per year) and cost avoided for tenants (aggregated as dollars per floor per year)
3. CO_2 emissions avoided from reduced power load demands (tCO_2-e, depending on energy source) and GWP avoided through refrigerant selection (tCO_2-e, depending on refrigerant). This is of further relevance with the Australian carbon price (starting at \$23/tCO_2-e) to be introduced in July 2012, making CO_2 emissions reductions a real currency.

So how do we dispense with the AHU room? My proposal is to separately handle the latent and sensible loads, using lightweight equipment that can be ceiling mounted.

8.5 Using Desiccant Wheels and Radiant Cooling

To eliminate the spatial requirement of the AHU room, the following changes are proposed, as illustrated in the schematic Fig. 8.1 and processes explained in Tables 8.2 and 8.3.
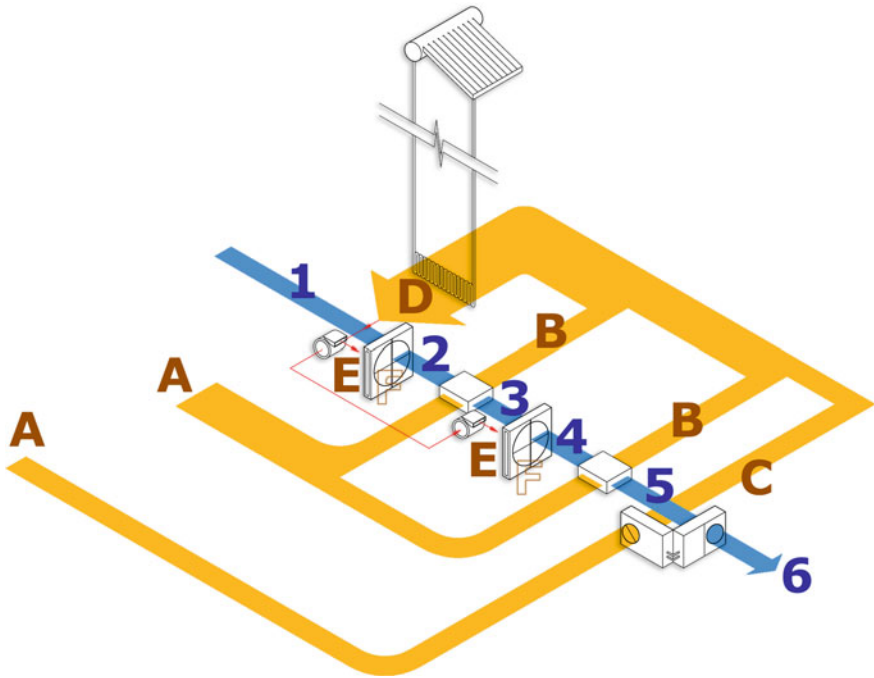
Fig. 8.1 Schematic of air flow. Processes 1–6 illustrate outdoor air → supply air. Proceses A–E illustrate extract/exhaust air → outdoor air

Table 8.2 Outdoor air is desiccated and cooled in a double cycle before the dry air is chilled by the air conditioning

Supply air process	
1	Outdoor air @33 °C, 57 %RH (Humidity ratio 18.3 g/kg)
1–2	Desiccant wheel dehumidification
2	Air @ 45 °C, 14 g/kg
2–3	Heat exchanger
3	Air @ 30 °C, 14 g/kg
3–4	Desiccant wheel dehumidification
4	Air @ 45 °C, 10 g/kg
4–5	Heat exchanger
5	Air @ 30 °C, 10 g/kg
5–6	Air-conditioning (sensible only)
6	Air @ 15 °C, 10 g/kg
7	Office air @ 25 °C, 50 %RH (Humidity ratio 10 g/kg)

Table 8.3 Exhaust air is used to cool the desiccated air (A–B), and part of it is heated by the heat rejected from the air-conditioning (A–C)

Exhaust air	
A	Office air @ 25 °C
A–B	Heat exchanger
B	Air @ 40 °C
A–C	Reverse a/c cycle (heat pump)
C	Air @ 50 °C
B–D and C–D	Air heated by solar-thermal collectors (with electrical boost)
D–E	Air @ 80 °C
E–F	Desiccant regeneration

Depending on availability it can be heated by solar thermal or an electrical circuit to regenerate the desiccants before being exhausted to the outdoors

1. Utilise desiccant wheels to handle the latent load of air-conditioning, making the resulting air chiller responsible only for sensory load
2. Use a 100 % fresh air supply to the ventilation rate for the occupancy required by code
3. Mount all plant equipment within a 1.5 m ceiling of the lift lobby
4. Introduce a radiant chilled aluminium ceiling that copes with the reduced air velocity by providing a lower mean radiant temperature
5. Introduce a displacement ventilation system that does not depend on high air velocity for mixing and pollutant extraction

The final point deserves particular elaboration. The most conventional delivery of conditioned air is by ducting to ceiling registers. Known as mixing ventilation, the supply air (comprising a mixture of roughly 20 % fresh air and 80 % return air) leaves these registers (also called diffusers) at fairly high velocity to enable mixing. Displacement ventilation demonstrates the engineering adage *the solution to pollution is not dilution*. Instead of mixing the air, supply air is delivered at low speed and low temperature (thus higher density) near the floor, effectively pushing the room air up into the ceiling return. In this scheme supply air is 100 % fresh outdoor air, and 'return' air is completely exhausted. Displacement ventilation systems require less flow rate and no recycled air, making the AHU much simpler.

To determine the efficiency, I use the psychrometric processes of Fig. 8.2 and conditions shown in Table 8.4. Since processes 1–5 are passive (except for fan power), the power required, psychrometrically speaking is:

$$\Delta h_{5-6} = 39.7 \frac{kJ}{kg \ of \ fresh \ air} \tag{8.1}$$

By reducing the intake to 100 % fresh air at a fifth the flow rate (Fig. 8.3), this compares very favourably against an AHU taking 20 % fresh air (33 °C, 57.3 %RH) and 80 % recycled air (25 °C, 65 %RH):
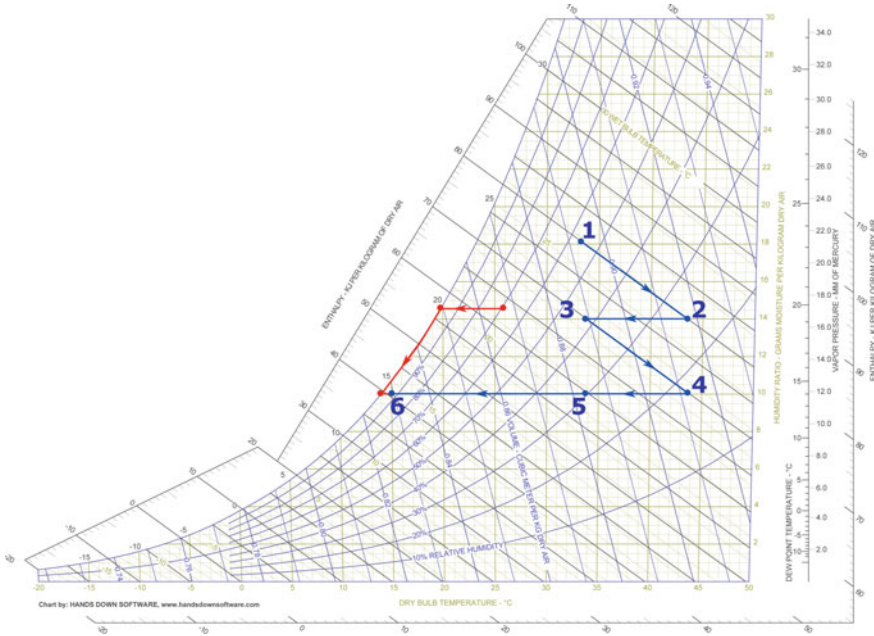
Fig. 8.2 Processes on psychromtric chart

Table 8.4 Assumed air conditions

	T(°C)	HR (g/kg)	h (kJ/kg)
Outdoor air	33.0	18.33	80.11
Supply air	15.0	10.00	40.28
Return air	25.0	12.96	58.08
Mixed air	26.6	14.04	62.48

$$\Delta h_{AHU} = 5 \times 22.2 = 111.0 \frac{kJ}{kg\ of\ fresh\ air} \tag{8.2}$$

Desiccant wheels are fairly light devices, requiring two 50 kg wheels (1.2 × 1.2 × 0.2 m) to provide the requisite dehumidification for an office floor of 90 occupants. The chiller load, being a third of the typical AHU and having eliminated the return air controls and dehumidification requirement, could amount to simply a single (or double) row cooling coil attachment to the VAV box.

Table 8.5 shows the potential savings and revenue from the AHU plant space liberated. Whilst the electrical savings benefits the tenant, it is the space savings from eliminating the AHU room that is more likely to convince the developers to adopt the technology as it represents revenue of concern to them.
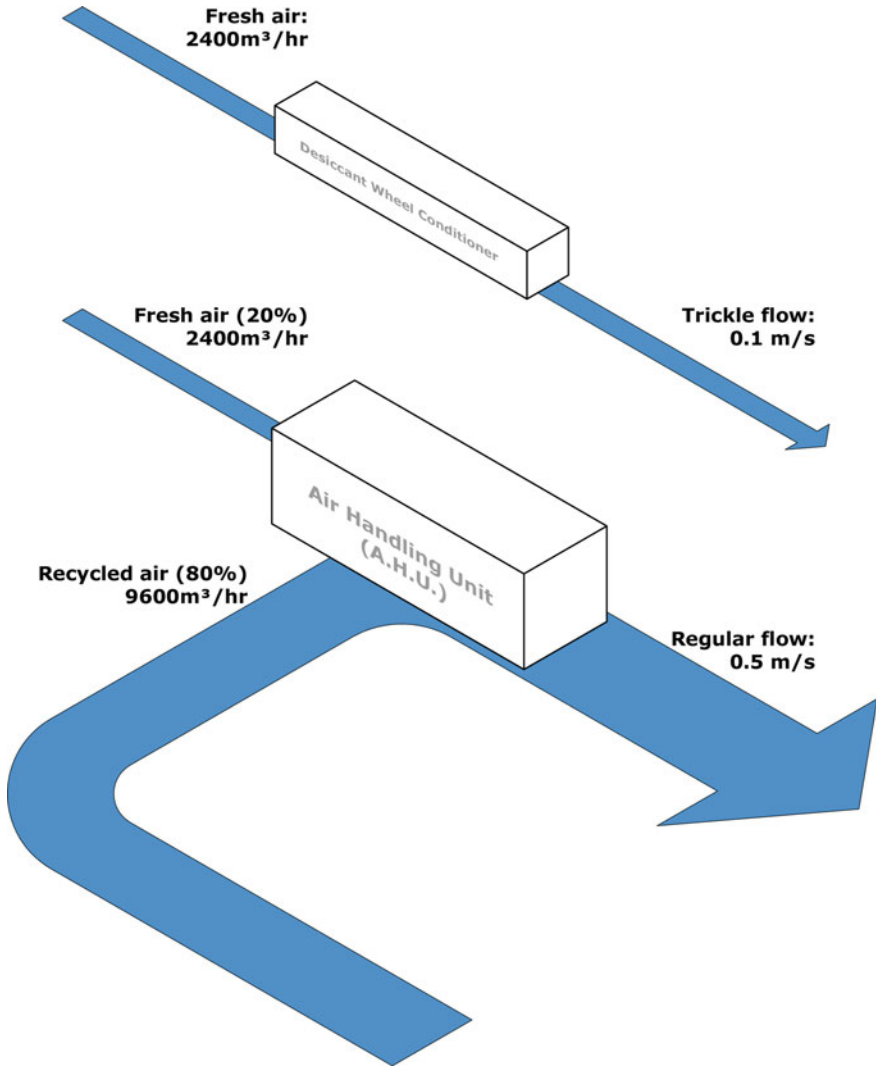
Fig. 8.3 Economy and better air quality by avoiding air recycling

Table 8.5 Calculations on the revenue generated with a conversion of plant area to leasable area (from project on file planned for Dubai)

Annual electrical savings	$334,000	205 tons CO2
Space liberated for annual revenue	$500,000	at $7.50 per sq foot/month in a premium location

Table 8.6 Two possible conditions for achieving a PMV of +0.5 (PPD = 10.2 %)	Two possible conditions for achieving a PMV of +0.5		
	Air temp	25.0 °C	
	Radiant temp	25.0 °C	22.6 °C
	Relative humidity	50 %	
	Air velocity	0.5 m/s	0.1 m/s
	Activity rate	1.2met	
	Clothing level	1clo	

By reducing the air-flow to a trickle of conventional quantities, better economy is achieved and symptoms of sick building syndrome minimised as these are commonly found by systems utilising recycled air. This however results in the following issues: (1) reduced air velocity for thermal comfort, and (2) ineffective mixing when adopting conventional ceiling air diffusers. I will now attempt to solve these with the same imperative of saving energy.

8.6 Radiant Cooling from the Ceiling

For an equivalent thermal comfort condition to a room with wind speed, v = 0.5 m/s, the office space can alternatively provide v = 0.1 m/s with mean radiant temperature (MRT) at 22.6 °C. This is equivalent to having 70 % of the ceiling at 19 °C whilst the rest of the surfaces are at air temperature of 25 °C (Table 8.6).

Chilled beams provide a small amount of radiant cooling but their coverage is often limited to a small part of whole ceiling coverage. Thus to rely on chilled beams to provide radiant cooling as the primary means of comfort would require temperatures that would risk falling below the dewpoint of the supply air, creating the risk of condensation.

A more effective way of providing radiant cooling would be to adopt chilled ceilings that cover most of the ceiling surface. This approach has been utilised in the following innovations, to which the proposed ceiling mounted air handler can dovetail:

1. a perforated ceiling; or
2. an evaporatively cooled ceiling

8.6.1 Perforated Ceiling

Radiant passive chilled beams developed by Frenger Systems Limited, UK (Fig. 8.4), features a ceiling plenum where air is cooled by chilled water, transferring the 'coolth' to the perforated aluminium ceiling as it descends into the occupied space. The chilled ceiling relies on a supply of preconditioned air to

Fig. 8.4 Radiant passive chilled beams above a perforated ceiling system. ©2011 Frenger systems, reproduced with permission

avoid condensation on the chilled coils in the ceiling plenum. With the proposed desiccant wheels, dry air can be supplied to the ceiling space to be chilled.

8.6.2 Cooling Unit by Loughborough University, UK

These ceiling tile replacements (Fig. 8.5) pass the return air over a wicking surface that cools the panels by evaporative cooling. The wicked ceiling panel operates

Fig. 8.5 Loughborough University's ceiling tile cooling unit, U.S. patent no. 7047752

with exhaust air that is not readmitted into the AHU, otherwise the excess latent load will burden the dehumidification cycle. The ceiling mounted air handler can take advantage of lower air temperatures to cool desiccated air though the heat exchanger (process A–B).

Of these two options, the second would be better suited to interface with the desiccant wheel AHU as it can be readily implemented with displacement ventilation: 100 % fresh conditioned air is introduced at low speed and low level, pushing the more buoyant, warm and polluted air to the ceiling where it is extracted over the ceiling tile cooling unit. Since the ceiling is not dependent on the supply air as the medium of heat transfer (in the instance of a perforated ceiling), the conditioned air can be supplied at a temperature much closer to comfort (~ 25 °C), the smaller ΔT corresponding to a higher COP.

The desiccant wheel & radiant ceiling system provides a commercially viable means of eliminating the AHU room, transforming what typically amounts for 5 % of the office floor plate to leasable area, a tangible benefit to property developers.

8.7 Reflections on the Desiccant Wheel AHU

English and Moate (2009) developed the *Innovation Development Early Assessment System* (IDEAS), a comprehensive risk evaluation plotted on a radar graph to identify areas of weakness in an innovation and business proposal, and assess how possible it was to improve on these areas. Forty criteria (see Table 8.7) are assessed in the system where each is scored on a five-point scale, totalled and expressed as a percentage of total possible score. A green light has a score of 80–100, yellow 60–79, and red below 60.

The business concept of the desiccant wheel AHU (DWAHU) was evaluated under *IDEAS* with a score of 72, which indicated 'satisfactory market viability but there are typically some concerns about risk and/or problems with the business

Table 8.7 IDEAS business feasibility evaluation list (English and Moate 2009)

Potential demand	Market approval	Competitive strength	Boundary risks
1. Market size	6. Need	11. Differentiation	16. Regulatory risk
2. Market growth	7. Recognition	12. Value	17. Technology risk
3. Market stability	8. Compatibility	13. Customer leverage	18. Environmental risk
4. Sustainability	9. Complexity	14. Supplier leverage	19. Socio-economic risk
5. Extensions	10. Distribution	15. Competitors	20. Dependence risk

Establishment risks	Skills and experience	Resources	Dollars and sense
21. Planning risk	26. Marketing expertise	31. Financial resources	36. Sales forecast
22. Marketing risk	27. Technical expertise	32. Physical resources	37. Profitability
23. Deliverables risk	28. Financial expertise	33. Human resources	38. Cost structure
24. Liquidity risk	29. Operational expertise	34. Intellectual resources	39. Financial structure
25. Personal risk	30. Managerial expertise	35. Network resources	40. Cash flow

model that need to be resolved.' (English and Moate 2009, p. 181) The greatest weaknesses were the supplier leverage, technology and dependence risks. The viability of DWAHU was contingent on the availability of desiccant with low regeneration temperature, of which 'only the last generation of adsorption desiccants achieve regeneration temperatures between 40 and 80 °C.' (Mazzei et al. 2005, p. 698)

The proposal was presented at the university business competition, and as one of the winners, subsequently recommended to the Patent Review Committee (PRC) of Uniquest, the university's commercialisation service provider. In technology innovation, patents protect investors' interest by offering litigative resolutions if an idea was copied. Since desiccant wheels already existed and were used in conjunction with air-handlers, the PRC had reservations if mounting a desiccant wheel in the ceiling constituted an *inventive step*. Working with desiccant wheel manufacturers was also a challenge as they kept the formulation of the low regeneration temperature desiccants a trade secret and were not willing to co-develop the technology with the university. None of the manufacturers approached were willing to supply the desiccants separately from the entire air-handling system, which indicated that the desiccants could not be distributed at a high enough profit; and also indicated a fear that the desiccants could be reverse engineered.

The inability to follow though with a patent was more than a stumbling block, it conclusively terminated further development of DWAHU and radiant ceiling concepts. The centrality of patents to the inventing-commercialising efforts can be illustrated in the following case study of the *Skytherm roof*.

8.8 Case Study: The Skytherm Roof

Building scientists have, for a long time, been pursuing the quest for totally passive buildings. The Skytherm roofing system designed by Harold Hay (1967) was in its time reported as the the only passive solution that could provide heating and cooling to most of United States (Cook 1989; Santamouris and Asimakopoulos 1996). The main feature was thermal storage by water contained in plastic bladders sandwiched between two roofs, an insulated upper roof and metal lower roof (Fig. 8.6). By selectively exposing the water bags for night cooling in summer, and day heating in winter, it was able to achieve all day, all year passive comfort.

In the 1970s, extensive validation was initially undertaken by the Trinity University (Cook 1989) and largely neglected for a period. It has most recently been studied for application in Iran where the effectiveness of the system was modelled for a 141 m^2 single-storey house in Shiraz, Iran, reducing heating demands by 86 % and cooling loads by 52 % (Raeissi and Taheri 2000). Research is currently undertaken by Cal Poly to bring the original Skytherm house located at Atascadero up to current building codes (Evelyn and Harold Hay Fund website, http://51.calpoly.edu/sites/ehhf/ index.html undated webpage).

Fig. 8.6 Skytherm house (Douglass 2007)

The main criticism for the Skytherm house has not been a matter of its performance but the reliability of a mechanism that moves insulated panels over the water bags (Givoni 1991). In a day when we can rotate entire floors of a skyscraper (like the Rotating Tower in Dubai), surely this should no longer be a valid reason for ignoring this idea. Or are there forces at play?

To solve a universal problem, a far-reaching solution was required. Godin in discussing how ideas became viral, said:

> The goal, of course, is to have an ideavirus so smooth that once someone is exposed to it, they are instantly hooked. A virus so powerful that all it takes is one guitar lick on the radio, one phrase in a book review, one glimpse of a website and you completely and totally "get it." And not only do you get it, but you want it. Now and forever. (Godin 2001, p. 98)

Skytherm cooling exemplified a revolutionary idea that was scientifically sound: the use of the night sky to provide radiant cooling to a roof thermal mass at night, which in turn provided radiant cooling to the space it covered in the day. Neither concept of radiant heat exchange could be easily grasped by the average
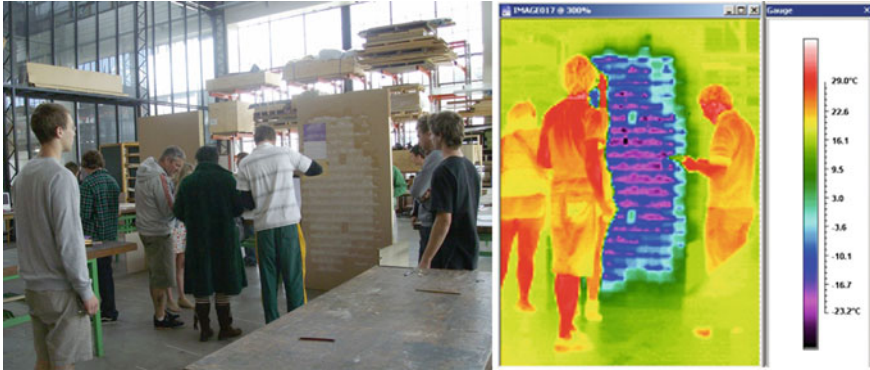
Fig. 8.7 Experiment to teach first year building technology and design students the concepts of radiant heating and cooling: MRT, emissivity and the inverse-square law

layperson. Yet both needed to be understood, one being the human skin sensitivity to radiant cooling, and the other that the night sky could function as a radiant heat sink.

Speaking from personal experience teaching architectural science, I have appreciated how foreign the concept of radiation appeared to first year students when encountering related topics like MRT, low-emissivity glass coatings, sarking and so forth. To communicate this concept I have employed common analogies of radiant heat (like bathroom lights, pop-up toasters and fire pots) and performed demonstrations with infrared spot thermometers and thermal imaging (Fig. 8.7). Despite my best efforts, the concept had only been vaguely understood and after a semester students typically cannot explain how frost could form on grass when both the air and soil temperatures were above freezing. Evidently, it was not *smooth* (in Godin's definition) to convey concepts surrounding radiation. It would therefore not be easy to educate the target market to understand Skytherm cooling.

This does not necessarily suggest that the target market can never be cognisant with Skytherm, it just meant it would eventually be a costly affair. It would involve large scale marketing and endorsement in order for the general public to understand and begin demanding it. Any investor will have to factor into his costs a marketing campaign for home buyers and the training of builders and electricians to install the proprietary roof system. The 'first to market' investor (roofing manufacturer or property developer) will have to bear this public relations campaign in the hope of recovering it subsequently. However, patents are typically valid for twenty years, so the original Skytherm patent has now become public domain material. With the twin deterrents of high education cost and no protection from copycats, it is unlikely that Skytherm will ever gain traction in the market.

Another important factor for the failure of Skytherm was personality. The complexity of the commercialisation process involves working with multiple parties (commercialisation managers, business mentors, venture capitalists, patent attorneys, etc.) and numerous bureaucratic layers (university, state and federal

government, and the various compartmentalised departments in each organisation). A close associate of Hay commented:

> 'Over time, people lost patience with Hay and then lost interest in his creation. Hay's combative personality and reluctance to let others join his mission scotched one potential deal and may have turned others off,' says Ken Haggard, who met Hay in 1972 when the architect was a young professor at Cal Poly San Luis Obispo. 'He's a caricature of the mad inventor. He's a genius. But he's also impossible. And he has not mellowed one iota.' (Douglass 2007)

8.9 The Commercial and Scientific Imperatives

> [In 1997 the Administration, with the backing of the solar industry, introduced a "Million Solar Roofs" initiative to install solar systems (mainly domestic hot water and PVs) on buildings. To my great (but predicted) disappointment, it fails to address the most obvious "solar" option of switching roof color (an almost free measure at the time of the next roof replacement, which accordingly has little backing from manufacturers—cheap solutions are not popular). (Rosenfeld 1999, p. 65)

For a solution to work, it had to be implemented. Whilst scientific merit is a key starting point, an idea based on good science does not in itself warrant success. Many obstacles impede the transition between research and reality. The commercial considerations can be surmised in the following insights:

1. In a capitalistic society, you needed people to buy your solution for you to solve their problems. The saleability of an idea had to be considered at the very conception of an invention.
2. If the idea was not 'smooth', it will be more costly for it to catch on. Marketing can consume a massive budget so an idea powerful enough to self-propagate as an ideavirus would greatly increase profit margins.
3. Investors expected you to protect their interests. The patentability of an idea was vital, so was the zeal manifested in ensuring good laboratory records, confidentiality agreements and patent rights enforcement.

For the innovation to have market sustainability, it could not be merely a marketing play, a technological breakthrough was vital. Industrial designer James Dyson puts it well in his advertising:

> Solve the obvious problems others seem to ignore.

The proverbial *elephant in the room* was the existing stock of buildings, a typical office building having a lifespan of 40 years (CIBSE 1999). An air-conditioning system that was more efficient could not be adopted unless it could be installed without inconvenience. As an improvement over current systems, it also had to attain 0 % PPD where each occupant decided on their own *perfect temperature*. Furthermore, with the Australian Carbon Price introduced in July 2012, the new system should not require refrigerants.

To embed the commercial and scientific imperatives, the brief was refined as follows:

Design a system that can provide air-conditioning to high-rise offices in the tropics that is more energy efficient, more space efficient, offers personalised control, requires no refrigerants and, above all, requires no installation.

Now, we are ready to solve what Dyson refered to as the 'obvious' problem.

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Chapter 9
Personal Air-Conditioning

Majority of air-conditioned offices rely on total volume air distribution (TVAD) to attain a fairly homogenised mix of fresh and recirculated air, supplied at a temperature and velocity that would satisfy most occupants.

> The aim of TVAD is to achieve uniform temperature and velocity in the occupied zone and environment designed for an "average occupant." This approach is too simplified and does not have the potential to satisfy a majority of room occupants because large differences exist between people with regard to the preferred environment. (Melikov 2004)

Based on survey responses, Brill (1984) concluded that thermal comfort 'complaints' were correlated to body size with smaller occupants, typically women, more inclined to complain about temperature fluctuations, especially it being too cool. It was concluded that 'purely environmental solutions to thermal comfort are probably unattainable, given that body type tends to alter responses so strongly.' (Federspiel et al. 1998, p. 174)

> While few have such control [over temperature of their workspace] (only 17 %), those who do are exceedingly more satisfied with their thermal environments. People who have adequate control over temperature experience fewer problems with their office being too cool or too warm, less temperature fluctuation, and more comfort. (Brill 1984, p. 174)

The lowest PPD achievable is 5 % under experimental conditions and 20 % in field studies. Thermal comfort in the future should therefore strive to attain 0 % PPD by offering personal control over the air-conditioning temperature. However, the perfect temperature is a delicate balancing act. Wyon (1989, p. 89) says, 'For sedentary activities such as office work or driving, it is my experience that a discrepancy of only 5 W/m^2 in either direction from thermoneutrality gives rise to a definite feeling of whole-body discomfort after 15–20 min.'

This chapter looks at how personal air-conditioning can be implemented in a way that does not involve large-scale installation or intervention.

9.1 Personal Environmental Modules, Task-Ambient Conditioning and Personal Ventilation

Occupants have become increasingly aware that there cannot be a universal optimum set of conditions for thermal comfort. Consequently, there has been a push for greater personal control over one's immediate thermal environment. This has led to the development of small, local cooling systems that supplant or supplement air-conditioning systems like the one illustrated in Fig. 9.1.

Personal environmental modules (PEMs) for example, feature a pair of desktop nozzles directed at a user's upper body and a radiant heat panel for the legs to create a microclimate that can be controlled to a user's specific requirement (see Fig. 9.2). This system, implemented in the Bank of America, and researched by UC Berkeley (Bauman et al. 1997) was found to reduce thermal dissatisfaction from 11 to 0 %. This is particularly remarkable since a single deterministic setting is unable to achieve 0 % dissatisfaction. Fanger's climate chamber based research allows for 5 % Predicted Percentage of people Dissatisfied (PPD) even when the Predicted Mean Vote (PMV) = 0. Field studies in air-conditioned offices place the PPD at 20 % even when PMV = 0 (Schiller 1990). The focus of task-ambient conditioning (TAC) is primarily on cold air-delivery to the occupant and it does not have the radiant heating panels and white noise generator of PEMs. TAC research has shown that it can also effectively deliver thermal satisfaction even at
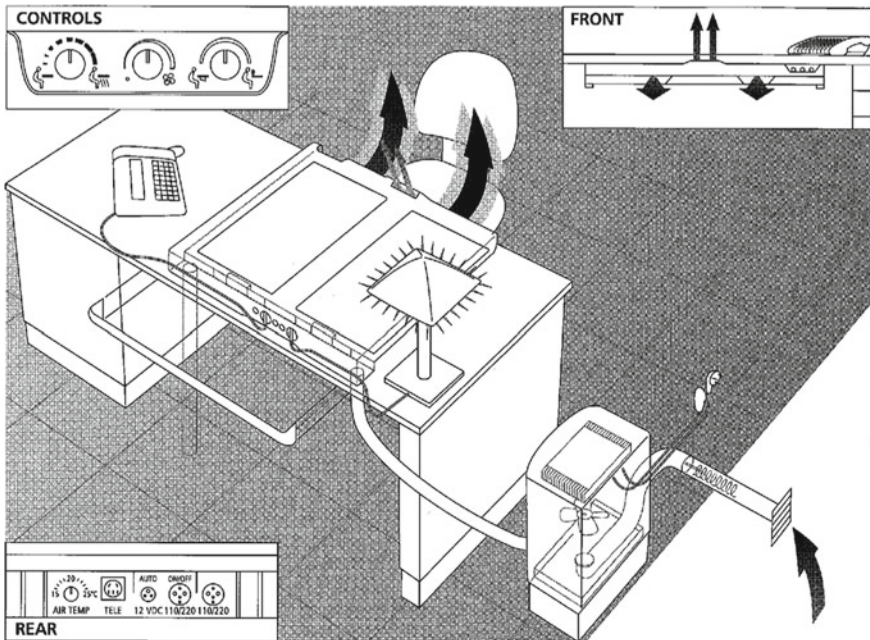
Fig. 9.1 Details of an environmentally responsive workstation (CIBSE 1999)
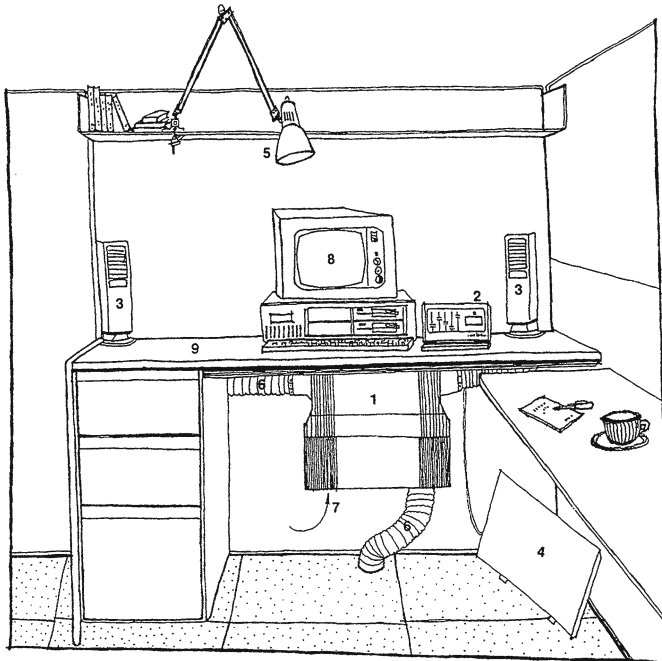
1 PEM supply module
2 PEM control panel
3 PEM supply nozzle
4 radiant heating panel
5 task light
6 flexible supply duct
7 recirculated room air
8 personal computer
9 desk

Fig. 9.2 PEM setup. (US patent 4875397, International publication number WO90/06476.)

ambient SET* values of 29–30 °C (Akimoto et al. 2010). TAC furthermore enables non-uniform conditions, which in certain tasks, like mathematics-based ones, were improved over a neutral condition (Zhang et al. 2010) (Fig. 9.3).

The PEM has a unique proposition, since in affording task cooling the central air-conditioning need not be solely responsible for regulating thermal comfort. In fact, with the use of PEMs, the central air-conditioning control can be at a higher setpoint. So instead of striving for PMV = 0 (24.8 °C, PPD = 5 %) we can allow an ambient temperature of PMV = 1 (28 °C, PPD = 26.1 %) with the PEMs supplying additional cooling as individuals require.

More recently, another UC Berkeley team showed that TAC (task-ambient conditioning, a terminology often used interchangeably with PEMs) systems could achieve personal comfort over a large air temperature range of 18–30 °C, with significant improvements to perceived air quality (Zhang et al. 2010).

Fig. 9.3 TAC setup in UC Berkeley's control environment chamber (*Source* Zhang et al. 2010)

In terms of operational energy, office productivity and, in particular, personal thermal comfort, TAC clearly outperforms traditional air-conditioning and mechanical ventilation (ACMV) systems in the office, yet they are not as mainstream as one would expect. The main problem with implementing TAC is the need for either a pressurized floor plenum or individual ducting to every workstation. Both of these methods require early specification or would otherwise incur a costly retrofit to the office in the future.

9.1.1 Challenges to TAC

Federspiel et al. (1998) studied the complaint logs of two office buildings and found the overwhelming majority of complaints (77–97 %) pertained to thermal sensation. He also noted:

> An important feature of … is that the stated temperature distributions overlap very little. If the hot and cold building temperatures had been held between 70 and 75 °F [21–24 °C] at all times, then approximately 96.5 % of the complaints would not have occurred. In other words, few of the complaints can be reasonably attributed to inter-individual differences in preferred temperature. Most are the result of poor control performance and faults and, therefore, represent potential cost savings. (Federspiel et al. 1998, p. 917)

This would, however, not necessarily argue against TAC. Federspiel's study was concerned with the primary source for complaints and how they could be minimised. However, having no complaints only indicate one is 'not uncomfortable'. The foreseeable future of thermal comfort is to bring us to the conditions that can be expressed as being 'very comfortable'. And when occupant's are at this state of mind, than the largest source of complaints to the building management would have also been eliminated.

9.2 An Introduction to DTAC

To introduce the concept of DTAC, an *elevator-pitch* delivered in the Launceston chapter of Pitch Club is reproduced. Presented before a panel of entrepreneurs, patent attorneys, accountants and business mentors, I was to deliver a 90 s pitch as if I was with a potential investor met by chance in a lift, hence the *elevator-pitch*. It is intended to be extremely concise with the key opportunities described together with a *hook* to occasion a subsequent meeting for a more detailed presentation.

> During winter we like to huddle around the kitchen where the oven gives us enough warmth to not require a heater. As a kid I often wondered why I couldn't do the same on a hot day: to leave the fridge door open so as to cool the kitchen.
>
> The thing is you can't!
>
> To air-condition a space you always need part of the system indoors, part outdoors and a connection. But what if we could do the air-conditioning entirely indoors? What if we could have a fridge that only gave cold air without hot air at the same time?
>
> *No*? But *what if*?
>
> We could then make air-conditioning much more personal. We could allow every person to choose the perfect temperature for themselves. We could save energy because we cool only the person not the whole space. We could integrate it into office furniture and reduce the central air-conditioning plant, thereby creating more leasable space. We could also easily supply these to the most susceptible in a heat wave, because we need no renovations.
>
> What if I told you we already have a working prototype and a provisional patent? What if I told you the proof of concept has been presented in *the* international conference for all things air-conditioning? What if I told you we have a Commercialisation Australia grant and are ready to look for a strategic partner to manufacture and distribute?
>
> Now what if I never got the chance to show you how it works? That'll be a shame! And if that happens, the contents of this file will just have to remain the 'what if' of science fiction.
>
> (Delivered by Author, 30 May 2012 at Hotel Grand Chancellor, Pitch Club Launceston)

In response to the limitations of TAC installation, a Ductless Task Air-Conditioning (DTAC) personal cooling device is proposed (Australian patent application number 2011902620). Cooling is provided by thermoelectric (TE) 'peltier' modules and heat is rejected to a phase change material (PCM). Instead of transferring heat to the outside of a conditioned space, the PCM will store enough heat for the cooling system to operate for eight continuous hours. At the end of each workday, the PCM that has melted will be left to solidify overnight (12–16 h) when the office is expected to be vacant. By using the PCM as a temporary heat sink, we can avoid the need for ducting cold air in or warm air out. Two controls on the faceplate allow occupants to regulate the cooling power and fan speed to their preference. These are illustrated in Fig. 9.4.

It should be highlighted that the use of the term 'ductless' takes a different meaning from an earlier use of 'ductless personalised ventilation' where conditioned air was supplied close to the floor adopting the displacement ventilation principle (Halvoňová and Melikov 2008, 2010). The ductless in DTAC refers to the total autonomy of the personalised unit from the AHU.

Controls
(Fan speed, TE power)

Variable speed
axial DC fan

Aluminium grille
heat exchanger

Thermoelectric (TE)
modules, 4 no.s

Heat sink fins

Drum filled with
phase change material
(PCM)

Condensate pan

dtac
ductless task
air–conditioning
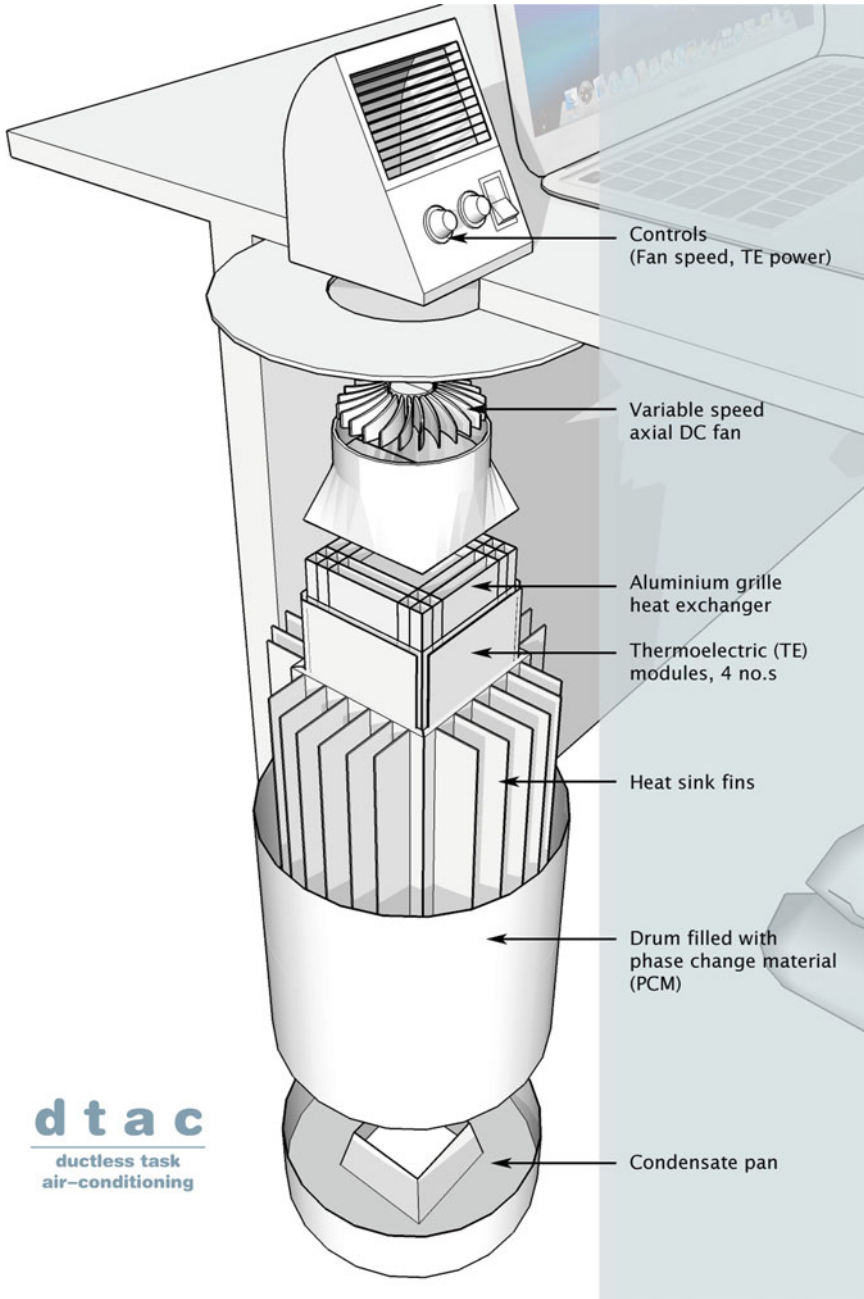
Fig. 9.4 DTAC assembly blow-up

9.3 DTAC, a Twist from TAC

For a new idea to sell well it should be easily understood. One recommended approach is to build on an already familiar notion. Known as "anchor and twist" the familiar concept becomes the anchor, with a new twist being the product differentiator (Heath and Heath 2007). For consumers who might not be familiar with TAC, task-ambient conditioning has many similarities to task-ambient lighting and the parallels are easy to grasp (see Table 9.1).

