4.2. SYNTHESIS OF HEAT EXCHANGE NETWORKS (HENs)

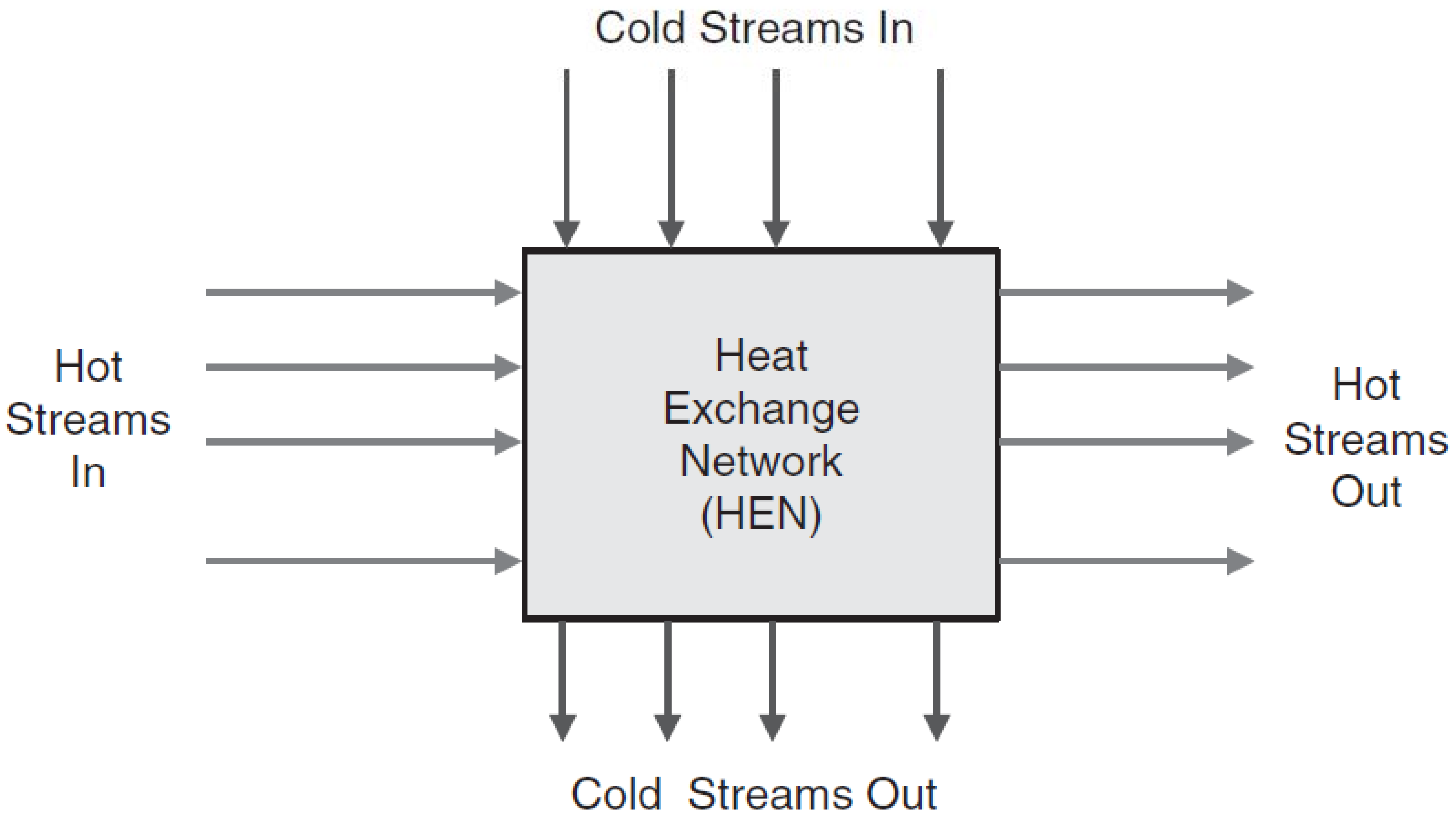
- In a typical chemical process, there are normally **several hot streams that must be cooled and several cold streams** that must be heated.

- The usage of external cooling and heating utilities (e.g., cooling water, refrigerants, steam, heating oils, etc.) to address all the heating and cooling duties is not cost effective.

- Integration of heating and cooling tasks may lead to **significant cost reduction**.

- The key concept is to transfer heat from the process hot streams to the process cold streams before the external utilities are used. The result of this heat integration is the simultaneous reduction of heating and cooling duties of the external utilities.

- For a given system, the synthesis of HENs entails answering several questions:
- Which heating/cooling utilities should be employed ?
- What is the **optimal heat load to be removed/added** by each utility?
- How should the hot and cold streams be matched (i.e., **stream pairings**)?
- What is the **optimal system configuration** (e.g., how should the heat exchangers be arranged? Is there any stream splitting and mixing ?)


Cold Streams In
Hot Streams In
Heat Exchange Network (HEN)
Hot Streams Out
Cold Streams Out

The problem of synthesizing HENs can be stated as follows:

- Given a number N_H of process hot streams (to be cooled) and a number N_C of process cold streams (to be heated), it is desired to **synthesize a cost-effective network of heat exchangers** that can transfer heat from the hot streams to the cold streams.

- Given also are the heat capacity (flow rate x specific heat) of each process hot stream, $FC_{P,u}$; its supply (inlet) temperature, T^s_u; and its target (outlet) temperature, T^t_u, where u=1,2, . . .,N_H.

- In addition, the heat capacity, $fC_{P,v}$, supply and target temperatures, t^s_u and t^t_v, are given for each process cold stream, where v = 1,2, . . .,N_C. Available for service are N_{HU} heating utilities and N_{CU} cooling utilities whose supply and target temperatures (**but not flowrates**) are known.

HEAT EXCHANGE PINCH DIAGRAM

- consider a heat exchanger for which **the thermal equilibrium relation governing the transfer of the heat from a hot stream to a cold stream** is simply given by

$$T = t$$

- By employing a minimum heat exchange driving force of ∆Tmin, one can establish a one-to-one correspondence between **the temperatures of the hot and the cold streams for which heat transfer is feasible**, i.e.,

$$T = t + \Delta T^{\mathrm{min}}$$

- For a given pair of corresponding temperatures (T, t) it is thermodynamically and practically feasible to transfer heat from **any hot stream whose temperature is greater than or equal to T to any cold stream whose temperature is less than or equal to t**.

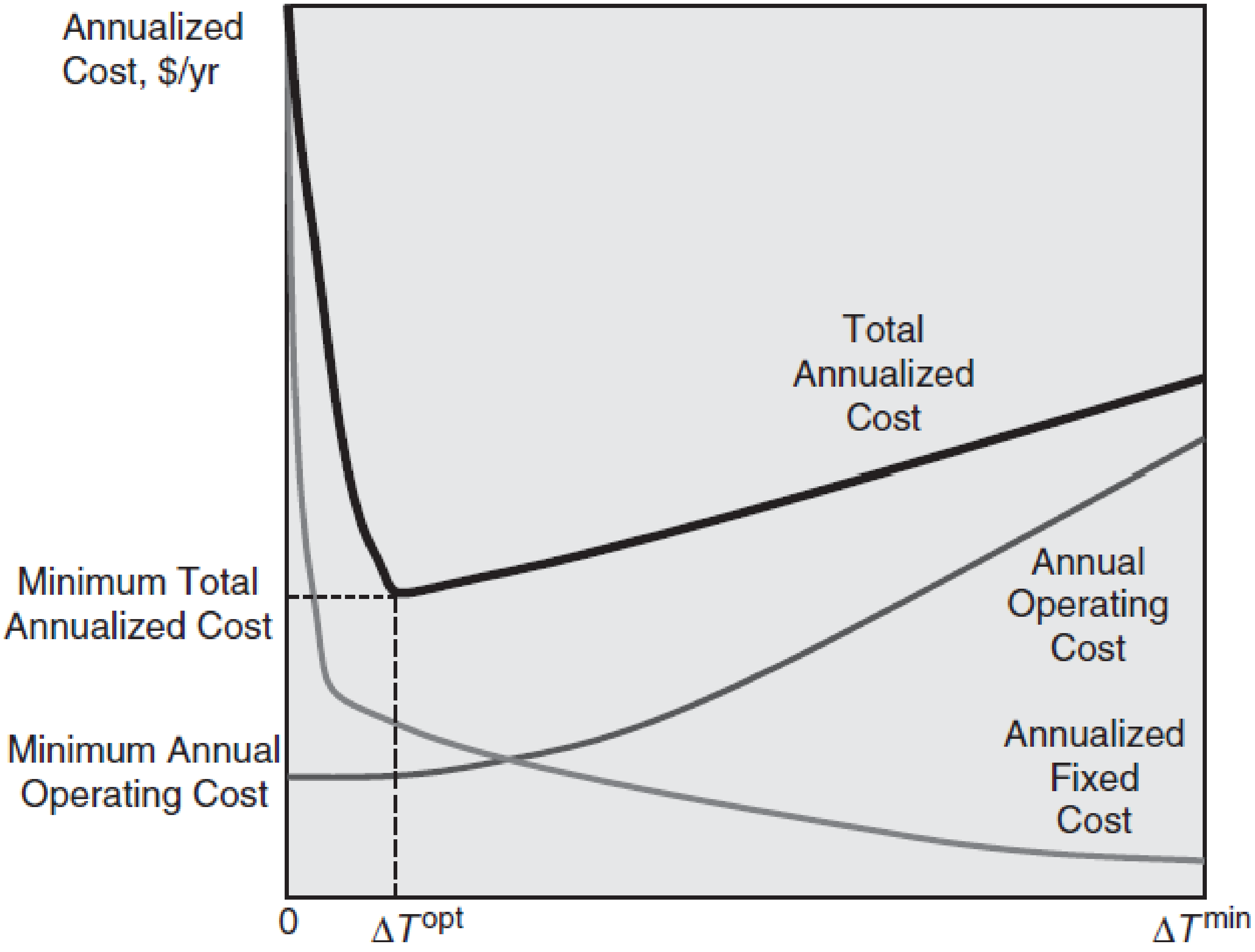
- Thermal equilibrium is a special case of mass exchange equilibrium with T, t, and ΔTmin corresponding to y_i, xj, and ε, respectively, **while the values of mj and bj are one and zero**, respectively.

- In order to accomplish the minimum usage of heating and cooling utilities, it is necessary **to maximize the heat exchange among process streams**. In this context, one can use a very useful graphical technique referred to as the ‘‘**thermal pinch diagram**’’.

ANALOGY BETWEEN MENs AND HENs

MENs	HENs
Transferred commodity: Mass	Transferred commodity: Heat
Donors: rich streams	Donors: hot streams
Recipient: lean streams	Recipient: cold streams
Rich composition: y	Hot temperature: T
Lean composition: x	Cold temperature: t
Slope of equilibrium: m	Slope of equilibrium: 1
Intercept of equilibrium: b	Intercept of equilibrium: 0
Driving force: ε	Driving force: $\Delta T^{\min}$

- Similar to the role of ε_j in cost optimization, ΔT^{min} can be used to trade off capital versus operating costs as shown in Figure below.



- The first step in constructing the thermal pinch diagram is creating a global representation for all the hot streams by **plotting the enthalpy exchanged by each process hot stream versus its temperature**.

- Hence, a hot stream losing sensible heat is **represented as an arrow whose tail corresponds to its supply temperature and its head corresponds to its target temperature**. Assuming constant heat capacity over the operating range, the slope of each arrow is equal to $F_u C_{P,u}$.

- The vertical distance between the tail and the head of each arrow represents **the enthalpy lost by that hot stream** according to the following expression:

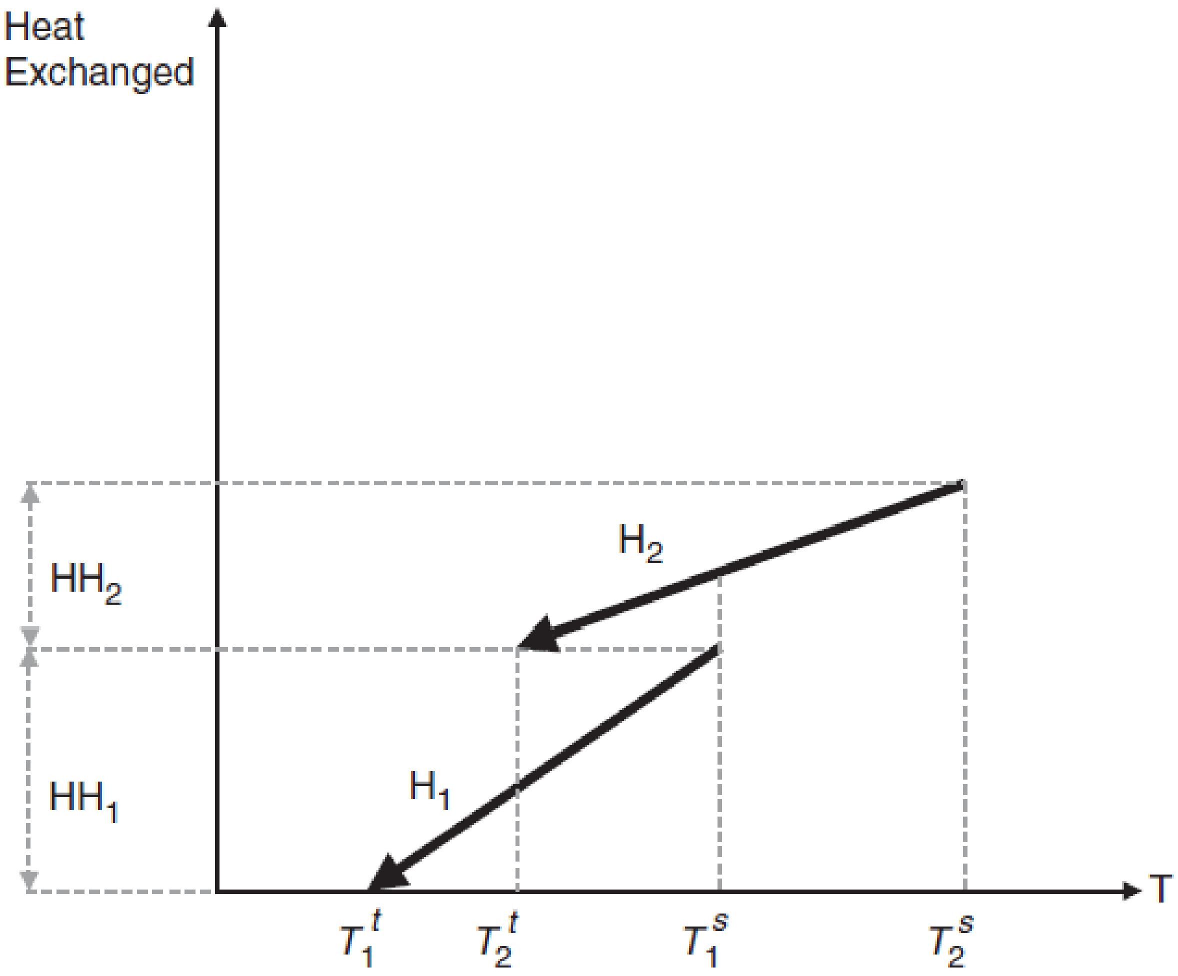
- Heat lost from the uth hot stream

$$HH_u = F_u C_{P,u}(T_u^s - T_u^t) \qquad \text{where } u = 1, 2, \ldots, N_H$$

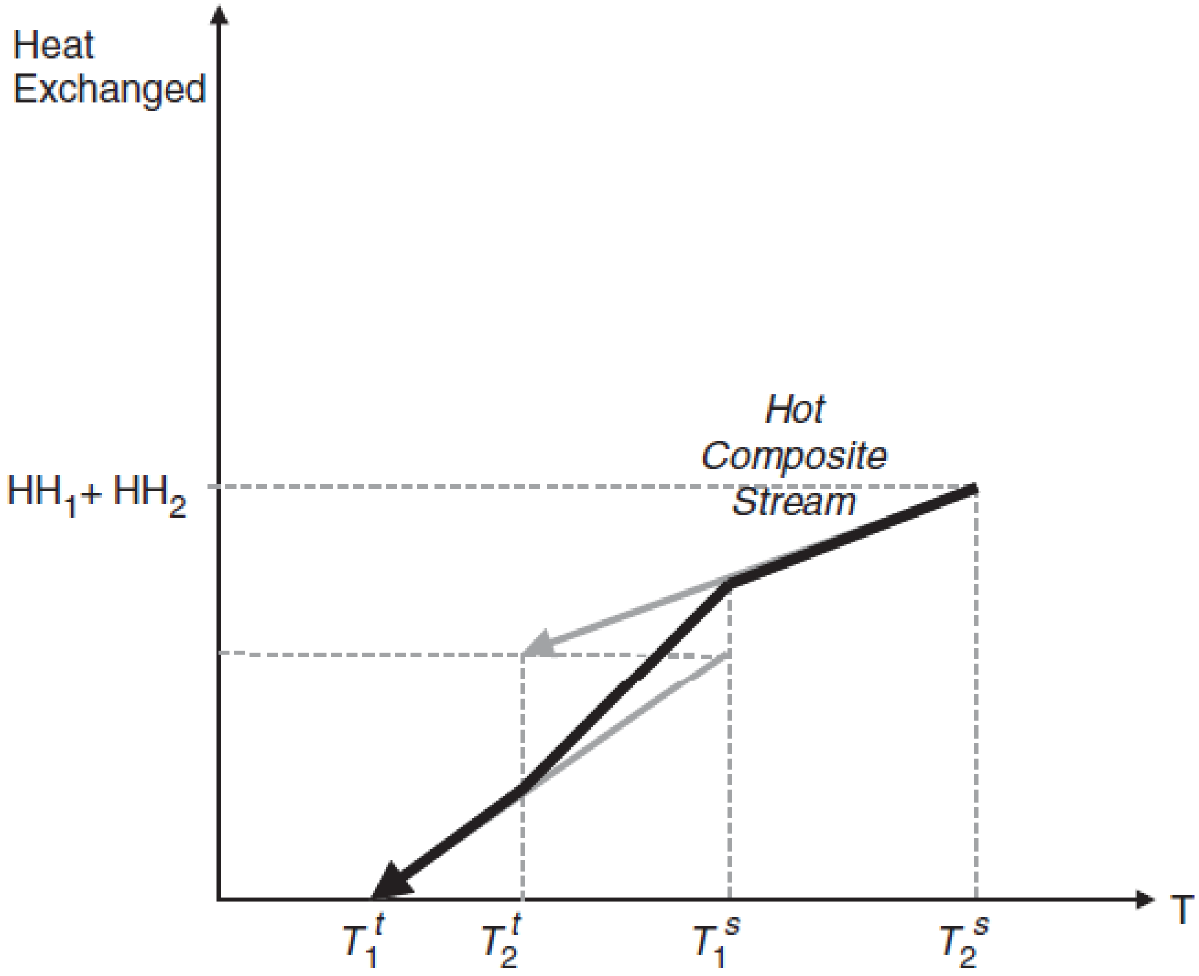
- Any stream can be moved up or down while preserving the same vertical distance between the arrow head and tail and maintaining the same supply and target temperatures.