Imagine an instance where a 60 W incandescent light is used for a bedroom. There would be enough ambient light to move around but insufficient illumination near the walls for reading. If however, we had a 10 W reading light (task lighting) and a 40 W ambient light, there is firstly an overall reduction in power consumption and secondly, an improvement in lighting performance. DTAC borrows from this idea that by separating task and ambient cooling loads, there are improvements both in cooling performance and efficiency.

> Piggybacking on existing products gives you a real advantage. You don't have to educate the world about your idea. You don't have to create a market for it; there already is a market for it. You don't have to invent or reinvent something brand new. It's your shortest, fastest route to licensing success. Because a simple improvement or a small incremental change to an existing product is often the easiest, fastest, most cost-effective, and most profitable way for companies to bring a new product to market. (Key 2011, p. 20)

9.4 Background Research for DTAC

Table 9.2 highlights the key operating parameters for the task side of TAC systems, determined from recognised research in the field.

Five different air terminal devices were evaluated by Melikov et al. (2002) seen in Fig. 9.5 comprising: movable panel (MP), computer monitor panel (CMP), vertical desk grill (VDG), horizontal desk grill (HDG) and personal environments module (PEM). VDG achieved the best ventilative exposure effectiveness (56 % of inhaled air being personalised when supplied at 10 l/s). Under non-isothermal conditions (T-amb = 26 °C, T-ss = 20 °C) the equivalent temperature difference for the head was 6 °C cooler with the VDG than without.

9.5 Key Parameters

The approximate parameters at which the TE modules will be operated, and which need to be experimentally validated, are tabulated in 9.3 (Table 9.3).

Four TE modules (each 40 × 40 mm) can be mounted on the square core, each pumping 36 W (Fig. 9.6) to give an overall Qc of 144 W. Even more can be

Table 9.1 Similarities between task lighting and task air-conditioning (Lord 2008)

Task lighting	Task air-conditioning
Task lighting generally requires ambient lighting as a supplement	Task air generally requires ambient air-conditioning as a supplement
Task lighting can reduce energy by reducing the intensity of ambient lighting	Task air can reduce energy by reducing the intensity of ambient air-conditioning
Task lighting is only about adding light—you cannot make a space darker than the ambient by operating task lights	Task air is only about adding cooling—you cannot make a space warmer than the ambient by operating task air
Task lighting without an ambient lighting system produces discomfort i.e. through contrast	Task air without an ambient comfort system produces discomfort i.e. through contrast
Task lighting is provided to cater for the differences in people and the tasks they need light for	Task air is provided to cater for the differences in people and their comfort preferences
Task lighting is often providing light well above minimum levels of lighting	Task air is often providing cooling and ventilation well above minimum levels for thermal comfort

Table 9.2 Reference parameters for sizing personal air-conditioning

Parameters		Remarks	Source
Power consumption	41 W		Zhang et al. (2010)
Cooling	60 W		Drake (2010)
Airflow	6–70 l/s		Bauman et al. (1997)
	7 l/s	Task, 50 cmh/person ambient	Akimoto et al. (2010)
	5 l/s	x2 diffusers per person	Drake (2010)
	3–20 l/s	Preferred	Melikov (2004)
Outlet velocity	1 m/s	200 mm from blower	Kaczmarczyk et al. (2004)
	0.4 m/s	400 mm from blower, low turbulence	Kaczmarczyk (2010)
	0.2–1.2 m/s	Preferred, to avoid draught discomfort	Melikov (2004)
Outlet temperature	18 °C	13 °C from VAV system	Bauman et al. (1997)
	15 °C	T-ambient = 25–27 °C	Drake (2010)
	dT = 3–4 °C	dT below ambient	Melikov (2004)

mounted if necessary. A balance needs to be struck between coldness (determined by ΔT) and power consumption (IV). Figure 9.7 shows the loss of efficiency (C.O.P.) with increasing values of ΔT.

At peak usage the amount of cooling is solely dependent on the TE modules. However, for continuous usage it is limited by the heat capacity of the PCM (Table 9.4). This heat is (1) rejected from the air stream and (2) generated by the TE circuitry. Assuming a TE C.O.P. of 0.46, operating for 8 h, the maximum

Fig. 9.5 Various air terminal devices studied by Melikov et al. (2002)
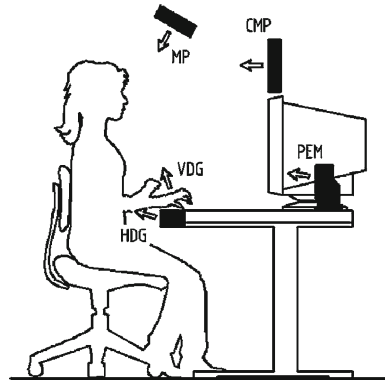
Table 9.3 Key parameters for DTAC

T_{mean}	28 °C (ambient air-conditioning)
T_{hot}	48 °C
T_{cold}	13 °C (also ambient dew point)
dT	35 °C
V_{in}	13 V
I	6 A (per module)
Q_c	36 W (heat absorbed per module)
C.O.P.	0.46 = 36 W/(13 V × 6 A)

continuous cooling that can be provided will be 26 W (small drum, Fig. 9.8 on left) or 198 W (large drum, Fig. 9.8 right). A range of drum sizes can be provided for different needs. The small drum would provide a degree of sensible cooling similar to the TAC (ignoring evaporative heat loss from fan speed), whereas the large drum can provide localised dehumidification and cooling in a non-air-conditioned office in the tropics.

9.6 DTAC Prototype Design

TE modules are used as a heat pump to transfer the heat from the air stream into a heat sink. By passing an electric current through these modules, the Peltier effect will cause the heat on one face of the module to be transferred to the other. It was determined from specifications that the optimum performance (in terms of coefficient of performance, C.O.P., and cost effectiveness) was achieved by running the TE modules at about half their specified maximum voltage, as seen in Table 9.5 (ZP9104 manufacturer's data). To be used effectively in air-conditioning applications, the hot side of TE modules needed to be maintained as close to ambient conditions as possible.

Fig. 9.6 Q–I (*Source* Technical data sheet for ZP9104)
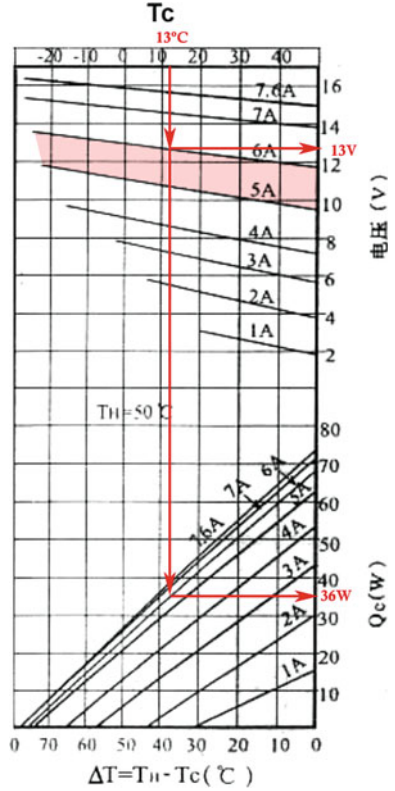
Fig. 9.7 C.O.P. as a function of temperature difference across the module at hot side temperature Th = 300 K. (Riffat and Ma 2004)
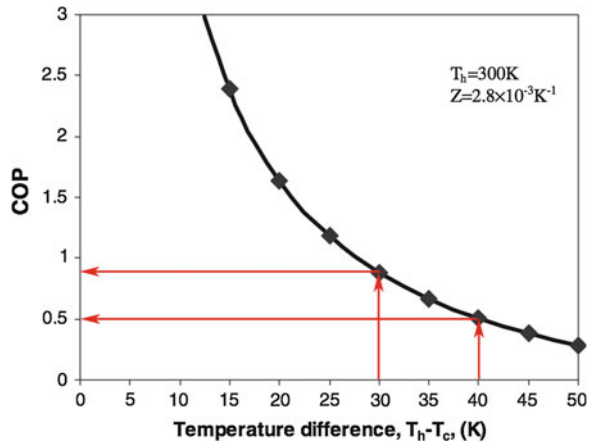
Whilst the DTAC unit is envisioned as a means of providing supplementary cooling to an already air-conditioned office, the experiments for a proof-of-concept were done in naturally ventilated offices at the University of Tasmania. Here the

Table 9.4 Properties of paraffin wax PCM, Rubitherm® RT42

RT42 performance characteristics	
Melting area	38–43 °C
	(typical being: 41 °C)
Congealing area	43–37 °C
	(typical being 42 °C)
Heat storage capacity	174 kJ/kg
Density solid	0.88 kg/l
Density liquid	0.76 kg/l
Volume expansion (in phase change range)	16 %
Heat conductivity	0.2 W/(m–K)
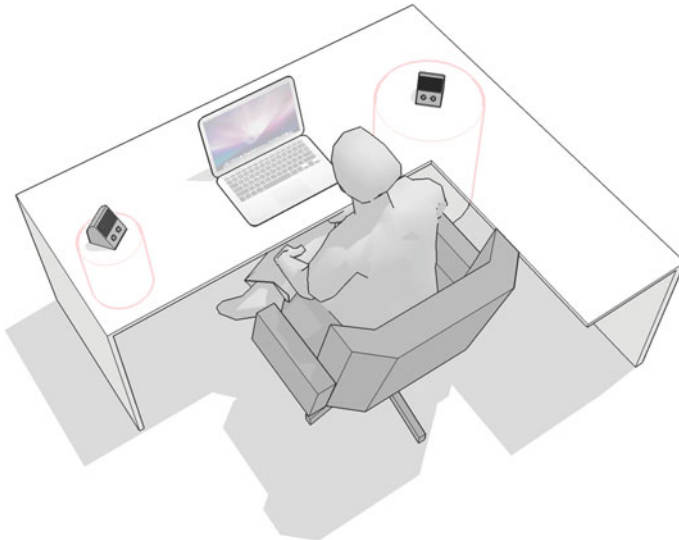
Fig. 9.8 Two drum sizes under the desk are illustrated here: on left small 10 l drum and on right large 75 l drum

eastern facing, fully glazed offices would approach 40 °C in summer. As such the PCM was selected based on a melting point of 42 °C, slightly above the hottest day of summer in Launceston of 40 °C even though this is well above the design conditions of 33.1 °C (AIRAH 1998). Any PCM with a similar melting point

Table 9.5 Efficiency of TE Modules (Th = 50 °C, 122 °F)

	@15 V (max)	@7 V
Current	7 A	3 A
Power draw	105 W	21 W
Q(c)	38 W	16 W
C.O.P.	0.36	0.76

could be used but a paraffin wax (Rubitherm RT42) was chosen instead of salt hydrates for its ease of containment, non-conductivity, non-toxicity and non-causticity. RT42 has a thermal capacity of 174 kJ/kg from 35–50 °C and expands by 16 % on melting (manufacturer's specifications). The PCM bath is designed to allow the molten wax to surface so that solid wax can be continuously gravity-fed to the base, which is in communication with the hot side of the TE modules, illustrated in Fig. 9.9.

The cold side of the TE modules was adhered to a cooling fin assembly by a high-conductivity thermal paste. Cooling fins were laser-cut from sheet aluminium (0.6 mm thickness) and spaced 2 mm apart as illustrated in Fig. 9.10. Each face was laminated with the same thermal paste. The assembly was finally pressed with a series of 4 mm diameter bolts.
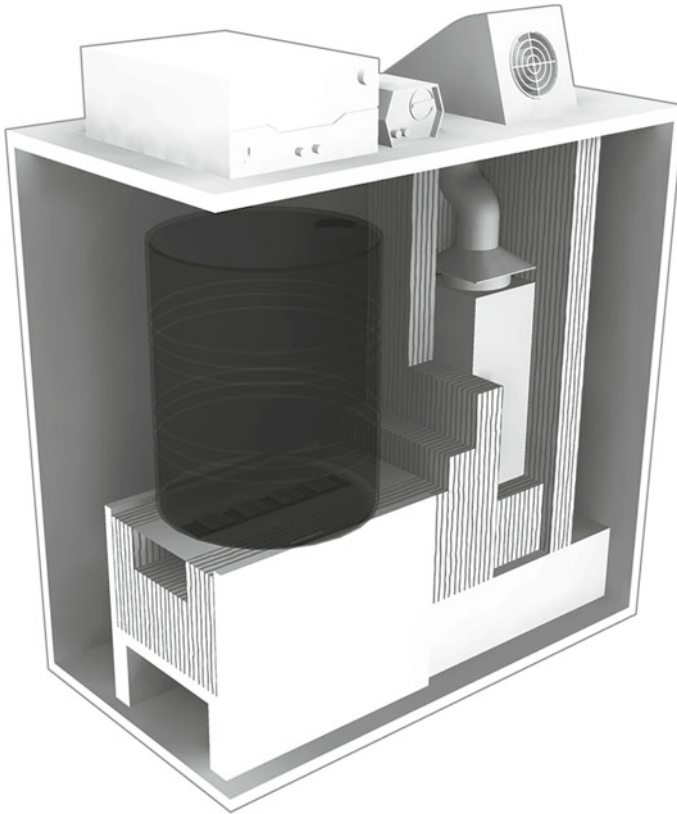
Fig. 9.9 CAD render of proposed DTAC design. Dimensions: 800 mm (L) × 450 mm (W) × 800 mm (H)

9.7 DTAC Performance Indicators and Methodology

The energy balance across the cooling fin can be seen in Fig. 9.11.

As a proof of concept it had to be demonstrated that dH < 0, i.e. H(ss) < H(amb). Where the absolute humidity was maintained across the cooling fin by an enclosure, it was sufficient to demonstrate that the temperature difference between ambient and supply air was negative, i.e. dT < 0.

The heat exchange system comprising cooling fins, TE modules and PCM drum was installed into an aluminium duct insulated with 50 mm expanded polystyrene. Data loggers for temperature and relative humidity were logged on Hobo U12 loggers and were placed in the locations as shown in Fig. 9.12. Redundancy was adopted with Lascar High Accuracy EL-USB2+ loggers in the areas that needed the most reliable recordings, in this case the ambient air and supply air. The finished product is seen in Fig. 9.13.

9.8 DTAC Discussion

Figure 9.14 shows the individual temperatures and the temperature difference between supply and ambient air, dT. This first DTAC prototype achieved an average dT = −2.54 °C (s.d. = 0.53 °C) for the first 3 h of operation, approaching the dT = −3 °C region recommended by Melikov. The efficacy of the DTAC is highly dependent on the ambient air temperatures, higher temperatures resulting in a larger dT. This is consistent with our understanding that since the PCM melts at a fixed temperature, the cooling fin temperature will remain
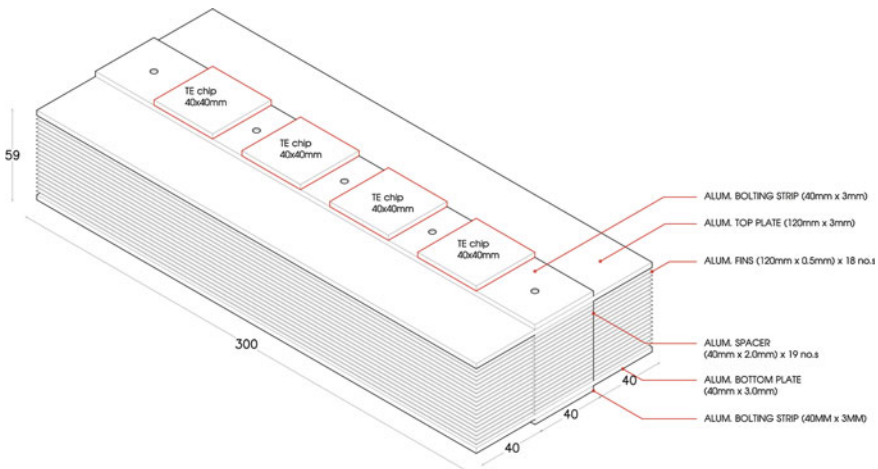
Fig. 9.10 Detail of cooling fin assembly

Fig. 9.11 Energy balance of cooling fin
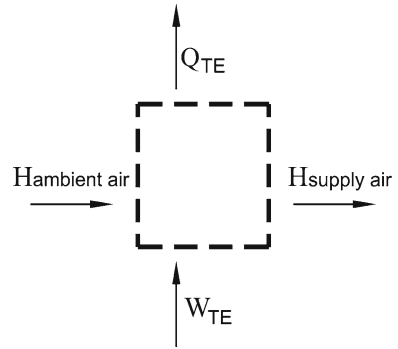
H_{ss}	Enthalpy of supply air
H_{amb}	Enthalpy of ambient air
W_{TE}	Work (electrical) input to TE modules
Q_{TE}	Heat produced (on hot side) of TE module

constant at a given voltage applied to the TE modules. As ambient temperatures increase so will the amount of cooling, shown by magnitude of the dT of supplied air as shown in Fig. 9.15. We can expect the trend to continue until the cooling fins approach dew point temperature. This allows DTAC to also serve a viable cooling function for naturally ventilated (NV) spaces. In this application, as demand for cooling increases with higher ambient temperatures, so does the degree of cooling provided to the supply air.

Fig. 9.12 Sensor positions when testing the DTAC
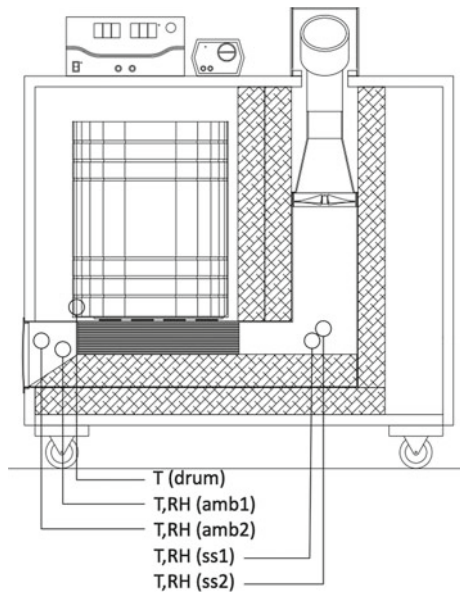
Fig. 9.13 Completed
prototype, slightly larger than
a regular office drawer
pedestal

The quantity of wax in the prototype of 5.3 kg (11.7 lb) and was adequate for 3 h of continuous use. As seen in Fig. 9.16, when the power supply was turned off at 5 pm, this drum required 7.5 h to reach the same temperature as the ambient conditions when it was turned off, and about 11 h for it to reach its minimum temperature. The TE modules were typically run at 10 V DC and drew 17 A (21.0 A cold rush, 16.8 A when PCM fully molten).

9.9 DTAC Energy Comparison

DTAC achieves energy economy by the following means:

1. Allowing the ambient cooling to be set at a higher level
2. Cooling the person directly
3. Responding to occupancy levels.

9.9.1 Higher Ambient Air-Conditioning Temperatures

Since the central air-conditioning will be supplemented with DTAC, it need not be solely responsible for cooling comfort. Consequently there will also be less reason to implement multiple safety factors that lead to oversizing. The ambient

(a)

(b)
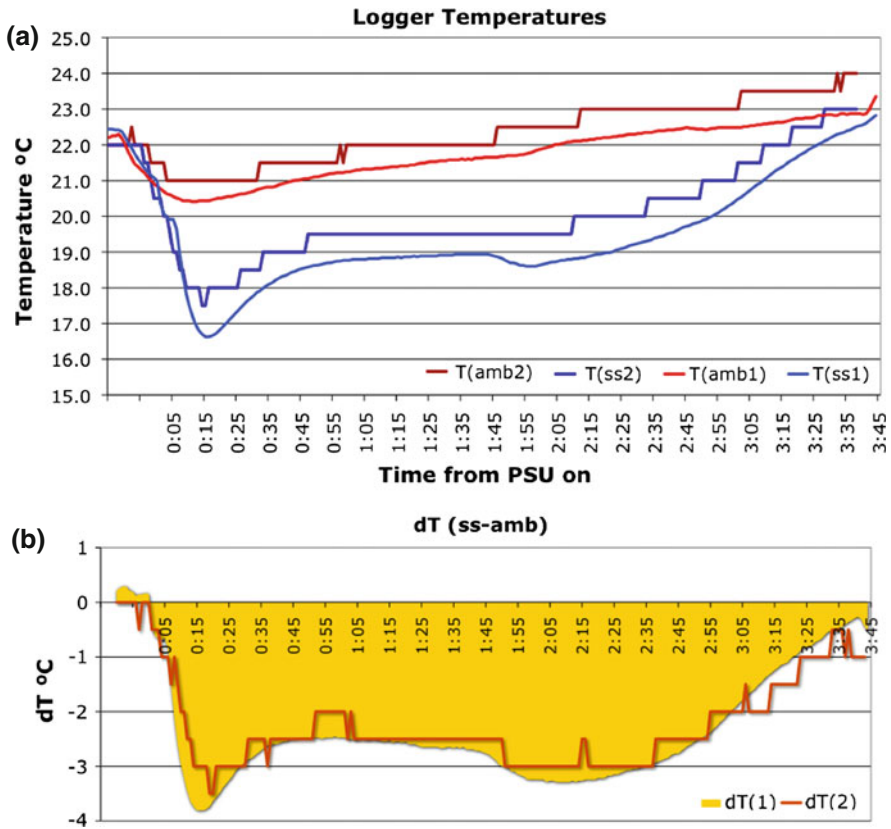
Fig. 9.14 **a** T plots of individual loggers and **b** dT plots when DTAC in operation

Fig. 9.15 Correlation dT to T(amb)

$$y = -1.2319x^2 + 52.215x - 555.8$$
$$R^2 = 0.88305$$
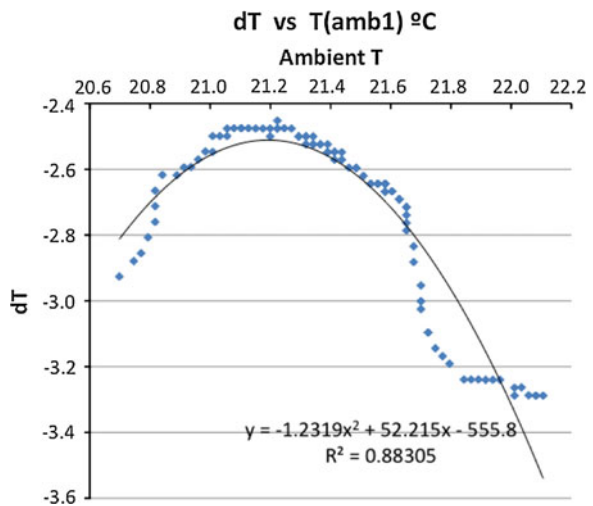
Fig. 9.16 Time taken for fully molten PCM to be regenerated after office hours
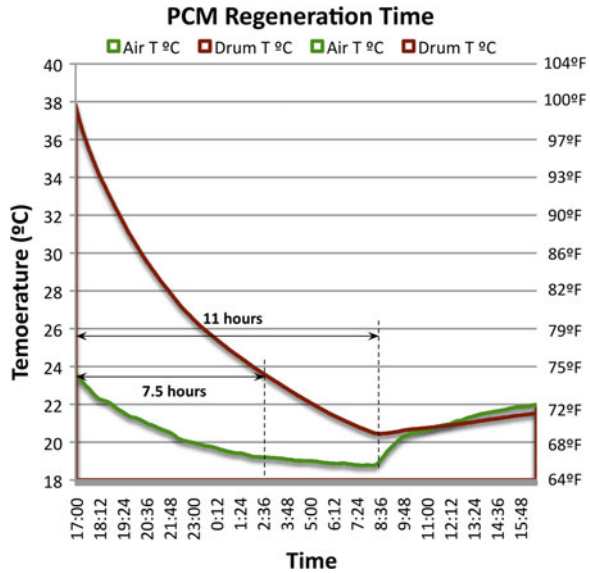
temperature could be set to the upper comfort limit, with those requiring more cooling opting to use DTAC.

Whilst there are savings here, the actual magnitude of savings would be hard to determine. The efficiency of AC induction motors (powering chillers, fans and pumps) as partial loading are not linear, i.e. an AC motor at 50 % duty typically consumes more than 50 % power.

9.9.2   Direct Occupant Cooling

This can be determined by taking the rule-of-thumb energy usage intensity per person, compared to the DTAC power consumption. It is assumed that the production model will provide adequate air-conditioning to the occupant so that the central air-conditioning can be supplied with half the power.

Two methods of estimating the personal cooling load are detailed in Tables 9.6 and 9.7, with the average occupant consuming 380–460 W of electricity for air-conditioning compared to 200 W with DTAC. The cost recovery period determined based on a retail price of $300 for the DTAC and current energy prices would range from 2.4 to 3.3 years (Table 9.8), assuming the power to the central air-conditioning can be halved with the adoption of DTAC.

The pricing of $300 was not determined as a multiple of expected manufacturing costs. Instead users of the prototype gave market feedback on the price they were prepared to pay for a new unit (see Fig. 10.27). As a reference, the prototypes were fabricated at a cost ranging from $1000 to $1200.

Table 9.6 Personal EUI based on data from Singaporean sources

Method 1 (Singapore statistics)		
Annual total power consumption (mean)	231 kWh/ sqm	Lee (2001)
Air-conditioning power usage (50 % of total)	115 kWh/ sqm	(Class B building) http://www.esu.com.sg/ beforeyoustart.php
	1,150 kWh/ pax	@ 10 sqm/pax
Hours of consumption (annual)	3030 h/year	Ding et al. (1983)
Energy usage intensity (EUI) method 1	380 W/pax	

Table 9.7 Personal EUI based on data from ASHRAE rule-of-thumb

Method 2 (ASHRAE, pocket guide p. 143)		
Average office occupancy	10.2 sqm/pax	ASHRAE
Average refrigeration load	7.4 sqm/kW	ASHRAE
Air-conditioning power usage	45.0 W/sqm	Assume C.O.P. = 3
Energy usage intensity (EUI) method 2	459 W/pax	Calculated

Table 9.8 Energy savings and cost recovery based on current electricity prices

DTAC economy	EUI 1	EUI 2
DTAC power consumption	180 W/pax	
Typical AC	380 W/pax	459 W/pax
Savings if central AC switched off	200 W	279 W
Savings if central AC on half load	100 W	140 W
Annualised savings (half load)	303 kWh	423 kWh
Electricity price	$0.30 /kWh	
Annual cost savings	$90.9	$126.90
DTAC retail price	$300	
Cost recovery from electricity saved	3.3 years	2.4 years

9.9.3 Occupancy Levels

If DTAC is fitted with an occupancy sensor, such that the device turns itself off when the occupant is absent, further economy is possible, leading to a shorter cost recovery period.

> In our calculations, we assumed 80 % workstation occupancy. Bauman et al. measured 70 % average occupancy in an office field study. Since TAC systems are automatically turned off when there is no occupant, this mode of occupant-sensitive environmental conditioning produces significant energy savings. (Zhang et al. 2010, p. 35)

9.10 DTAC Competition: Other Personal Air-Conditioners

In the commercial office sector, desk and ceiling fans have limited application due to the adverse effects of strong breezes on paper and hair. The preference for most workers is still to have some form of air-conditioning which generally refers to any device capable of reducing ambient temperature. A number of personal cooling devices have been in the market with heat rejection achieved by melting of ice or requiring a vent to the nearest window. These devices do not provide adequate cooling or prove to be simply too cumbersome.

Besides task-ambient conditioning systems discussed earlier the market for personal cooling devices can be divided into five categories:

1. Portable room air-conditioners with the need to discharge hot air from the compressors.
2. Evaporative coolers that reduce temperature by increasing humidity.
3. Battery or USB powered fans passing air over water or ice.
4. Inside coat cooling with moving air supplied by hoses.
5. Cooling vests utilising PCM or chemical reactions.

These categories have been tabulated in 9.9 to demonstrate the degree to which they address the following criteria:

1. No increased humidity
2. Self-containment
3. Suitability for indoors
4. Capable of daily usage for 8 h
5. Acceptable for use in an office environment
6. No installation required.

If a selection was made on a personal air-conditioning system that delivered cool air to the face without increasing the humidity (absolute), the ideal, and in fact only, option is that of task-ambient air-conditioning systems (TACs). However, these systems need to be specified at the fit out phase, or else they become very costly to implement subsequently (Table 9.9).

DTAC is in a unique position of being implementable in the existing stock of office buildings, which make up the overwhelming majority of buildings for the immediate future. Table 9.10 shows how it performs against the earlier criteria.

9.11 DTAC Markets Identified

Having noted the importance of addressing a market imperative in the earlier chapters, the prospective markets for the DTAC are further identified as follows:

Table 9.9 Metric for comparing existing technologies, sourced from respective manufacturers. Unbranded products sourced from multiple retailers

Category	Product/Features		Power	No increased humidity	Self-contained	Suitable for indoors	8 h/day use	Acceptable in office	No installation needed	Price
1	**Toshiba KYR-25CO/XC1** Compressor driven. 2.5 kW mobile air-conditioner, hot vent required		1050 W	✓	✓	✓	✓	✓	×	$478
1	**American Comfort Min0069 Cooler** Personal air-conditioner and dehumidifier, no venting (heat returned to indoors)		250 W	✓	✓	✓	×	×	✓	$230
2	**Sunpentown SPT SF-608R** Evaporative air cooler		60 W	×	×	✓	✓	✓	✓	$75–138
3	**Herman Miller C2** TE module to deliver cold air with heat exhausted at rear		60 W	✓	×	✓	×	✓	✓	$140
3	**Desktop Air-Conditioner (unbranded)** Fan blows over frozen bottle		5 W (fan)	✓	×	✓	×	✓	✓	$36–$60
3	**Cooling collar (unbranded)** Battery powered fan over small reservoir		Battery (AA)	×	×	×	×	×	✓	$20
3	**Yiwu Jeddah Personal air-conditioner** Portable fan-driven evaporative cooler		5 W	×	×	×	×	×	✓	$40

Table 9.9 (continued)

Category	Product/Features		Power	No increased humidity	Self-contained	Suitable for indoors	8 h/day use	Acceptable in office	No installation needed	Price
3	**02Cool 1086 Cool Box** Mist blower with Ice compartment		Battery (SLA)	×	×	×	×	×	✓	$297
4	**Kuchofuku air-conditioned Jacket** 2 electric fans puff jacket which exhausts at cuffs and collar		Battery (lithium)	✓	✓	×	✓	×	✓	$140
4	**EntroSys** Personal motorcycle air-conditioner utilising thermoelectric modules		Battery (motor-bike)	×	×	×	×	×	✓	Preorder only
4	**Vortec Cooling Vest** Filtered compressed air passed through vest in small tubes		1800 W (air compressor)	✓	×	×	✓	×	✓	$114–$199
4	**Steele/Kappler/Texas** Cool vest, PCM cool packs recharged by dipping in ice water		N.A.	✓	✓	×	×	×	✓	$250–$275
5	**JCU Cool Me Vest** Disposable vest, where pouring water on it triggers chemical reaction to keep firefighters cool		N.A.	✓	✓	×	×	×	✓	Not market yet

Table 9.10 DTAC in the comparison metric

Category	Product/feature	Power	No increased humidity	Self-contained	Suitable for indoors use	8 h/day use	Acceptable in office	No installation needed	Price
N.A.		200 W	✓	✓	✓	✓	✓	✓	$300 (appox.)

UTAS
Ductless Task Air-Conditioning
Refrigeration from thermoelectric modules with temporary thermal storage in phase change material

1. Existing air-conditioned offices where erratic performance of the cooling system is a regular source of complaints. The DTAC can provide extra cooling when the ambient source is insufficient.
2. Existing air-conditioned offices keen on saving energy by implementing a higher temperature set point. By using DTACs, building managers can afford to have a higher thermostat set point. Moreover, since offices are seldom fully occupied it makes sense that temperatures should not be tuned to maximal occupancies.
3. Non-air-conditioned offices in temperate regions where the number of cooling days do not justify central air-conditioning. The DTAC is easily installed, with minimal requirements: a hole cut into the table and any available power socket.
4. Newly built offices. The TAC system has been simulated and shown to require far less energy (26–39 % summer savings, Zhang et al. 2010) than conventional HVAC systems. By focusing on personal cooling instead of space cooling, the TAC can provide a higher degree of thermal satisfaction with less energy. New buildings based on the TAC model can thus afford to have much smaller chiller plants and AHU rooms. The DTAC builds on the TAC advantage by eliminating ductwork.
5. Naturally ventilated offices in the tropics. Whilst the adaptive model of thermal comfort allows for a larger range of temperatures in which an occupant is comfortable as opposed to deterministic comfort, it is highly possible that there will still be a preference for cooling beyond the range of ceiling fans. A modified DTAC, with a much larger volume of PCM and the condensate collected or pumped to a bottle, can provide an easily installed and energy frugal personal cooling system.

9.12 DTAC Conclusion

In the DTAC prototypes which have been primarily hand-built, the overall system C.O.P. of 0.2 can be greatly improved with the following upgrades through mass manufacturing:

1. Tank and cooling fins surfaces that interface with TE modules to be engineered to 0.01 mm tolerance with a fly cutter instead of being manually lapped with sand-paper
2. Cooling fins as a solid piece formed by aluminium extrusion instead of being laminated with thermal paste
3. PCM set to a lower melting point e.g. 26–30 °C when DTAC is used to supplement ambient air-conditioning
4. Use of thermal tunneling devices in place of TE modules.

However, as a proof of concept I am satisfied that the DTAC is capable of delivering air cold enough to approach thermal comfort if a difference of less than 3 °C cooling below ambient supply air is all that is needed. I have also shown that the PCM is capable of unassisted regeneration within the overnight hours.

Mainstream TE modules are not, as yet, very efficient. With a C.O.P. of 1 for the TE modules (manufacturers specifications) and a measured C.O.P. of 0.2 for the DTAC system, much more can be done to improve the efficiency of the DTAC unit to bring it on par with the central air-conditioning system. The main attractiveness of DTAC remains its low consumption of about 200 W (measured from power socket) compared to the 380–460 W/person in central air-conditioning due to the relatively small amount of refrigeration needed for task air-conditioning. In Chap. 10 we will see the experiments to ascertain if this can adequately allow occupants to work in naturally ventilated offices during summer, or to what extent the ambient air-conditioning set-points can be increased.

TE modules have an efficiency of 5–15 % (against the theoretical Carnot limit) which is much lower than vapour compressors of about 50 %. Other solid-state refrigeration technologies like electron tunneling devices (Walitzki 2009) under research show potential to surpass the efficiency of compressors (Dieckmann et al. 2011). These thermal tunneling devices convey the active (hot) electrons across a vacuum, allowing heat to be pumped one way without being conducted back, with a 55 % Carnot efficiency projected. If these efficiencies are realised with the aforementioned improvements, DTAC could be operated at under 50 W.

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Chapter 10
Field Testing DTAC, Methodology and Results

10.1 Background to the Field Trial

The Ductless Task Air-Conditioning (DTAC) system was developed for supplementary personal cooling to office occupants. DTAC utilised thermoelectric (peltier) modules for heat exchange into a phase change material (PCM) as heat sink, allowing workspaces to be air-conditioned with no installation. The process of prototyping and optimising this unit is covered at length and in detail in Appendix 1. The final DTAC Mark-4 prototype was capable of supplying air at 4–10 °C below ambient, depending on the external ambient temperatures and the fan speed. To test if this amount of cooling was sufficient for human comfort, a field trial was organised.

10.2 Field Trials in NV Offices

10.2.1 Purpose of Field Study

The field study was designed to ascertain the degree to which ambient air-conditioning set-point can be raised with the use of supplementary air-conditioning. This may overlap with existing research with existing studies on task-ambient conditioning (TAC), Personal Environmental Modules (PEM) and personal ventilation (PV). It was very possible that if DTAC's cooling capacity (flow rate and supply temperature) were comparable to TAC, then the thermal comfort outcome would also be similar.

10.2.2 Methodology

Eight participants in the field trials were divided into two groups: one group to field test the DTAC system while the other control group will concurrently use a fan-only unit. After one week (5 working days), the groups had a swap of

Fig. 10.1 a Participant using DTAC unit. **b** Participant using fan-only unit

appliance and repeated the test. Invitations were sent to all staff at the School of Architecture and Design, and of the 10 who responded the first 8 respondents were selected for the trials (Fig. 10.1).

Trials were run from 15 Feb 2011 to 1 Mar 2011. Participants were required to fill up online survey forms comprising:

1. Start of the day comfort questionnaire.
2. Comfort questionnaire to be filled every hour on the hour.
3. End of day.

Questionnaires indicated clothing, metabolism and stress level. Feedback on the efficacy of DTAC or fan-only units was collected in the following areas: thermal comfort, air quality, office productivity, general well-being and background noise. The questionnaires were based on the following references:

1. Appendix E: Thermal Environment Survey of ASHRAE 55 (2004): Thermal Environmental Conditions for Human Occupancy
2. ISO 7730 (2005): Ergonomics of the thermal environment—Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria
3. Bedford (1936): The Warmth Factor in Comfort at Work. Rep. Industr. Hlth. Res. Bd., No. 76, London.

The surveys were based on two theories of thermal comfort. Deterministic thermal comfort theory underlies the bulk of air-conditioning research and is based

Table 10.1 Thermal sensation scale

Describe your thermal sensation:	
1	Cold
2	Cool
3	Slightly cool
4	Neutral
5	Slightly warm
6	Warm
l	Hot

on laboratory work by volunteers (often students) in climate chambers doing simulated work for 2–3 h. Adaptive thermal comfort underlies natural ventilation research and is based on field studies by office workers (typically in the tropics) performing their actual occupation through the day. The two schools differ in approach, application and method. As the DTAC field trial was performed in a naturally ventilated building, both scales were used.

The first was Predicted Mean Vote (PMV) from the deterministic thermal comfort theory which relates six variables (clothing, metabolism, T, RH, MRT, wind velocity) to a vote (Table 10.1).

By comparing the Actual Mean Vote (AMV) to the PMV, I expected to see an improvement with the fan-only unit and a further improvement with DTAC.

The other indicator was to use a combination of a 6-point comfort scale (Table 10.2).

A third scale is based on the Bedford scale (Bedford 1936) commonly used in England (Table 10.3).

Table 10.2 General comfort sale

How comfortable are you feeling with regard to temperature?	
1	Very uncomfortable
2	Moderately uncomfortable
3	Slightly uncomfortable
4	Slightly comfortable
5	Moderately comfortable
6	Very comfortable

Table 10.3 Thermal comfort scale

Which best describes your thermal comfort?	
−3	Much too cool
−2	Too cool
−1	Comfortably cool
0	Comfortable and neither cool/warm
+1	Comfortably warm
+2	Too warm
+3	Much too warm

10.2.3 Temperature and Relative Humidity Logging

Outdoor Temperature (T) and Relative Humidity (RH) were taken at my office above an open window. Indoor T was taken inside my office at three levels (as stipulated by ASHRAE 55): 0.1, 0.6 and 1.1 m from floor. Globe T was taken at 1.1 m (instead of 0.6 m stipulated by ASHRAE 55) as a more accurate representation of radiant heat on the head, especially that which was contributed by computer monitors. A 38 mm table tennis ball was used instead of the 150 mm copper globe in favour of its faster response and equivalent accuracy (Humphreys 1977). Air velocity was taken at 1.1 m, to correspond with globe T in order to calculate mean radiant temperature (MRT). Indoor RH was taken at 1.1 m. The measurements within my office would be similar to the other offices as all offices had the same facing and were of the same size.

T and RH were logged on Hobo U12 data loggers with built in sensors. Air velocity was read by Kimo CTV100 hot wire anemometer and logged on Hobo U12. Logging was set to 1 min intervals.

10.2.4 Response Rate

The participation rate for the first week was rather low. After speaking to the participants the consensus was to switch to a paper survey in place of online survey forms. The time taken to fill up each online survey had been about 90 s, and we expected the paper surveys to substantially reduce that time, making it quicker and more convenient. The other advantage of a tabulated survey form was that it imposed a subconscious pressure to be more conscientious if a participant had left too many blanks in the responses. A further advantage was that if one was sensitive enough and so inclined, one could reflect a degree of comfort to a decimal placing. The Majority (7 of 8) preferred the paper survey immediately. Despite this, the response rate in Fig. 10.2 was rather disappointing.
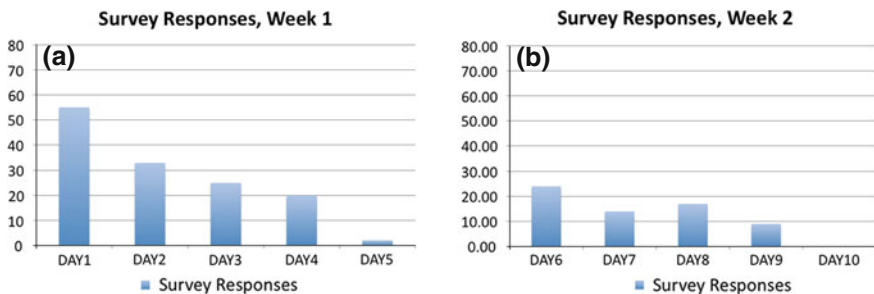
Fig. 10.2 Number of responses received for thermal comfort survey in **a** week 1 **b** week 2

10.2.5 PMV and AMV Results

Whilst not the most representative of natural ventilated buildings, it was expected that the PMV could still be a baseline reference in an office had there been no supplementary personal cooling. The improvement from using a fan could be seen from the difference between AMV (fan only) and PMV, and a further improvement could be expected between AMV (DTAC) and AMV (fan only).

The results for the first day was the most complete and yielded no conclusive evidence if either the DTAC or fan-only units improved the actual vote against what would have been predicted (Fig. 10.3 and Table 10.4).