- Similar to the graphical superposition described in mass exchange network, one can create a hot composite stream using the diagonal rule. The following Figures illustrate this concept for two hot streams.
- Next, a cold-temperature scale, t, is created in one-to-one correspondence with the hot temperature scale, T, using .

$$t = T - \Delta T^{\min}$$



REPRESENTING HOT STREAMS

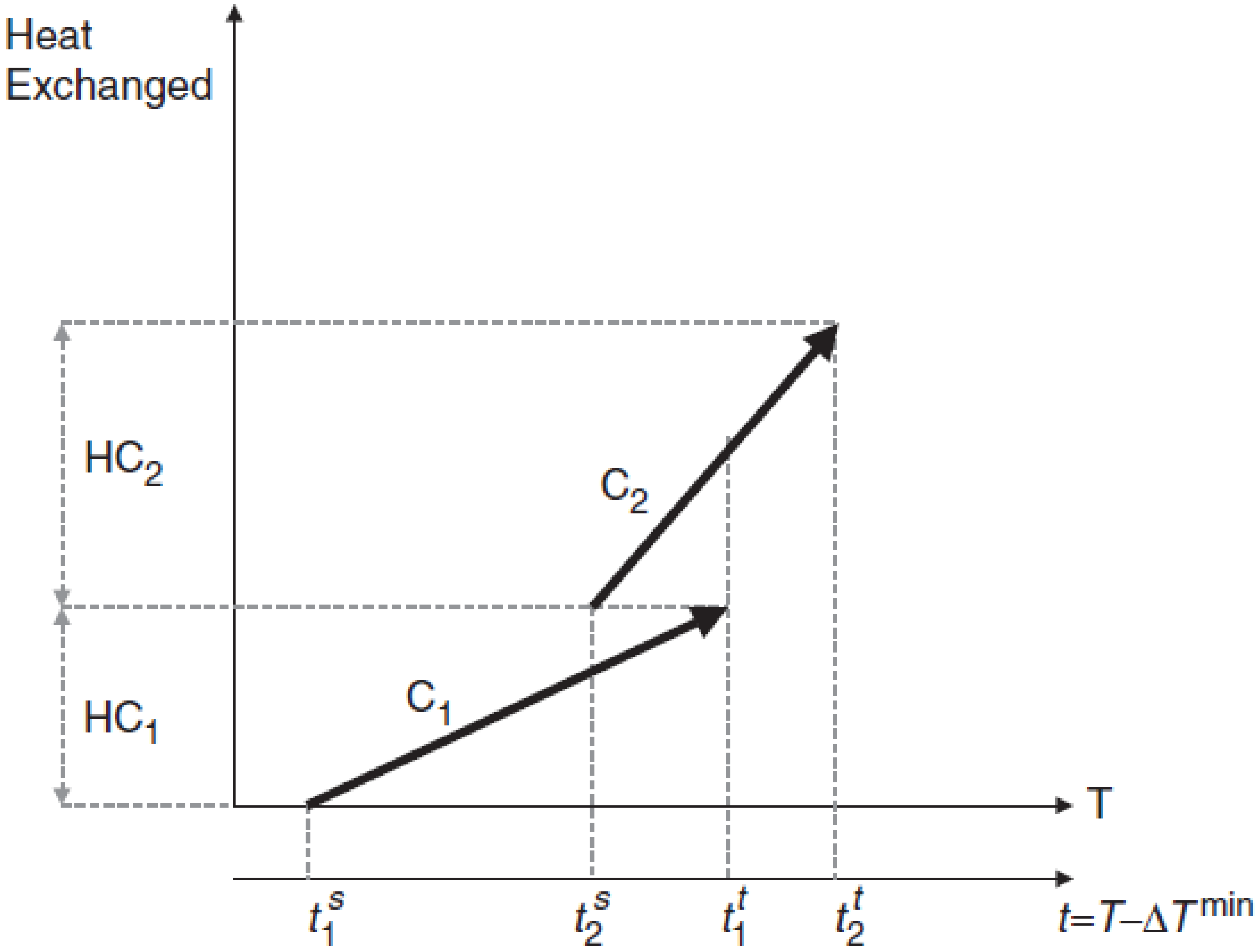


CONSTRUCTING A HOT COMPOSITE STREAM USING SUPERPOSITION (DASHED LINE REPRESENTS COMPOSITE LINE)

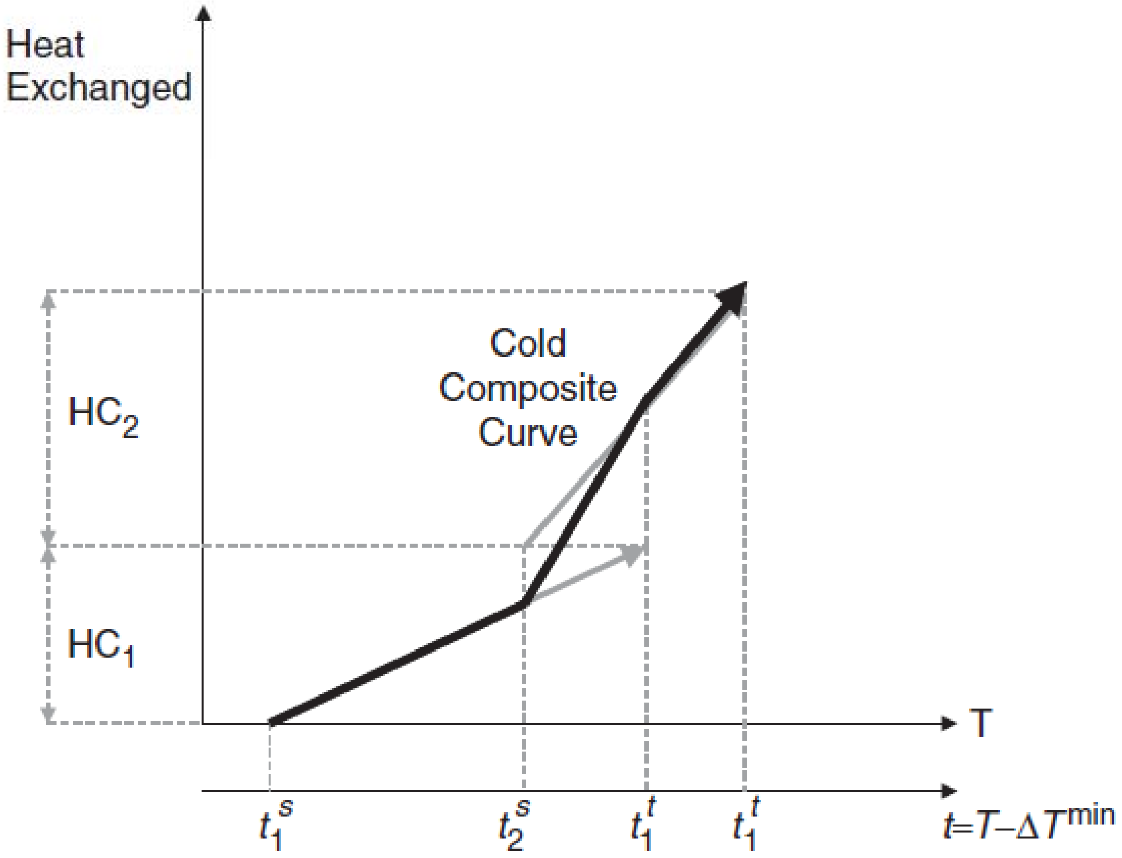
- The vertical distance between the arrow head and tail for a cold stream is given by Heat gained by the vth cold stream

$$HC_v = f_v c_{p,v}(t_v^{\mathrm{t}} - t_v^{\mathrm{s}}) \qquad \text{where } v = 1, 2, \ldots, N_{\mathrm{C}}$$

- In a similar manner to constructing the hot-composite line, a cold composite stream is plotted



REPRESENTING COLD STREAMS

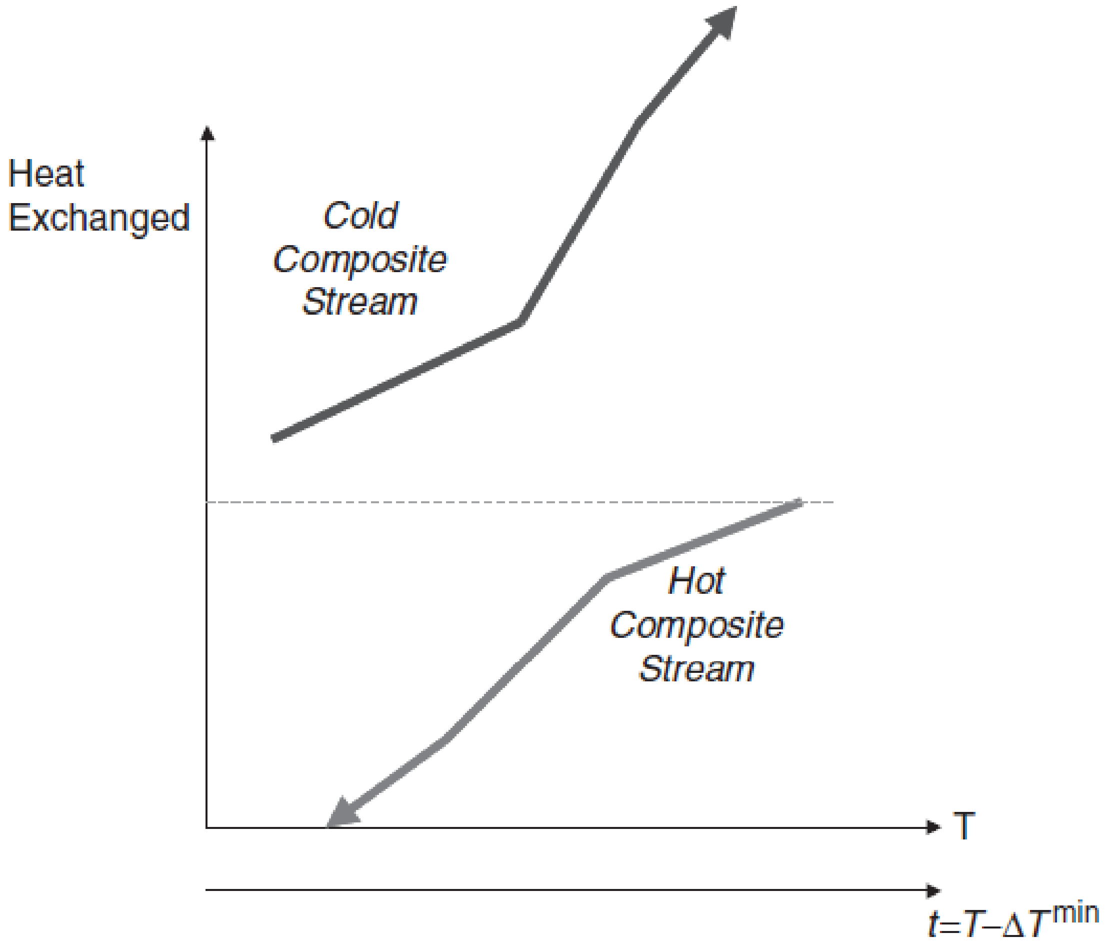


CONSTRUCTING A COLD COMPOSITE STREAM USING SUPERPOSITION (DASHED LINE REPRESENTS COMPOSITE LINE)

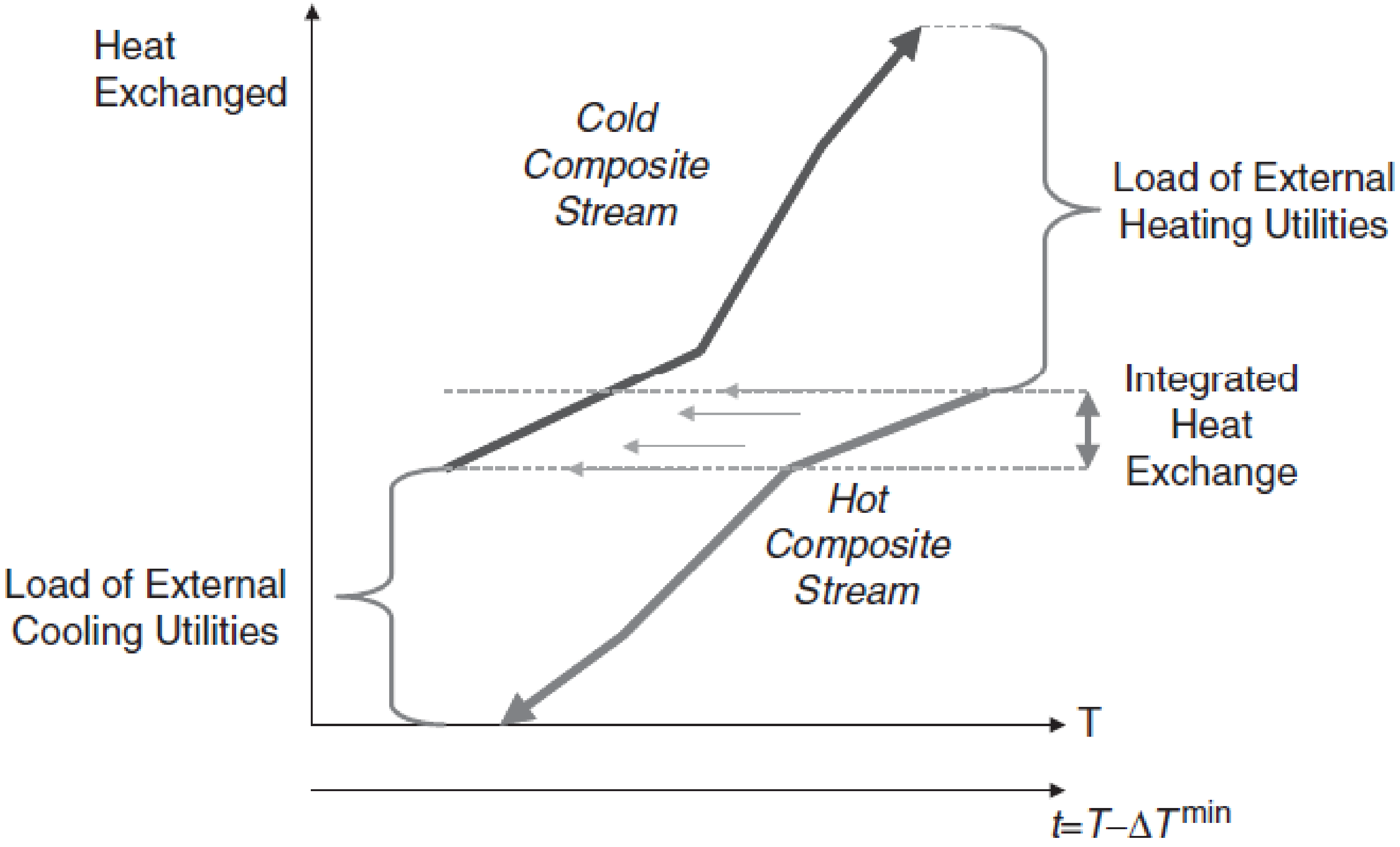
- Next, both composite streams are plotted on the same diagram.

- On this diagram, thermodynamic feasibility of heat exchange is guaranteed when at any heat exchange level (which corresponds to a horizontal line), **the temperature of the cold composite stream is located to the left of the hot composite stream** (i.e., temperature of the hot is higher than or equal to the cold temperature plus the minimum approach temperature).