10.2.6 Thermal Sensation Results (Based on Adaptive Thermal Comfort Studies)

The thermal sensation votes were plotted against the average effective temperature of the hour prior to the vote taken, i.e. the sensation vote as filled out at 10 a.m. was plotted against the average effective temperature from 9.01 to 10.00 a.m. Where:

$$T_{effective} = 0.5 \cdot T_{air} + 0.5 \cdot MRT \tag{10.1}$$

The decision to use effective indoor temperatures instead of outdoor air temperatures was due to the large amount of glazing found in the offices where the experiment was conducted. All offices were fully glazed on one side (3 × 1.8 m) and would account for a substantial amount of radiant heat.

The aim was to determine a linear function between thermal sensation vote and T(effective) which could then determine the neutral sensation temperature, T(neutral), when vote = 0. Due to the additional cooling that each device offered, it was expected that the fan only regression would have a higher T(neutral) than the adaptive thermal comfort models would predict, and the DTAC regression an even higher T(neutral) value, showed in the plot of Fig. 10.4.

With the fan only units, T(neutral) worked out to be 20.8 °C. Based on a weak correlation ($r^2 = 0.3$) the data suggests that occupants would have a neutral sensation with a small fan at an effective indoor temperature of 20.8 °C. The DTAC regression would suggest a T(neutral) of 47.9 °C. However, the DTAC correlation was so weak ($r^2 = 0.01$) I cannot say with any degree of certainty that 48 °C would be the optimum indoor temperature with DTAC. In fact, with the weak correlation, it would be more accurate to infer that indoor T (x-axis) and the thermal sensation vote when using DTAC (y-axis) had little correlation. This would support the position that DTAC can be an effective personal cooling unit, such that actual thermal sensation could not be accounted for in terms of ambient temperature fluctuations.
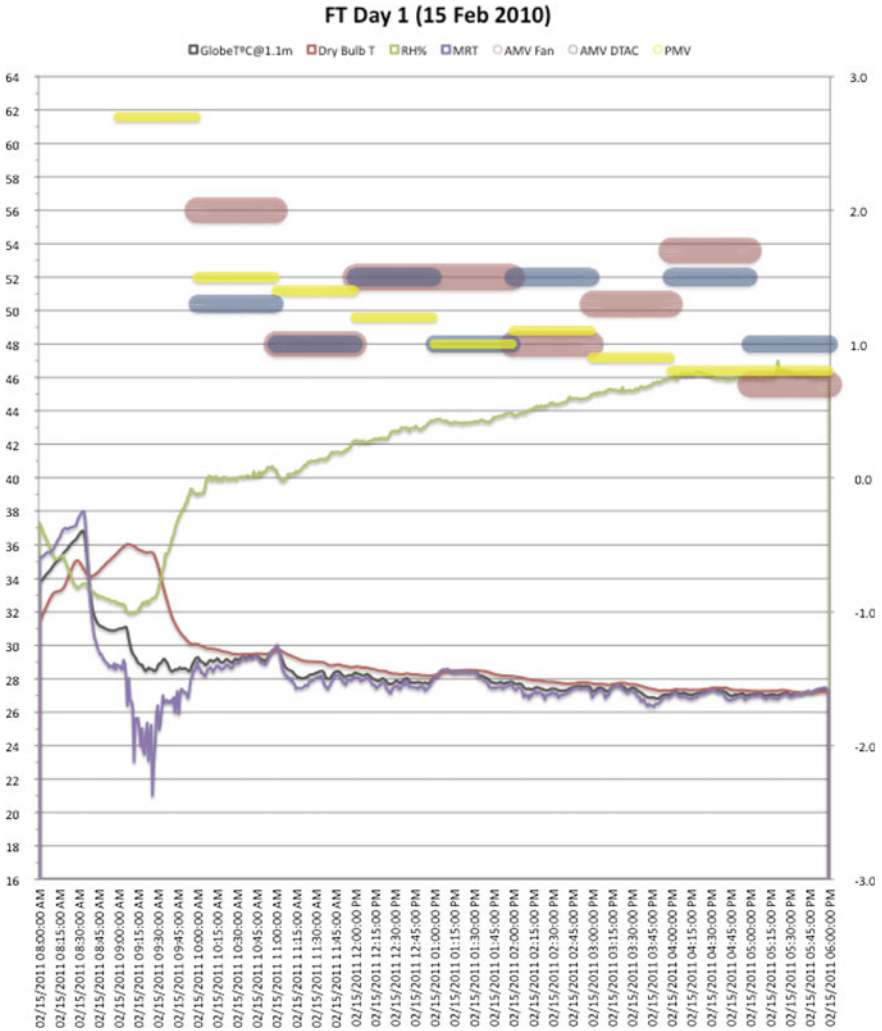
Fig. 10.3 Plots of environmental thermal factors on left vertical axis: dry bulb T, globe T, relative humidity, MRT. Votes (PMV, AMV-Fan and AMV-DTAC) are the *thick horizontal bars* read to the *right vertical axis*

10.2.7 Concerns

10.2.7.1 Climate

Late February was typically the hottest period in Tasmania. However, in this particular year (2011) the summer was unusually cool, with very few days requiring any supplementary cooling.

Table 10.4 Differences in votes between predicted and actual with use of fan-only and DTAC units

Time	PMV	AMV FAN	AMV DTAC	ΔVote (Fan)	ΔVote (DTAC)
10 a.m.	1.5	2.0	1.3	0.5	−0.2
11 a.m.	1.4	1.0	1.0	−0.4	−0.4
12 p.m.	1.2	1.5	1.5	0.3	0.3
1 p.m.	1.0	1.5	1.0	0.5	0.0
2 p.m.	1.1	1.0	1.5	−0.1	0.4
3 p.m.	0.8	1.1	1.5	0.9	0.1
4 p.m.	0.8	0.1	1.0	−0.1	0.2
Average difference in vote				0.2	0.1
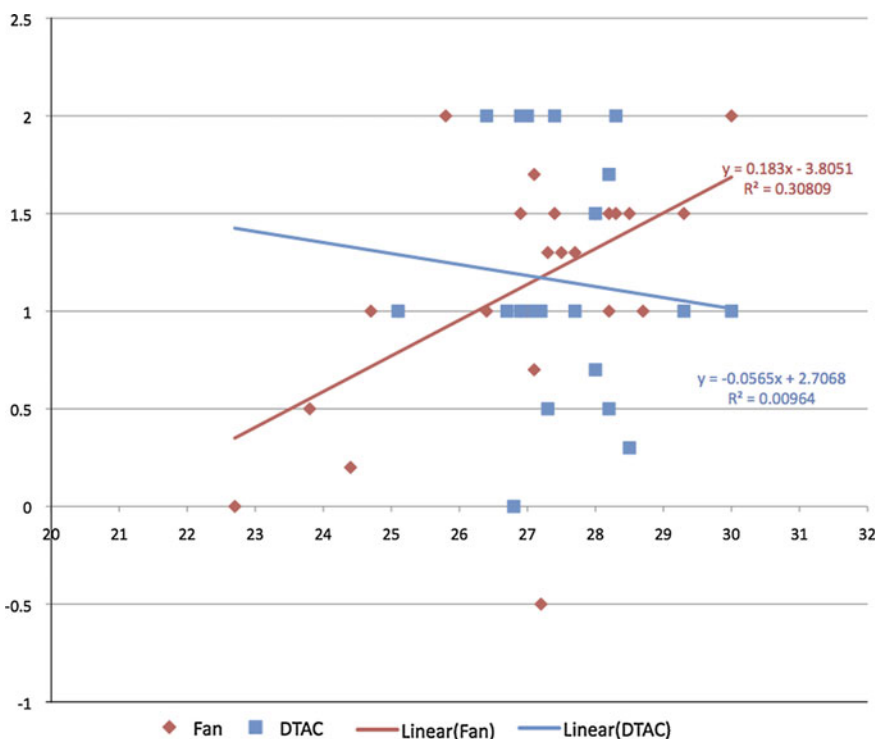
Fig. 10.4 All data points of actual votes, and the corresponding effective T plotted for fan-only (*red*) and DTAC (*blue*). Fan votes show a weak correlation ($r^2 = 0.3$) and DTAC votes show no correlation with T ($r^2 = 0.0$)

10.2.7.2 Sample Size

The amount of funds and the time required to fabricate each DTAC unit limited the number of participants to four in the DTAC group and four in the fan-only control group. Whilst the outcome of 162 actual data points was comparable to many

Table 10.5 Current experiment (Law) compared with the sample size of similar studies

Law	162 (actual) of 640 (planned) data points
	8 participants (4 DTAC, 4 control) $\times$ 8 surveys/day $\times$ 10 days
Zhang (2010)	270 data points
	18 participants (9M, 9F) $\times$ 5 conditions
	(ET 18, 19.9, 24.2, 27.5, 29 °C) $\times$ 3 surveys (1 per hr)
Kaczmarczyk (2004)	180 data points per session
	5 sessions simulating different work
	e.g. text correction, addition on PC, text typing, addition on paper and text typing
	each session 5 groups $\times$ 6 subjects
	Series 1 (Tamb 23 °C) $\times$ 4 delivery conditions
	(PVS@20 °C, PVS@23 °C, PVS recirculated, mixing ventilation)
	Series 2 (Tamb 26 °C) $\times$ 2 delivery conditions (mixing, PVS)
Kaczmarcyk (2010)	180 data points
	3 survey (every 5 min) $\times$ 4 $\times$ 15 min exposures (50 % with PV, 50 % control)
	8 desk (4 PV, 4 none)
Akimoto (2010)	96 data points (2005) and 240 data points (2006)
	8 participants (2005: 6M 2F) 20 participants (2006: 12M 8F)
	3 days (TAC off, TAC full open, TAC controllable), 4 surveys daily
Amai (2007)	96 data points for each TAC (standard, 3DU, PEM, RCU, RCU + meshchair, TU)
	24 participants (12M 12F) $\times$ 4 surveys (25 min from start then every 60 min)
Bauman (1997)	212 data points
	53 participants, 1 survey $\times$ 4 periods
	Original 42 PEMs (total of 3 buildings) + 36 control (10 to12 per building)
	4 measuring periods (Baseline Mar, Post PEM normal 10–11 July
	Post-PEM set-up 24–25 July, Post PEM set-down 31 July)
	post: 28 PEM + 25 control = 53 participants
Post (1993) [in Baunman (1997)]	200 data points
	100 participants (27 weeks before, 24 weeks after), 370 units in WBM building

similar studies (Table 10.5), I felt a need for more thorough field testing. The table shows a summary of similar recent studies, none of which had been done in naturally ventilated buildings:

10.2.7.3 Response Rate

The response rate was fairly low. For some days there was virtually no response. The participants were predominantly lecturers who could not fill up the surveys when they were holding classes or meetings. Out of a total of 640 expected responses there was only a quarter of actual responses.

10.2.7.4 Wax Capacity

The quantity of wax in the DTAC units allowed typically 2.5 h of use at maximum cooling. Whilst this coincided with the morning when the offices were hottest due to a north-eastern facade, this meant that no supplementary cooling could be offered in the afternoon.

10.2.8 Next Steps

Without conclusive data, I had to plan another round of field trials. With the unreliability of the initial sample group to fill out the comfort surveys, one could either conduct an objective study or another round of field trials with paid participants voting on sensation and comfort (subjective study).

To conduct thermal comfort studies with objective measurements, four regimes existed:

1. Use of human subjects with surface and core temperatures measurements
2. Use of thermal mannequins and either measure changes to surface temperature, or measure energy needed to maintain constant surface temperatures
3. Use of heated sensors according to guidelines of ISO 14505-2 (2006) 'Ergonomics of the thermal environment—Evaluation of thermal environments in vehicles—Part 2: Determination of equivalent temperature'
4. Use of environmental measurements (MRT, air T, wind vel, RH) and relate these to the ISO 7730 'Ergonomics of the thermal environment—Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria'.

The use of human subjects would require monitoring of skin and core temperatures of subjects. Core temperatures were traditionally measured with rectal thermometers. Alternatively task-ambient air conditioning studies done at the Lawrence Berkeley National Laboratory (Zhang 2010) used transducer pills to monitor body core temperature. For an 8-participant, 10-day trial, the ingestible pills and data recorders would cost a total of $34,000 and was deemed too costly. Moreover the pills were designed for studies of heat/cold stress and may not accurate indicate thermal comfort as the range of temperatures in the office was unlikely to perturb core temperatures. It was also uncertain if the readings could be significantly altered by the consumption of hot/cold food and beverages. In Zhang's study (Zhang 2010), the pills were mentioned in the methodology but no results were presented. She did not respond to a private enquiry on the matter.

The use of a thermal mannequin was deemed to be financially prohibitive at this stage. A quote from one supplier (Kanomax, U.S.) came to $300,000. Moreover,

Fig. 10.5 Example of
measuring set-up with several
ellipsoid sensors mounted on
rig simulating a seated person
(ISO14505:2, 2006)
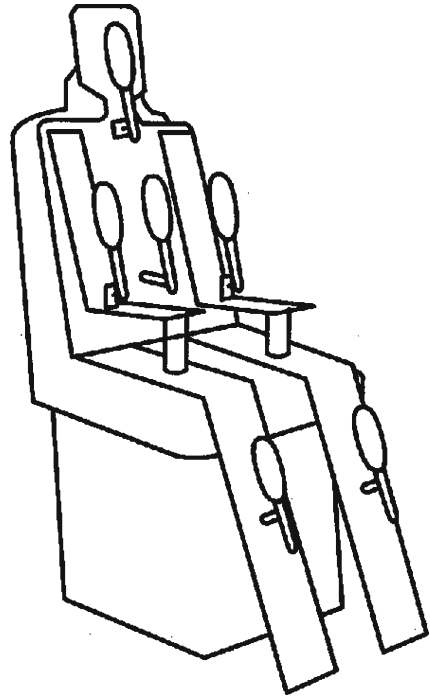
since there were more than one thermal mannequin supplier, there would be a need
to validate the accuracy of thermal mannequins to real life examples.

A modification from the heated mannequin would be to use heated sensors
mounted on a rig exemplified in Fig. 10.5 from the ISO 14505 Standard. Vehicular
comfort standards are, at this time, the only ones that acknowledge the effects of
localised cooling. The shortcoming in this approach was the uncertainty regarding
the transferability of vehicular thermal standards to the office. In Chap. 4 we also
expressed concern that mannequins could not simulate the mechanisms of SBC,
and that the summation of skin temperatures weighted by area did not express the
sensitivity of particular areas, especially of the face, to cooling.

The PMV is an accepted standard under ISO 7730 and ASHRAE 55. The
ASHRAE standard recommends that dry bulb temperature be taken as the average
of three heights (0.1, 0.6 and 1.1 m) with MRT and RH measured at 0.6 m for
seated occupants. DTAC focussed on cooling the upper body and the face in
particular. Since only the topmost sensor would be exposed to the cooled stream,
would the cooling effect only be a third of the overall sensation? Other than air
temperature, all measurements were taken at only one level as representative of
that experienced across a whole person. It was therefore difficult to determine how
net wind velocity was to be aggregated, for example with a fan velocity of 1 m/s
on the face and 0.2 m/s background air speed.

The efficacy of DTAC thus had to be experimentally determined in two steps:

1. The occupant, with estimated clo and met values and controlled environmental variables, would answer the thermal comfort questionnaire to ascertain a match between his/her sensation to PMV.
2. The occupant will subsequently switch on the DTAC, and the efficacy of it determined by any significant changes from feedback through the questionnaire.

10.3 Climate Chamber Setup

The aim was to control the air and mean radiant temperatures of the Climate Chamber (CC), together with humidity and air speed. Volunteers were given a task that simulated work which took three hours to complete, the first hour without DTAC and the next two hours with the DTAC switched on and controlled to make themselves as comfortable as possible.

10.3.1 Room Setup

A room within the School of Architecture and Design of the University of Tasmania was designated as the CC. The room was equipped with a centrally controlled panel heater and had no windows. T-air and T-globe was logged at the position where the participant would be seated at three heights (0.1, 0.6 and 1.1 m, according to ASHRAE 55). The logging was done over a few days at each stage as the room was set up:

1. Panel heater (under central automated hydronic control) only
2. Panel heater + humidifier (cool mist)
3. Panel heater + humidifier (warm mist)
4. Panel heater + humidifier (warm mist) + 1 kW oil-fin heater on electronic thermostat.

10.3.2 Room Environment with Panel Heater Only

The room has proven to be an excellent choice as a climate chamber, with the air and globe temperatures having a near-perfect correlation ($r^2 = 0.998$, Fig. 10.6). When applied in the operating range of 25–30 °C and the target temperature of 28 °C, the difference between air and globe temperatures were negligible.

This eliminates the entire argument of what ratio of air temp vs MRT we should adopt to determine effective temperature. As a countercheck, the Hobo loggers were verified against high accuracy digital loggers (± 0.2 °C), labelled "EL2Tair" below with excellent correlations (also Fig. 10.6, Table 10.6).
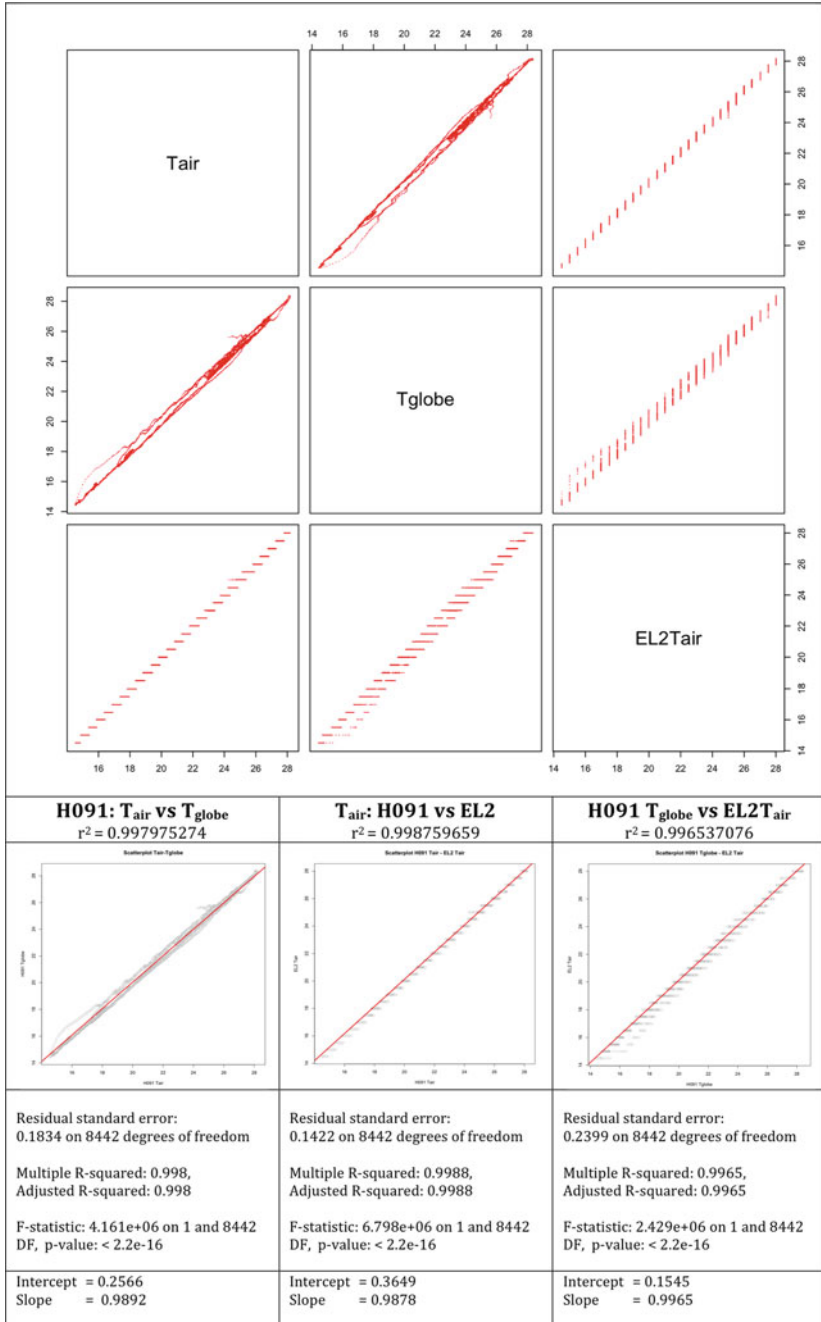
Fig. 10.6 Correlation of air temperature (Tair) and globe temperature (Tglobe), verified against a new high accuracy digital logger (EL2Tair)

Table 10.6 Using linear correlations, the T-globe can be predicted with very good accuracy from T-air, and shown that difference between the two values is negligible

T air	T globe	dT
25.000	24.981	0.013
28.000	21.954	0.046
30.000	29.933	0.061

10.3.3 Why 28 °C?

The ISO 7730 (2005) standard acknowledges the difficulty in determining the PMV without accurate instruments, and allows that 'the verification may be based on the equivalent operative temperature range' (see Table 10.7). Assuming summer conditions for offices in category C, the highest acceptable temperature is T(ambient) = 24.5 + 2.5 = 27.0 °C, on which another 1 °C was added to move it just out of the acceptable range.

10.3.4 Oil-Fin Heater and Humidifier

An ultrasonic humidifier was installed and run. Ultrasonic humidifiers work by agitating the water that sat over a ~ 1 MHz piezo-electric speaker. The droplets formed were small and light enough to suspend in air and vaporised by absorbing ambient heat. This cold steam, and consequently an evaporative cooling effect, resulted in air temperatures dropping significantly whenever it was operated. When run in "ultrasound + heat" mode, the excellent correlation prior to the operation of the humidifier was restored (Fig. 10.7).

Having earlier established the close interchangeability of air and globe temperatures, the aim was for a smaller fluctuation of temperatures. The panel heater did not keep the temperature of the occupied area stable enough, so an oil-fin heater controlled by a digital thermostat was added. The loggers were placed at 1,100 mm from floor level at the precise location where participants would sit. Measurements were taken at table top (750 mm) to determine if it would be a suitable proxy for the conditions experienced by the occupant and the correlation was good, $r^2 = 0.86$, intercept = 0.77, slope = 0.98 (Fig. 10.8). The weaker r^2 was due to a more compressed range of 25–28 °C measured by digital loggers which resolved to 0.5 °C. Also the switching on and off of the oil-fin heater did result in time lags between the different measurements. Stratification was also observed with air T at 1,100 mm having a 1 °C variance with that at 600 mm (Fig. 10.9). Air velocity was logged consistently at 0.02 m/s. As temperatures were maintained at 28 °C, it became less important to strive for a tight correlation.

Table 10.7 Example design criteria for spaces in various types of buildings ISO-7730 (ISO 2005)

Type of building/space	Activity W/m²	Category	Operative temperature °C		Maximum mean air velocity[a] m/s	
			Summer (cooling season)	Winter (heating season)	Summer (cooling season)	Winter (heating season)
Single office Landscape office	70	A	24.5 ± 1.0	22.0 ± 1.0	0.12	0.10
Conference room Auditorium		B	24.5 ± 1.5	22.0 ± 2.0	0.19	0.16
Cafeteria/ restaurant Classroom		C	24.5 ± 2.5	22.0 ± 3.0	0.24	0.21[b]
Kindergarten	81	A	23.5 ± 1.0	20.0 ± 1.0	0.11	0.10[b]
		B	23.5 ± 2.0	22.0 ± 2.5	0.18	0.15[b]
		C	23.5 ± 2.5	22.0 ± 3.5	0.23	0.19[b]
Department store	93	A	23.0 ± 1.0	19.0 ± 1.5	0.16	0.13[b]
		B	23.0 ± 2.0	19.0 ± 3.0	0.20	0.15[b]
		C	23.0 ± 3.0	19.0 ± 4.0	0.23	0.18[b]

[a] The maximum mean air velocity is based on a turbulence intensity of 40 % and air temperature equal to the operative temperature according to 6.2 and Figure A.2. A relative humidity of 60 % and 40 % is used for summer and winter, respectively. For both summer and winter a lower temperature in the range is used to determine the maximum mean air velocity
[b] Below 20 °C limit (see Figure A.2)

10.3.5 Selection of a Suitable Proxy

A tower was used to mount the loggers at the heights 0.1, 0.6 and 1.1 m. Placed at the location where participants were expected to sit it was set to log over a few days with heaters, humidifiers and oil-fin heater on.

By comparing the linear correlations of the temperature logs, it was found that the readings on the tower, including air and globe temperatures, all had a very strong correlation (r-sq > 0.98). Making it possible to extrapolate the other readings with a single record of temperature, proposed to be the air temperature at 1.1 m being the most representative of the occupant's head.

At the same time loggers placed on either side of the table were also run to determine which would be a suitable proxy. The left side of the table top was nearer the oil-fin heater and naturally had a weaker correlation with the rest (Fig. 10.10). Having found that the one on the tabletop right had a much closer relationship with T(air@1.1 m), a check was done with all readings on the tower to verify that the linear correlation was very strong (r-sq > 0.98, Fig. 10.11). With the linear relationships established, we could extrapolate all the temperatures with one measurement if needed.
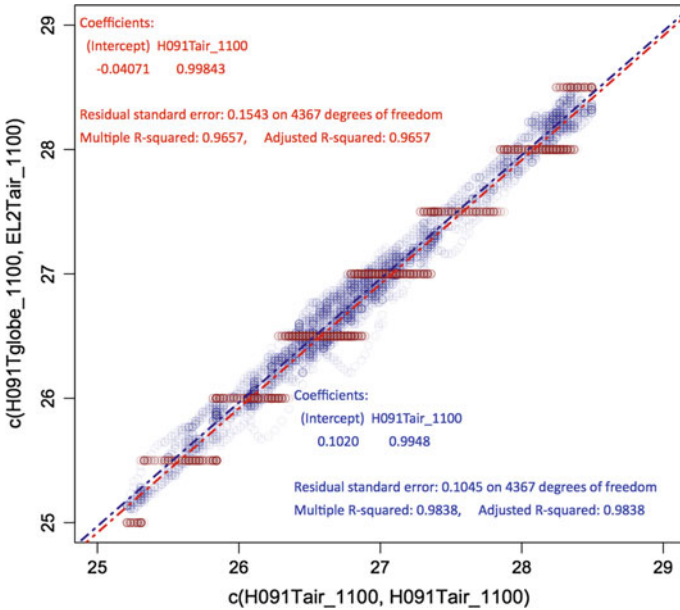
Fig. 10.7 Scatterplot after humidifier installed and run at "ultrasound + heat" mode. Correlation of T-air vs T-globe (*blue*) and T-air vs EL2Tair (*red*) show a near perfect linear correlation and negligible difference in intercept and slope. For all practical purposes, the measurements of air temperature and globe temperature were interchangeable

10.3.6 Sample Size

12 volunteer students were deemed to be sufficient for the CC trial. A total of 17 volunteers signed up. With more than the required number, after the first 12 had completed the trial, subsequent volunteers were not informed (single-blind) that the power supply unit had been disconnected from the TE modules, making the DTAC effectively a fan-only system. However, a total of only 14 eventually participated (12 using DTAC, 2 fan-only) as a number of students had taken ill and were advised not to participate.

10.3.7 Productivity Indexing

In Chap. 3 (thread 8) we saw how the means of measuring productivity remained highly disputed. In studies with objective measures of productivity, a battery of tests include a mix of typing, arithmetic (or Sudoku), learning and memory. However, in the case of students at the School of Architecture and Design, it was deemed that these tests would not be reflective of their strengths or inclinations. Instead, they were put through a design challenge for a task I felt was achievable
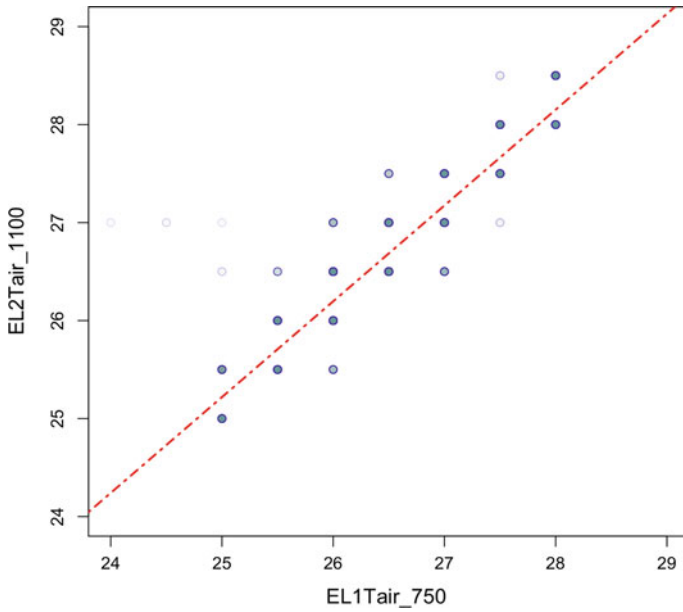
Fig. 10.8 Scatterplot of high accuracy (±0.2 °C) digital loggers at table top height (750 mm) and at ASHRAE recommended 1,100 mm
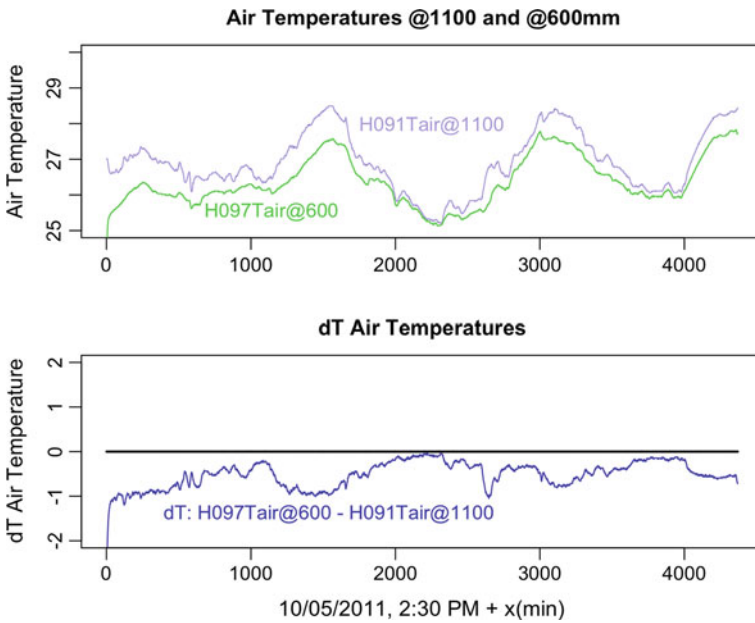
Fig. 10.9 Temperature of air at different levels. The greatest dT corresponds to the highest temperature, indicative that air was not mixed but stratified
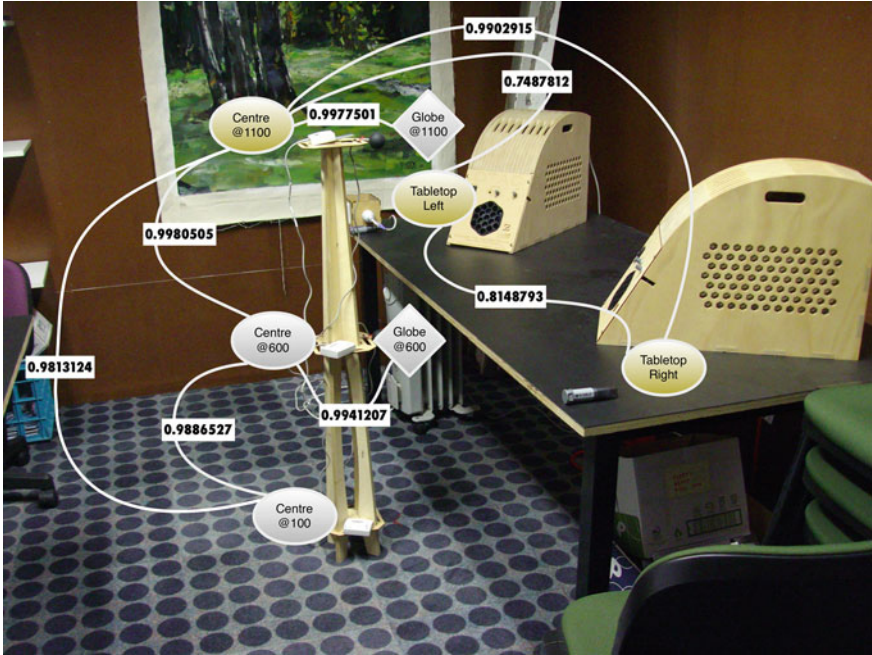
Fig. 10.10 r^2 of different positions compared primarily with centre of table air T at 1,100 mm

within the three-hour period planned. The assessment rubric was available to participants so that they knew the largest portion of marks went into the design resolution which typically was the most time-consuming process. This would encourage those that finished early to keep working for the whole duration. They were also told that the winner of the design challenge, as determined by staff judges of the School, would receive a new Apple iPad2.

Being a design challenge, the aim was not to measure productivity directly but to make a reasoned assumption that participants were both highly challenged and highly motivated. This was predicated on providing the participants with an achievable task, a pressure to complete it on time (neither early nor late) and an attractive incentive.

10.3.8 Time of Experiment

The experiment was conducted at the same time each day, from 1 to 4 p.m. This would minimise variations in the room temperature, which was connected to the central heater and, from earlier climate chamber measurements, had shown a climb from 7 to 9 a.m. and drop from 6 to 7 a.m. The effect of circadian rhythm, known to cause metabolism to fluctuate through a 24-hour cycle (Ladou 1982; Zhang 2003) would also be minimised.
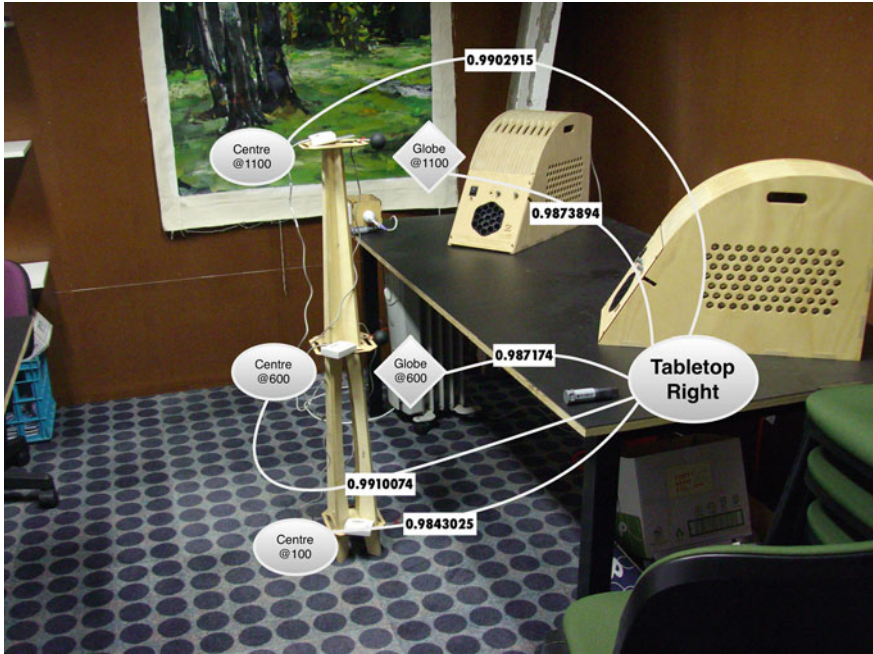
Fig. 10.11 r^2 of different positions compared to *tabletop right*

10.3.9 Participants

Participants were volunteers from the first year cohort of the Building Technology and Design course for which I was a tutor. They had recently completed their first semester which introduced them to the concept of climate responsiveness in buildings, heat balance and thermal comfort. Having themselves completed graded assignments on evaluating thermal comfort of buildings they were deemed to be relatively astute to the parameters used to evaluate thermal comfort.

Participants were told to abstain from the field trial if they were not feeling well. Running a fever, for example, would have greatly increased their metabolism (Sapolsky 1990). They were also discouraged from listening to music or consuming caffeinated drinks during the experiment. After each survey, scheduled every 30 min, they were to have a stretch break and walk around the room for 1–2 min. A 3-axis accelerometer was strapped to their waist and logged at 0.1 s intervals.

To keep the conditions of the room constant they were encouraged to use the washroom prior to the experiment and not leave the climate chamber during the experiment.

10.3.10 The Design Challenge

Participants were each provided an A3 sheet with complete instructions and space for their design (Fig. 10.12). Unlimited rough paper was provided for sketches which were not judged.

As first year students, they could possess a large deviation in graphical abilities and the design challenge had to underrate this aspect so that they were focussed on the intellectual part of the challenge: to think laterally and cyclically. No internet research was allowed during the challenge. A parental filter was installed on the web browser to limit access to only the websites associated with the experiment.

Reference numbers (CC-01–CC-14) were used as pseudonyms instead of names so as not to bias the judging process. Only the researcher knew the identities and was not involved in judging.

Participants were briefed that penalties will be imposed for any failure to fill up their thermal survey vote completely and punctually as this would have undermined the purpose of the experiment.

The following brief was provided:

Design a collapsible stand that can be easily deployed every morning and kept in storage every afternoon, being able to fit through a door (0.8 × 2.1 m) in collapsed form. Located along the public walkway beside the School of Architecture and Design, UTAS, it will provide outdoor shelter for 4 adults from strong winds but still allow the patrons to enjoy the sun if they wish. Design it to be used in all seasons and made attractive to students of

Fig. 10.12 Design challenge A3 sheet with reference number, brief and rubric

the School in particular, where they will use it not just to drink coffee but to brainstorm and discuss ideas.

Present on this A3 sheet (which will be the only material judged):

- conceptual sketches of parts; and
- an overall perspective of the final design

The challenge was scored on the following rubric:

Humour (10 %) Demonstrate a punchline in design that will make the public smile but is not cheesy.

Graphical presentation (20 %) Demonstrate clarity in illustration and annotations that give the judges a clear understanding of the finished item. Lateral thinking (30 %) For coming out with solutions that are not commonly seen yet solve the problem elegantly.

Resolution (40 %) All key parts of the design communicate with same language and refinement.

10.3.11 Schedule

The experiment (Fig. 10.13) consisted of an initial briefing to check their state of health, and ensure that their meals were taken and that they had visited the washroom. The design challenge was left on the table face down.

The researcher would guide them through the first survey and answer any questions. He would then leave the room and they would commence on the IQ test for about 20–25 min. After another survey they would commence on the design challenge. An announcement on the computer would remind them to fill up the survey every 30 min.

10.3.12 IQ/Memory Test

Participants would spend about 20–25 min in a memory and intelligence test designed by Robert Lodgie from the University of Edinburgh (BBC, web page no
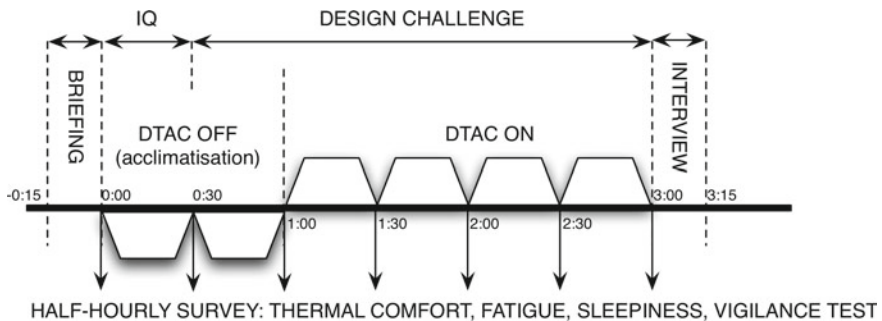
Fig. 10.13 Structure of three-hour climate controlled field trial
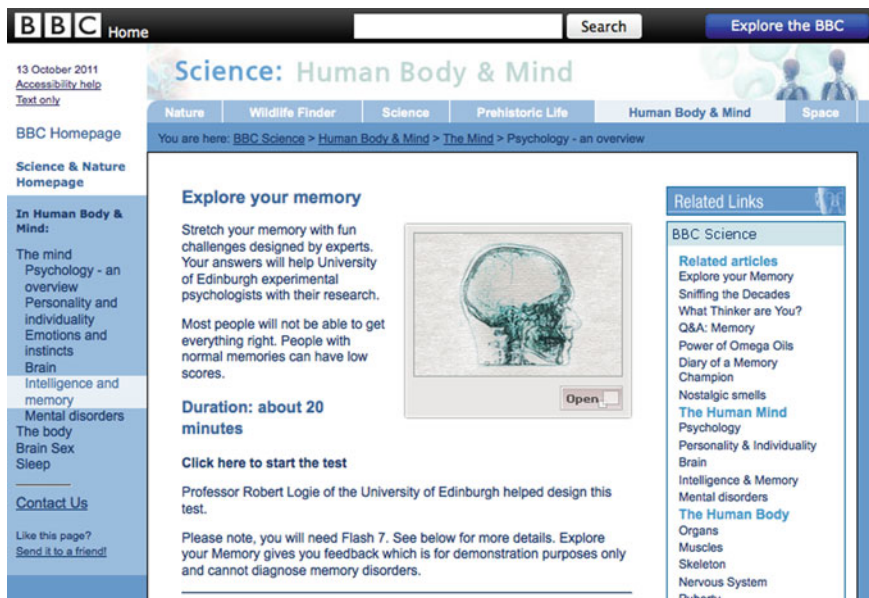
Fig. 10.14 Memory challenge (webpage no longer available, previously http://www.bbc.co.uk/science/humanbody/mind/surveys/ memory)

longer available, Fig. 10.14). The test was engaging and would initiate the participants into an aroused mental state for the design challenge. Expecting that some participants might have come for the challenge all psyched up (as they would for an examination), the test was also intended to take their minds off from the design challenge as a stressful and examination-like procedure, and more like an activity that would be representative of a creative workplace.

10.3.13 Survey Questions

Thermal Sensation: 7-point scale based on studies in deterministic thermal comfort from Fanger's PMV as adopted by ISO 7730 (ISO 2005) and ASHRAE 55 Standard (ASHRAE 2004; Table 10.8).

Thermal Comfort: 6-point scale based on Schiller's work (Schiller 1990; Table 10.9). An important contribution of her work was the observation that a neutral sensation did not necessarily equate to being the most comfortable. She measured an optimum temperature which was 2.3 °C cooler than the predicted neutral temperature (at PPD = 5 %).

General Comfort: 7-point scale based on Bedford Scale (Bedford 1936; Table 10.10) which is adopted in a number of adaptive thermal comfort studies.

Karolinska Sleepiness Scale (KSS): 9-point scale in Table 10.11.

Table 10.8 Thermal sensation scale

Thermal sensation scale	
3	Hot
2	Warm
1	Slightly warm
0	Neutral
−1	Slightly cool
−2	Cool
−3	Cold

Table 10.9 Thermal comfort scale

Thermal comfort scale	
6	Very comfortable
5	Moderately comfortable
4	Slightly comfortable
3	Slightly uncomfortable
2	Moderately uncomfortable
1	Very uncomfortable

Fatigue scale: 30-point scale (Table 10.12) covering three categories of subjective symptoms with a pattern of fatigue suggested by Yoshitake (1973) (in Tanabe 2004). With the following patterns of classification:

- General pattern of fatigue: $1 > 3 > 2$
- Typical pattern of fatigue for mental work and overnight duty: $1 > 2 > 3$
- Typical pattern of physical work: $3 > 1 > 2$

10.4 Field Trial Results

Due to the large number of results, the discussion is not presented as a separate section but follows immediately after each test result.

Of the 12 volunteers that tested the DTAC, one responded as "hot", "very uncomfortable" and "much too warm" for all entries. As his responses were

Table 10.10 General comfort scale

General comfort scale	
7	Much too warm
6	Too warm
5	Comfortably warm
4	Comfortable and neither cool nor warm
3	Comfortably cool
2	Too cool
1	Much too cool

Table 10.11 Karolinska
Sleepiness Scale

Karolinska sleepiness scale	
1	Extremely alert
2	Very alert
3	Alert
4	Rather alert
s	Neither alert nor sleepy
6	Some signs of sleepiness
l	Sleepy, but no effort to keep awake
8	Sleepy, some effort to keep awake
9	Extremely sleepy-fighting sleep

markedly distinct even from the outliers in the data pool, he was excluded after I consulted with a statistician from the School of Mathematics and Physics. The remaining 11 participants (7 male, 4 female, average age 23.5 ± 7.3 yr) were asked, at the end of the trial, what settings they ran DTAC on and how they found the design challenge (Tables 10.13).

On a subjective level there was little difference in attitude to the design challenge amongst participants. The general sentiment was that the challenge was engaging, set at the appropriate difficulty and within a reasonable time frame. Participants thus found themselves highly motivated and the task very enjoyable (possibly even *too enjoyable*). The design challenge however, did not adequately replicate the stressfulness of a working environment with a low self-evaluated stress score, this is something worth improving in future experiments. Figure 10.15 shows an example of a test participant.

In contrast, the operational settings showed high variability in preferred setting. The fan speed was typically operated in the middle range and support the applicability of computer fans for task cooling in Schivaon's (2009) thesis. The high cooling setting of the units, particularly the one on the right, is indicative that participants found the units underpowered. There was a general preference to control the unit on the right side—possibly due to all participants being right-handed, but one wonders if it could also relate to the task being concentrated on right-brain creativity.

The thermal comfort and sleepiness responses have been summarised in the following plots (generated in the statistical software R) with the following symbols (Table 10.14, Fig. 10.16).

Each of the responses is studied statistically in further detail with the rationale shown in Table 10.15.

10.5 Statistical Significance

The results of the climate chamber trials were analysed statistically to answer the following considerations:

Table 10.12 Fatigue scale

Three categories of subjective symptoms of fatigue		
Category 1	Category 2	Category 3
My head is drooping	I can't think clearly	I have a headache
My whole body is getting tired	Talking would take some effort	My shoulder muscles are tense
My legs are getting tired	I am starting to feel nervous	My back hurts
I can't stop yawning	I can't concentrate	Breathing takes an effort
My mind is blank	I am losing interest in my work	I feel thirsty
I am starting to feel drowsy	I am starting to forget things	My voice is probably hoarse
My eyes are getting tired	I am uncertain	I feel giddy
I feel stiff and clumsy	I am worried	The small muscles around my eyes are twitching
I would be unsteady on my feet	I am sitting badly	My limbs are shaking
I feel like lying down	I feel impatient	I feel unwell

Fig. 10.15 One of the field trial participants during the design challenge

Table 10.13 Feedback on the use of DTAC and opinion of the challenge

Enquiry	Mean (on scale of 0–10)	s.d.
Typical DTAC setting		
Left fan	4.7	±4.1
Left cooling	5.6	±3.8
Right fan	4.2	±3.6
Right cooling	7.3	±3.8
How challenging did you find the task, where 5 = typical day		
Mental load	5.9	±1.4
Stress level	2.5	±1.4
Difficulties of task	6.1	±1.6
Motivational level	7.8	±1.8
Enjoyability of task	8.4	±1.5

Table 10.14 Key to plots

Box-plot	Median	Bold blue line
	25th and 75th percentile	Boxed
Line-plot	Mean	Red dot
	± standard deviation (s.d.)	Dotted red line

1. Determine if the δ, the change in vote (before and after DTAC usage), is of significant magnitude compared to the σ, the standard deviation of the sample means.
2. Determine if the change in vote is indicative of a trend by a paired t test with a $p < 0.05$.
3. Quantify the improvements by determining a threshold criteria and the percentages that fell within the criteria before and after DTAC usage.

The first two considerations are summarised in this section. The third is expanded with details of each survey.

The σ helps ascertains if the movement has any significance above the 'noise' level. A δ-value greater in magnitude than σ-value would be indicative of a statistically significant movement (Table 10.16).

Where:

σ	Standard deviation of the sample means, $\sigma = SD/\sqrt{n}$
δ (mean)	Difference in vote between average before and average after DTAC switched on
δ (just)	Difference in vote between just before and just after DTAC switched on

Using a criteria of $p < 0.05$, the paired T test showed that the results had little statistical significance (Table 10.17), except for the General Comfort when participants were exposed to either condition for 0.5 h ($p = 0.05$). The population sample is an acknowledged weakness in this study and a p value < 0.05 was difficult to achieve with 11 participants.
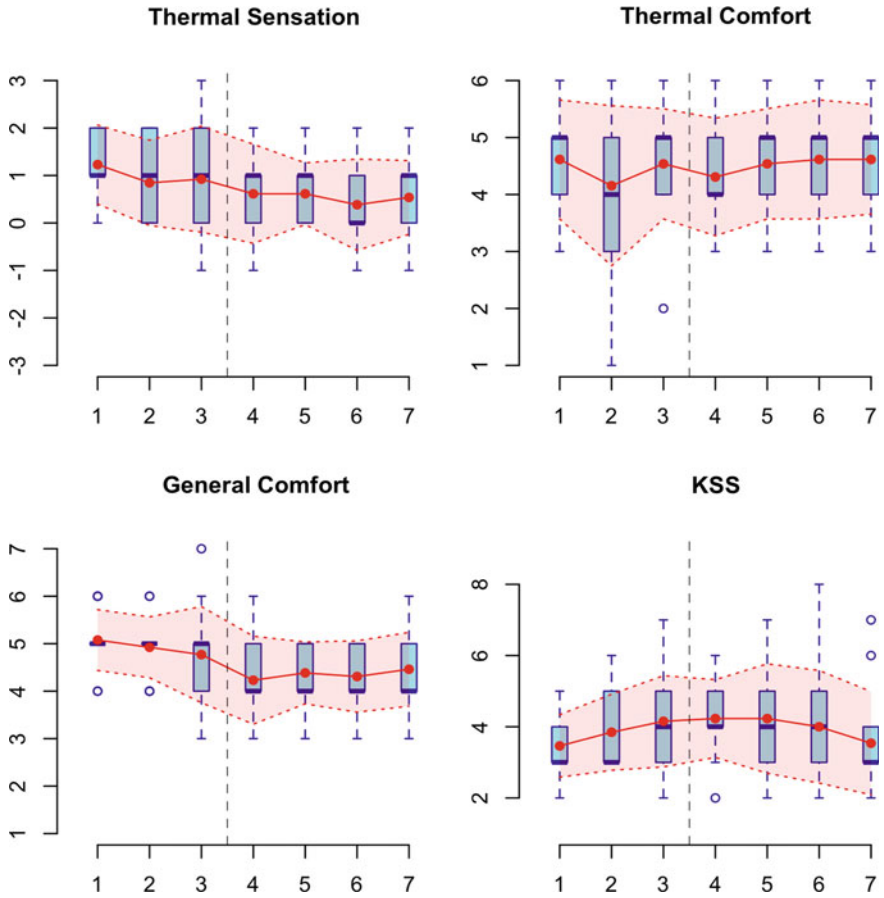
Fig. 10.16 Overview of survey responses (n = 11). *Vertical scale* are cumulative responses, *horizontal scale* are feedback rounds every 30 min

Where:

P	*P* value
rd	Feedback round in survey
2	Survey at 0.5 h (DTAC off)
3	Survey at 1.0 h (DTAC off)
4	Survey at 1.5 h (DTAC on for 0.5 h)
5	Survey at 2.0 h (DTAC on for 1.0 h)
rd 2:4	Comparing 0.5 h in climate chamber vs 0.5 h use of DTAC
rd 3:5	Comparing 1 h in climate chamber vs 1.0 h use of DTAC

Table 10.15 Rationale for statistical tests used

Analysis	
Mean before DTAC	Mean of all votes before DTAC used (feedback rounds 1–3)
Mean after DTAC	Mean of all votes after DTAC used (feedback rounds 4–7)
Delta AMV	Difference = after—before
Just before DTAC	Mean of votes in feedback round 3
Just after DTAC	Mean of votes in feedback round 4
Delta	Difference = just after—just before
s.d.	Standard deviation of all rounds
σ	Standard deviation of the sample means (all rounds)
p (rd 3i5)	p value of t test between feedback of round 3 and round 5, where occupant has acclimatised 1 h to chamber, and 1 h to DTAC respectively

10.5.1 Thermal Sensation (ASHRAE Scale)

After DTAC was switched on there was an overall move of 0.5 vote towards a sensation of thermal neutrality (0-value). Based on an acceptable threshold of ± 1 (slightly warm, neutral, slightly cool) the thermal acceptability by 58 % of the participants before DTAC was improved to 84 % after that (Table 10.18).

10.5.2 Thermal Sensation, Normalised

The data was further refined by accounting for variations in clothing insulation. At the end of the experiment, participants had been interviewed on their clothing at the start and end, and at which point they had made the change. The clothing ensemble was converted to clo insulation values using the ASHRAE 55 standard, with the average determined to be 0.694 clo. Based on the following variables (Table 10.19), the PMV was determined to be 1.1.

Table 10.16 Significance in change in vote after operating DTAC

Test	σ	δ (mean)	δ (just)	Significance	Change in vote after DTAC use
Thermal sensation	0.30	−0.50	−0.27	Significant	From feeling slightly warm toward feeling neutral
Thermal comfort	0.35	−0.05	−0.27	Almost significant	Less comfortable
General comfort	0.24	−0.61	−0.45	Significant	From comfortably warm towards comfortably neutral
KSS	0.37	0.00	0.09	Not significant	More sleepy

Table 10.17 One-tail T test results before and after using DTAC

Test	p (rd 2:4)	p (rd 3:5)
Thermal sensation	0.62	0.21
Thermal comfort	1.00	0.85
General comfort	0.05	0.14
KSS	0.56	0.89

With PMV = 1.1 as a baseline (PMV_0), and a PMV based on actual observed clothing (PMV_1) a correction factor was determined as follows:

$$\Delta PMV = PMV_1 - PMV_0 \tag{10.2}$$

The actual votes were passed through this correction factor to yield a normalised thermal sensation vote, plotted in Fig. 10.17.

$$Vote_{TS\ corrected\ for\ clo} = AMV + \Delta PMV \tag{10.3}$$

Before DTAC was switched on, the AMV of 1.17 (average of first hour) and 1.11 (just prior to DTAC use), which was in excellent agreement with what was predicted by Fanger's model of PMV = 1.1. This provides further evidence of the viability of the selected room as a climate chamber and accuracy of the experiment. Furthermore, it was also reasonable to assume that one hour was sufficient for the participants to acclimatise to the climate chamber conditions even though the experiment was conducted during winter.

After correcting for clothing variation, we note an overall move of 0.4 vote towards a sensation of thermal neutrality (Table 10.20). Based on an acceptable threshold of ±1 (slightly warm, neutral, slightly cool) the thermal acceptability by 16 % of the participant before DTAC was improved to 29 % after that. Compared to the previous result before correcting for clothing we see a substantial drop in the number of participants to be found within the acceptable range. Clothing variation could account for a correction of −0.25 to +0.46 of AMV which was sufficient to move a large number of marginal cases beyond the threshold of acceptable thermal comfort. In other words, had the occupants not been allowed to seek their own adaptation by a change of clothes, and all made to wear 1.1 clo worth of dressing, only 16 % would have found it acceptable without DTAC and 29 % with DTAC.

10.5.3 Thermal Comfort

After DTAC was switched on there was no discernible change in thermal comfort (Table 10.21). In the PEM field study (Bauman 1997) only those who indicated they were either very uncomfortable or moderately uncomfortable (1–2 on the scale) were deemed as uncomfortable. Based on this threshold, thermal discomfort of 6 % before DTAC usage was decreased to 0 % after that.

Table 10.18 Thermal sensation response to use of DTAC in climate chamber

Table 10.19 Conditions that yield a PMV = 1.1

Clothing (clo)	0.7
Air temp. (°C)	28
Mean radiant temp. (°C)	28
Activity (met)	1.1
Air speed (m/s)	0.05
Relative humidity (%)	40

Majority of the votes (82 %) were in the comfort range (4–6) before and during DTAC and indicate that even though the sensation was different, there was no discernible impact on comfort. 15 % delivered a vote of 'very comfortable' before DTAC (mostly on the first survey) compared to 9 % during DTAC. This suggests that upon entering the heated climate chamber from the cold outdoors many found the (alliesthesia) change pleasing.

10.5.4 General Comfort (Bedford Scale)

After DTAC was switched on there was a notable 0.61 vote overall improvement towards being "comfortable and neither warm nor cool", with a 0.45 improvement occurring at the interval immediately following the switching on of DTAC (Table 10.22). Based on a threshold of 3–5 (comfortably warm, comfortable and neither cool nor warm, comfortably cool) the general comfort of 79 % of participants before DTAC was increased to 98 % after that.

Thermal Sensation   **Thermal Sensation, corrected for clo**
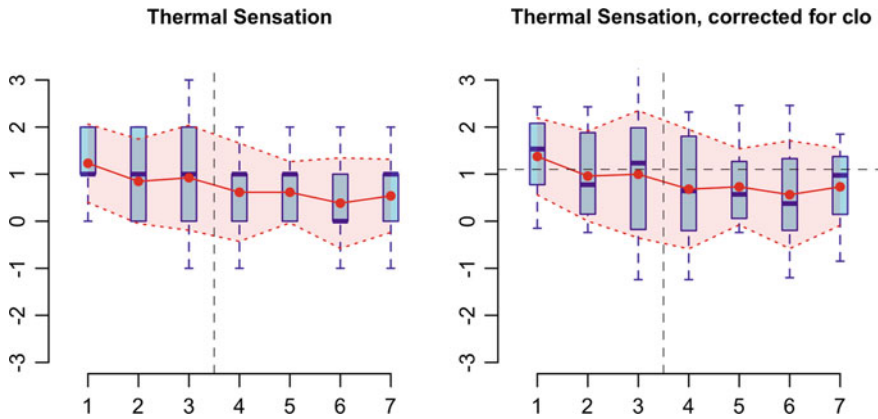
Fig. 10.17 Thermal sensation before and after correction for clo variation

10.5.5 Karolinska Sleepiness Scale

Referring to Table 10.23 at the start and end of the trial, the task itself would largely account for the participants alertness and override the environmental drivers. As such the first and last interval (feedback round 1 and 7) have been omitted. It can be said there was no change in sleepiness according to the KSS, or that alertness or wakefulness was maintained with the use of DTAC. This is bolstered by the trend of increasing sleepiness observed from intervals 1 to 3, for which it could have been extrapolated to 5 (green dashed line. see figure) instead of being maintained at 4 (Fig. 10.18).

Table 10.20 Thermal sensation response to use of DTAC in climate chamber, corrected for variations in clothing

Thermal Sensation (corrected for clo)			
Y-Scale		mean before DTAC	1.17
3	Hot	mean after DTAC	0.76
2	Warm	Delta AMV	-0.41
1	Slightly Warm		
0	Neutral	just before DTAC	1.11
-1	Slightly Cool	just after DTAC	0.85
-2	Cool	delta	-0.25
-3	Cold		
		s.d. (before DTAC)	1.36
		σ	0.41
		p (rd 3:5)	0.29

Table 10.21 Thermal comfort response to use of DTAC in climate chamber

Thermal Comfort		
Y-Scale	mean before DTAC	4.39
6	Very comfortable	mean after DTAC	4.34
5	Moderately comfortable	Delta AMV	-0.05
4	Slightly comfortable		
3	Slightly uncomfortable	just before DTAC	4.45
2	Moderately uncomfortable	just after DTAC	4.18
1	Very uncomfortable	delta	-0.27
		s.d. (before DTAC)	1.17
		σ	0.35
		p (rd 3:5)	0.85

Table 10.22 General (Bedford) comfort response to use of DTAC in climate chamber

General Comfort (Bedford Scale)		
Y-Scale	mean before DTAC	4.97
7	Much too warm	mean after DTAC	4.36
6	Too warm	Delta AMV	-0.61
5	Comfortably warm		
4	Comfortable and neither cool/warm	just before DTAC	4.82
3	Comfortably cool	just after DTAC	4.36
2	Too cool	delta	-0.45
1	Much too cool		
		s.d. (before DTAC)	0.81
		σ	0.24
		p (rd 3:5)	0.14

10.5.6 Comparison with Fan-Only Control

After the initial 12 participants had completed the trial, the power supply to the TE modules was disconnected, making the 'cooling' control a dummy. The 'fan only DTAC' was tested on the last two participants who were not notified of the changes (single-blind), and the results overlaid in Fig. 10.19 to compare with the rest of the group.

Table 10.23 Sleepiness response to use of DTAC in climate chamber

Sleepiness (KSS)		
Y-Scale	mean before DTAC	4.00
9 extremely sleepy-fighting sleep	mean after DTAC	4.00
8 sleepy, some effort to keep awake	Delta AMV	0.00
7 sleepy, but no effort to keep awake		
6 some signs of sleepiness	just before DTAC	4.09
5 neither alert nor sleepy	just after DTAC	4.18
4 rather alert	delta	0.09
3 alert		
2 very alert	s.d. (before DTAC)	1.23
1 extremely alert	σ	0.37
	p (rd 3:5)	0.89

Fig. 10.18 Projection of sleepiness based on trend before DTAC being switched on
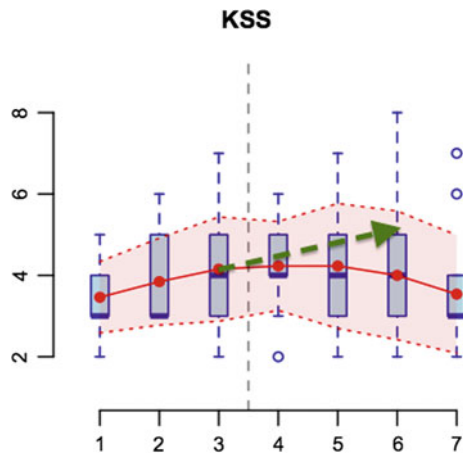
Due to the small sample size, the results from the blind trial can only be tentative. Most of the responses fall within one standard deviation, suggesting that the fan-only group responded as well to the fan as the DTAC group with the whole cooling system. The engineering rationale is explained in a later section on *Target Cooling*.
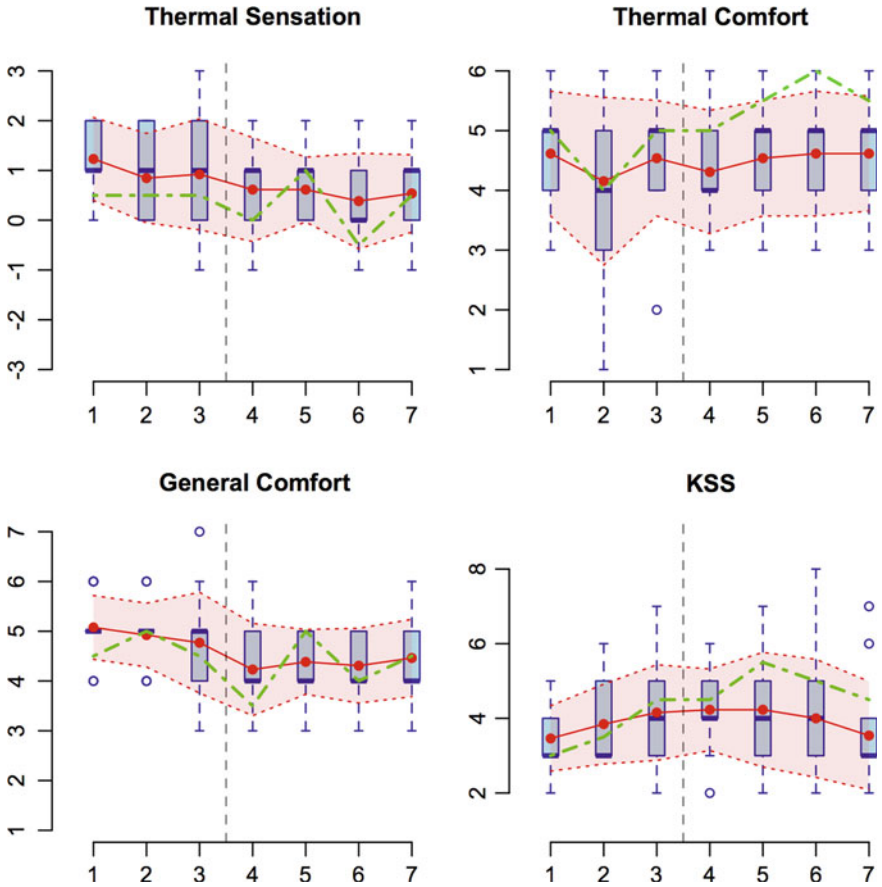
Fig. 10.19 Mean sensation, comfort and sleepiness votes of 'fan-only' participants control group (n = 2, *green dotted line*) overlaid on DTAC group (n = 11)

10.5.7 Cognitive Tests (n = ll)

As an objective indicator of the fatigue expressed by participants, the cognitive tests have been established as indicator of performance under varying thermal environments. Transient heat fatigue causing decreased productivity, alertness, coordination and vigilance (Kroemer et al. 1997 p. 214).

In shooting competitions (Broad 1997) ambient temperatures were found to impede psychomotor performance (including vigilance and cognitive capability) well before physiological performance.

Fig. 10.20 Webshots of the online visual reaction test (http://cognitivefun.net/)

10.5.8 Visual Reaction Test

The visual react test (Fig. 10.20) measures the mental alertness of the participant. Participants are required to stare at a small red dot till it turns green after a random duration and either click the mouse or hit the space bar. After 5 rounds the average reaction time is calculated.

Variations of this visual reaction test experiments have been used to index the following: (1) Heat and thermal stress (Hancock 1986; Manton 1988). (2) Air ions and performance (Charry 1987). (3) Sleep deprivation (van Hoof 2008). (4) Self assessed productivity in offices (Humphreys and Nicol 2007). (5) Sick building syndrome (Wargocki 1999)

10.5.9 Stroop Colour Test

The Stroop Colour Test (Fig. 10.21) measures the mental effort required to correctly identify words that contradicted the colours they were displayed (interference) against words stating the same colour (normal). The interval between these two cases was known to increase with increasing fatigue. This test has also been adopted in a few preceding studies with Sick Building Syndrome (Wargocki 1999), negative ions (Hedge 1987) and metabolism (Fairclough 2004).

10.5.10 Cognitive Test Results

All improvements at the first interval (between the first and second tests) showed a marked improvement (see Table 10.24) and were statistically significant (paired t-test, $p < 0.05$) indicating that this improvement was not the outcome of natural variation. At the next interval, between tests 2 and 3, we observe the improvements are marginal and statistically insignificant, with the exception of the Stroops interference test. There is strong suggestion that there was a learning and familiarisation phase in the cognitive tests which was overcome after the first run. The
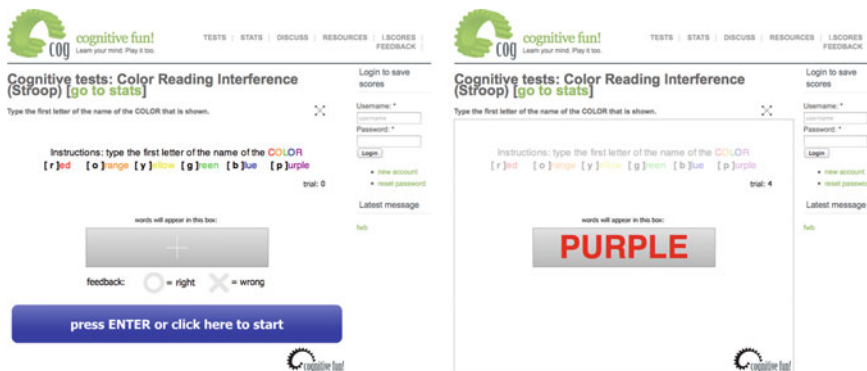
Fig. 10.21 Webshots of the online visual Stroop colour test (http://cognitivefun.net/)

Table 10.24 *P* values of paired *t* test of cognitive tests

Test	Improvement over interval		
	1–2	2–3	6–7
Visual reaction time	12.8 %	−3.3 %	−14.3 %
p-value	(0.046)	(0.537)	(0.004)
Stroops, normal time	20.7 %	−3.8 %	
p-value	(0.047)	(0.384)	
Stroops, interference time	18.9 %	9.6 %	
p value	(0.040)	(0.026)	
Stroops, percentage correct	2.5 %	2.3 %	
p value	(0.215)	(0.022)	
Positive percentage values indicate improvement			

counterintuitive nature of the Stroops interference test however, required a longer familiarisation period.

During the conduct of the experiment, the researcher would guide them through the first round of tests and would then leave the climate chamber, returning only minutes before the last test. He observed that some participants had become so acquainted with the Stroops test they would position their fingers on selected keys to achieve a better score.

In recognising that there was a familiarisation period, the first return of cognitive test results has been omitted in comparing the pre-DTAC and post-DTAC results. In both the visual reaction and stroops tests the result show little variation after the first interval, suggestive that there is no significant improvement in the use of DTAC. In the visual reaction test we do however observe a 14.3 % downswing (p-value < 0.005) in the last interval, indicative that sustained vigilance had been associated with a period of mental exertion right up to, but not beyond, the completion of the design challenge.

Table 10.25 Summary of Stroops test

	Improvement (%)	P value
Visual reaction time	2.05	0.512
Stroops normal reaction time	15.23	0.001
Stroops interference reaction time	8.55	0.035
Stroops percentage correct	0.35	0.326

Fig. 10.22 Stroop interference interval for participants in climate chamber
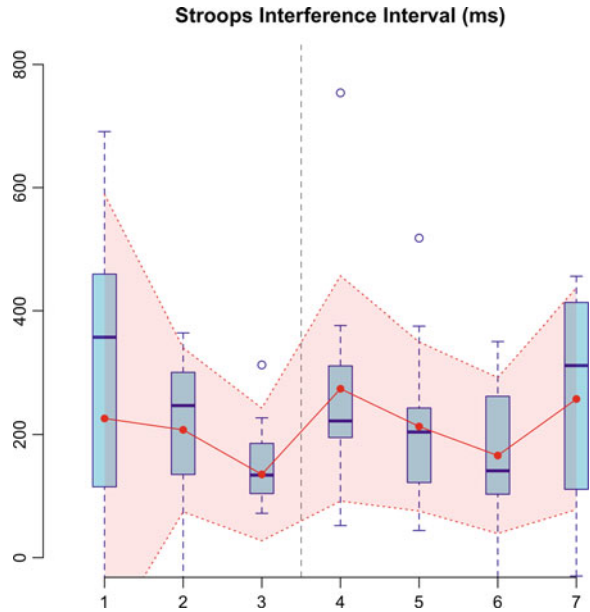
There was no significant improvement in vigilance (as reflected in the visual reaction results, p > 0.5). Directed attention (as reflected by the Stroops test) did show a slight improvement, indicative of a decrease in attentional fatigue with the use of DTAC. However, we cannot rule out the possibility that there was already a trend towards shorter reaction times with greater familiarity to the regime. If there was a familiarisation pattern, it should affect both the normal reaction time and interference reaction time. By observing the interval between these two times we can see if the intervals were shortened with the use of DTAC (Table 10.25).

$$t_{interference\ interval} = t_{interference} - t_{normal}\ (ms) \qquad (10.4)$$

In plotting the Stroop interference interval (Fig. 10.22), there appears to be neither an improvement nor indication of a trend There is thus a strong case that it was the familiarisation process and not the DTAC that had led to the improved reaction times in the Stroops tests. It is noteworthy that the Stroop tests performed in air-quality experiments (Wargocki 1999) also showed little statistical difference (3.1 % effect, p value = 0.10) to different pollution loads.

Whilst there has been no improvement to the cognitive performance of the DTAC it is also true that there has been no deterioration in psychomotor performance, which would have been an indication of fatigue, with the continued use of DTAC.

10.5.11 General and Marketing Feedback

At the end of the trial, each participant gave general feedback on how they felt the DTAC performed and how they felt the improvements should be prioritised, see Fig. 10.23.

10.5.12 Expectations (n = 14)

On a five-point Likert scale participants expressed their expectations (Fig. 10.24).

10.5.12.1 Ease of Use (Score = 1.6, s.d. = 0.51)

The DTAC had a main switch and two controls for fan speed and cooling power. The familiarity of this method of control and ease in which it could be operated gave this a high score in exceeding expectations.

10.5.12.2 Reliability (Score = 1.43, s.d. = 0.76)

Within the two hours where DTAC was in operation for each participant there was no instance of malfunction.

10.5.12.3 General Comfort (Score = 1.13, s.d. = 0.74)

The difficulty of attaining a vote of 'very comfortable' remains a big challenge, and is reinforced with the general comfort being marginally better than meeting expectation.

10.5.12.4 Thermal Comfort (Score = 1.0, s.d. = 0.76)

The thermal comfort score was that of just meeting expectation. This would be the area where users would have the most demanding expectations. This was evident in this category, where it obtained the lowest satisfaction score and largest diversity in opinion.

CC - General feedback

1. End of DTAC Trial General Feedback

General and marketing feedback after the completion of trials.

1. Has the performance of DTAC in the following areas met your initial expectation of a personal air-conditioner:

	Exceeds expectation	Meets expectation	Neutral	Dissatisfied	Very dissatisfied
Thermal comfort	○	○	○	○	○
General comfort	○	○	○	○	○
Ease of use	○	○	○	○	○
Reliability	○	○	○	○	○

Other (please specify)

_____

＊2. What is the maximum price (AU$) you will pay for a DTAC unit?

○ No more than $100
○ No more than $200
○ No more than $300
○ No more than $400
○ No more than $500
○ Other maximum:
    _____

＊3. Rank the following complaints as they apply to you in the last few hours of use:

	Most concerned					Least concerned
Difficult to regulate coldness	○	○	○	○	○	○
Unit takes up too much desk space	○	○	○	○	○	○
Difficult to regulate fan speed	○	○	○	○	○	○
Noise annoyance	○	○	○	○	○	○
Dry eyes	○	○	○	○	○	○
Respiratory irritation	○	○	○	○	○	○

Other (please specify)

＊4. For the next version of the DTAC, rank the following upgrades you would wish to see.

	Highest Priority						Lowest priority
Quieter operation	○	○	○	○	○	○	○
Colder air	○	○	○	○	○	○	○
Dehumidifying capability	○	○	○	○	○	○	○
More powerful fan	○	○	○	○	○	○	○
Air filtering capability	○	○	○	○	○	○	○
Automatic sweeping louvers	○	○	○	○	○	○	○

Your dream list:

＊5. If we implement your top two choices, how much more are you willing to pay for an upgraded DTAC unit?

○ another $20
○ another $50
○ another $100
○ Other sum:
    _____

6. Please leave your general imperessions

Fig. 10.23 End of trial general feedback survey web page

Has the performance of DTAC in the following areas met your initial expectation of personal air-conditioner:
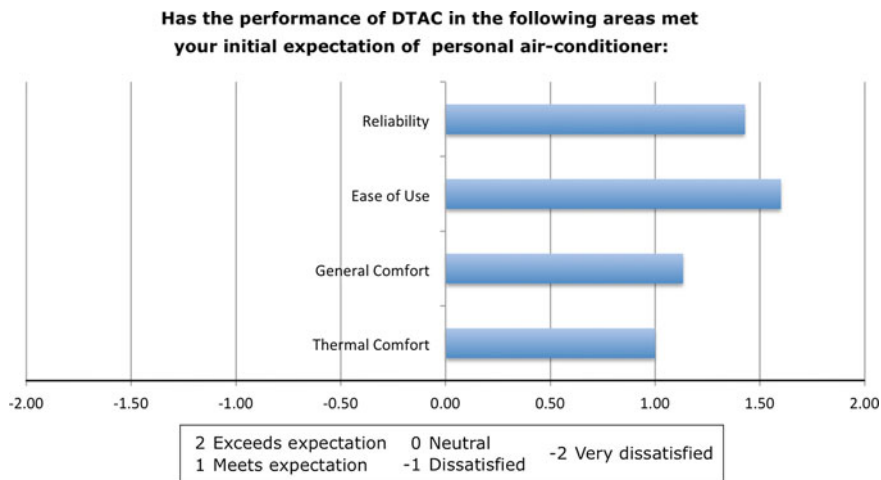
Fig. 10.24 Satisfaction with DTAC in meeting expectations for the criteria of reliability, case of use, general comfort and thermal comfort

Whilst the optimum comfort is a subjective issue, we have established that this is typically lower in temperature than a neutral vote. The supply air temperature of the DTAC was clearly not able to bring the conditions within the optimal comfort range. The supply air temperature should be further lowered so that a comfort vote in the range of $-1 < \text{PMV} < -0.5$ could be achieved.

It is also likely that the issue of noise, which should have been an issue with general comfort rather than thermal comfort, was confused by some participants. Where participants felt a constant annoyance with the acoustic environment, they mentioned that they could have also been more demanding on their thermal environment.

10.5.13 Future Upgrades (n = 14)

Having tested the DTAC for a reasonable period of two hours, participants gave feedback on what they considered to be their most important complaint. These were weighted from a score of least concern of 0, to most concerned of 5 (Fig. 10.25 and Table 10.26).

The number of participants who voted in each category were tallied and assigned a complaint score as follows:

$$Score = \frac{\sum (count \times score)}{\sum (count \times highest\ score)} \times 10 \qquad (10.5)$$
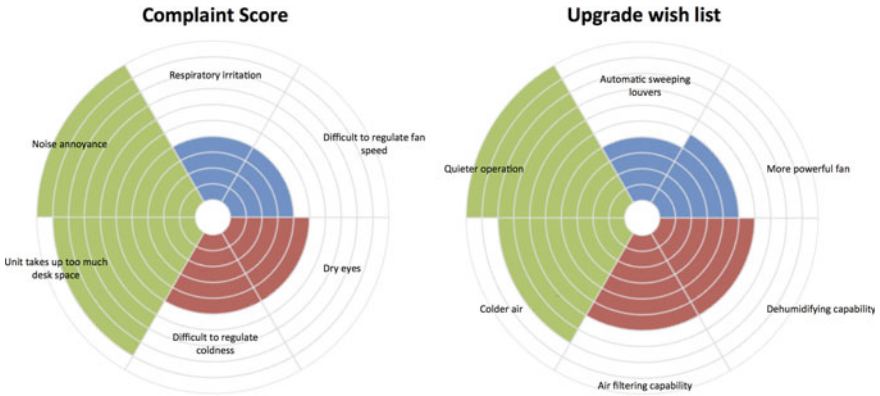
Fig. 10.25 General feedback upon completion of trial

Table 10.26 General feedback upon completion of trial

Complaint score		Upgrade wish list	
(higher = more dissatisfied)		(higher = higher priority)	
Noise annoyance	10.00	Quieter operation	10.00
Unit takes up too much desk space	9.55	Colder air	8.13
Difficult to regulate coldness	5.97	Air filtering capability	6.26
Dry eyes	5.67	Dehumidifying capability	6.04
Difficult to regulate fan speed	4.78	More powerful fan	5.49
Respiratory irritation	4.03	Automatic sweeping louvers	4.73

10.5.13.1 Noise

Noise ranked as the most unacceptable complaint. The only sounds coming from the DTAC unit would have been primarily from the fan, with a very small contribution from the buzzing in the iron core transformers of the power supply units. After the field trial, the noise level was measured with a sound level meter, Digitech QM-1589 (accuracy ±1.5 dB, time weighted to 1 s). The noise from both DTAC units were measured at different settings on the fan controller and measured at the seated head level. This was found to be up to 22.4 dBA higher than the ambient background level (Table 10.26). For a mentally productive environment like the office this level of noise would be unacceptable. Since the noise annoyance featured highly in the complaint score it is not surprising that this was also ranked the highest priority for future upgrades.

For a sample of how significant 22.4 dB is, it will be roughly equivalent to the difference between the first and last steps in this audio clip: http://www.animations. physics.unsw.edu.au/waves-sound/quantifying/ downloads/quantifying_1dBnoise. swf.

Setting	Sound Level (dBA)
O	39.4
0	46.3
1	48.9
2	52.0
3	52.9
4	56.7
5	58.3
6	60.8
7	61.8
8	61.4
9	61.4
10	60.6
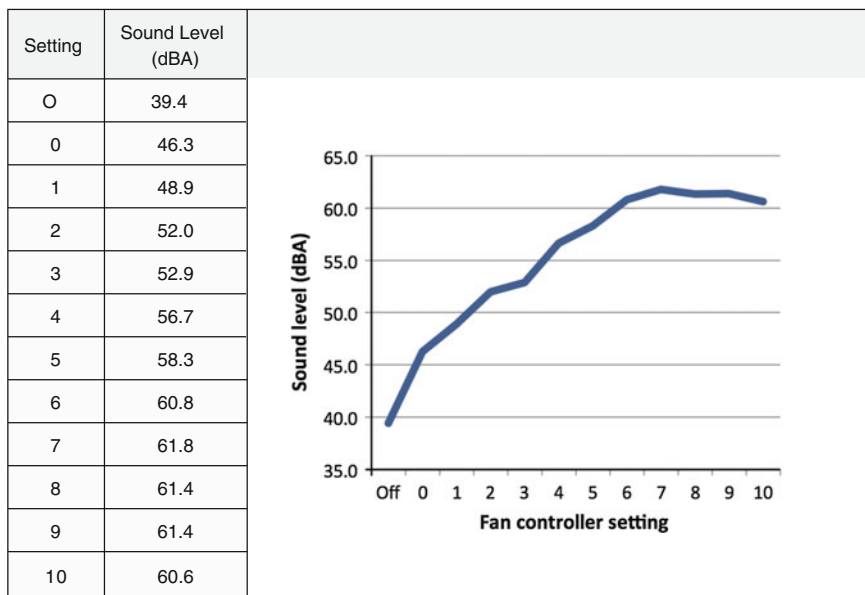
Fig. 10.26 Sound level measured with Digitech QM1589 set to 'Slow', 'A' Rated (dBA). Recorded at 1.1 m height between two DTAC units both with fans on. Average of readings values taken increasing fan controller (0–10) and decreasing (10–0)

Even thought the fan noise was significant, I personally felt that it was not as drastic as measured and suspect the wind could have generated more crackle on the sound level meter than was audible, like someone blowing into a microphone. Fig. 10.26.

10.5.13.2 Cooling

Even though DTAC improved thermal comfort to a mean of 0.76, within the neutral band ± 1 in the ASHRAE Scale, it is evident from the wish list that this needs to be further improved. Thus even though the use of DTAC approaches the neutral point on both ASHRAE and Bedford scales, users expressed more could be achieved for them to feel 'very comfortable'. Taking into account the earlier discussion on the preference to be slightly cool in Chaps. 3 and 4, the thermal comfort scale underestimates the preferred coldness due to the concentration of heat in the head from mental metabolism, the ideal would be to see that occupants would have a system that rated -1 (slightly cool) on the ASHRAE scale or 3 (comfortably cool) on the Bedford scale. The 'right' temperature for mentally productive work would always be slight cool for the rest of the body.

10.5.13.3 Desktop Space Usage

The DTAC prototypes had been built as desktop units to avoid the need for drilling holes into the tables and the use of long ducts which would incur a higher static pressure and refrigeration loss. The prototypes used in the climate chamber were originally designed to be used in different offices and were thus fabricated as desktop units. It is clearly understandable that users prefer to have as much real estate as possible on their desks.