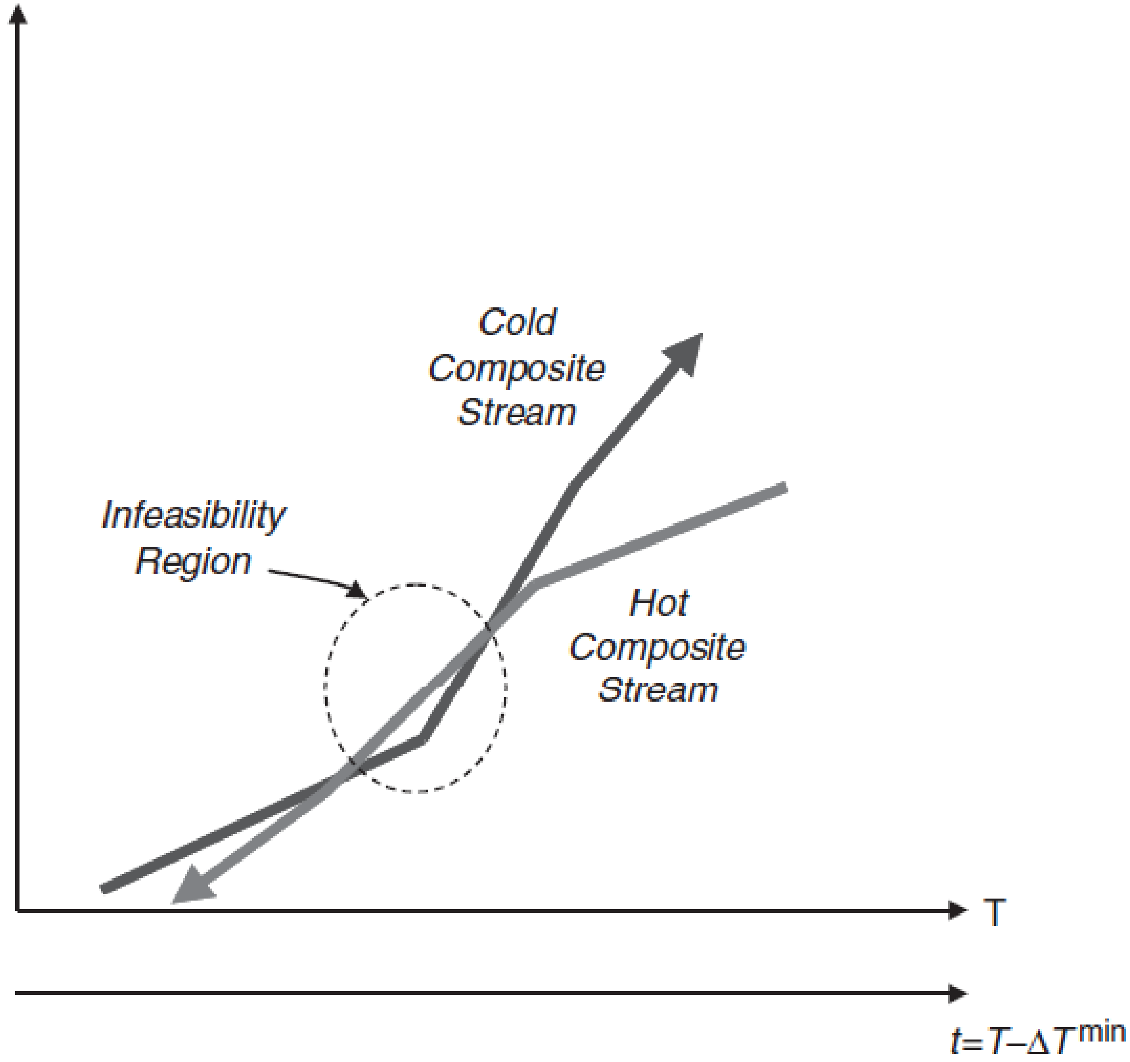
- Hence, for a given set of corresponding temperatures, **it is thermodynamically and practically feasible to transfer heat from any hot stream to any cold stream**



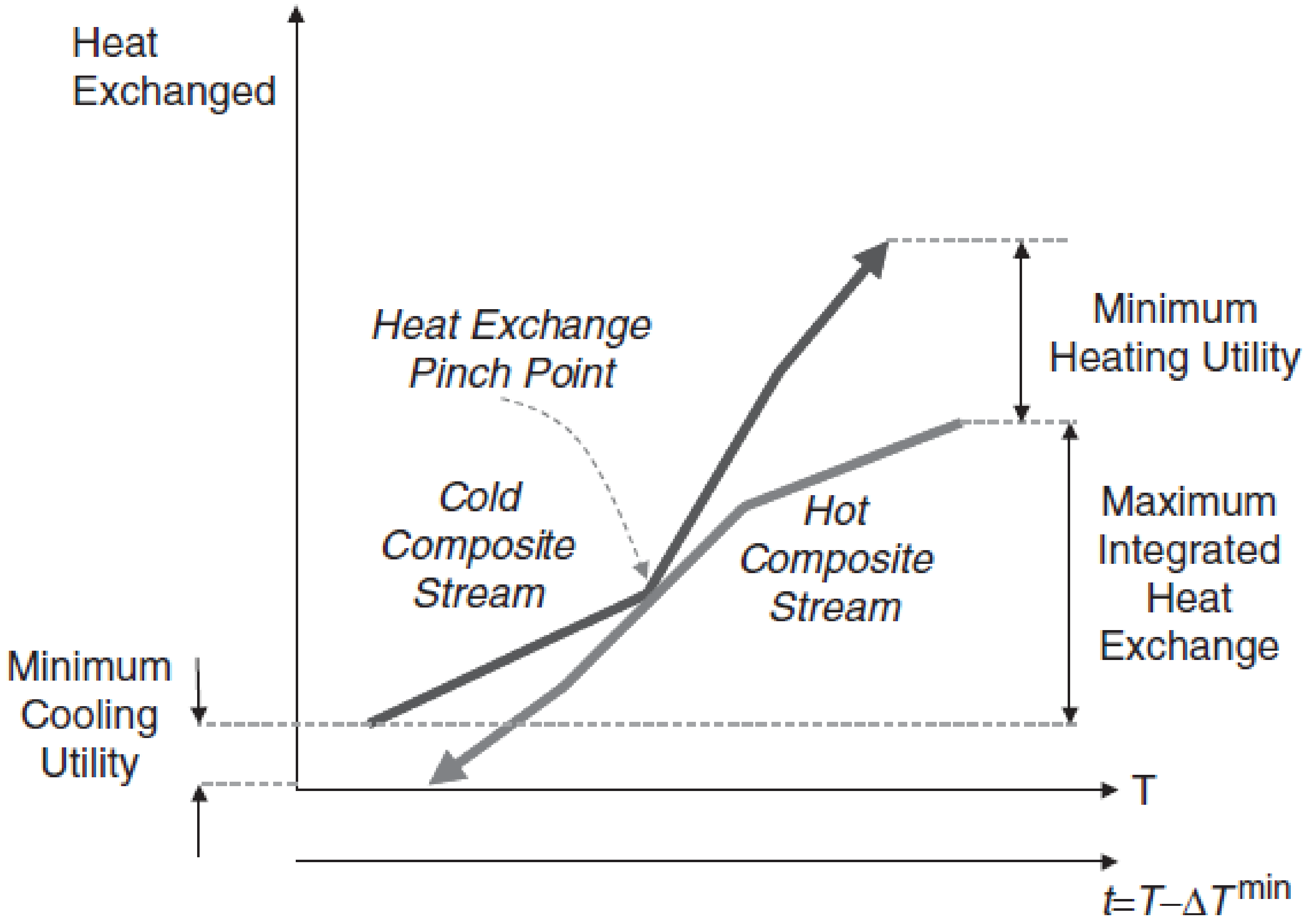
PLACEMENT OF COMPOSITE STREAMS WITH NO HEAT INTEGRATION



PARTIAL HEAT INTEGRATION



INFEASIBLE HEAT INTEGRATION



THERMAL PINCH DIAGRAM

- The cold composite stream can be moved up and down **which implies different heat exchange decisions**.

- For instance, if we move the cold composite stream upwards in a way that leaves **no horizontal overlap** with the hot composite stream, then **there is no integrated heat exchange between the hot composite stream and the cold composite stream**.

- When the cold composite stream is moved downwards so as to provide some horizontal overlap, **some integrated heat exchange** can be achieved.

- However, if the cold composite stream is moved downwards such that **a portion of the cold is placed to the right of the hot composite stream**, thereby **creating infeasibility** .

- Therefore, the optimal situation is constructed when the cold composite stream is slid vertically **until it touches the rich composite stream while lying completely to the left** of the hot composite stream at any horizontal level.

- Therefore, the cold composite stream can be slid down until it touches the hot composite stream. **The point where the two composite streams touch is called the ''thermal pinch point''.**

- one can use the pinch diagram to determine the **minimum heating and cooling utility** requirements

- Again, the cold composite line cannot be slid down any further; otherwise, portions of the cold composite stream would be the right of the hot composite stream, causing thermodynamic infeasibility.

- On the other hand, if the cold composite stream is moved up (i.e., passing heat through the pinch), less heat integration is possible, and consequently, additional heating and cooling utilities are required.