10.5.13.4 Cooling Control

In order to achieve this, the feedback indicated that more powerful TE modules (ranked 2nd priority) should be used instead of more powerful fans (ranked 5th priority).

10.5.13.5 Future Upgrades

The use of axial fans on the faceplate had clearly been the main factor in the noise annoyance to users. Whilst this configuration provided a reasonable flow rate with low power consumption (max. 7 W) it did not attenuate any of the noise generated. Moreover the refrigerated air was passing over the fan motor which would invariably overheat with extended use. A scroll fan would be a more efficient alternative, being able to handle larger static pressures and flow rates, and a motor can be located external from the impeller and air stream. A more effective cooling fin and a lower melting point PCM would result in more cooling without needing to increase the TE cooling effect with more modules or running them at a higher voltage.

10.5.13.6 Pricing

The modal group comprising 46 % of the participants indicated that they were willing to pay up to $300 for a unit, i.e. $600 for the two unit set-up for the experiment (Fig. 10.27). This price point indicated a readiness to adopt DTAC as a direct consumer purchase, rather than a building or engineering component. If treated as an accessory, the visual presentation of the item becomes significant, requiring the employment of industrial designers to imbue the device with a contemporary presence. Further thought also needed to be given into how DTAC can be customised to the various tastes of consumers.
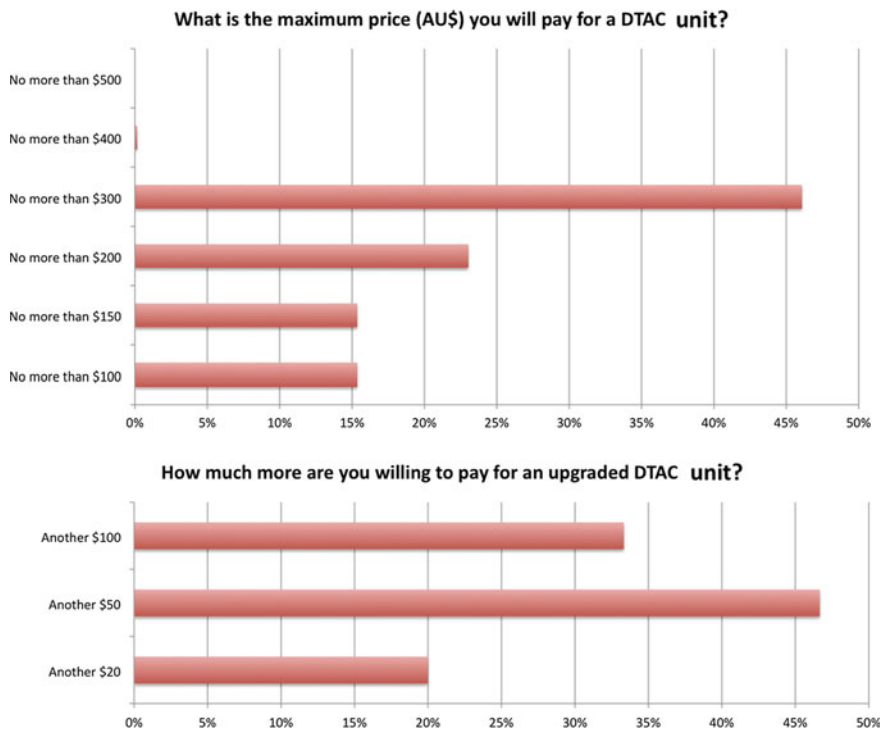
Fig. 10.27 Percentage of participants nominating recommended retail value and upgrades

10.5.13.7 General Feedback

Participants were free to leave feedback, the following were collected and reproduced in full with minor language editing:

> very easy to use and efficient at cooling. if noise was less would be perfect
> noise only disrupts when one needs [quiet] to generate idea, but when one is doing work like drawing, noise fades out.
> very impressed with the dtac unit overall. performs well and produces a lot less noise than anticipated
> incredibly easy to use; great design; styling, materials, simple appearance good air pressure with a range of speeds and temperature
> i think that the dtac system is great. personally it really satisfies my needs for a cooling method in a confined space. i would happily purchase one for a
> desk top situation.
> it functions great for cooling. and controls great. looking forward for the new prototype
> it looks great and functions great too. looking forward for the next prototype. cheers
> really alleviated any uncomfortableness of being too warm and is easy to use. it is only slightly noisy but you get used to it pretty quickly.

Table 10.27 Evaporative cooling on an adult in conditions of o.6clo, 23–9 °C, 50 %RH (Cagge 1986)

Activity	Respiratory moisture loss (heat loss)	Perspiration rate (heat loss)	Skin moisture loss (heat loss)
Resting 1met (105 W)	12 g/h (21 W)	No perspiration	20 g/h (84 W)
Walking 3met (315 W)	37 g/h (65 W)	241 g/h	38 g/h (161 W)

over all it works well. the size and noise are the only issues.

works great but the noise can be distracting especially when on high fan speed which was needed to cool me. cooler air may help this

quite noisy, [not effective]… in adjusting the maximum cool temperature…

10.6 Target Cooling

DTAC predominantly cools the head and upper body. Whilst the psychrometric relationships are well understood (between temperature, humidity and enthalpy), the relationship between T and wind velocity is not.

To better understand the thermodynamic relationship, the head is simplified to a sphere 150 mm diameter at 34 °C. Only the dry heat loss is considered in this model as the restorative moisture loss will be equivalent with or without fan movement, and the perspiration rate is negligible for (Gagge 1986; Table 10.27).

Using Whitaker's correlation (Whitaker 1972) in (Incropera and DeWitt 2007) the forced convection can be determined from the relationships:

$$\overline{N}u = 2 + \left(0.4Re_D^{1/2} + 0.06Re_D^{2/3}\right)Pr^{0.4}\left(\frac{\mu}{\mu_s}\right)^{1/4} \qquad (10.6)$$

$Nu = \frac{hD}{k_\infty}$	Nusselt number
$h = \frac{Q}{4\pi D^2(T_0 - T_\infty)}$	Convective heat transfer coefficient for sphere

Note that Whitaker uses a convective coefficient with area of sphere as $4\pi D^2$ instead of $4\pi r^2$. It is unclear if Whitaker's correlation can be used to determine free convection when vel = 0 m/s. In the temperature range 20–34 °C, the velocity where the Archimedes number was 1 (where Ar = Gr/Re^2) was at vel = 0.2 m/s. Since Ar = 1 indicates the condition where forced or free convection rates would be comparable, this vel would represent the lower limit of forced convection. Figure 10.28 shows how this was found to be in close agreement with Churchill's correlation free convection of a sphere (in Incropera and DeWitt 2007):
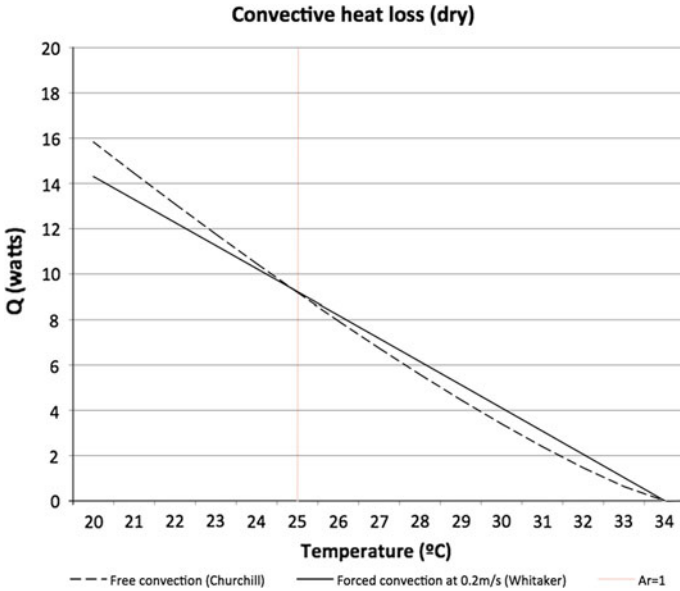
Fig. 10.28 Plots of free convection (Churchill) and forced convection at 0.2 m/s (Whitaker)

$$\bar{Nu} = 2 + \frac{0.589 Ra_D^{1/4}}{\left(1 + (0.469/\,Pr)^{9/16}\right)^{4/9}} \tag{10.7}$$

Q-conv (heat loss from forced convection) demonstrates a linear relationship with temperature in the target range studied (20–34 °C) when velocity is fixed (Fig. 10.29).

This model allows us to look at each velocity as removing a multiple of heat beyond natural convection (Table 10.28). So at 0.5 m/s, forced convection cools 1.61 times (or 61 % more) than free convection. We can see from this the efficacy of even a small amount of air movement, and this relationship continues way beyond the 2 m/s practical limit for wind directed on the face.

Finally, assuming the heat produced by the head is 20 W under no physical exertion (Cabanac 1995) we can plot the dT and V combinations to extract that amount of heat from the head (Figs. 10.30, 10.31).

The room T is here assumed as 30 °C (to fit the regression analysis where the power function cannot accept 0 or negative dT values). In the climate chamber where ambient T was 28 °C and typical fan speed was about 1 m/s, where only 2 °C cooling was required. At a velocity of 1 m/s, this model approximates well with the experimental findings for a target T $\approx$ 26 °C. On top of this model it is recommended to have an extra margin to cater for mental metabolism of an active mind and for the transient demand for extra cooling after having lunch in warm eateries. Whilst increasing wind velocity is the energetically efficient mode of

Convective heat loss (dry)
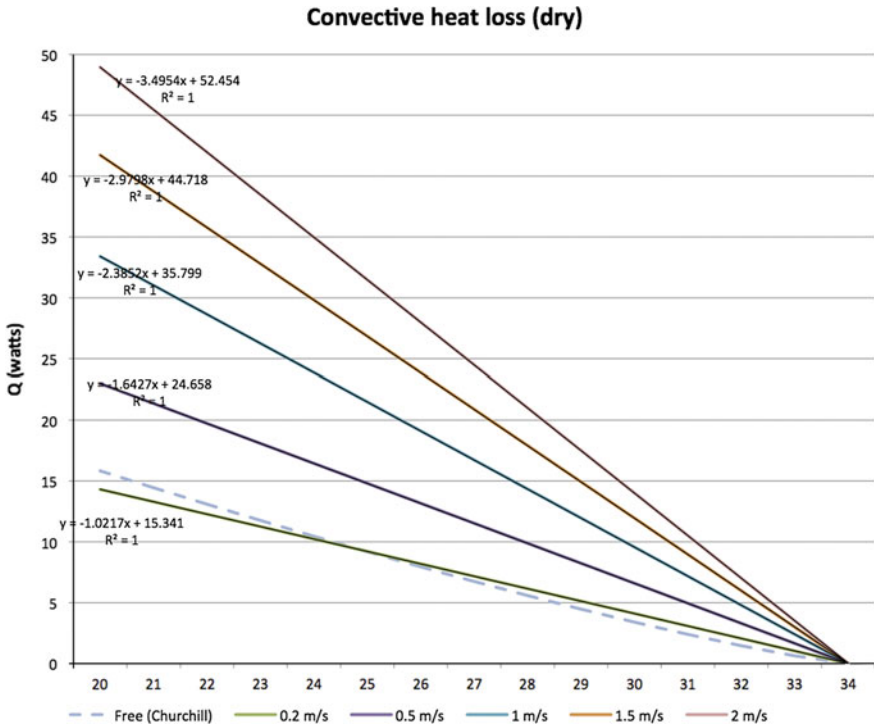
Fig. 10.29   Convective heat loss at various velocity and temperatures

Table 10.28   Nusselt number and cooling as a multiple of free convection at wind velocities from 0.2 to 3.0 m/s

Wind v (m/s)	Nu	Cooling multiple
0.2	21.06	1.00
0.5	33.86	1.61
1.0	49.16	2.33
1.5	61.42	2.92
2.0	72.05	3.42
2.5	81.61	3.88
3.0	90.42	4.29

improving convective cooling, from the field trials with staff it was found that user satisfaction was rapidly lost if strong winds were deemed to mess the hair, dry contact lenses or dehydrate skin. 1 m/s will be the preferred upper limit for prolonged air movement across the face. Further cooling will have to be delivered by lowering air temperature.
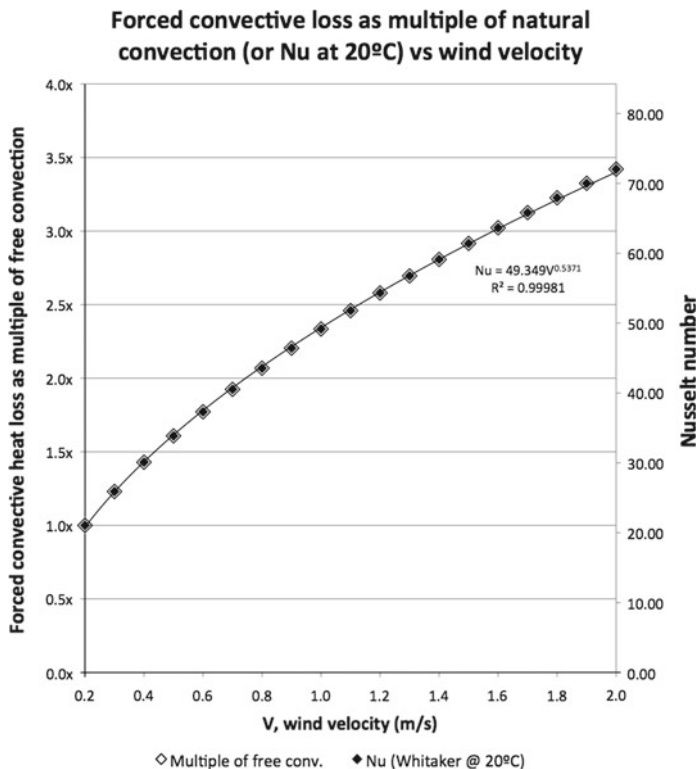
Fig. 10.30 Forced convective heat loss (as a multiple of natural convection) at various wind velocities

10.7 Concluding Thoughts on the Experiment

Field trials were held with DTAC and a fan-only control in naturally ventilated offices with staff volunteers but the lack of diligence in filling up the questionnaire yielded no meaningful results. Even so there were intriguing outcomes from the experiment.

1. Through discussion with the staff involved in the trial, the tedium of filling out survey forms was clear, and this task was found to be an intrusion into the routine and focus for work, committed as they would have liked to have been for the experiment. Under these circumstances, one was less likely to contemplate the state of mind which expresses satisfaction with the thermal environment, and more inclined to get through the task of filling the survey and returning to work. Under work pressure it was apparent that the most convenient response was to pick a vote in the mid-range.
2. Some staff were also particularly pedantic about the semantics of the survey, which brings to mind the differences in attitudes between students (typical of

dT and V combination to effect 20W cooling
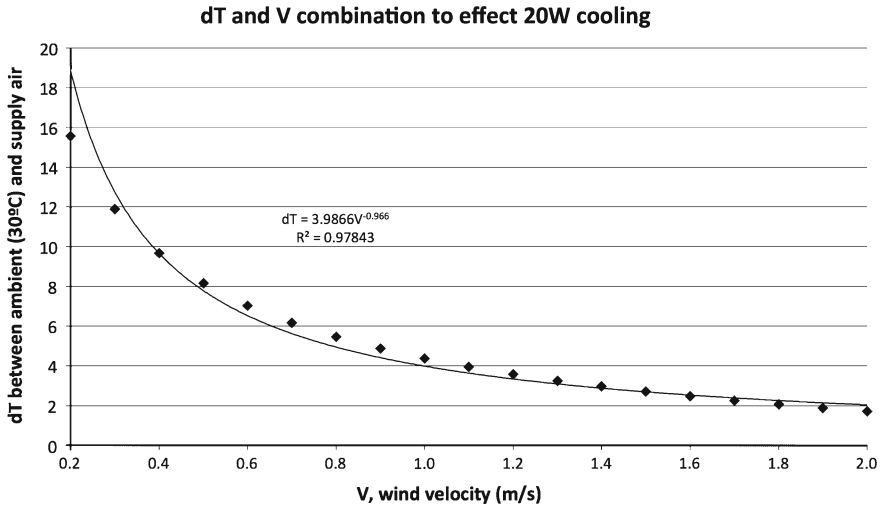
Fig. 10.31 Combined relationship between dT and v to effect 20 W of cooling

climate chamber experiments) and academics or other mature thinkers, who were as concerned with the connotation of words as they are with its denotation. For example, would a vote of 'very uncomfortable' be taken as an imprecation on fellow architects who designed an environmentally sensitive building making assumptions for greater adaptive opportunities?

3. With older participants, the demand on the environment tended to be more onerous. A number of participants could not isolate thermal comfort from other aspects of comfort and felt that the entire environment (including the seating, lighting, acoustics and air quality) had to be taken into account of their state of mind for them to be 'thermally comfortable'.

4. Making an experiment successful, even amongst academics, was secondary to their core work. Better results could be obtained by working with students, who are not distracted with other priorities.

Hence subsequently, a climate chamber was set up for a trial using students working towards a prize. The experimental method showed that occupants in an otherwise uncomfortable condition could be cooled to (only just) comfortable conditions with DTAC. The acceptability of the conditions match the design parameters for personalised ventilation (see Table 9.2) from other researchers. Calculations showed that the primary cooling effect was that from air movement, and this was confirmed by the similar results of the 'fan only' blind test.

DTAC however, did not deliver as expected in bringing sensation to 'slightly cool' and comfort to 'very comfortable'. As fan speeds were approaching the acceptable draft limits, it appears that the cooling power should be increased in a manufactured version to cater to more demanding occupants and conditions.

Fan noise was expressed to be a major annoyance in the use of DTAC. Participants gave feedback that if the fan was quiet they would have been more inclined to turn up the fan and not rely so much on TE cooling. The drone of the fan actually made some participants more sleepy. The air movement was also found to be the most responsive to control and achieving the desired comfort.

Greater cooling and quieter operation are the priorities for future development of DTAC. We will consider a few others in the next chapter.

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Chapter 11
Future Research

11.1 The Future of DTAC

Up to the end of this thesis the DTAC has been developed solely to improve personal thermal comfort by providing a stream of air that has been chilled a few degrees below ambient conditions. As a complete personal climate control solution it will have to address indoor air quality as well. Preliminary thoughts for the future design is illustrated in Fig. 11.1 with suggested IAQ improvement in Fig. 11.2. A two-stage IAQ improvement is proposed:

1. removal of particulate matter and gaseous pollutants
2. sanitisation of cool air

11.1.1 Air Filtration

Air filtration is one of the most effective and affordable methods of improving air quality. Fisk (1999) estimates the maintenance of filter at $23/pax/yr for high efficiency (0.3 μm) filter replacement. Since DTAC only filters the air that is delivered directly to the occupant, the cost of maintaining air filters will be even lower than this. At the same time it must be appreciated that the occupants are unlikely to replace the filters unless it is easily accessible and the improvements to air quality is perceivable. The production version of DTAC will need to feature a front-access filter that can be easily swopped without tools and without dust balls falling around. This "quick swop air filter" can even be maintained by contractors that periodically replace all the DTAC filters in the office floor.

Particulate matter can be removed by a number of established means like particulate filters, electrostatic filters or High Efficiency Particulate Air (HEPA) filters. Where DTAC is used as a supplementary air-filter and air-conditioner, the assumption is that the ambient air will already be regulated in humidity and particular matter. Only a MERV 13 or finer filter is required to remove the small

Fig. 11.1 Renders of DTAC as a product. The aim is to minimise the footprint and contain at least 20 l of PCM. The fan has been located to the furthest position from the occupant's hearing to minimise fan noise, and changed to a centrifugal fan to handle the higher static pressures associated with the small blower hose. There are preliminary thoughts as to how the filters should be designed
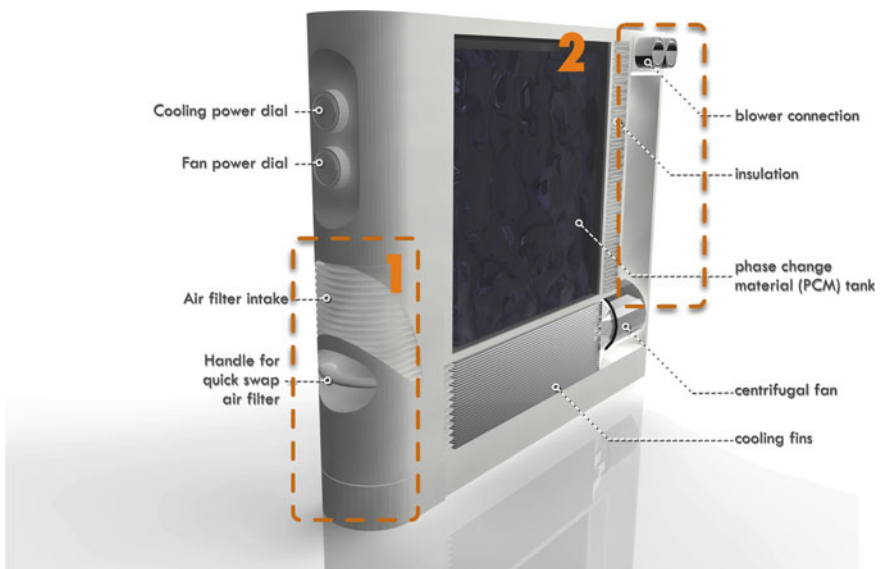
Fig. 11.2 Two main areas of improvement to IAQ. The quick swap filter in region 1 provides dehumidification, particulate filtration and gas filtration and is user-operated. Sanitisation occurs at region 2 and because of safety concerns, should only be maintained by specialist

particles and improve air quality. Electrostatic and HEPA filters also work better where particulate loads are not high.

In some rapidly developing cities pedestrians and motorcyclists often travel with masks and give some indication to the degree of pollution. If DTAC was used in a naturally ventilated application in a polluted city then it may warrant a two-

stage filter, suh as a MERV 8 pre-filter followed by a MERV 13 final filter. With the higher static drop a more powerful fan will be needed. Though this will result in higher fan noise, it can be assumed that will be less of a concern in naturally ventilated buildings along busy roads.

11.1.2 Dehumidification

DTAC was intended to be operated only above dew point. As such the cooling fins have not been designed to be self-draining, and no condensate collection or discharge has been built in. The energy needed to dehumidify air through the TE modules at present efficiencies are not attractive.

If dehumidification was necessary, such as in tropical natural ventilation, a desiccant should be employed to strip moisture from the air stream. The desiccant can be placed in a microwave oven at the end of the day to regenerate it, and left to cool, as the heat from the freshly microwaved desiccant will increase the cooling load. Furthermore, as the enthalpy of dehumidification will increase sensible heat, it is best when the desiccant is cooled before it is used. When the DTAC is switched off, the cartridge should automatically seal itself to reduce exposure of the desiccant to ambient moisture whilst it is cooling down.

As filtrating, disinfecting and gas removing processes are enhanced by dehumidification, the desiccant pack/honeycomb should be located upstream of the other processes.

11.1.3 Removal of Gaseous Pollutants

It needs to be clarified that CO_2 is not associated with SBS under concentrations of 5000 ppm (Wyon 2000). In the office environment, the monitoring of CO_2 is not so much a matter of concern in itself, but as a proxy for ventilation rates, Batterman and Peng (1995) intimate, 'Probably the most important use of CO_2 is as a crude indicator of ventilation efficiency, showing whether the supply of outdoor air is sufficient to dilute air contaminants.' (Batterman and Peng 1995)

One of the benefits of personal ventilation is that it brings freshly filtered air, together with a proportion of outdoor air, into the breathing zone. DTAC on the other hand is limited to the air that is already in the room which is mixed with materials and equipments that are off-gassing. There is an engineering adage, 'The solution to pollution is not dilution' Hence, gaseous pollutant sources are best stemmed at source. Failing which, the option for DTAC is to have gas filtration.

To have ductless improvement of IAQ, two methods exist:

1. Use of organisms to absorb and/or break down the compounds
2. Use of solid filters that trap the compounds
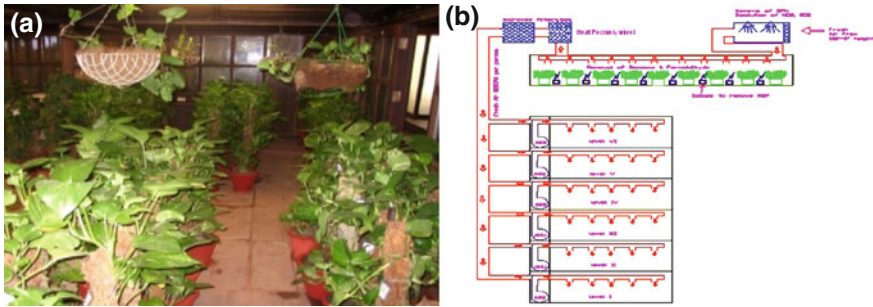
Fig. 11.3 a Rooftop green house and **b** ACMV system schematic of Paharpur Business Centre and Software Technology Incubator Park (www.pbcnet.com)

One way of dealing with the excessive pollution in New Delhi, India, is to utilise areca palms (oxygen production) and money plants (VOC absorption), as recommended by Meattle (2009) who implemented a roof floor of indoor plants as the "outdoor air supply" for the ACMV system at the Paharpur Business Centre and Software Technology Incubator Park. Figure 11.3 shows a photograph of the green house and the ACMV schematic. The main disadvantage of this system is the increased latent load from the water sprays and plant transpiration.

Alternatively a NASA report (Wolverton et al. 1989) explicated relationship of indoor plants and air quality, especially when air was passed through the root system (see Fig. 11.4) as the soil microorganisms are 'capable of biodegrading toxic chemicals when activated by plant root growth.' (p. 15)

The use of indoor plants is possible in offices with abundant natural light and will work for the perimeter of fully-glazed offices. For non-organic pollutant removal, molecular sieves can be employed. Predominantly used for gas purification, molecular sieves can strip vapour molecules by trapping them in the crystalline lattice sized for a particular kinetic diameter. Alternatively an activated carbon honeycomb can remove odours, beside VOCs.

Fig. 11.4 Indoor air purification system combining houseplants and activated carbon. (Wolverton et al. 1989)
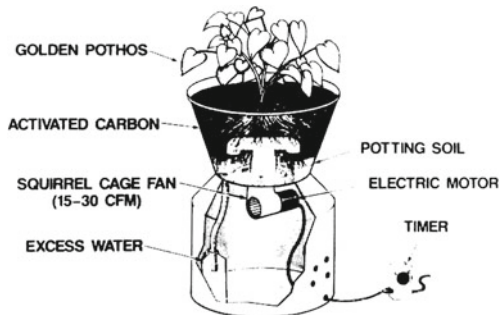
11.1.4 Disinfection with UV and Photocatalyst

A recent study undertaken in a university classroom found that the human microbial taxa unique to the human skin (*Propionibacterineae, Staphylococcus, Enterobacteriaceae,* and *Corynebacterineae*) were enriched by 3.5 times relative to outdoor airborne bacteria (Qian et. al. 2012).

In hospitals UV-C arrays are installed in ducts to sanitise the supply air. These are characterised by high intensity tubes as the flow rates are high and consequently the exposure time short. To maximise the exposure time in the DTAC, UV-C tubes will be best installed not with air filters but at the risers after the fan. To further improve on sanitisation, TiO_2 photocatalysts can be employed in conjunction with UV-C (Hashimoto et al. 2005; Chuaybamroong et al. 2010).

11.1.5 Thermal Variation

A Toyota patent (Taniguchi and Aoki 1993) expresses the need to solve the problem of thermal monotony in the car when the target temperature is reached and suggests that comfort, after acclimatisation to, eventually becomes discomfort. Thermal variation can be achieved by changing the blower velocities or supply temperature. Taniguchi's patent suggest that velocity variations, whilst technically easier to implement, result in noise disturbance. Variable refrigerant flow and variable refrigerant volume are technically complex processes with vapour-compression cycles, but varying refrigerant loads are straightforward with TE modules. It only requires a PSU with variable regulated output voltage (and the accompanying current draw). Automatic thermal variation can be created with a wave generator in line with the voltage selector (potentiometer). The wave amplitude and interval will need future testing to be determined, my preliminary estimate is between ± 0.5 V and ± 2 V of the selected voltage, and over a wave period of 2–15 min.

11.1.6 Industrial Design

To bring the product to market, funds were raised through the *Commercialisation Australia Skills and Knowledge Grant* for the purposes of engineering optimisation of the cooling fin design and the industrial design.

Industrial design plays a major part in making the sale. It is the crucial last step where research ideas are prepared for a pitch to likely investors and manufacturers. A render by Sydney-based industrial designer *Tiller Design* is illustrated in Figs. 11.5 and 11.6. A particular point made to the industrial designers was that it was not solely a matter of appearance, but noise generated from devices could also influence the perception of quality (Fenko et al. 2011).

Fig. 11.5 Industrial designer's artist impression (Tiller Design)
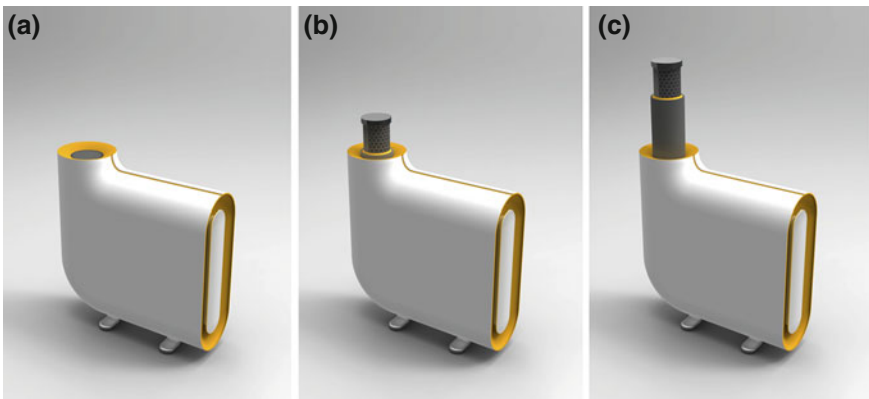
Fig. 11.6 DTAC in various applications: (**a**) with blower grille fully retracted, (**b**) to be used beside a sofa or bed as a standalone unit, and (**c**) with the turret raised to meet the table surface so that the grille can be retracted and made flush with tabletop (Tiller Design)

11.1.7 Usage by the Elderly

The elderly can be especially at risk because perception of ambient temperature is poorer, so they do not always recognise that they are over heating [Kovats 2006 in (Nicholls et al. 2007)].

Whilst the elderly are highly prone to heat injury in a heat wave, they are also the most resistant to having air-conditioning installed for reasons of cost and inconvenience. DTAC circumvents these issues, and as a personal device it can offer the added functionality of alerting the user of the need to switch it on under high ambient temperature.

> Or, as a classic example, normal body temperature, 98.6 degrees [37°C], does not change with age. Nevertheless, aged bodies are impaired in mounting a thermoregulatory stress-response, and thus it takes the bodies of the elderly longer to restore a normal temperature after being warmed or chilled. (Sapolsky 2004)

If a cellular mobile service can be integrated in the DTAC it can receive weather forecasts over SMS (Short Message Service), together with heat wave alerts of the type proposed by Nicholls et al. (2007) discussed in Chap. 2. A warning light on the DTAC unit will be illuminated when extra cooling is recommended for the current weather conditions.

11.2 A Possible Future for Thermal Comfort Research: Research-Innovate-Commercialise

Thermal comfort is a complex problem. There are many theories, each attempting to explain the desire for comfort and how it is achieved. Yet each theory is fraught with limitations. To make this problem worse, everyone is, in a sense, an authority on thermal comfort. This is because the variables that affect comfort have to be aggregated into a perception, and one is after all the best judge to his own perception of comfort. So one can only know for oneself whether one is comfortable. If we agree that the occupant knows best, then there is clear indication that the thrust for the future is in a more customisable micro-climate. However whilst personal ventilation already exists, it cannot be readily implemented in existing offices.

Thermal comfort researchers may need to go beyond describing the conditions of comfort, and embark on designing the implements that achieve those conditions. The call of the future is to go beyond data analysis, and to design, engineer and manufacture. If we agree with Richard Levin that 'the fate of the planet depends on our ability… to solve society's most pressing problems' (Gallagher 2011), then the call of the future is for solutions, which means researchers also have to invent.

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Chapter 12
Conclusion

I have written this thesis not only as a document for examination, but as an account of a four-year long research program. Thus, even though DTAC was the culmination of this program, this thesis is not about DTAC as a technology in itself. Instead I have looked at the state of the world and the role that air-conditioning has played in it, especially in knowledge-based economies located in the tropics, for which I have used my homeland Singapore as a case in point. I have presented my understanding of how the air-conditioning problem came to be and how it has persisted despite the research behind adaptive comfort standards that evidence the possibility of comfort without air-conditioning even in challenging climates.

In Chap. 2 we set the context of the problem, presenting the immoderate adoption of air-conditioning as a significant contributor to the global warming phenomenon.

In Chap. 3, I have made the distinction between temperature that is comfortable for work as opposed to being comfortable for relaxation. Whilst self-evident, I have laboured the need to distinguish between muscular and mental metabolism, showing how under real-world work scenarios the physiological stress response has been one that generally increases core temperatures, especially the brain temperature, even though office occupants are typically seen to be as sedentary as a relaxed person in terms of physical metabolism.

I have argued that it is the *quality of comfort* that differs between the adaptive comfort standard and the deterministic one. The adaptive model works on the premise that occupants in an equatorial climate tolerate much higher temperatures by adaptation. However, I theorised that this tolerance comes with relinquishing the speed of mental performance, a sacrifice that is deemed too costly in a knowledge-based economy like Singapore. Thus, we find that in Singapore, and other tropical cities where occupants have been routinely exposed to air-conditioning, the preferred indoor temperatures are much closer to PMV standards. This acclimatised addiction is not merely physiological but psychological as well. Decades of marketing where air-conditioning was presented as a the enabler of greater productivity has been imbibed by consumer society today, transforming a luxury good into a present day necessity.

Mental metabolism explained why an occupant would choose air-conditioning over natural ventilation. It further explained the preference for colder temperatures in the field compared to the climate chambers on which PMV was derived. However, how credible was this theory? In Chap. 4, we looked at the evidence for the heating of the brain under stress, and the need for the brain cooling mechanism to protect this vital organ.

From here we could have jumped to Chap. 9 where the solution to an over-heated brain was provided by means of an invention for facial cooling, but I have chosen not to make this leap. In Lakatos' words, this would have stripped the *proof* from the *proof-ancestors* and presented it in a pretentious and peremptory manner.

Hence in Chap. 5 I explained how different methods of cooling could be determined and ranked by comfort energetics. With $\frac{Watts}{Vote}$ as a common unit to compare cooling techniques, dehumidification was clearly an energetically inef-ficient approach and was investigated at length to challenge the accepted norm of an optimum RH range. In the tally, the two most efficient cooling methods were refrigeration of air and moving it with low-power computer fans. Both of these were later adopted in DTAC.

In Chap. 6 I explained why the research program, and consequently this thesis, have been structured on heuristic principles. I have retained much of the method of Lakatos and included a few more considerations to facilitate the technology transfer from academia to the world of commerce.

In Chaps. 7 and 8 I detailed the inventions preceding DTAC and why, even though failing to solve the problem, they have nevertheless enriched the final solution. My failings, together with those of other sound scientific ideas discussed in case studies, can be accounted for by their lack of commercial consideration. In these chapters I demonstrated the integral role of commercialisation in a problem-solving program.

Finally, it was the invention of DTAC (Chap. 9) that satisfied the commer-cialisation test. The invention was subject to experimentation firstly to prove it could cool air and regenerate the PCM overnight, and secondly to prove that it could improve the thermal comfort of occupants. Through a series of optimisation efforts (appendix 1), the first criteria was satisfied. The second however, had not been unequivocally determined in the field trials (Chap. 11), though there were indica-tions that it could have been achieved had the cooling fins been more efficient. Falling beyond the scope of the present study and budget, I left that as one of many things to be improved on in future versions of DTAC, as proposed in Chap. 12.

During my candidature I have had, on occasions, to justify:

1. why inventing should be considered as a legitimate part of academic research,
2. why commercialisation should be considered in research,
3. Why problem-solving should be considered an acceptable method.

To this I respond, it is a matter of being relevant.

Firstly, when scientists are liberated from preconceived limitations, many important discoveries and inventions have emerged (New Scientist 2009). Often

the distinction between weird and wonderful is a question of an invention's relevance to humanity—we dismiss as incredulous an invention with no practical worth. It is the academic moorings that keeps innovation on a purposeful path. In this sense, an invention is the outcome and embodiment of academic knowledge. Inventing is a form of applied research that keeps basic research relevant to society at large. It makes theory practical, and thus relevant.

Secondly, being scientifically sound has also been demonstrably inadequate to solve problems, as seen in the case studies of the Solar Chimney, Australian 2020 Stationary Energy Plan and Skytherm Roof. Scientists need to consider the commercialisation of their research in order to have a path to market in a capitalistic society. We need to steer from the mentality that scientists are only concerned with producing the bitter-pill and an imaginary *someone else* will convince the politicians and citizenry to swallow it. As illustrated in the imaginary (Socratic) dialogue with mock investors (Chap. 6), the solutions from research need to be relevant to the business interest of investors, and this must happen at the very inception of any innovation-based research program. This alternative mind-set sits uneasily with many academics, but is central if an idea is to survive outside the university.

Thirdly, thermal comfort is an architectural problem because it involves an appreciation for architectural science that is antecedent to architectural design. Failure to view comfort as a design consideration is precisely one of the causes for the business as usual scenario in instances where architects have abdicated this responsibility to other professionals who have no direct influence on design.

Hence, thermal comfort should be fundamental to building design and operation, with the expectation of consuming as few resources as practical.

Additionally, the design-critique process distinct to Architecture among academic disciplines, is the accepted pedagogy of design instruction, and a system that lends itself well to problem solving. We have seen that research-based problem solving requires researchers to navigate very complex issues involving an interdisciplinary understanding. In my case, it has been the following:

1. Engineering: calculations and optimisation. Ability to use physics to model, simulate and predict outcomes.
2. Medical physiology: understanding the stress response, thermal regulation and brain cooling.
3. Sociology: the role of marketing, mass-consciousness and consumer society.
4. Philosophy: an epistemological approach to sensation, using alliesthesia and hedonism to explain comfort and behaviour. Cognitive performance in the global workspace theory.
5. Professional exposure: understanding motivational drivers behind architects, engineers and property developers.
6. Commercialisation: sensitivity to price signals, market positioning. Being able to pitch, to take commercial considerations into the design process. Understanding the real-world impediments to implementation.

These disciplines had to be understood and their implications consolidated into a comprehensible and actionable proposition. My training in architecture has

helped me appreciate complex problems and to handle multiple considerations concurrently. Particularly relevant was the use of *design thinking* where the search for an answer was not directed to a research question, but to a design brief.

Throughout this thesis spanning wide-ranging disciplines, one of the challenges was finding the most appropriate and telling illustrations. In my case (and true to my Singaporean identity) I have used food in many analogies; talking of sushi, Pepsis, coffee and connoisseurs (to name a few). If you will indulge another note on food, I would leave you with a concluding observation from Singaporean engineer Lee Eng Lock (Hawken et al. 1999, p. 123):

> To save land (very costly in Singapore), he [the engineer] untangles and compacts plant layouts so they take up less space, yet are easier to maintain. Space, money, metal, energy, time, words—he uses just the right amount of every resource, in the right place and time and manner. Every input and result is measured, nothing is guessed. Energy is used frugally, then recaptured and reused until almost nothing is left. When he was once congratulated on devising an especially clever way to use a building's outgoing air to pre-dry its incoming fresh air, using no energy and no moving parts, Mr. Lee replied: 'Like Chinese cooking. Use everything. Eat the feet.'

In a world with diminishing energy sources and alarmingly dwindling environmental sinks, the approach that we take towards attaining thermal comfort will play a huge role in its future.

References

Hawken, P., Lovins, A. B., & Lovins, L. H. (1999). *Natural capitalism: The next industrial revolution*. UK: Earthscan.
New Scientist. (2009). *How to make a Tornado: The strange and wonderful things that happen when scientists break free*. London: Profile Books.

Chapter 13
Appendix: Building and Optimising the DTAC

This appendix explains how the DTAC was developed and optimised in a step-wise process. The advances have been categorised by the components (instead of chronologically) for clarity. The following aspects of DTAC were analysed:

1. Overall design changes in four generations of prototypes
2. Fan selection and positions
3. Airflow
4. Air handling
5. Cooling fin heat exchange
6. Thermal interface materials
7. Thermal storage tank: the wax bath.

13.1 Overview of Prototypes

13.1.1 DTAC Mark-1

As the general parameters were not established at this point, an oversized pedestal was designed to give flexibility in terms of housing the apparatus and the gamut of sensors. Of particular consideration was the size of the PCM tank and it was designed to house a 20 L paint drum as the PCM container. The cooling fin assembly could take up to four TE modules. The initial double $-45°$ bends in the duct were intended to reduce drag but were subsequently simplified to a 90° elbow for ease of fabrication (Fig. 13.1).

The original intent was to develop DTAC simultaneously with Desiccant Wheel Air Handling Unit (for the ceiling-mounted DWAHU) in the following configuration (Fig. 13.2):
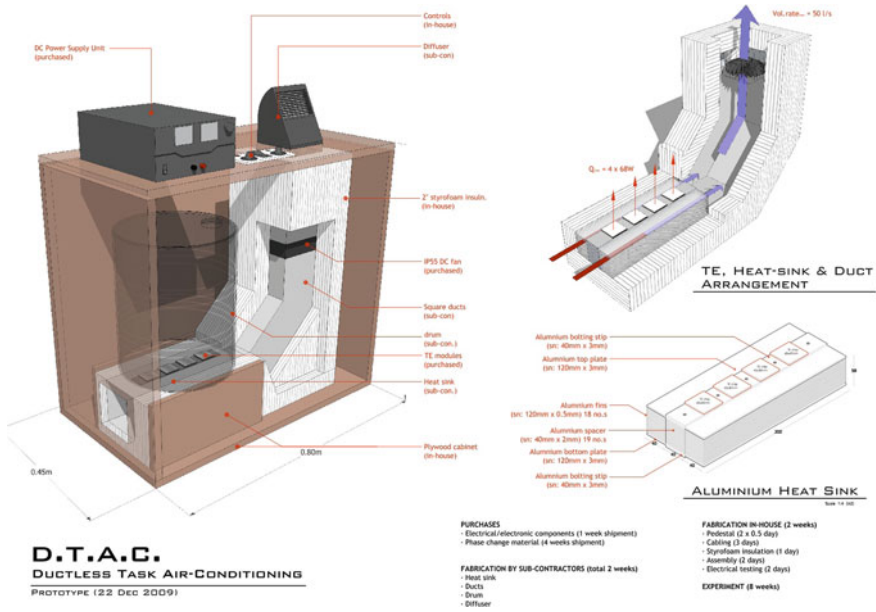
Fig. 13.1 DTAC Mark 1 prototype design
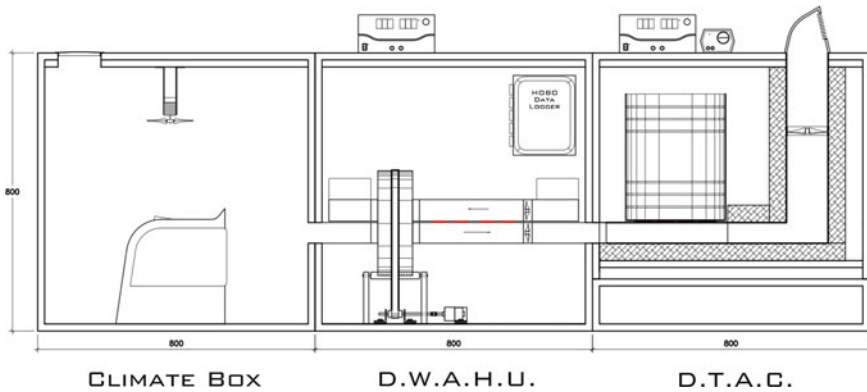
Fig. 13.2 Experiment setup to test (1) supply of hot-humid air simulating outdoor tropical air (2) desiccant dehumidification and pre-cooling simulating DWAHU ambient air-conditioning, and (3) personal air-conditioning of cooled air, simulating DTAC

1. Climate box equipped with heater and humidifier to supply warm-humid air
2. DWAHU box equipped with rotating desiccant wheel to dehumidify the air-stream, supplying warm-dry air (Fig. 13.3)
3. DTAC box equipped with TE modules and PCM to cool air-stream thus supplying cool-dry air.
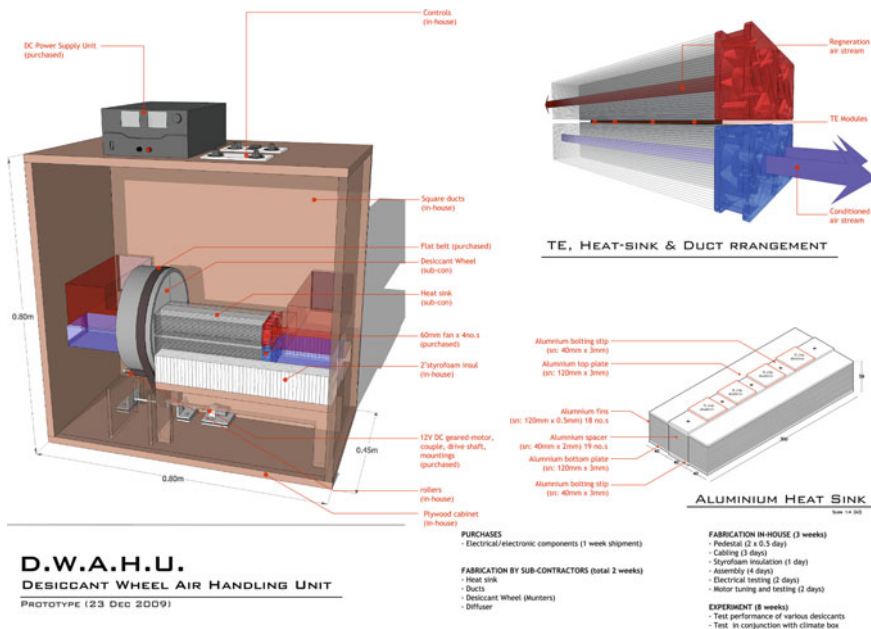
Fig. 13.3 DWAHU design. A desiccant wheel is rotated by a step-motor and hot-humid air is passed through it. The air emerges from the wheel dry and warmer. The air is chilled by TE modules, with the rejected heat passed to the exhaust air stream that regenerates the desiccant

The DWAHU concept was not prototyped due to the lack of commercialisation potential as determined by the university's technology transfer office. Existing desiccants with low regeneration temperature are commercially used in proprietary systems but I could not find a manufacturer willing to supply the desiccants separately from the system. This raised suspicion on the extent to which these desiccants could be regenerated with exhaust heat from air-conditioning condensers. There were also technical issues, which were at that time not resolved:

1. Development of suitable seals to allow rotation of drums without leakage. The initial plan was to design a desiccant wheel that rotated 90° at timed intervals. An inflatable seal would deflate to allow a quarter-turn rotation, then reseal and the fans resumed. It was uncertain if such a seal would work
2. The potential desiccants were silica gel, 13X molecular sieve and coconut pith. All desiccants can regenerate partially even with mild heat but it was uncertain if adequate regeneration could be achieved with TE modules.

Mark-1 enabled the determination of the melting characteristics of wax and gave the empirical knowledge to develop the wax-bath in Mark-2. The cooling fin design has remained unchanged in further prototypes other than in altering its length.

13.1.2 DTAC Mark-2

Mark-2 was designed as a demonstrable portable prototype to fit in a *Pelicase* suitcase. In order for it to be able to demonstrate the technology at business competitions and to prospective investors, one side of the box was left exposed so that the contents and processes could be visible (Fig. 13.4).

To simplify the airflow there were no flexible hoses or funnels, the casing and acrylic cover would contain the airstream. By creating a circuit with a switch each to 2 modules and 4 modules, there could be the option, at fixed voltage, to select low (2 modules), medium (4 modules) and high (2 + 4 modules). The prototype carried a 12 V, 9Ah sealed-lead acid (SLA) battery and an external PSU could either power the modules or recharge the battery with the circuity sketched in Fig. 13.5.

On reflection, the modules that were switched off would have become thermal bridges to return heat back from tank to cooling fins. All modules needed to be on, and preferably at the same voltage. Airflow was very poor without a honeycomb or proper duct. It was likely that the supply side of the fan was highly turbulent, and exacerbated by the funnelling into the fins. Consequently the flow was indiscernible. The internal battery also turned out to be a constant issue with weight and airport security. Overall views are shown in Figs. 13.6, 13.7 and 13.8.

Whilst Mark 2 was not a successful prototype, a number of manufacturing and testing protocols were determined in this stage:
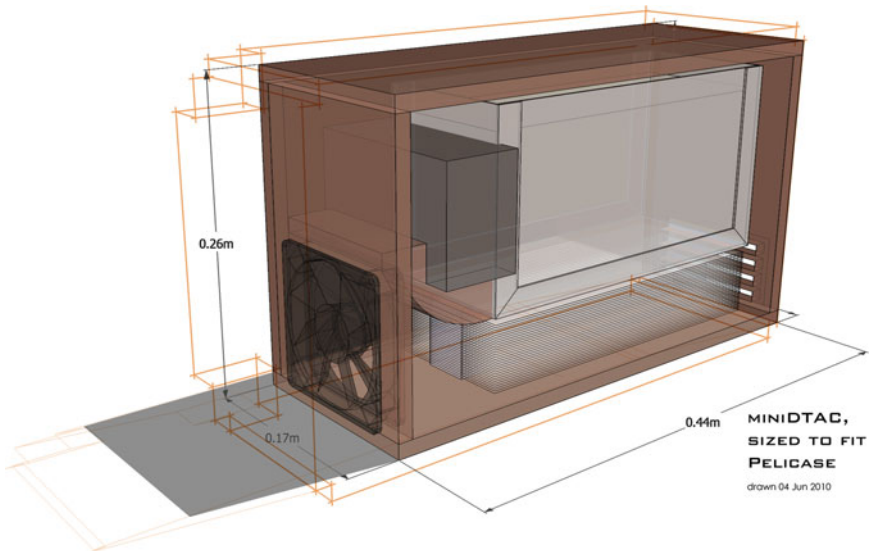
Fig. 13.4 Design of Mark-2
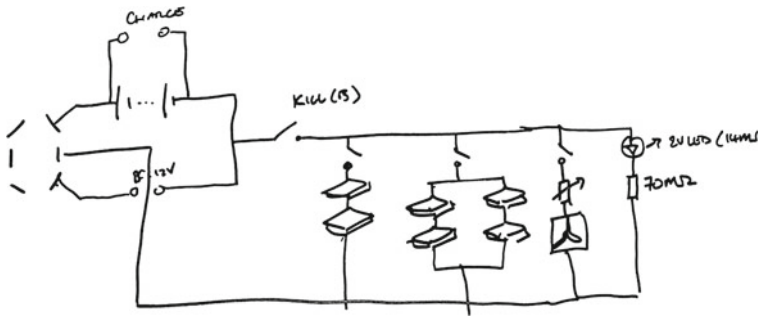
Fig. 13.5 Circuit diagram to enable selection between battery and PSU operation, and between 2-, 4- or 6-module operation
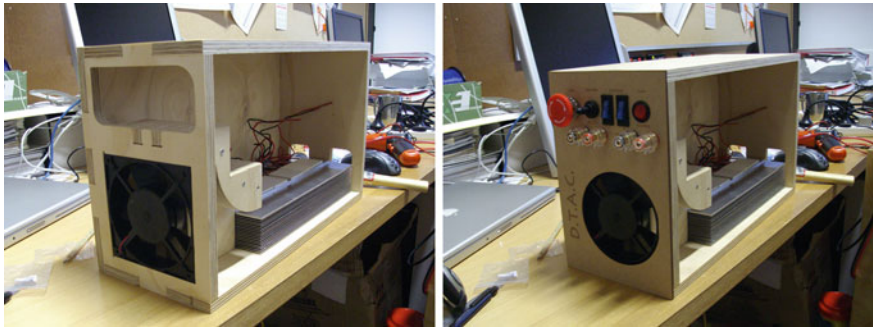
Fig. 13.6 Mark 2 with cooling fins and faceplate
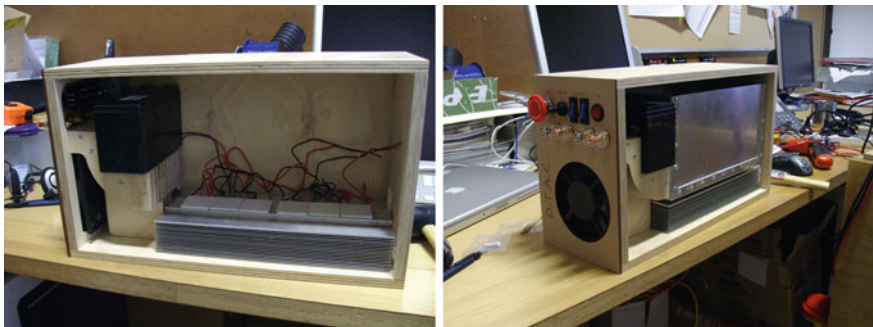
Fig. 13.7 Mark 2 with battery and PCM tank

Fig. 13.8 Mark 2 in the pelicase

1. Wax bath designed with double-tank and method to allow molten wax to breach surface
2. The leeward side of the fan was highly turbulent and unsuitable for funnelling. The air stream should be "pulled" though the fins and not "pushed" through them. A honeycomb on the leeward side would be advantageous
3. Tank cannot be painted
4. Clamps and vices could minimise the air gaps that would otherwise jeopardise heat transfer (Fig. 13.9).

13.1.3 DTAC Mark-3

A lighter unit was needed for ease of transport. Mark-3 was designed to use less material, with a truss structure to make contents visible. A honeycomb pattern was cut where material mass could be further reduced. The battery pack and power supply was separated from the unit. Fan was moved to the faceplate to improve flow (less turbulent flow when pulling air through the fins instead of pushing it). A small fan controller was included and concealed within the cabling space. This allowed a preselection of what speed the fans would spin at when switched on. The faceplate was simplified to just have 2 switches: one for the TE modules to cool the fin so that viewers could touch and feel them get cold, and one for the fan to drive the cooled air. Cooling fins were contained in a 3 mm-thick MDF duct, which could be cut and glued with better economy, higher accuracy and tighter tolerance than an aluminium one, which had to be cut, folded and riveted. PCM tank was designed to contain 1 L which would could be operated for about 30 min,

Fig. 13.9 Use of clamps to minimise TIM thickness was effective and routinely adopted in future prototypes

just sufficient for a demonstration, and with less PCM it solidified faster and was ready for transport sooner after the demonstration. Preparation of the tank is shown in Fig. 13.10, the cooling fins in 13.11 and 13.12. Figure 13.13 shows the completed prototype.

The engagement of a specialist supplier of TE modules instead of a general electronic supplier, enabled the specification of close height matching of ± 0.025 mm. The axial fan was relocated to the face plate, and used in conjunction with honeycomb. This gave a much higher face velocity.
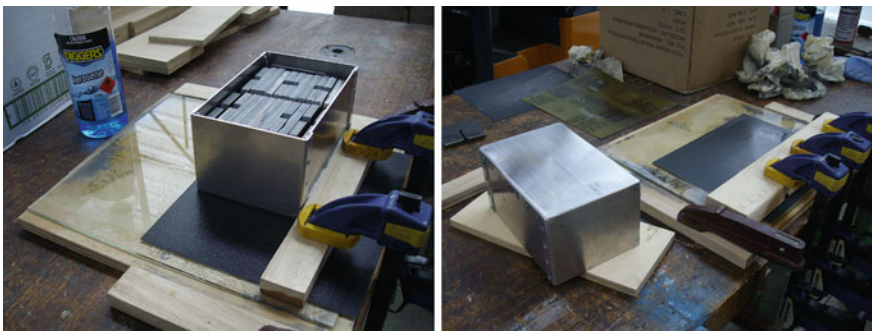
Fig. 13.10 Weights in tank for better consistency in lapping process
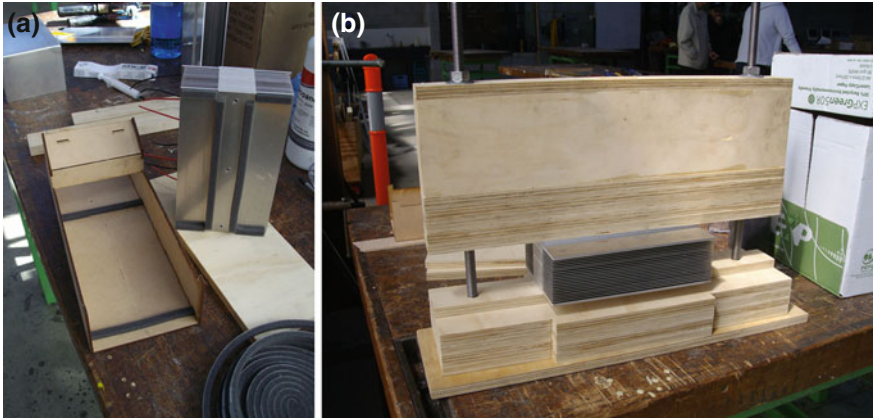
Fig. 13.11 **a** Duct made of MDF, laser cut and glued. **b** A rig was designed to apply pressure evenly on the cooling fin assembly
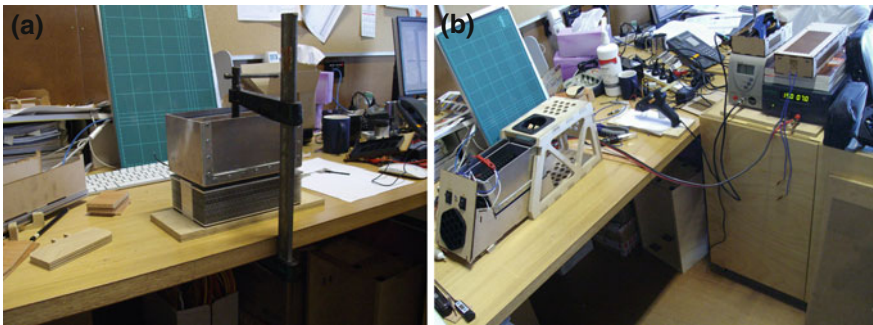
Fig. 13.12 **a** Tank being clamped to cooling fins. **b** Testing and melting of PCM

Fig. 13.13 Completed Mark-3 prototype

13.1.4 DTAC Mark-4

As part of the field trial, Mark-4 (Figs. 13.14, 13.15, 13.16, 13.17, 13.18, 13.19, 13.20) was designed for pilot production of 4 units (Fig. 13.21). The control group would be using 4 fan-only units (Fig. 13.22) which were essentially fans paired with the honeycomb and equipped with a controller. As multiple units of Mark-4 were to be made by hand, the main considerations were:

- *Buildability.* Parts were CNC routed with minimal time spent assembling. No varnish was used to reduce off-gassing during the trial. Rigs were built to facilitate assembly of parts that required more attention to detail and consistency.
- *Consistency.* The following parameters were kept constant: press forces, sanding weights and number of repetitions, PCM weight and power supply output voltage. Finally, each DTAC unit was measured to have similar performance. Specialist suppliers were sought for TE modules (Tellurex) and paraffin wax (Rubitherm) to ensure repeatability.
- *Safety.* As a prototype to be used by general participants, safety issues were a concern. A thermostat circuit breaker (opening $T = 60\ °C$, reclosing $T = 40\ °C$) would switch off the unit and prevent it from overheating. To avoid the vents being covered (by books and files), it was designed as a curved top to discourage placement of objects. Extra vents were made in the sides and rear of the casing. Each units was also installed with a fast- blow fuse (2.5 A) at the IEC connection. Earthing links were made to the tank and cooling fins. The casing was made of plywood and MDF with no exposed metal parts to minimise risk of electric shock. High voltage (240 V) cables were double-insulated. Connections were soldered and double shrink-wrapped. Low voltage (24 V) cables were specified to carry current with at least 25 % margin. Power cords were all tested and tagged by the School technical officer. The electrical circuit
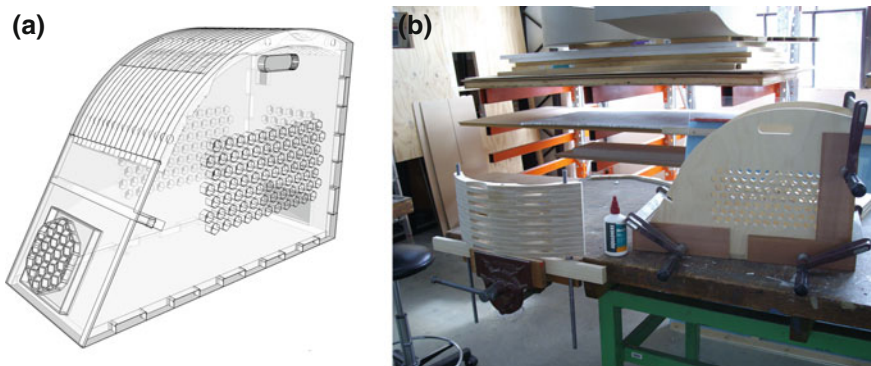
Fig. 13.14 **a** Design of field trial prototype, and **b** assembly of *top-shell* and casing

Fig. 13.15 Overview of production at the workshop

and prototype was presented to a technical officer conversant with electrical work. Briefing sessions and user manuals were provided to all participants.

The PSU was initially a switch mode PSU (25 V with control to trim ±3 V). The degree of control was found to be inadequate to regulate the temperature of modules. The limited power output required 2 no.s PSUs (with separate controllers). Later, a

Fig. 13.16 To ensure consistency, **a** the torque applied to the nuts was measured, and **b** weights applied, number of strokes and angle of strokes in sanding were kept consistent
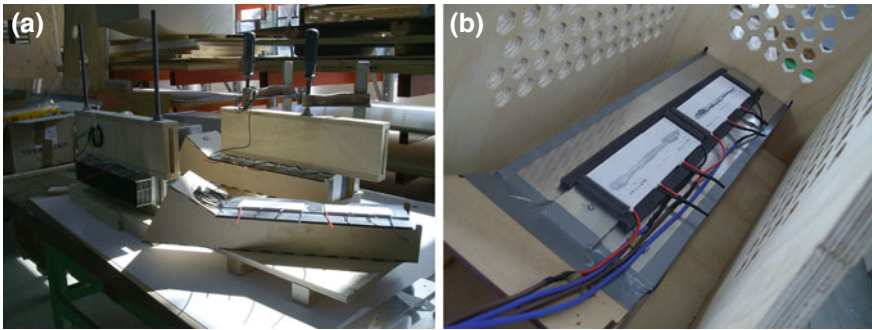
Fig. 13.17 **a**-*left* Cooling fin assembly being pressed, **a**-*rear* TE modules being fixed onto cooling fin assembly and **a**-*foreground* complete fin and TE modules, **b** TE modules with thermal paste, ready to receive tank
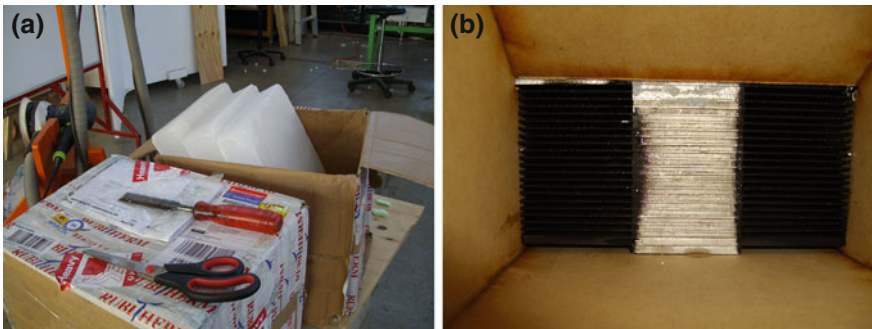
Fig. 13.18 **a** PCM as delivered. **b** On a particularly humid day, the cooling fins were below dew point when run without the fan. With the fan on, the fins have never encountered condensation
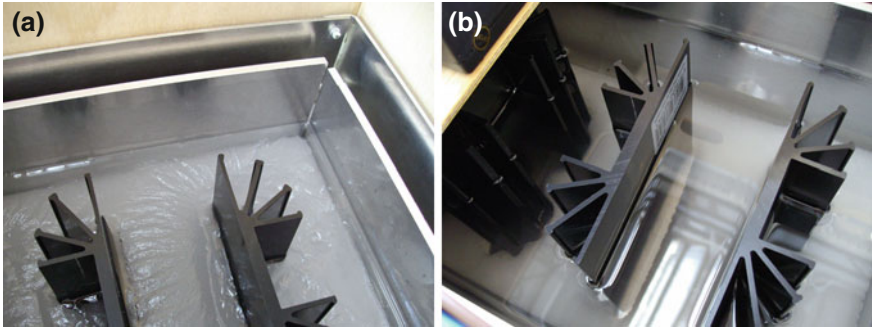
Fig. 13.19 **a** Breach of surface by molten wax. **b** Solid wax sinks to feed the hot base

Fig. 13.20 **a** Melting of wax in DTAC. **b** Setup for data logging of test run

Fig. 13.21 Completed
DTAC prototype Mark-4

Fig. 13.22 Completed fan-only prototype

0–24 V power supply was reselected (8 V each to 3 × TE modules) which allowed selection from the full range.

13.1.5 Prototype Summary

In summary the prototype performance, established methods and recommended upgrades are tabulated in 13.1 and illustrated in Fig. 13.23.

13.2 Airflow, Fan Position

12 V DC (direct current) 120 mm axial fans were selected for high volumetric flow rate and large selection range. Typically used in PC cooling applications they were easily accessible and could be selected based on fan speed (RPM), flow rate (m^3/h or l/s), and sound rating (dB) and the ease of coupling with 12 V fan controllers.

Recognising the moderately dusty environments of the workshop in which the DTAC would be fabricated, fans with IP55 rating were used. This gave greater confidence that the fan performance would not change substantially from the manufacturer's specifications over extended use.

Q   What is IP55?

A   IP stands for Ingress Protection. The digits rate solid and liquid ingress respectively. IP55 has limited ingress protection against dust, and protection

Table 13.1 Key measurements and reflection in prototypes Mark-1 to Mark-4

Prototype	dT(ini),	dT(ss)	cooling duration	Methods/applications established	Recommended upgrades
Mark 1	−4.1 °C	−2.0 °C	3 h 45 min	Method of getting wax to sink, fan selection, cooling fin assembly and dimensions	Remove funnel (increases static pressure substantially thus lowering flow rate)
Mark 2	−2.0 °C	n.d.	5 h+	Double-tank design, clamping of all thermally conductive elements to reduce space	Fan needs to be relocated for better flow, omit selective switching of modules, alternative to using clamps on cooling to ensure even distribution of pressure, need for internal ducting
Mark 3	−12.0 °C	−3.5 °C	20 min	Heat sink included within double tank, rig for pressing fins, fan controller, sanding of tank and plates with weights on glass	Larger PCM tank, longer cooling fin assembly, bolting of assembly needed on top of clamping with TIM
Mark 4	−16.0 °C	−8.0 °C	3 h 30 min	Measured torque on rig for consistency, use of engineered cast iron flat for sanding	Heating of cooling fin to improve TIM conductivity, topple switch, lower melting point PCM

dT(ini) = initial T of cooling fin-lowest T of cooling fin. dT(ss) = ambient T-lowest supply T. "n.d." not determined as flow rate was too low

against low pressure jets of water (http://www.sensorsone.co.uk/ip-rating-checker.html).
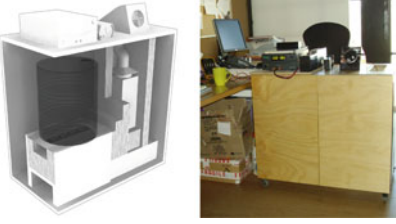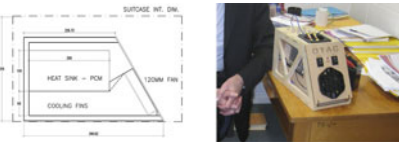
The following positions for fan placement were tested with similar results of ∼4 m/s:

1. Axial fan placed immediately after bend in duct
2. Axial fan placed at supply end of duct
3. Axial fan placed at ambient end of duct.

In all cases it was found that when coupled with a honeycomb, the flow rate could be improved by about 50 %.

The shortcomings of axial fans were that:

Fig. 13.23 CAD drawings
and completed prototypes

- Axial fans typically handled lower static pressures than centrifugal fans. Particular attention had to be paid to minimising flow turbulence in the wake of the fan.
- Axial fans in the 120 mm range were designed for cooling computers by extracting heat from case. As such it did not matter that the motors were inside the fan. Since the DTAC was working with fairly low refrigeration loads (~ 60 W), the heat from the fan motors (7 W) could significantly negate the cooling output.
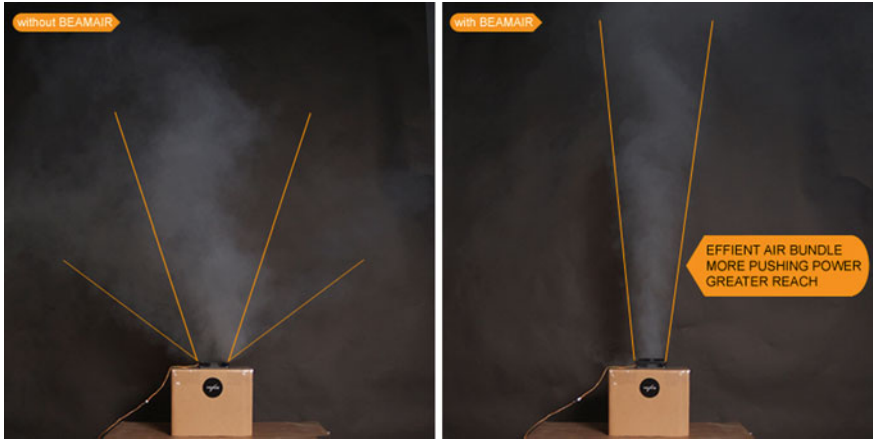
Fig. 13.24 Honeycomb with claims by manufacturer to reduce turbulence and improve flow rate (Reproduced by permission of Nexus Technology.)

Fig. 13.25 Honeycomb and spacers to create a flushed face on which to bolt the funnel

13.3 Airflow

The cooling fins required the duct to have a rectangular cross-section, whereas the blower grille had a circular connector. A funnel was fabricated to mate the different sections and designed to fit over the circular opening of the (square) fan. When the funnel was used directly with the fan the exit flow rate was <0.5 m/s. The angle of the funnel was deemed too steep for this flow. A honeycomb (Nexus Beamair) positioned in the wake of the fan substantially improved flow (Figs. 13.24 and 13.25). Even so there were substantial losses with the funnel (see Table 13.2).

Table 13.2 Wind velocity readings at various stages in the assembly

Setup: fan at 12 V in duct at supply end	Anemometer reading (m/s)	Section width ∅ (mm)
Fan alone (calculated)	3.7	120
Fan alone	∼4	120
Fan + honeycomb	∼6	120
Fan with funnel (calculated, no loss)	10.8	70
Fan with funnel	<1	70
Fan + honeycomb with funnel	6.9	70
Fan + honeycomb with funnel and hose	5.8	70
Fan + honeycomb with funnel and cooling fins	3.3	70
Fan + honeycomb with funnel, with hose connector, blower grille	3.9	70
Fan + honeycomb with funnel, with hose connector, blower grille and cooling fins	2.3	70

Measured values, unless indicted as derived from calculations

13.4 Blower Housing

A manufactured blower grille was purchased through the Mazda 3 vehicle dealership carrying spare parts. The housing was fabricated to drawings and specification (Figs. 13.26 and 13.27) by a plastic specialist with the following steps:

- acrylic laser cutting according to drawings
- heat folding
- side walls (with offset) fused to the folded profile using chloroform
- offset removed by router to give a seamless finish.

13.5 Internal Ducts

Internal ducts were fabricated from 2 mm sheet aluminium and insulated in 50 mm thick polystyrene. Joints were further covered in duct tape to minimise leakage. A foam draft tape was used to seal gaps internally and still allow for parts to be removed and adjusted. Due to the high cost of fabricating the aluminium ducts, they were changed to MDF subsequently, which could be made in the School workshop.

As an under-table pedestal, the Mark-1 ducts had a 90° elbow (Figs. 13.28, 13.29, 13.30, 13.31) which connected to a flexible conduit. It was designed as a straight path in Mark-2 (Fig. 13.32) with no discernible airflow so the heat exchangers were salvaged and used in a MDF duct (Fig. 13.33) for further testing. Having found the MDF duct viable, subsequent Mark-3 and Mark-4 versions were redesigned to have a 30° bend after the cooling fins that connected to the fan

DIA 0.08m

0.13m   0.24m

0.12m
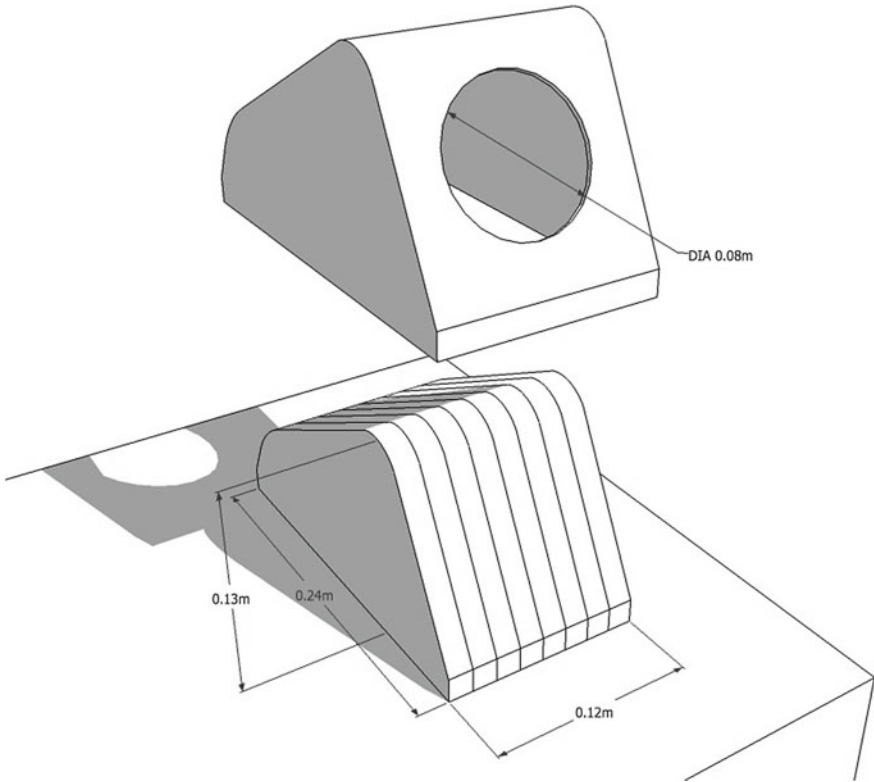
Fig. 13.26 Plug design for forming the profile
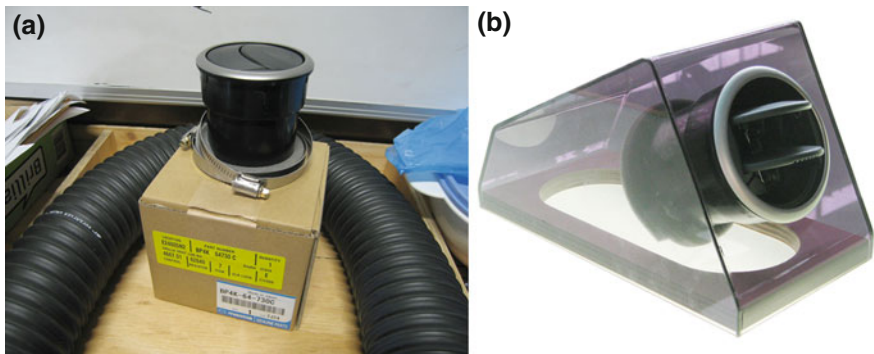
Fig. 13.27 **a** Purchased blower grille. **b** Acrylic housing

(Fig. 13.34). This proved to be a far more efficient, with a Loss Coefficient correction of 0.13; compared to 1.0 for a 90° bend (Australian Institute of Refrigeration, Air Conditioning and Heating 1995, p.4.05).
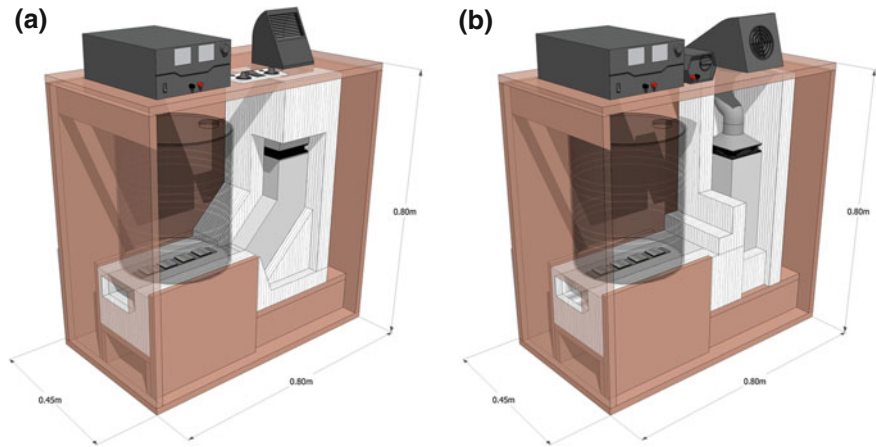
Fig. 13.28 **a** Initial duct design with $2 \times 45°$ bends when turning from *horizontal* to *vertical* causing less turbulence and lower pressure drop. **b** Fabricated design for cost economy with a 90° elbow

During one of the preliminary test for the field trial prototype (Fig. 13.35), one of the units (FT1) had a supply air temperature close to ambient even though the cooling fins were about 4 °C below ambient (Figs. 13.36 and 13.37), indicative of a leak in the system. The most likely cause of the leak was the gap between the straight edges of the fan enclosure and the MDF duct. This region was patched with a foam tape (Fig. 13.38) which eliminated the problem.

13.6 Manufacture

After cutting on a CNC router (Fig. 13.39a), assembly and installation of hinges, castors and piston stays (Fig. 13.39b), the pedestal was varnished with two coats of polyurethane (Fig. 13.40). Despite being left to dry for a week, it was still off-gassing an odour for months after application and a distinct smell of the solvent was noticeable upon entry into the office in the morning. In future it should be either left unfinished or finished with a water-based varnish.

In the early stages of prototype testing, before the cooling fins were enclosed, the indicator used was dT(ini)—the temperature difference between the initial temperature and the current one. This was measured by using a thermocouple connected to a digital multi-meter (accuracy ±2 %) with PC connection and logged for 8 min at 1 s intervals. After 8 min the temperature would typically stabilize.

As the conductivity of aluminium is about 10,000 times that of air, any imperfections in the surfaces (like dents and burrs), especially in the 2 mm aluminium spacers, could push the fins apart. Even a microscopic film of air would reduce the conductivity of the cooling fin assembly by a few orders of magnitude.

Fig. 13.29 Isometric design
of duct, funnel and cooling
fin assembly
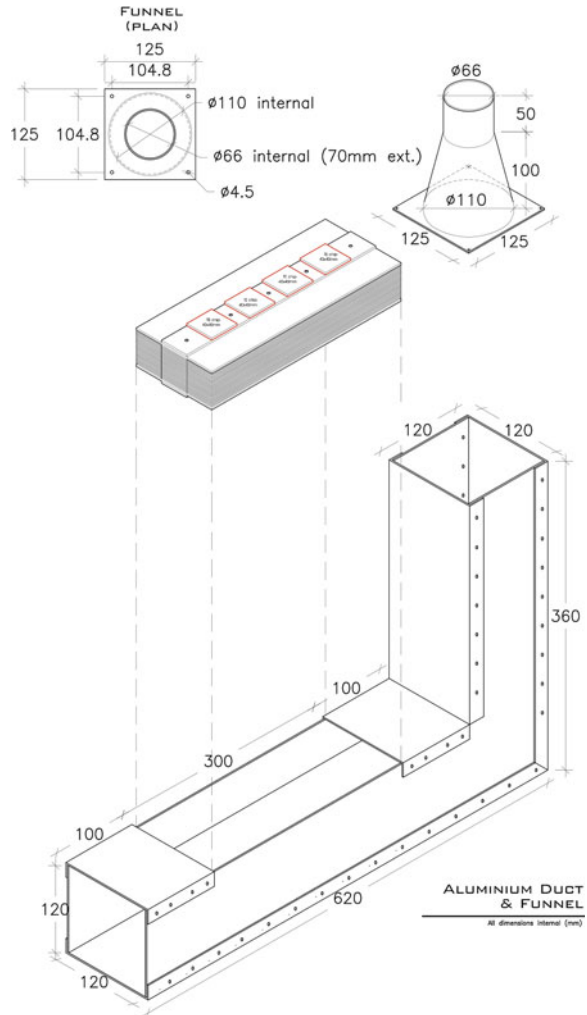
The dT(ini) tests thus gave early feedback if performance had been compromised
at any point in the assembly of DTAC. Figure 13.41 shows an example of the tests
done during the following stages:

- Tank for PCM, TE modules and cooling fin held by clamps
- Clamps removed
- Tank and cooling fins moved into pedestal
- PCM added, fan off
- Fan switched on.

An axial fan (120 mm) was used to move the air through a honeycomb and
funnelled to a 70 mm diameter outlet where wind velocity was measured by a vane
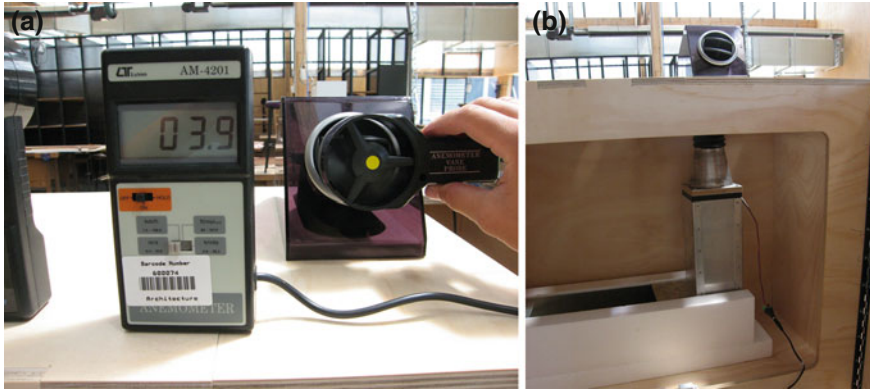
Fig. 13.30 a Air speed measurement from blower grille, **b** blower grille connection to duct

Fig. 13.31 Cooling fins to half the duct height with lower half blocked with polystyrene. Foam tape around the polystyrene block prevented air flow from bypassing the cooling fins

anemometer. No fan controller was used. When the fan was switched on the velocity was between 2.3 and 2.4 m/s.