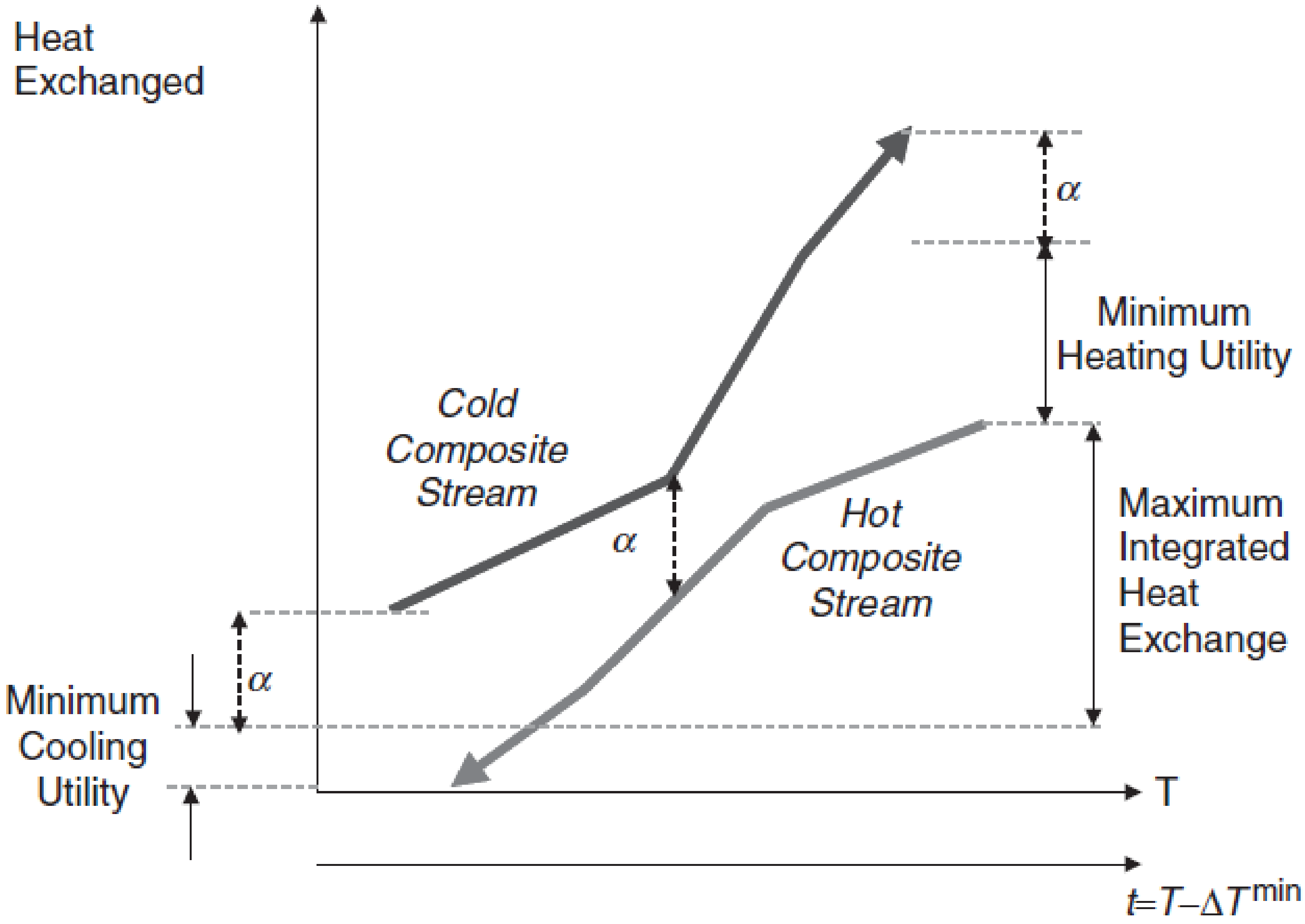
- Therefore, for a minimum utility usage the following design rules must be observed:
  - No heat should be passed through the pinch.
  - Above the pinch, no cooling utilities should be used.
  - Below the pinch, no heating utilities should be used.

- The first rule is illustrated by next Figure. The passage of a heat flow through the pinch (α) results in a double penalty: an increase of α in both heating utility and cooling utility.

- The second and third rules can be explained by noting that above the pinch there is a surplus of cooling capacity.

- Adding a cooling utility above the pinch will replace a load that can be removed (virtually for no operating cost) **by a process cold stream**.

- A similar argument can be made against using a heating utility below the pinch.