Similar dT(ini) tests were run at different voltages for the TE modules which were rated for a maximum input voltage of 15 V. Near this maximum voltage the heat produced on the hot side of the modules could not be effectively removed, causing the cold side to rise above ambient temperature. The best outcome was achieved by running the modules at 7.5–10 V as seen in Fig. 13.42.

13.7 Cooling Fin Assembly

13.7.1 Design

Based on earlier concept of a vertical heat-exchange configuration, it was possible to select an off-the-shelf fan assisted heat sink. However, the fin arrangement was
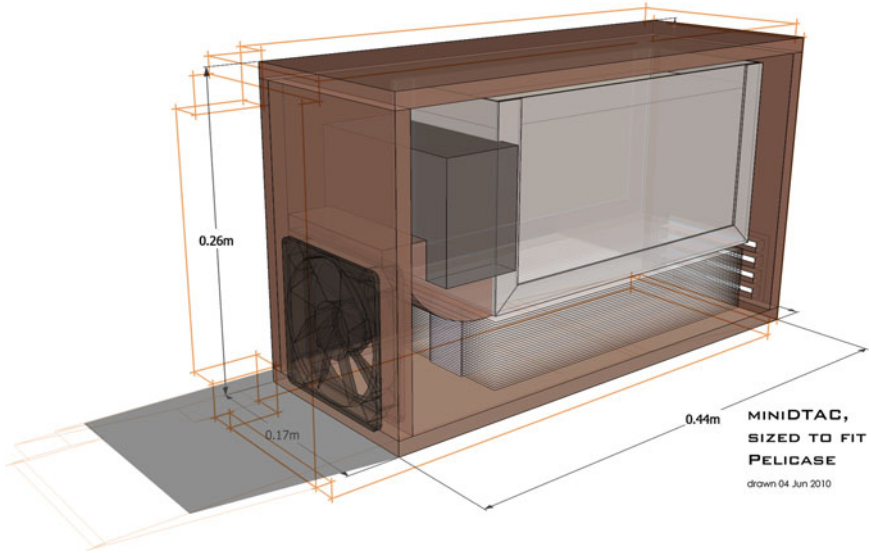
Fig. 13.32 Mark2 with a curved funnel. This prototype showed too much turbulence and a honeycomb was deemed necessary. In addition the cooling fins were repositioned at the windward side of the fan in subsequent prototypes
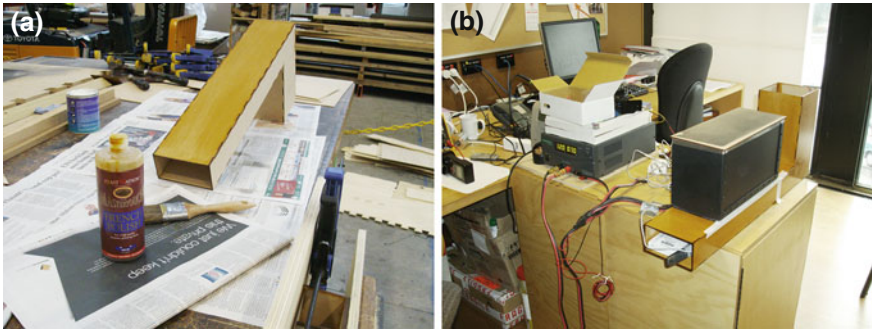
Fig. 13.33 **a** Laser cut 3 mm MDF duct being glued with PVA and coated with two coats of shellac for air-tightness, **b** shown here being used with Mark 2 tank

not suitable for ensuring that the fin T and airstream T were close in magnitude. A cooling fin was designed as a honeycomb with TE modules on either side of the fins (Fig. 13.43).

There were however risks that the heat from the PCM tank had many possible return points into the supply air stream (Fig. 13.44). This design also required very tight tolerance between PCM heat sink—TE modules—cooling fin honeycomb on both sides.
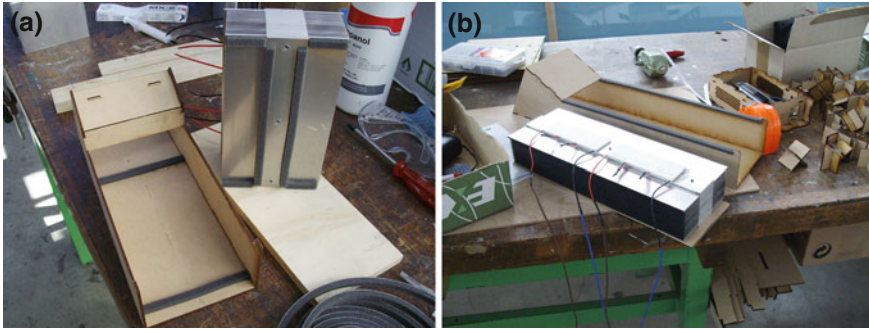
Fig. 13.34 MDF ducts redesigned for minimal bends subsequently used for **a** Mark-3 and **b** Mark-4
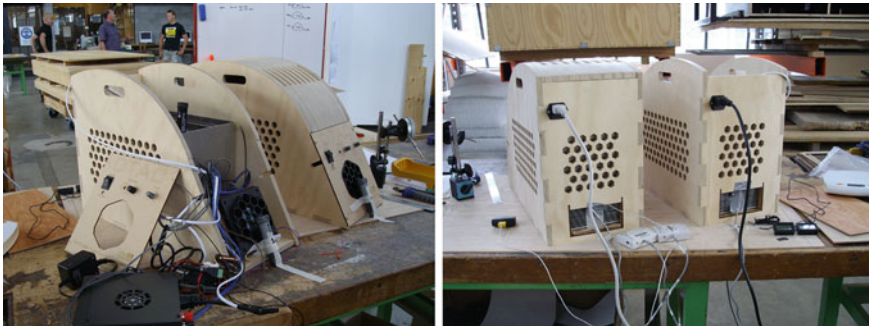
Fig. 13.35 Test of field trial (*FT*) units, FT_1 and FT_2

For ease of fabrication the cooling fin was redesigned to have all TE modules on only one side (Fig. 13.45). The fins were protrusions of 0.6 mm plates sandwiched in 2 mm spacers as the central core (Fig. 13.46). The fin density was determined as what was required for forced convection to ensure adequate interaction of the air stream and fins. The heat extracted from the fins would be transported to the central core and pumped to the PCM by the TE modules. The central core was designed around the 40 mm dimensions of the TE modules and the fin lengths were 40 mm on each side to meet the duct dimensions for fitting a 120 mm fan.

13.7.2 Cutting, Filing and Cleaning

A guillotine was available in the workshop to cut aluminium. However, the spacers needed to be 'dead flat' with no bends in the pieces and were thus cut commercially by laser. The laser left burrs on one side of the plates as some of the molten aluminium did not vaporise and re-solidified on the underside. This was found to
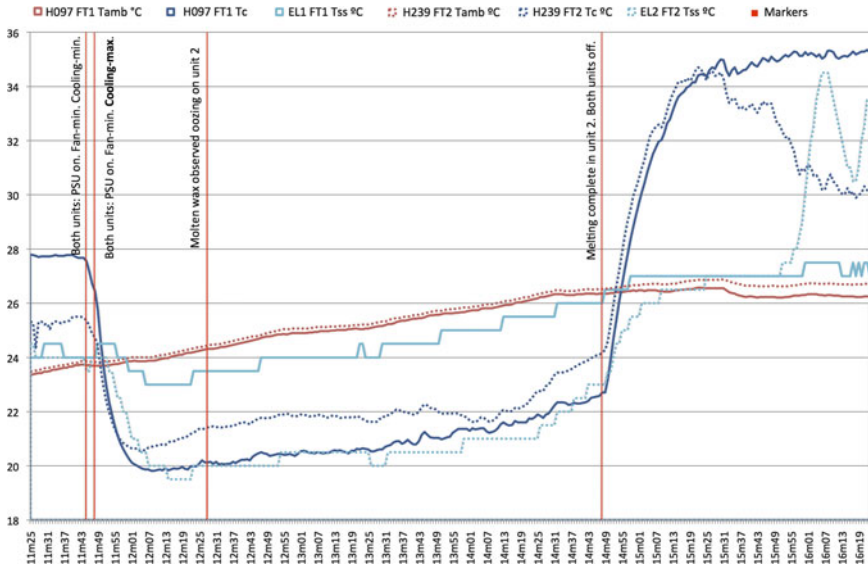
Fig. 13.36 Two units of field trial DTAC, FT$_1$ and FT$_2$ being tested concurrently. Readings from placements are colour coded, with solid line for FT1 and *dotted* for FT$_2$. T-ambient (*reds*) shows a close match of conditions. T-cold side (*dark blues*) show a match of about 1 °C. T-supply air (*cyans*) indicate that FT$_1$ (*solid line*) is supplying air that is only very slightly cooled. This cannot be due to a malfunctioning heat exchanger as the cold sides are showing significant lower than ambient temperatures. This is most likely due to a leaky system so that the fan is not drawing air through the cooling fins but predominantly from the ambient. FT$_2$ (*dotted*) is supplying air colder than the cold side. This is certainly not the case in reality. The method of adhering the Hobo sensors to the cooling fins will read a higher than actual temperature, and is an acknowledged weakness in this measuring procedure

be a greater problem with the thicker plates due to the higher conductivity of their larger sections. Burrs on the edge were removed manually with a single-cut file, and from the holes with a countersunk drill (Fig. 13.47). All the fins and plates were then cleaned with industrial grade (99.8 %) isopropyl alcohol.

13.7.3 Cooling Fin Selection

The spacers had a variety of defects. Those with no visible defects were classified as "Grade A". Those with minor scratches and pits were "Grade B" and those with minor bumps "Grade C". Those with scratches and pits would still have the majority of the surface in contact with adjacent plates, whereas those with bumps, often as a result of molten splatter, would trap a film of air, with significantly lower conductivity. The spacers were then assembled in the order A–B–C with the best quality spacers nearest the TE modules.
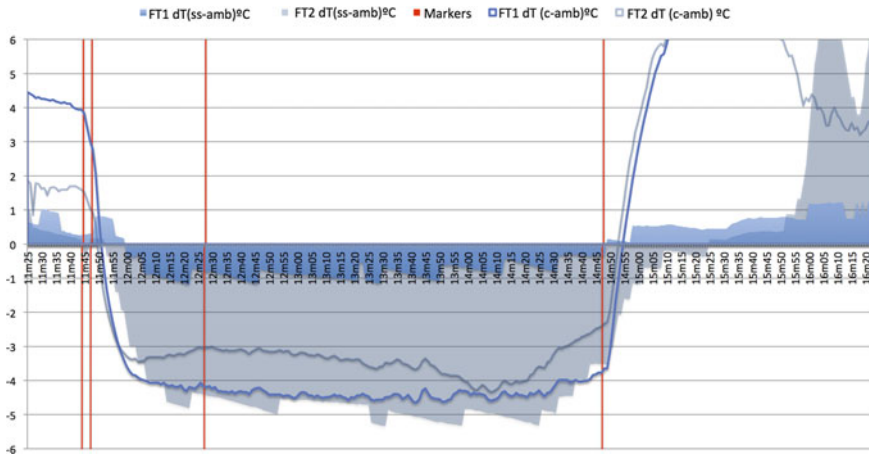
Fig. 13.37 Same data as above presented as ΔT. *Shaded areas* show ΔT (supply T-ambient T), and *lines* show ΔT (cold T-ambient T) FT$_1$ is being cooled (*blue line*) by 4–5 °C but supply air is only slightly below ambient (*blue area*). FT$_2$ is cooled (*grey line*) by 3–4 °C but supply air is colder than cooling fin (*grey area*). This confirms the earlier suspicion that FT$_1$ is leaky and the cooling fin temperatue of FT$_2$ is inaccurately read
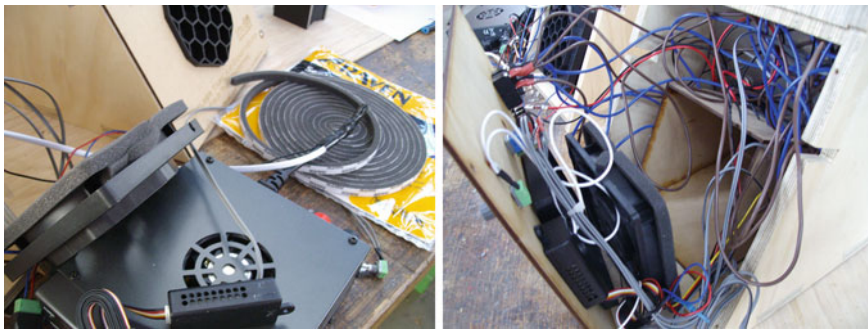
Fig. 13.38 Foam weather tape around fan to ensure a snug fit

The assembly was bolted down with small bolts ($\emptyset = 4$ mm) to keep the spacers in contact with the fins (Fig. 13.48).

13.7.4 Assembling the Cooling Fin

The fins were initially intended to be simply bolted together with the bolts pressing the plates together for sufficient contact. A quick test with 2 TE modules and an aluminium heat sink gave a result of ΔT of 0.5 °C below ambient when measured from the furthest fin (Fig. 13.49). The spacers were rebolted with a layer of MX2

Fig. 13.39 **a** 12.5 mm plywood after being cut by the CNC router, **b** assembly and attachment of ironmongery

Fig. 13.40 Application of polyurethane varnish

thermal transfer paste (Fig. 13.50, thermal interface materials will be discussed in depth in the next section) to give ΔT of 2 °C below ambient.

To build a more robust cooling fin assembly for transport in Mark-2 and Mark-3, thermal adhesives were used. This required a more complex assembly as the 2-part epoxy-based thermal adhesive would cure within minutes once mixed. Two each of spacers and fins were glued and clamped for 5 min before the next batch of adhesive was mixed (Fig. 13.51). This resulted in an inseparable assembly that also required a long time to fabricate.
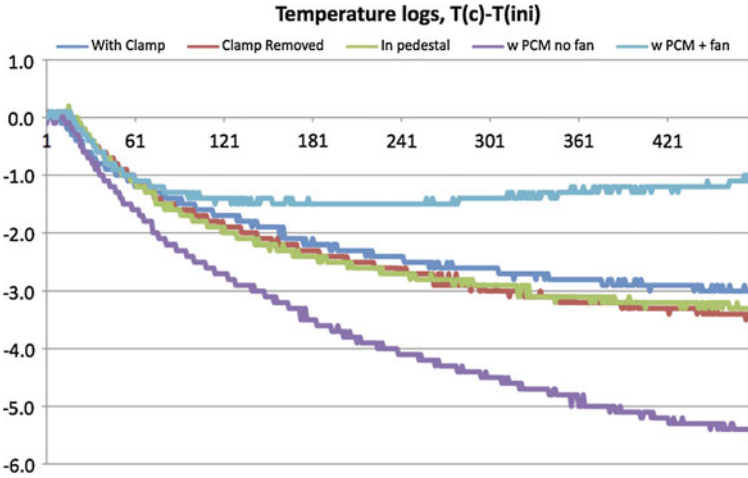
Fig. 13.41 dT from initial temperature at various stages in assembly
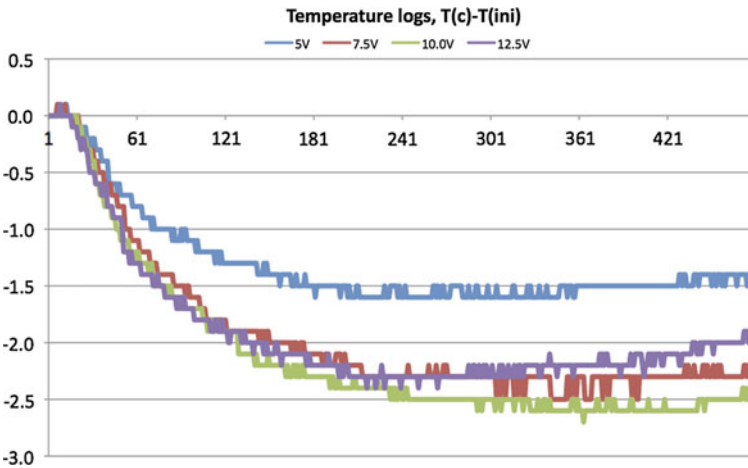
Fig. 13.42 dT from initial temperature applying different voltages across TE modules

It was difficult to ensure that the cooling fins were being pressed level with clamps, as one side could be tighter than the other. A pressing rig was constructed for Mark 3 to keep the press level (Fig. 13.52). In Mark 4, the torque was measured with a hanging scale to keep the pressure level on both sides of the rig (Fig. 13.53).

The force on the press could be determined with the following equation, rearranged from Laird Technologies (2010):

$$F = \frac{\tau N}{kD} \tag{13.1}$$

F	press force	N
τ	torque	Nm
N	number of bolts	2
k	coefficient of torque	0.2
D	diameter of bolt	0.012 m
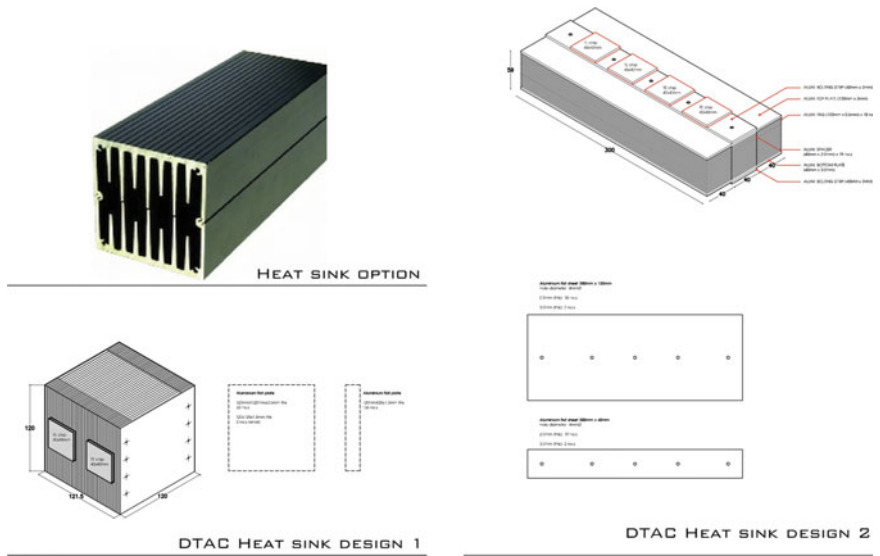
Fig. 13.43 Cooling fin selection and development: "heat sink option" an off the shelf fas-assisted heatsink suitable with an 80 mm fan was later felt to be unsuitable as the air stream will be moving too quickly through it and remain close to ambient temperature. "Design 1" was the initial design for cooling fins in a vertical position, later felt to be unsuitable as heat will not conduct well from fins to heat pump. "Design 2" is based on a core where the bulk of conductive heat transfer occurs, before spanning to individual fins

At a final torque of 90 N × 0.32 m, the press force on the cooling fins assembly was about 2.4 tons.

13.7.5 Coating on Cooling Fins

Since the radiant transfer could be improved significantly with painting, in the final field trial prototype (Mark-4) the cooling fins were coated in two layers of spray paint (Figs. 13.54 and 13.55).
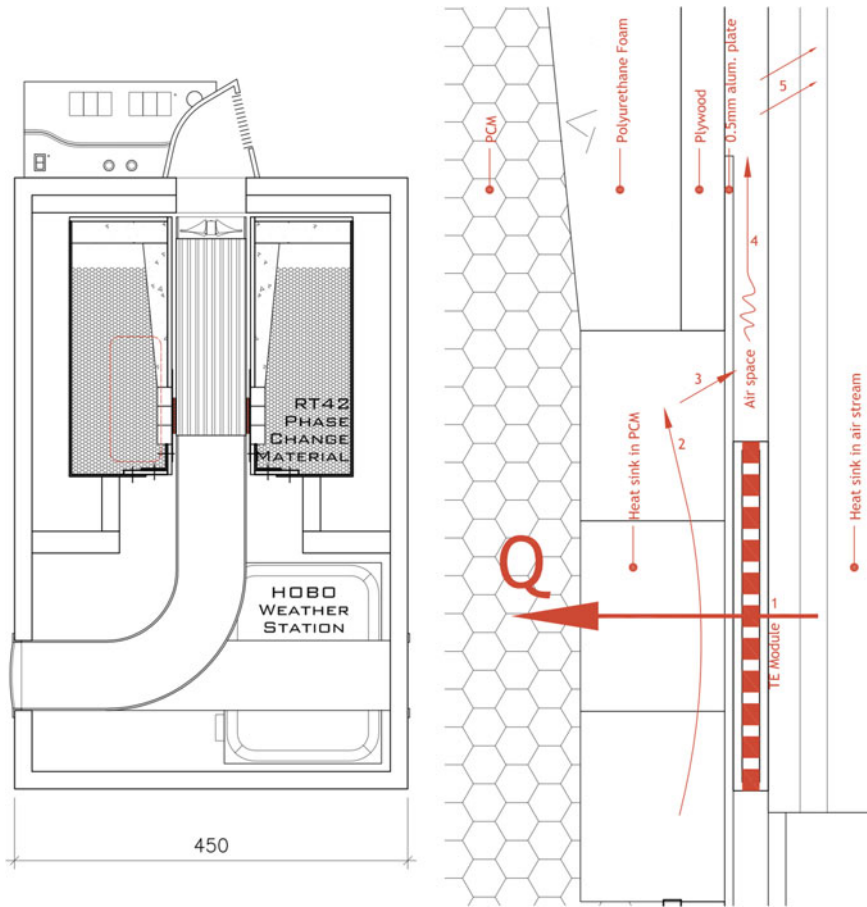
Fig. 13.44 Issues found with working with a vertical cooling fin design: (*1*) Heat removed from air stream by TE modules to the PCM. An aluminium plate is screwed into the plywood with a sealant to precent PCM leakage. (*2*) To assist in the transport of heat, aluminium fin/pin heat sinks help to dissipate the heat. Polyurethane foam is proposed to prevent heat from PCM returning to the air stream. (*3*) However, heat from the heat sink will still convect in the air cavity. (*4*) The heated plume will rise the height of the heat sink and may leak back into the supply air stream. Note that TE modules need to be at the bottom as the PCM expands 16 % when melted. (*5*) Throughout this time, heat will be conducting back into the cooling fins

13.7.6 Performance of Cooling Fins

The fin bypass efficiency can be determined by the following equation:

$$\eta_{bypass} = 1 - \frac{T_{ss} - T_{amb}}{T_c - T_{amb}} \tag{13.2}$$
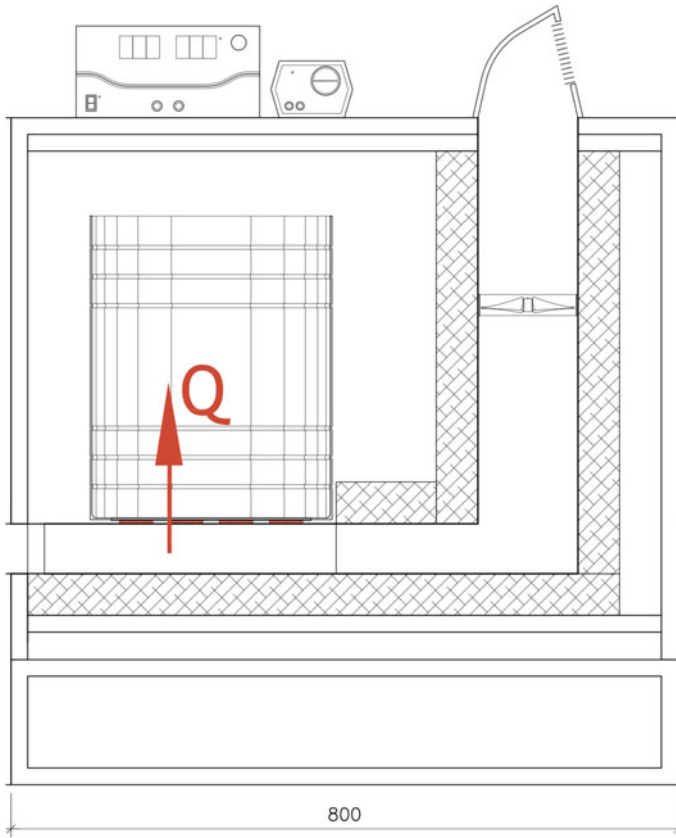
Fig. 13.45 Merits of adopting a horizontal heat sink arrangement. By separating the PCM tank from the air stream, much better insulation can be achieved with more economical insulation (50 mm expanded polystyrene). The convective effects of a rising hot plume are also avoided by having the PCM above the cooled air stream. The PCM tank, thus separated, can be more accessible for change and will have less leakage problems compared to the previous design. However, condensation is not easily drained in this configuration

However, the cold side temperature was difficult to determine with the fins each having a slightly higher temperature as they were spaced further from the TE modules. Another approach was taken using supply-ambient air temperatures, and the cooling output of the TE modules based on manufacturer's data sheets. It was determined that the cooling fins delivered only 16 % of the potential cooing power (Table 13.3).
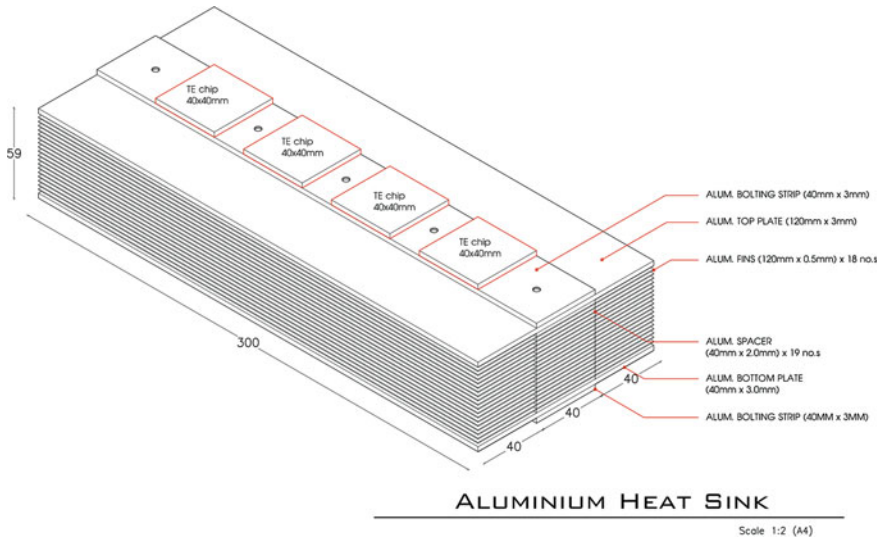
Fig. 13.46 Detail of cooling fin assembly
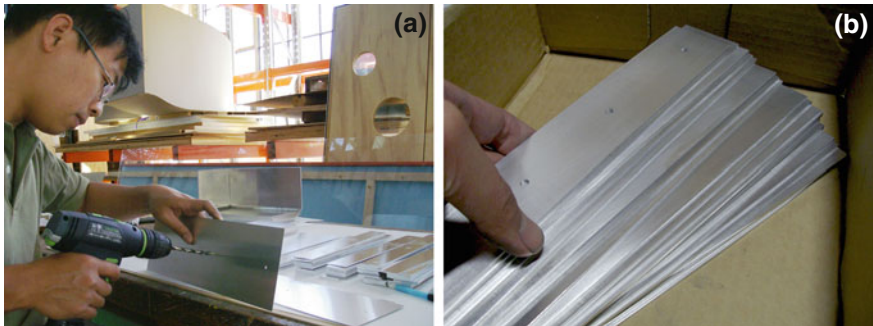
Fig. 13.47   a Plates being counter sunk to remove any burrs from the laser process. **b** Spacers after being filed and cleaned

13.8 Thermal Interface Materials

Thermoelectric modules (TEMs) maintain a ΔT between the two sides, often referred to as the hot and cold terminals. The notion of a 'cold' terminal may, however, be misleading. If heat from the hot junction is not removed, a fully loaded TEM (15 V, $\Delta T = 40$ °C) will have the hot side heated in excess of 120 °C within a few seconds. The 'cold' side would follow closely at a scalding 80 °C. In order for the cold side to be below ambient, the hot side should not be allowed to exceed 60 °C, and ideally should not exceed the melting point of the PCM by a few degrees celsius.

Fig. 13.48 Cooling fins assembled with bolts

Fig. 13.49 Setup to test efficacy of heat transfer through the spacers of the cooling fin

Direct contact with the aluminium heat sink did not provide sufficient conductivity to get T-cold to be under ambient. The conductivity of air is 4 orders of magnitude lower than aluminium (Table 13.4) and even a microscopic film of it would require a significant dT to conduct heat (Fig 13.56).

The ΔT required to transmit heat Q across a micrometer (μm) thickness was determined with the following equation:

$$\Delta T/\mu m = \frac{Q}{k \cdot A \cdot 10^6} \tag{13.3}$$

Q	heat flow	60 W
k	conductivity	W / mK
A	area of TE module	$0.04x0.04\,\text{m}^2$
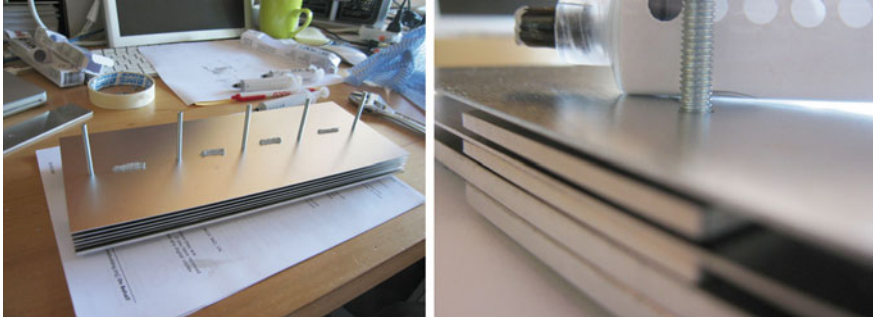
Fig. 13.50 Application of MX_2 thermal paste between layers
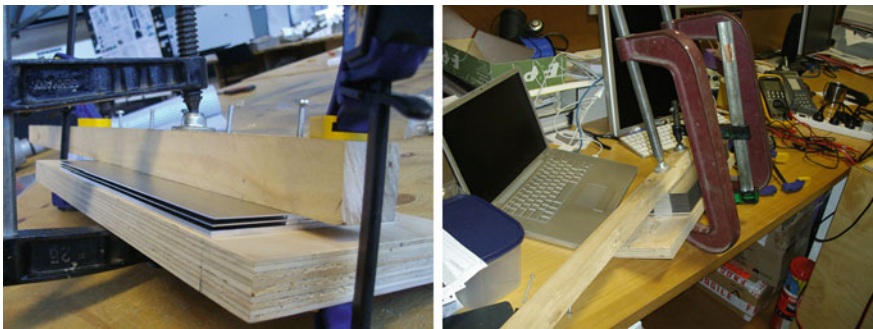
Fig. 13.51 Fins were pressed wit clamps to minimise thickness of thermal interface material. With the thermal adhesive it was assumed that the compactness will remain even when the clamps were taken off

Fig. 13.52 **a** Mark-3 fin press. **b** Mark-4 fin press

Fig. 13.53 Hanging scale being used to determine torque applied equally to both bolts on threaded rods
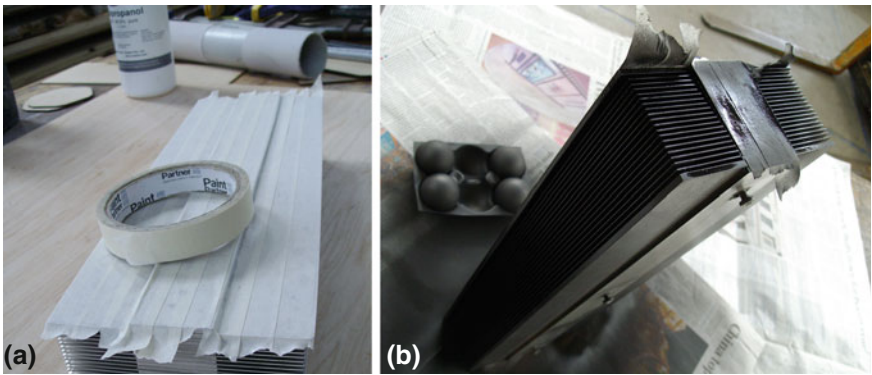
Fig. 13.54 **a** The top plate of the cooling fin assembly was masked to retain its low emissivity, and reduce radiant heat gained from the underside of the tank. **b** Each sweep of the spray was targeted parallel to the fins to coat as far into them as possible
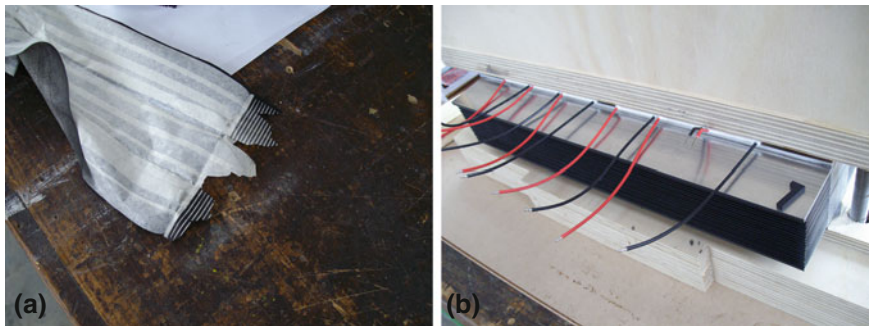
Fig. 13.55 **a** Masking tape check to see that the paint had reached the 40 mm depth on either side of the spacers. **b** Painted cooling fins being assembled with TE modules

Table 13.3 Determination of cooling fin efficiency

T_{amb}	24 °C	Measured (Hobo logger)
T_{ss}	20 °C	Measured (Hobo logger)
T_h	50 °C	Assumed
V	8 V	Read from PSU
I	4.5 A	Manufacturer data sheet
Q_c	35 W per module	Manufacturer data sheet
v	0.6 m/s	Measured (vane anemometer)
H_{amb}	54.60 kJ/kg	Psychrometric software (HR: 12 g/kg assumed)
H_{ss}	50.48 kJ/kg	Psychrometric software (HR: 12 g/kg assumed)
vol_{spec}	0.85 m^3/kg	Psychrometric software
$\dot{vol}$	0.00678 m^3/s	$v \times \pi \times (\emptyset/2)^2$
$\dot{mass}$	0.007974 kg/s	$\dot{vol}/vol_{spec}$
P_{cool}	32.8 W	$(H_{amb} - H_{ss}) \times \dot{mass}$
$6 \cdot Q_C$	210 W	6 modules
Cooling efficiency	16 %	$P_{cool}/6 \cdot Q_C$

Table 13.4 Conductivity of materials

Material	Conductivity (W/m·K)	$\Delta T/\mu m$
Aluminium {Szokolay 2008}	236	<0.001 °C
Aluminium grade 5052 (manuf. specs.)	138	<0.001 °C
Aluminium grade 5083 (manuf. specs.)	120	<0.001 °C
Air {Szokolay 2008}	0.025	1.5 °C
Silicone {engineeringtoolbox.com}	0.1	0.375
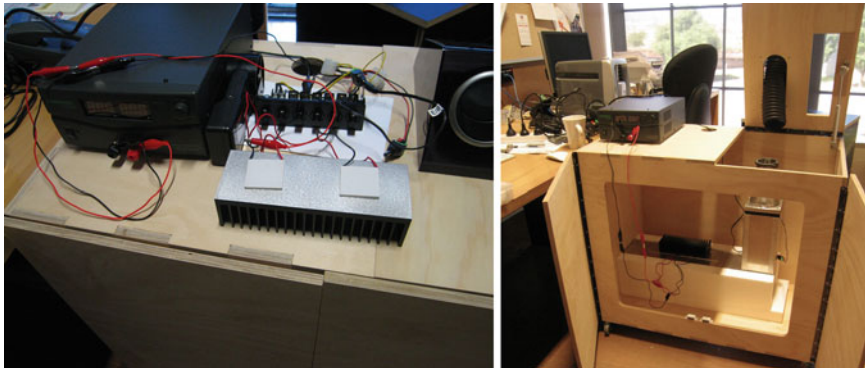
Fig. 13.56 TE modules placed in direct contact with heat sink with no effect. Without a TIM the heat transfer was minimal

In order to exclude air from impeding the heat exchange, a variety of thermal interface materials (TIMs) were used, with the cheapest options tested first. The following factors proved significant to the right selection of TIM:

1. Workability

2. Containment
3. Rigidity
4. Conductivity.

13.8.1 Workability

Though the generic heatsink compound with 25 % silver particles had reasonably high conductivity it was difficult to work with. Surfaces had to be cleaned before the compound was spread on with a credit card. A measure of skill was required to ensure it was applied evenly. When performed across multiple modules it was difficult to determine if they were all of equal thickness. It was was also humanly impossible to ensure that no air became entrapped when the PCM tank was subsequently pressed over it (Fig. 13.57).

13.8.2 Containment

The application of proprietary thermal compounds from the *Arctic Silver*® (a specialist supplier of TIM) could overcome a number of these limitations. Applied as a blob in the centre of a cell, it would spread over the surface when pressure was applied. This excluded the air from the mating surfaces and compensated for the variability in thicknesses between TE modules. To be effective, the compound had to be applied liberally to spread over the surface completely. These products were however designed for CPU applications where it did not matter if it bled over the edge of the chip, as long as it did not conduct electricity. However, with TE modules, the hot and cold terminals had to be thermally broken and any excess compound that flowed beyond the hot surface could become a thermal short-circuit with the cold junction (Fig. 13.58).
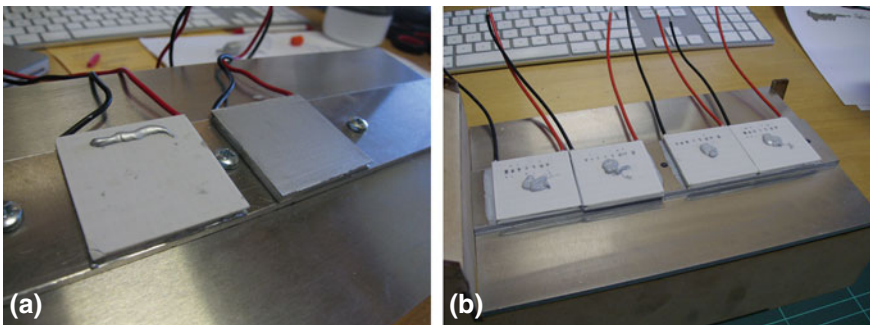

Fig. 13.57 a TE module on left has a blob of silver particle themal paste. When spread evenly it will look like the module to its *right*. **b** An alternative TIM, the Arctic Silver® MX2 compound. Manufacturer's recommendation to dispense a blob and apply pressure with heat sink to spread it
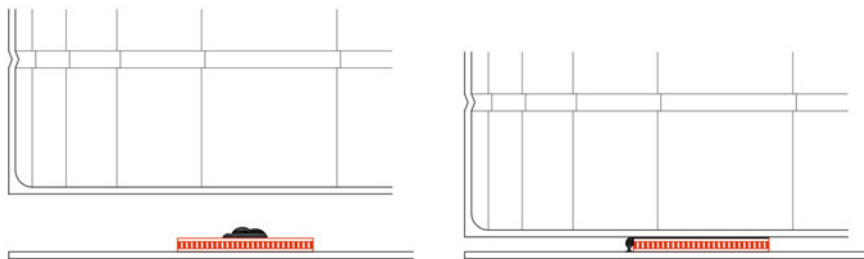
Fig. 13.58 Thermal bridging as excess paste bled over the edge

Fig. 13.59 CAD of mould
silicone jacket for TEM
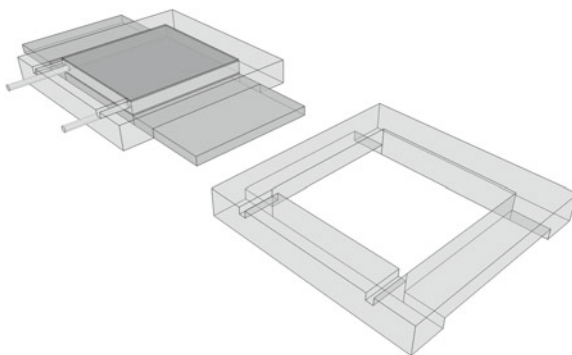
The overflowing of the compound could be overcome by designing a silicone
spacer that fitted snugly over the TEM in order to keep the surfaces separate and
prevent the compound from overflowing (Fig. 13.59).

The moulding design however required far more expertise than the researcher
had and did not cure and release from the mould properly (Fig. 13.60).

13.8.3 Rigidity and Conductivity

To circumvent the thermal short-circuit, a solid TIM was evaluated. This was a
0.5 mm thick thermal transfer pad that had adhesives on both sides, something
similar to a foam double-sided tape (Fig. 13.61). It was easy to cut to the exact
dimensions with no bleeding, easy to apply and being slightly compressible, it
could tolerate the variation in height across the TE modules, and, more signifi-
cantly, the PCM container base. The adhesive had a measure of tackiness which
could also tolerate vibrations and movement better, being able to re-adhere itself.