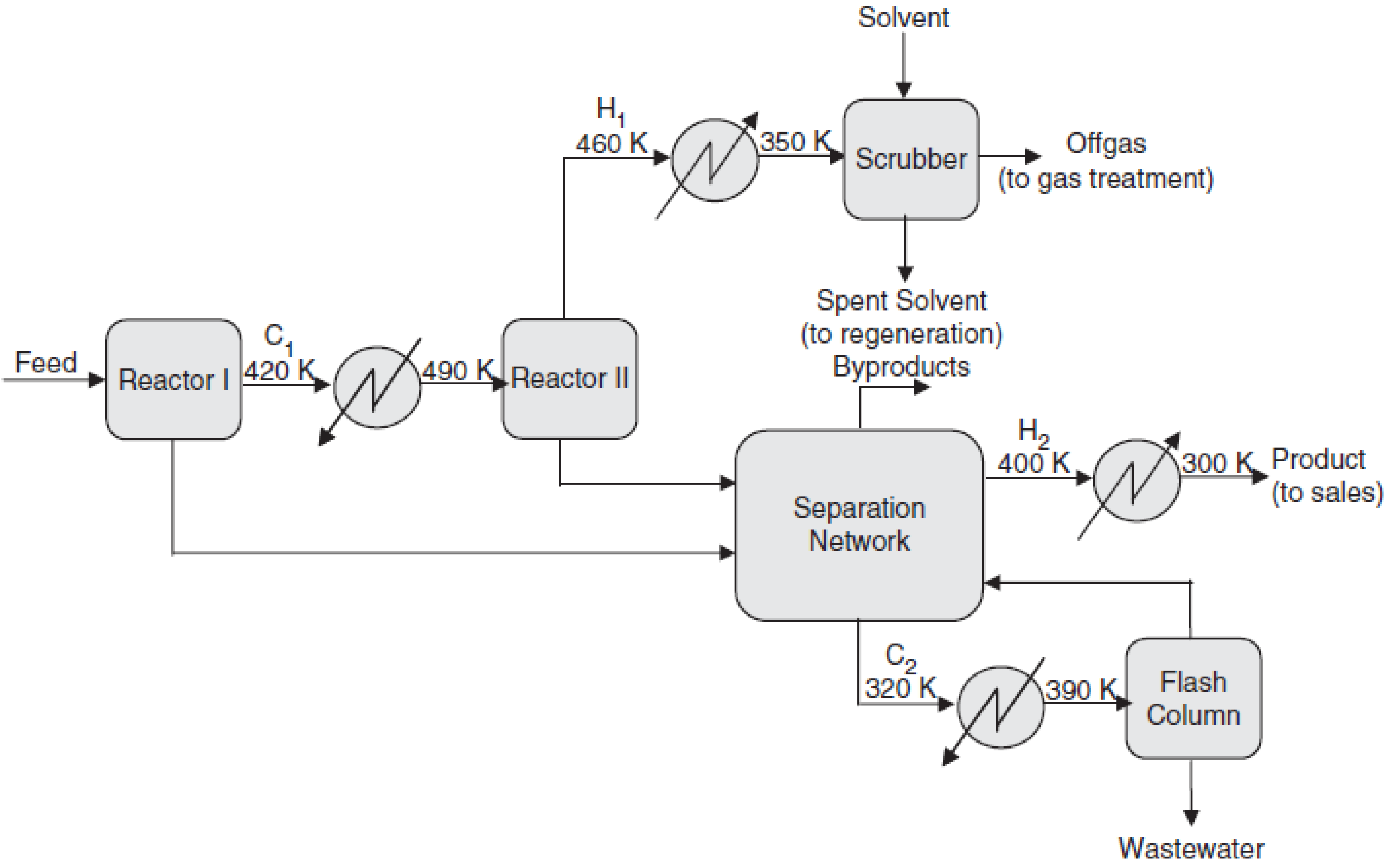
PENALTIES ASSOCIATED WITH PASSING HEAT THROUGH THE PINCH

EXAMPLE UTILITY MINIMIZATION IN A CHEMICAL PLANT

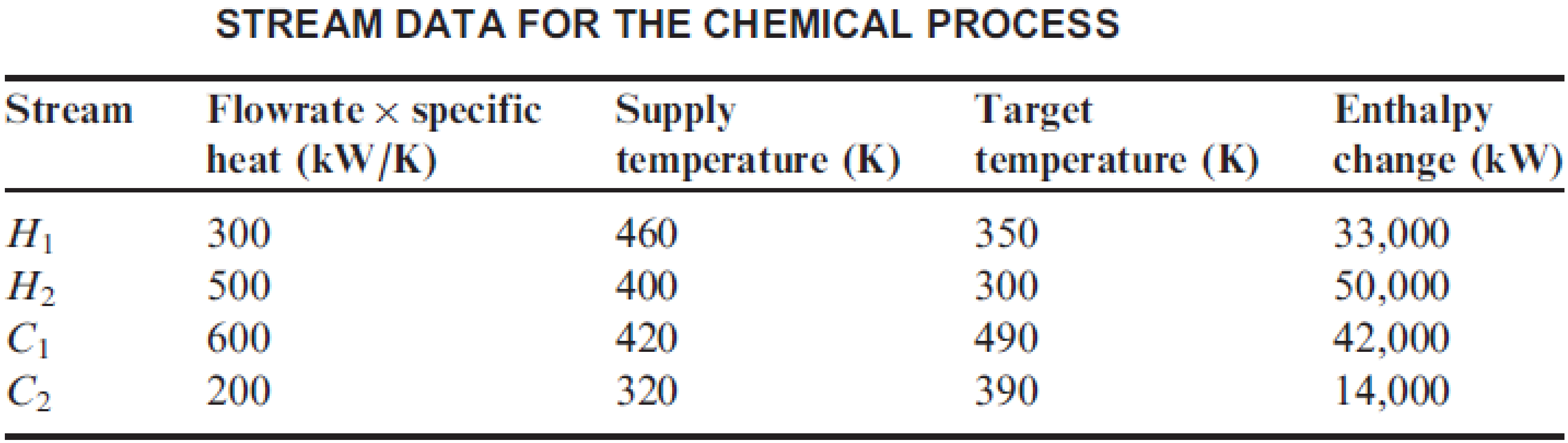
- Consider the chemical processing facility illustrated in Figure below. The process has two adiabatic reactors. The intermediate product leaving the first reactor (C1) is heated from 420 to 490K before being fed to the second reactor.

- The off-gases leaving the reactor (H1) at 460K are cooled to 350K prior to being forwarded to the gas-treatment unit. The product leaving the bottom of the reactor is fed to a separation network.

- The product stream leaving the separation network (H2) is cooled from 400 to 300 prior to sales. A byproduct stream (C2) is heated from 320 to 390K before being fed to a flash column. Stream data are given.



SIMPLIFIED FLOWSHEET FOR THE CHEMICAL PROCESSING FACILITY



STREAM DATA FOR THE CHEMICAL PROCESS

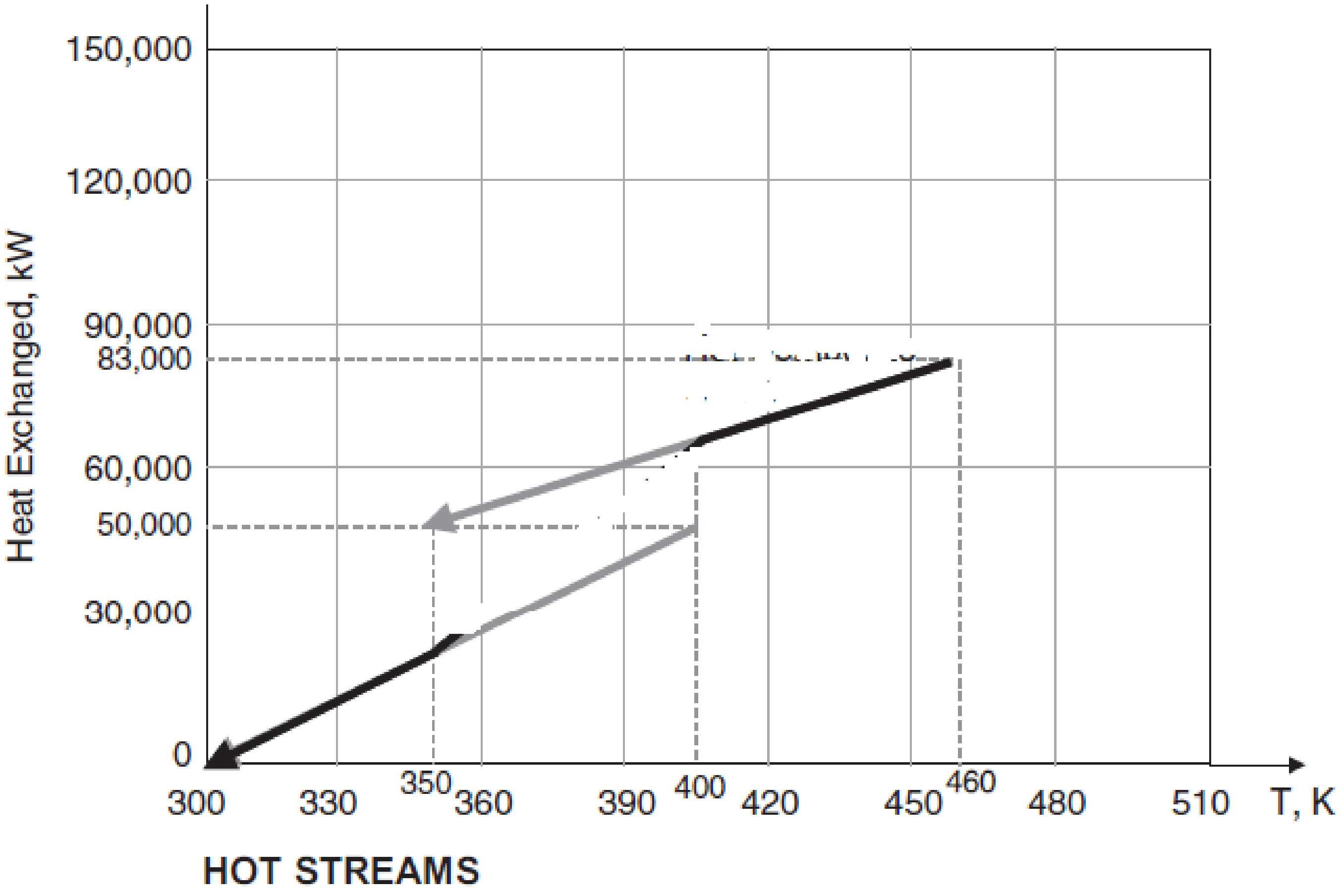
Stream	Flowrate × specific heat (kW/K)	Supply temperature (K)	Target temperature (K)	Enthalpy change (kW)
H_1	300	460	350	33,000
H_2	500	400	300	50,000
C_1	600	420	490	42,000
C_2	200	320	390	14,000

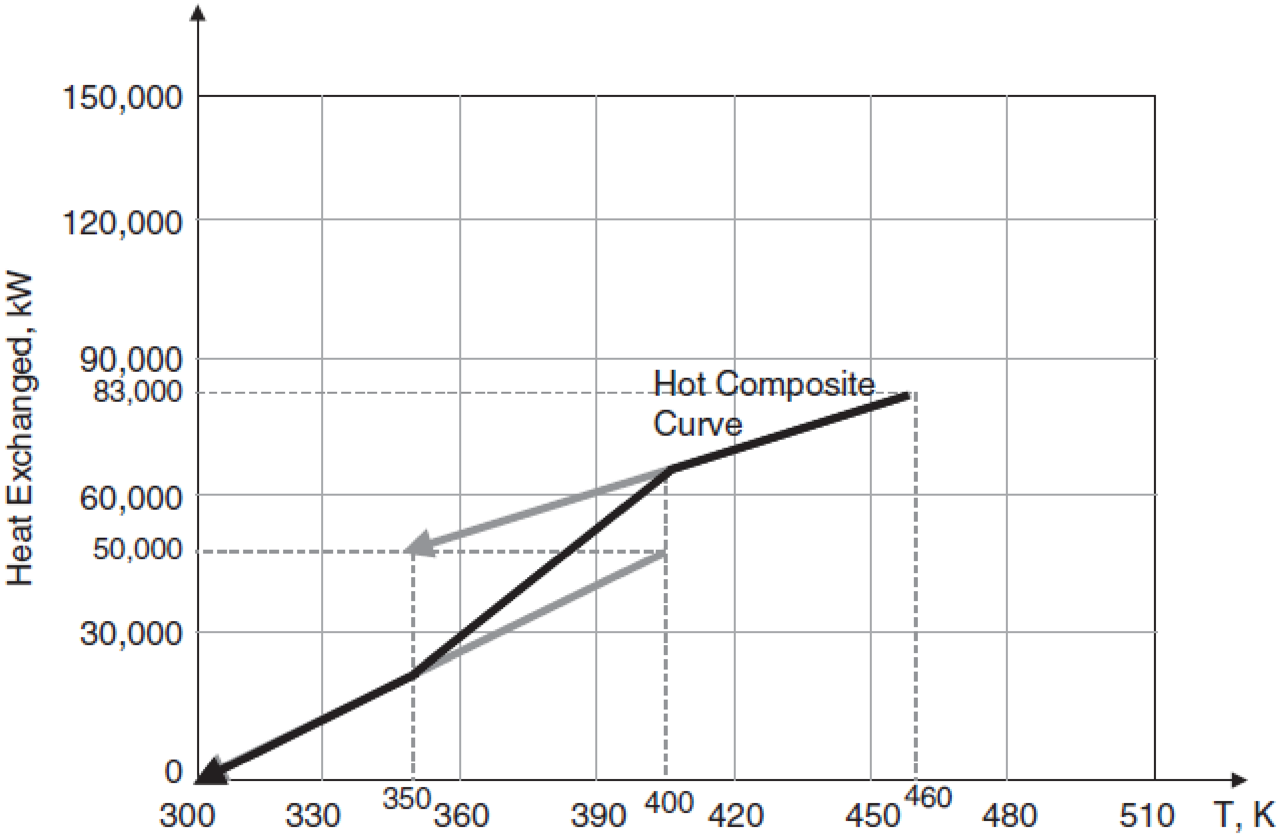
- In the current operation, the heat exchange duties of H_1, H_2, C_1, and C_2 are fulfilled using the cooling and heating utilities. Therefore, the current usage of cooling and heating utilities are 83,000 and 56,000 kW, respectively.