The pads were applied with a 3 mm aluminium hot-plate sandwiched between
the hot junction and the tank (Fig. 13.62). The infra-red reading of the hot-plate
would give an indication of the T-hot, from which the T-cold could be estimated
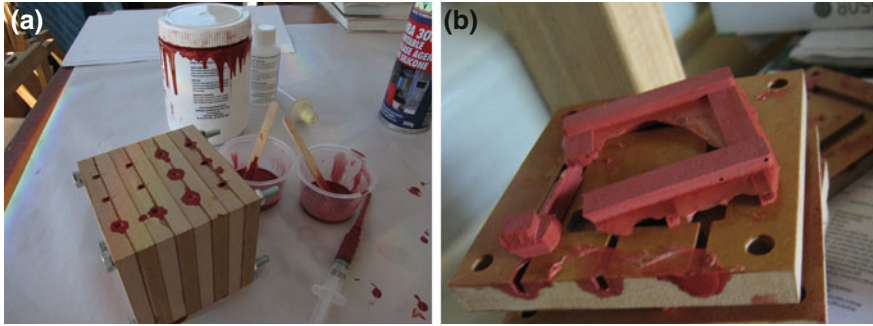
Fig. 13.60 **a** Mould cut into MDF and silicone injected into mould. **b** Silicone pads breaking as they did not release properly from the moulds
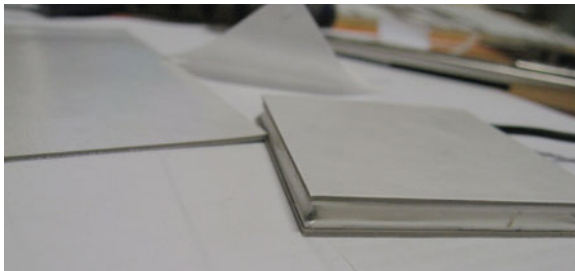
Fig. 13.61 Thermal transfer tape affixed to both sides of module
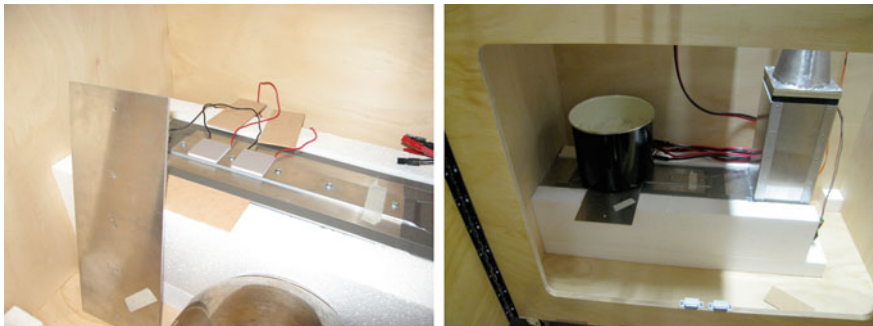
Fig. 13.62 An aluminium "hot plate" positioned between TE modules and PCM tank to give a reading of T-hot

based on the ΔT for given voltage-current combinations. As a rule-of-thumb, ΔT (TE modules) was taken as 30 °C.

Due to its lower conductivity and greater thickness these pads required a significantly higher ΔT to drive the same amount of heat (Table 13.5). With the thermal transfer pad, the hot side had to be more than 12 °C above PCM melting

Table 13.5 Conductivity and thickness of TIM

Thermal interface material	Abbreviation	Conductivity (W/mK)	Nominal thickness (mm)	ΔT (for 60 W) (°C)
Generic 25 % silver heatsink compound		4	0.1	0.9
Thermal transfer tape		1.6	0.5	11.7
Arctic Silver® MX-2 Compound	MX2	∼8	0.1	0.5
Arctic Silver® 5	AS5	∼8	0.1	0.5
Arctic Silver® 2-part epoxy adhesive	2PEA	∼8	0.2	0.9

Conductivities are often not available and are estimated based on comparative performance

point, and the cold side more than 12 °C below ambient before the any heat could be transferred from air stream to PCM, creating an extra 24 °C burden on the TE modules to pump heat against. It was clear that this was the crucial failure of a thick and thermally resistive TIM.

13.8.4 Coming Together

For TIMs to work well, there needs to be minimal thickness. This requires the TE modules to be levelled, and all plies of the cooling fin to be pressed securely (Figs. 13.63 and 13.64).

In Mark 1, to simplify the variables a high quality thermal paste was used (MX2). Mark 2 was designed as a portable prototype and 2PEA was used throughout. However, this meant that no parts could be recycled. With this consideration, Mark 3 had a permanent bond on the cooling fins (2PEA) and a semi-permanent interface between the TE module and the tank with MX2. Each layer was glued, clamped and left to cure. As this process was very laborious, in Mark 4, the cooling fins were not permanently fixed. A bead of AS5 or MX2 was applied on the spacer, and a few layers were pressed together in one go. The TIMs used are tabulated in 13.6.

The appropriate use of TIMs are highly specific to manufacturer's specifications. With the use of Arctic Silver® MX2, the best conductivity, according to the manufacturer, is after the CPU has gone through a few cycles of intense use. This is because the paste has a reduced viscosity at higher temperatures (>60 °C) and flows into the microscopic gaps to improve conductivity. If fins were to be manufactured according to the methods for this prototype it would be recommended that heat (e.g. from a heat gun) be applied to the cooling fins to a temperature of 60–80 °C whilst they are being held in the pressing rig.
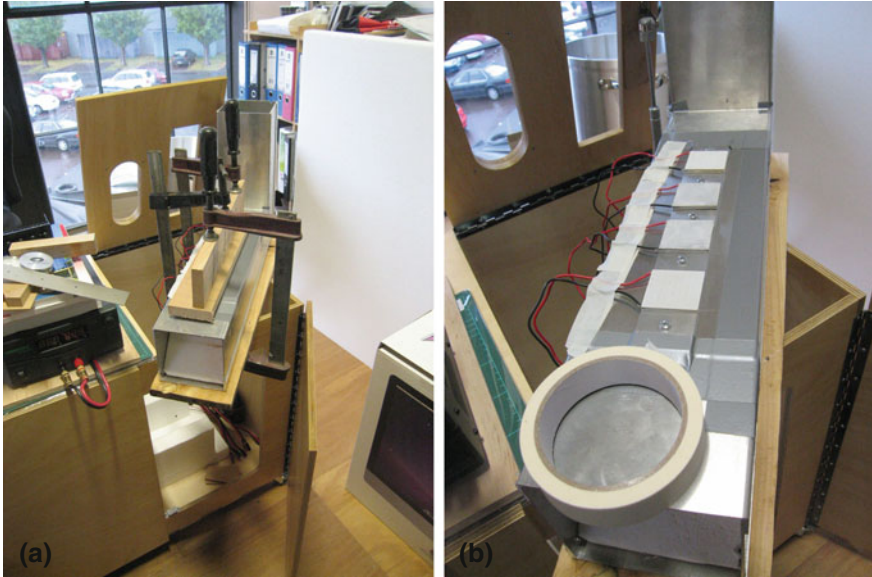
Fig. 13.63 **a** TE modules being clamped to cooling fins with an MX$_2$ TIM. **b** TE modules after pressing

Fig. 13.64 Checking levelness of TE modules after pressing
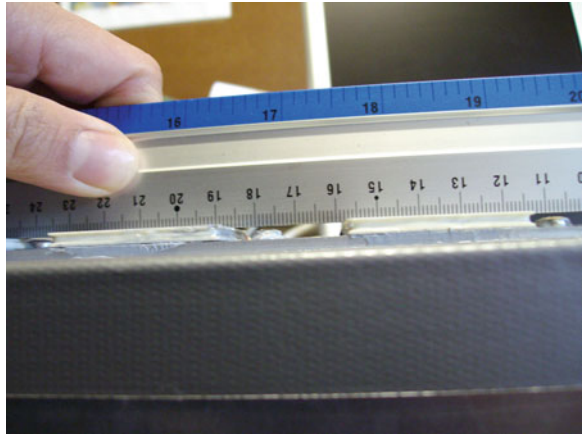
13.8.5 Coating on Tank

In order to take accurate thermal images, the tank was painted with two coats of matte black spray paint to increase the emissivity (Fig. 13.65). This greatly increased the accuracy of the thermographs and also reduced the erroneous reading of reflections (Fig. 13.66). However, the angle of incidence had to be maintained at close to the normal. Angles too obtuse rendered a cooler reading than at a normal angle.

Table 13.6 TIMs used in the prototypes. MX_2: AcrticSilver MX_{-2}; AS_5

	Mark 1	Mark 2	Mark 3	Mark 4
TE hot side	MX2	2PEA	MX2	MX2
TE cold side	MX2	2PEA	2PEA	MX2
Cooling fins	MX2	2PEA	2PEA	AS5 or MX2
Inner tank	–	2PEA	2PEA	2PEA

Arctic Silver® 5; 2PEA: Arctic Silver® 2-part epoxy adhesive

Fig. 13.65 Tank and fins coated with 2 layers of matte *black spray paint*

The tank was expected to be fully molten by under 30 min. The experiment however ran for almost 5 h before the surface of the tank was consistently and clearly above the PCM melting point (Fig. 13.67).

Even thought the surface area to volume ratio was significantly higher with a small tank, such an outcome was not expected. This prompted a calculation to compare the convective heat loss with the radiant loss of

1. uncoated aluminium ($\varepsilon = 0.10$)
2. matte black paint ($\varepsilon = 0.95$).

The calculations are elaborated in the next section and summarised in Table 13.7.

The calculations show how the radiant heat loss of the uncoated aluminium tank would have been about half that from convective heat loss. However, the application of the paint resulted in the radiant heat loss being 4.5 times that of convection. Whist this would allow the same amount of PCM to melt over a longer period, the heat would have been immediately released back into the environment, which would contradict the intent of using the PCM tank as a thermal store.

The tanks in future prototypes were never painted, but were cleaned instead to reduce emissivity from the layer of dirt accumulated during fabrication. However, with the striking difference in the overall heat transfer with a high emissivity paint, the paint was put to a different application, for example on the cooling fins.
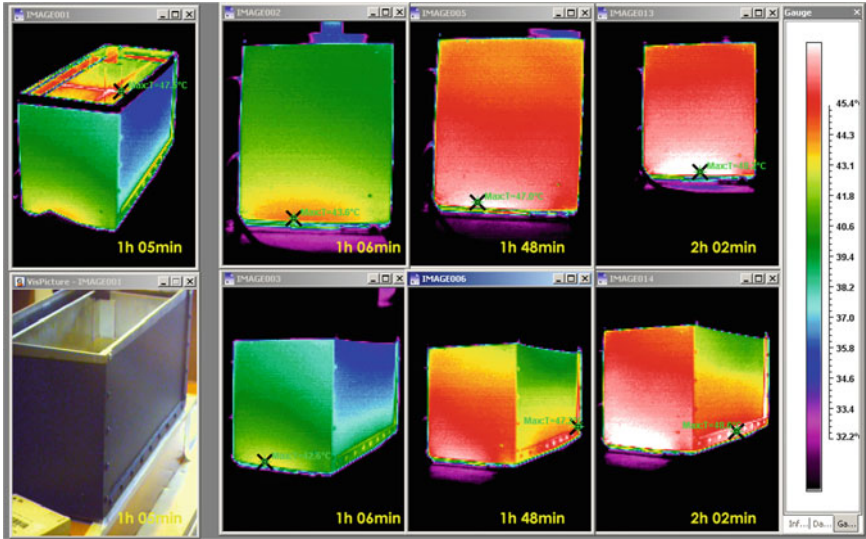
Fig. 13.66 *Black* painted tank with thermographs at normal (*above*) and at an angle (*below*) taken within seconds of each other
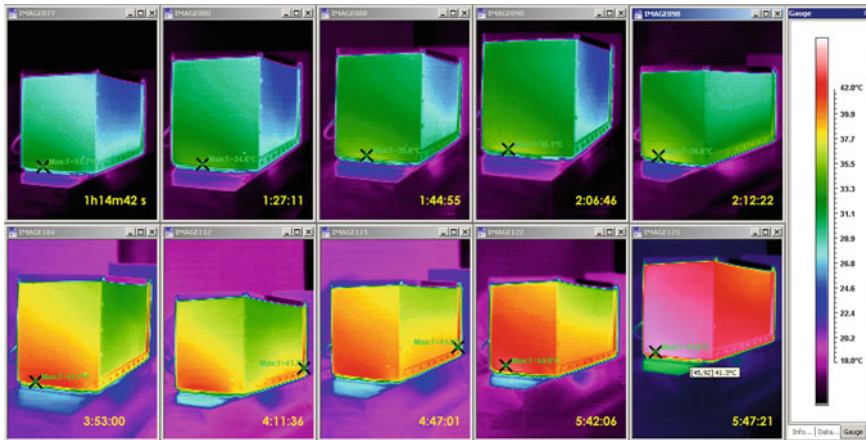

Fig. 13.67 Thermographs showing total melting after about 5 h

Table 13.7 Summary of heat loss quantities

Heat loss mechanism	Heat loss per unit area (W/m^2)
Convection	122
Radiation $\varepsilon = 0.10$	58
Radiation $\varepsilon = 0.95$	552

13.8.6 Determining the Heat Loss of PCM Tank to Convection and Radiation

Calculations following are based on Incropera and DeWitt (2007).

Heat balance of PCM tank:

$$q = q_{conv} + q_{rad} \tag{13.4}$$

To compare the convective and radiant heat loss per unit area,

$$\frac{q_{conv}}{A} = h(T_S - T_\infty) \tag{13.5}$$

$$\frac{q_{rad}}{A} = \varepsilon\sigma\left(T_s^4 - T_{sur}^4\right) \tag{13.6}$$

13.8.6.1 Heat Loss from Free Convection

For a flat plate

$$Ra_L = \frac{g\beta(T_s - T_\infty)L^3}{\alpha v} \tag{13.7}$$

Ra_L	Rayleigh number for flat plate	
g		9.8 m/s^2
$\beta = \frac{1}{T_f}$	where $T_f = 300\,\mathrm{K}$	$3.33 \times 10^{-3}\,\mathrm{K^{-1}}$
T_s	Surface temperature	45 °C
T_∞	Ambient air temperature	20 °C
L	Characteristic length	0.2 m
α	Thermal diffusivity	$2.25 \times 10^{-5}\,\mathrm{m^2/s}$
v	Kinematic viscosity	$1.59 \times 10^{-5}\,\mathrm{m^2/s}$

The free flow convection can be assumed to have laminar flow, with the following expression:

$$Nu_L = 0.68 + \frac{0.670 Ra_L^{1/4}}{\left[1 + (0.429/Pr)^{9/16}\right]^{4/9}} \tag{13.8}$$

Nu_L	Nusselt number for flat plate	
Ra_L	Rayleigh number for flat plate	1.82×10^7
Pr	Prandtl number	0.707

Heat transfer coefficient:

$$h = \frac{Nu_L \cdot k}{L} \tag{13.9}$$

h	Convective heat transfer coefficient	W/m^{2}K
Nu_L	Nusselt number for flat plate	37.0
k	Thermal Conductivity	2.63×10^{-2} W/mK
L	Characteristic length	0.2 m

So the heat loss due to convention can be derived as follows:

$$\frac{q_{conv}}{A} = h(T_s - T_\infty) \tag{13.10}$$

h	Convective heat transfer coefficient	4.87 W/m^{2}K
T_s	Surface temperature	45°C
T_∞	Ambient air temperature	20°C

From which we find $q/A = 122\,\text{W/m}^2$

13.8.6.2 Heat Loss from Radiation

Radiant heat loss:
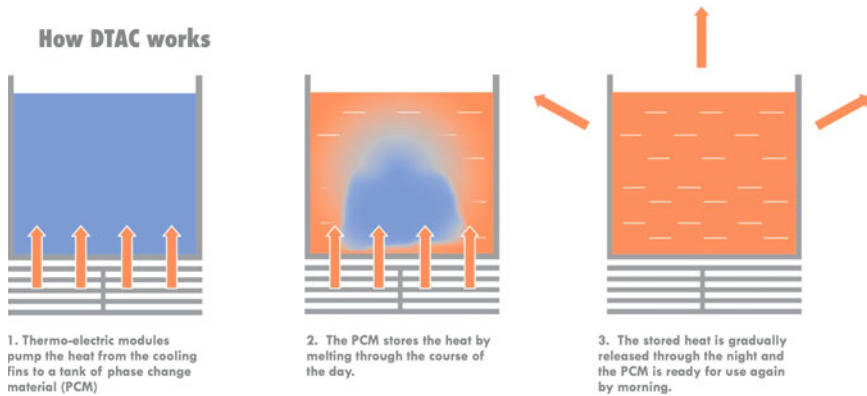
$$\frac{q_{rad}}{A} = \varepsilon\sigma\left(T_s^4 - T_{sur}^4\right) \tag{13.11}$$

ε	emissivity	
σ	Stefan–Boltzman constant	5.67×10^{-8} W/m^{2}K^4
T_s	Surface temperature	318 K
T_{sur}	Surrounding temperature	293 K

For uncoated aluminium ($\varepsilon = 0.10$), $q/A = 58\,\text{W/m}^2$ for matte black painted aluminium ($\varepsilon = 0.95$), $q/A = 552\,\text{W/m}^2$

How DTAC works

1. Thermo-electric modules pump the heat from the cooling fins to a tank of phase change material (PCM)

2. The PCM stores the heat by melting through the course of the day.

3. The stored heat is gradually released through the night and the PCM is ready for use again by morning.

Fig. 13.68 Simplified conceptual illustrations on how the PCM was melted and regenerated

13.9 Working with Phase Change Materials: The Magic's in the Box

The PCM tank was originally envisioned as merely a container for the PCM. Since the solid density was higher than the liquid form of the paraffin wax, it was expected that once melting was initiated, the molten wax would float to the surface and a continuous supply of solid wax will be gravity fed to the base until it was all melted (Fig. 13.68). In practice, there were more complications than anticipated.

13.9.1 Enamel Pot

The tank initially conceived was simply an empty tin of paint. However, these tins have a lip on the bottom rim that protrudes beyond the base. As a result the base of the drum will not rest on TE modules. A metallic container (with an enamel paint coat) which did not have protrusions was selected to replace the drum (Fig. 13.69).

A problem quickly emerged: the hot side of TE modules, T-hot, was at 85, or 45 °C in excess of the melting point of the PCM, before the PCM melted. At this temperature, even the cold side was above ambient and heated air was being supplied from DTAC. Clearly, for the supply air to be chilled, the primary issue was to keep T-hot as close as possible to 40 °C, the PCM melting point.

Two possibilities would have caused the elevated T-hot:

1. Heat was not reaching the tank
2. Heat in the tank was not effectively dissipated into the PCM.

Fig. 13.69 An enamel container was used to melt the PCM. To enable a reading of T-hot, a 3 mm aluminium plate was used with a contactless thermometer reading the infrared emission off a piece of masking tape

To improve the conductivity from TE module to tank, a silver heat-sink compound was used as TIM. It was found the spread was limited, indicative that the contact areas was much smaller than the TE surface. The enamel pot base was not level enough for effective conduction, and so a heavy-base saucepan was used instead.

13.9.2 Stainless Steel Saucepan

To ensure that the problem was not with the cooling fin assembly, a chilled saucepan (simulating refrigeration from the TE modules) was placed on aluminium spacers (to simulate the thickness of TE modules, Fig. 13.70) and on top of the cooling fins. A dT (supply-ambient) of −2 °C was logged for almost three hours.

Fig. 13.70 Stainless steel saucepan holding a water and a frozen bottle to simulate the refrigeration from TE modules
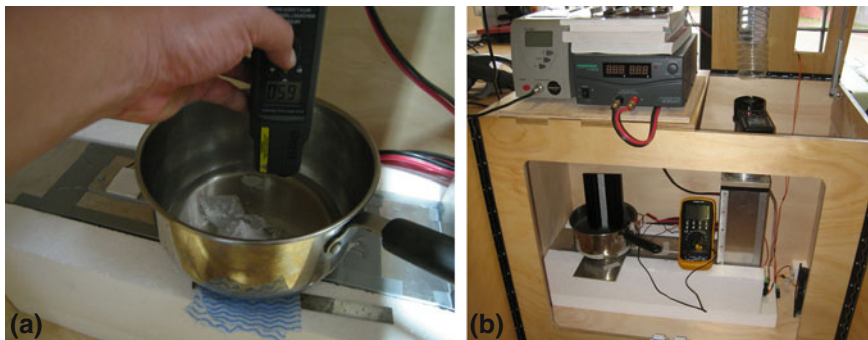
Fig. 13.71 **a** Fresh wax being added to the saucepan. T-hot with the saucepan was significantly lower than with the enamel pot but still significantly higher than PCM melting point. **b** A heat sink placed in the middle of the saucepan to allow molten wax to rise. However, solid wax continues to stick to the sides, away from the base and heat sink

Satisfied that if cooling was delivered to the fins there would be a recordable difference in air temperatures, the problem was narrowed down to either the TE modules or tank. The aluminium spacers were replaced with TE modules and the PCM melted in the saucepan (Fig. 13.71).

As fresh solid wax was being manually added to the tank (Fig. 13.71a), the dT was negative transiently. After the wax had fully melted and re-solidified, the cooling could not be repeated. In fact the molten wax, though less dense, did not float to the surface but was trapped between the hot base and the solid top. Even with a heat sink inserted to help the molten wax breach the surface the solid wax would stick to the tank walls and not sink (Fig. 13.71b).

If the wax could be made to sink, the base of the tank would naturally be kept close to 40 °C and enable the cold side of the TE modules to reach below ambient. It was clear that the tank conductivity was a key aspect to solving this challenge.

13.9.3 Aluminium Tiffin Tin

Since the challenge was to get the wax to sink consistently, this part of the problem could be compartmentalised and tested. A TE module was attached to the underside of an aluminium tiffin tin (of approximately 1 mm thickness), the wax melted, cooled and repeated. Working with a small quantity of wax permitted more tests to be performed each day, and experimenting outside the DTAC gave more flexibility to observe the wax (Fig. 13.71) and take temperature readings and thermographs (Figs. 13.72, 13.73).

After developing a method for getting the wax to detach and sink, the next step would be scale it back up and introduce the new tank to the DTAC.
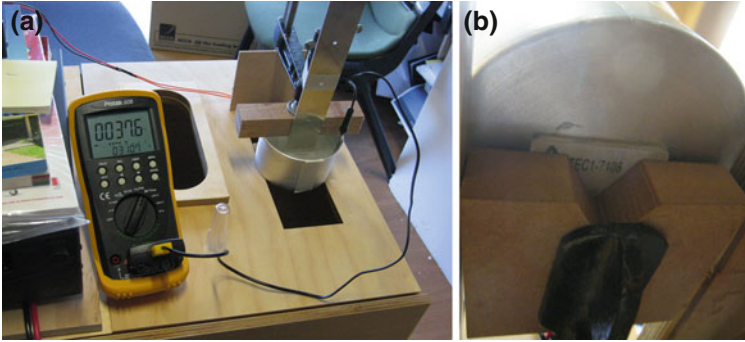
Fig. 13.72 a Observing if a highly conductive tank with a conductive strip would allow the wax to detach and sink. **b** Underside of tiffany tin. A notch allows infrared temperature readings to be taken
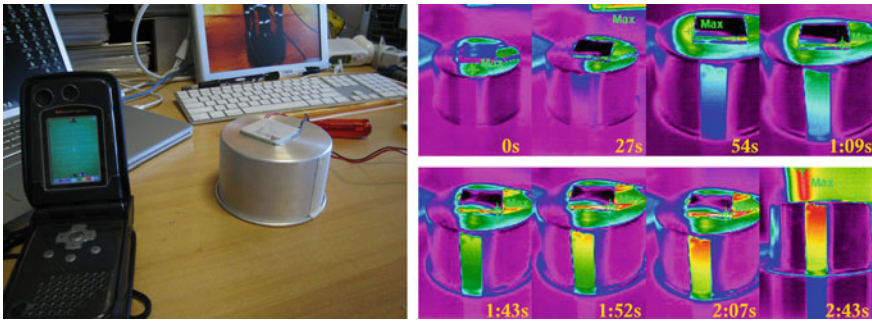
Fig. 13.73 Thermal images of test. The rim furthest from the TE module was only 3 °C higher than the base, where the TE was attached

13.9.4 Aluminium Stockpot, Engineered

A 32 L aluminium stockpot, 3 mm thick was used as PCM tank. Even though the base was visibly flat there was at least 2 mm variation in the level between the centre and outer base. For cooking ($\Delta T = 100\text{–}200$ °C) such a tolerance might be acceptable, but in the DTAC ($\Delta T < 30$ °C) any gap would compromise performance. The base of the pot was engineered and levelled by a fly cutter. The maximum variation in base level was 0.15 mm without a heat load. It was expected that even a small temperature variation (as little as 20 °C) would result in some differential expansion. After measuring the base for levelness (procedure shown in Fig. 13.74) the stock pot was assembled with the duct using clamps (Fig. 13.75).
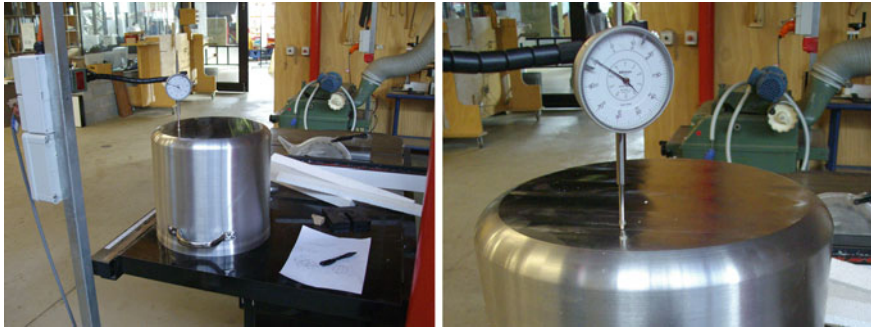
Fig. 13.74 Stockpot with additional engineering done to base, being measured for variations in level with a dial gauge

**Fig. 13.75** Engineered stockpot being clamped to cooling fin assembly in duct

13.9.5 Developing the Wax Bath

Looking back at the previous attempts we can see that when heat was applied to a stainless steel tank it was not effectively conveyed to all the wax. The steel, as most alloys, was a fairly poor conductor and the wax remained solid against the walls and would not sink without being forced down (Fig. 13.76).

The possible alternatives were to consider containers made of metals other than stainless steel. Whilst copper was more conductive than aluminium (Table 13.8) it was about 3−5 times the price per unit weight and was not suitable for laser

Fig. 13.76 Stainless steel
tank, due to poor conductivity
wax cannot detach from walls
to sink
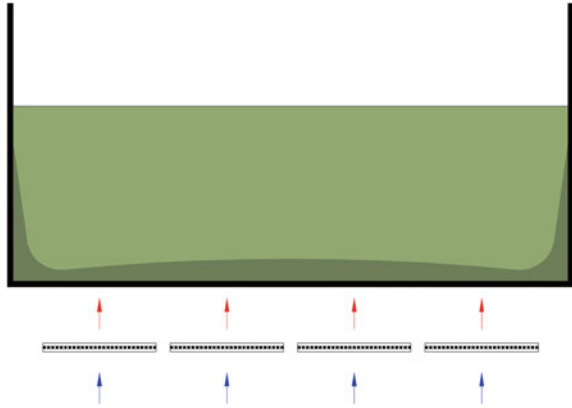
Table 13.8 Conductivity of
possible materials for use
PCM tank (Szokolay 2008)

Material	Conductivity (W/mK)
Aluminium	236
Copper	384
Stainless steel	24

cutting: molten copper was highly reflective and caused the laser to bounce in
unpredictable fashion. Water-jet cutting (where a fine abrasive is carried by a high
pressure water jet) or electron discharge machining were the only computer-aided
manufacturing methods available for working with copper, and both came at much
higher price than laser cutting.

Changing the tank to aluminium (wall thickness 1 mm) helped the detachment
slightly (Fig. 13.77) but complete detachment was only achieved with a thick-
walled drum (3 mm). Two problems became apparent.

Firstly, despite the solid wax being denser than the surrounding liquid, the solid
wax that had fully detached still remained afloat. Closer inspection revealed a
depression in the middle of the wax. When wax solidifies, a skin is formed on the
surface—where the heat loss is greatest and hence solidification quickest. As the
wax continues to cool it contracts. Since the edges of the top skin have already
adhered to the walls of the tank, these edges remain at the same level as the rest of
the wax shrinks. The resultant form is a block with a depression in the middle. It is
this bowl-shaped geometry that gives the solid wax enough buoyancy to remain
afloat despite being "denser" (Fig. 13.78).

Secondly, heat was emitting on either sides of the thick walls: into the wax as
desired, but also out of the tank into the space—something that should be post-
poned till all the wax had melted. A double-wall tank (Fig. 13.79) was needed so
that the bulk of the heat would be conducted through the thick walls of the internal
aluminium tank. The function of the outer walls were only for containment and not
heat transfer, these could be made of a thin alloy. With the double-tank the wax
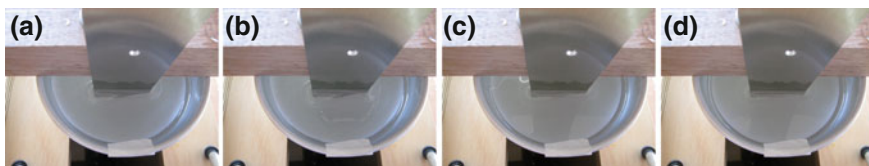
Fig. 13.77 Time lapse photography at 1 sec intervals. **a** wax detaches from stip and wall, **b** some of the molten wax rises to top and flows into the depression, **c** wax begins to sink, **d** solid wax fully submerged

Fig. 13.78 Total detachment achieved with thick walled aluminium tank but shape of solid wax, as explained by Archimedes principle, remains buoyant
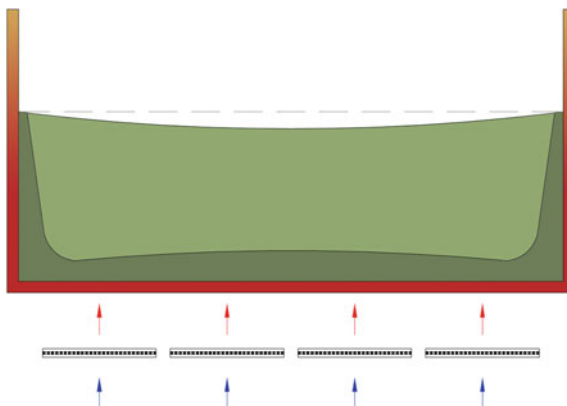

Fig. 13.79 *Double-tank*: an inner highly conductive and thick profiled *inner wall*, and a low conductive and thin profiled *outer wall*
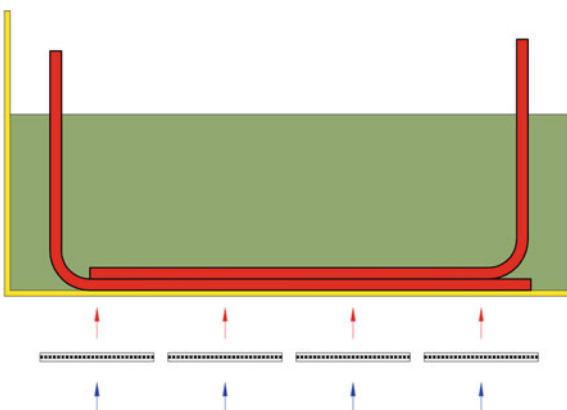
could be made to melt inside-out, effectively using the wax in the cavity between the double-wall as an insulator until it melted.

An extruded profile was added to puncture the wax (Figs. 13.80 and 13.81). It allowed heat from the base to be transmitted to the top, creating a channel for the lighter molten wax to breach the surface. When enough molten wax reached the top, the solid wax sank and provided a continuous feed of solid wax to the base of the tank.

Fig. 13.80 Final solution
that worked: double-wall bath
with a means of perforating
the *top*
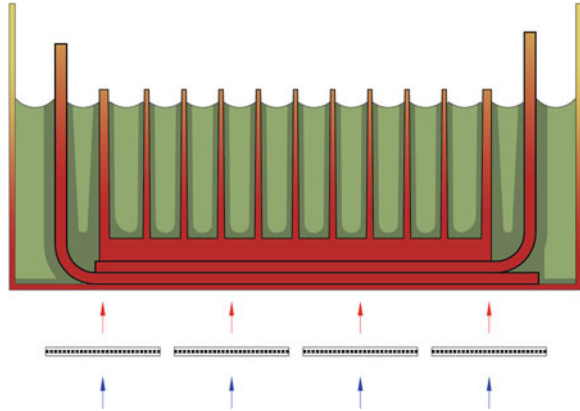
13.10 Prior Art

During the prior art search, Peter Carr's invention (2002, US patent 6481213)
emerged as a similar system featuring the use of thermoelectric modules (as heat
exchanger) and the use of phase change materials (PCMs, as heat sink). He
envisioned the PCMs to be enclosed in an insulated container to store 'coolth'. The
proposed PCMs were (1) water–ice or (2) clathrate hydrates. Both substances had
their phase change occurring below ambient conditions.

   The main advantage of this selection of PCMs is that very low temperatures can
be obtained. However, there were a number of significant disadvantages working
with a change of phase below ambient temperatures.

1. As proposed in his patent, the PCM needed to be prepared beforehand. A timing
   mechanism was required to freeze the PCM before its daily operation. If the
   timer was designed to start the freezing on Monday morning the unit will not be
   able to provide air-conditioning if someone worked during the weekend. This
   also limited the use of the air-conditioner to only such applications where
   demand could be scheduled.
2. When all the units were timed to be charged they will concurrently reject heat
   into the space. This would become problematic to anyone remaining in the
   office during that time.
3. The frozen PCM needed to be contained in an insulated container. Standard
   insulation like extruded polystyrene would add substantial space to the unit.
   High R-value insulation like polyurethane/silicone would add substantial cost
   to the unit.
4. Being in a solid state, a secondary fluid was required to carry their stored
   'coolth' to the heat exchanger. This required the extra mechanism of pumps and
   heat exchangers.
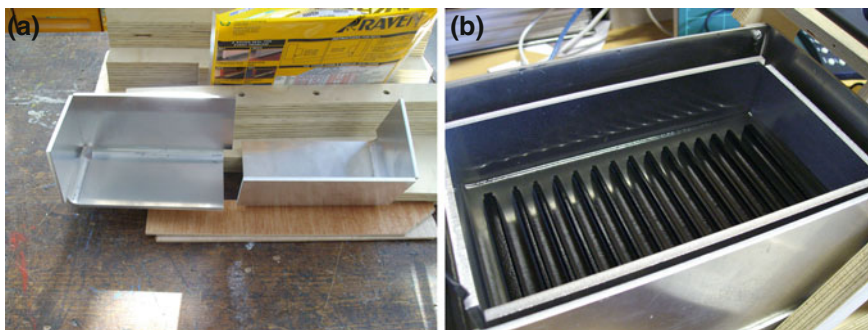
Fig. 13.81   a The *inner-wall* made from 4 mm folded aluminium sheets, and **b** the tank with heat sink and partially melted wax

13.10.1 DTAC's Differential

My work with DTAC had been to use a paraffin wax PCM that melted at 40 °C. The outlet temperature of 19–22 °C are not as low as Carr's at 16–18 °C, but would have been sufficient to provide personal comfort to most people. As the phase change occured above ambient conditions, it has the following advantages:

1. The wax can be solidified passively.
2. No timing and circulating mechanisms were required.
3. Pre-charge the PCM need not be scheduled.

   The wax expanded when it melted and this behaviour allowed me to design a tank where solid wax was continuously fed to the hottest part of the heat exchanger. Thermoelectric modules maintain a temperature difference at a certain voltage. So a module at 8 V can maintain a ΔT of 20 °C. If the hot side became too hot (e.g. >60 °C) the cold side would not be cold. The key to getting the wax to work with thermoelectric modules was to suppress the hot side temperatures near PCM melting point. This proved to be very challenging technically.

13.10.2   Uniqueness of DTAC

Whilst Carr's patent had mentioned the use of phase change materials, his embodiment required the use of an insulated PCM that had a melting point below ambient. Having a PCM that melted above ambient temperatures has many advantages, primarily that once ready it is always ready to be used. However, the passive supply of solid wax to the melting surface (bottom of tank in DTAC) has its technical challenges which were overcome with the design of the PCM bath.

13.11 Stream Analysis and Conclusion

In summary, the development of DTAC can be defined in two stages:

1. Proof of concept, contingent on being able to deliver air cooler than the ambient.
2. Optimisation, developing the heat exchange system to deliver air as close to the theoretical limit as possible.

If constructed in a negative, the problem for the proof of concept was that the supply air was too warm. A stream analysis (Adams 2001) could be constructed by linking the cause of each problems and categorised according to components (Fig. 13.82). A problem with many arrows in is a key symptom and one worth quantifying by detailed measurements. A problem where many arrows emerge, directly or indirectly, is a core issue. In the prototyping of DTAC, the cooling fin being not cold enough was a key symptom. Thus measuring the cold fin was the main indicator of a successful or failed attempt at air-conditioning. Getting the wax to sink in DTAC was the core problem.

The stream analysis helped consolidate the issues and determine the intellectual property strategy. For DTAC, a patent had to be sought particularly for the wax melting mechanism. This mechanism presented the most challenge and required the most innovation in resolving.

Optimisation of air movement and heat transport has been undertaken with the action research framework: plan → act → observe → reflect.

The ability to undertake digital manufacturing in the School of Architecture and Design workshops made it possible to have fairly short cycles of action research, and the ability to fabricate many components in-house kept costs low and permitted more iterations.

It is acknowledged that optimisation has only been taken in preliminary steps here. The need to rely heavily on TIM in the fabrication of the cooling fin assembly is a major drawback to the performance of the prototypes. Cooling fins are typically formed with a combination of the following processes: drop-forging, extrusion and brazing. These processes are not available for small scale prototyping. The optimisation of the cooling fins for mass-production will be the primary focus of future work.

Prototyping has been an invaluable part of the learning process, as many complications cannot be anticipated simply by doing calculations and modelling. Furthermore, modelling is eventually subject to validation with real-world experiments and is never a substitute for this process. Prototyping was the vital step that was impossible with the Rain Tower, and extremely difficult for the desiccant wheel AHU without industry support.

For the necessary IP protection, the patent required a *reduction to practice*: essentially a demonstration of how an idea could be made to work, something
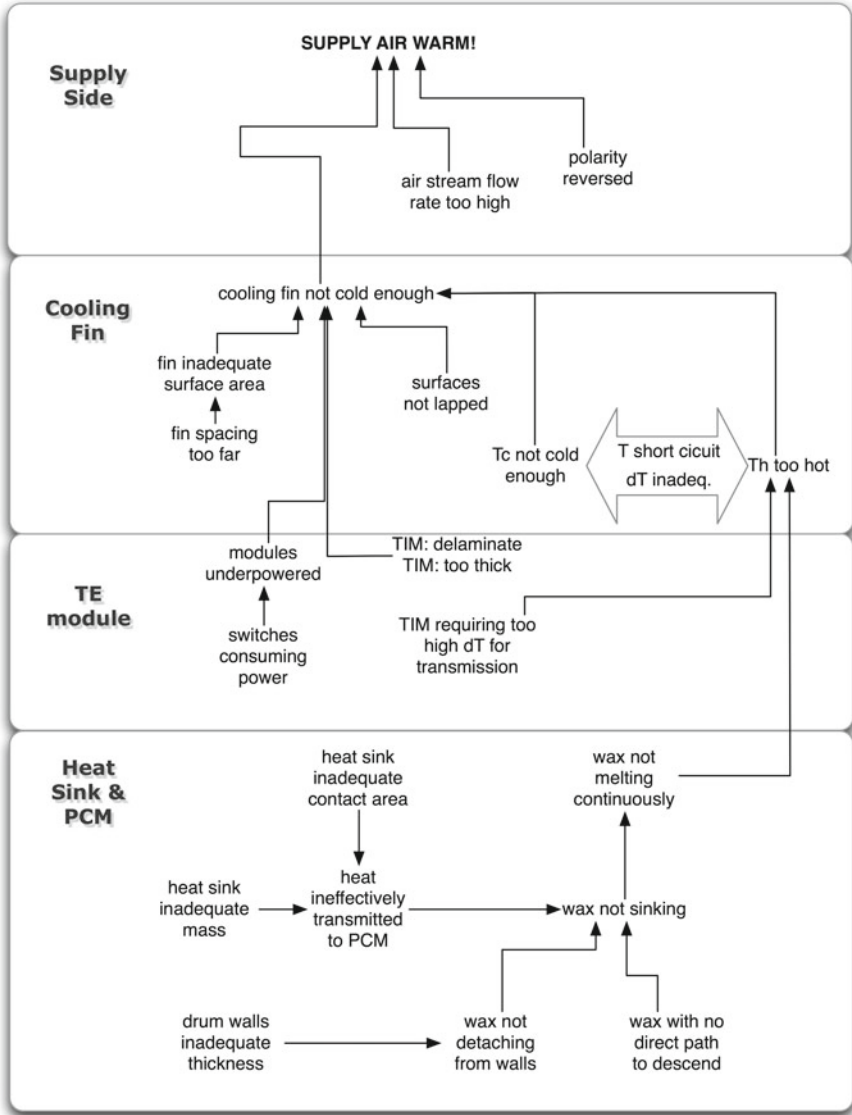
Fig. 13.82 Stream analysis of DTAC prototype supplying warm air

more than a mere figment of imagination. Whilst the concept of personal air-conditioning was not novel, and the idea of using TE modules with PCM had prior art, it was still possible to define the characteristic uniqueness of DTAC originating from the PCM bath design.

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Curriculum Vitae

Tim Law is a building technology lecturer in the School of Architecture & Design, University of Tasmania. He invented the Ductless Task Air-Conditioning (DTAC) unit as part of his PhD studies to demonstrate how a design method could be a viable way of solving complex cross-disciplinary problems. DTAC and his other air- conditioning inventions have received multiple awards in business competitions and commercialisation grants. Tim and his inventions have appeared in the Examiner newspaper and Australian Broadcasting Corporation news.