- The objective of this case study is to use heat integration via the pinch diagram to identify the target **for minimum heating and cooling utilities**. A value of $\Delta T^{\min}$ =10 K is used.

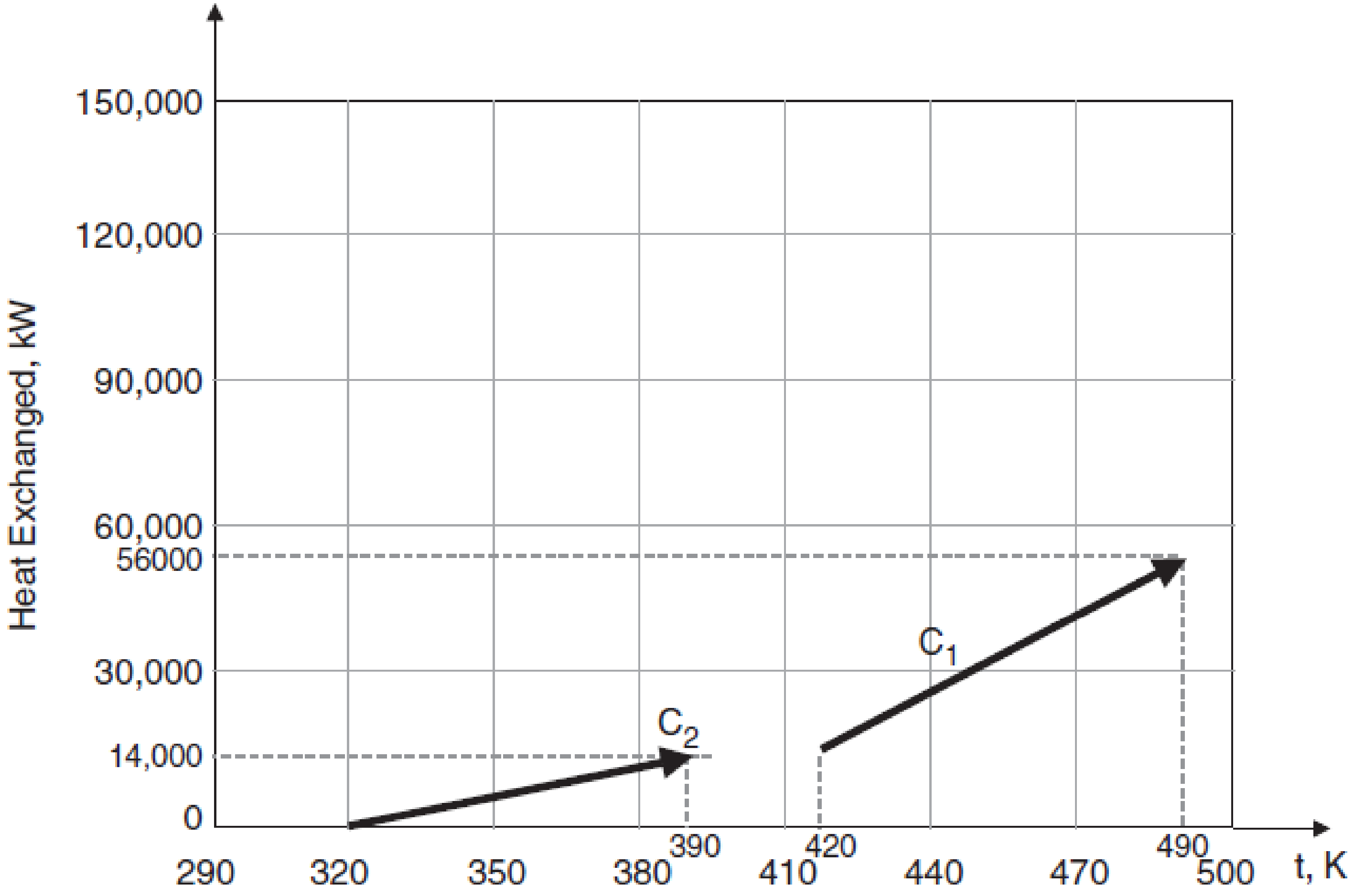
SOLUTION

- The Figures below illustrate the hot composite stream, the cold composite stream and the pinch diagram, respectively.

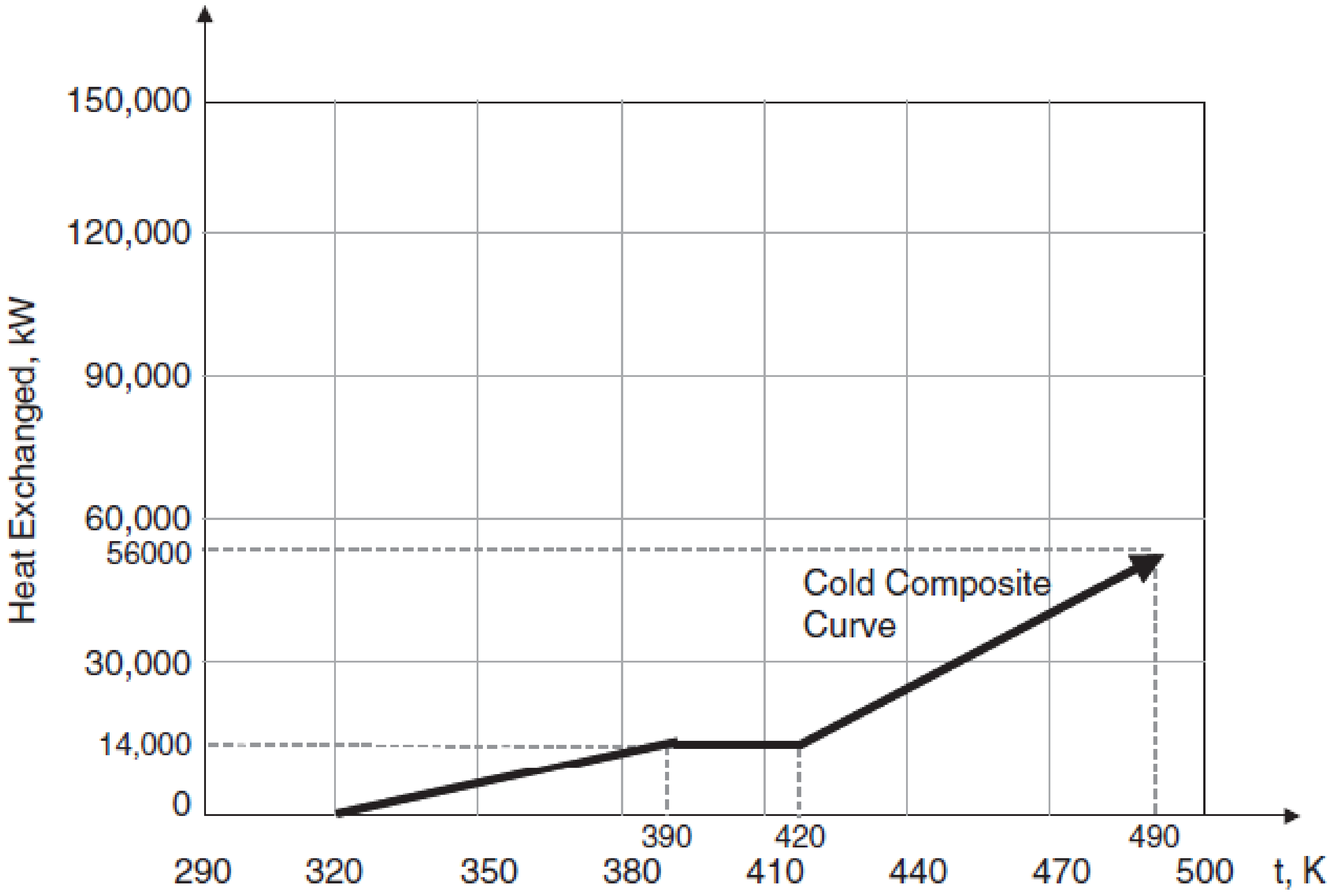




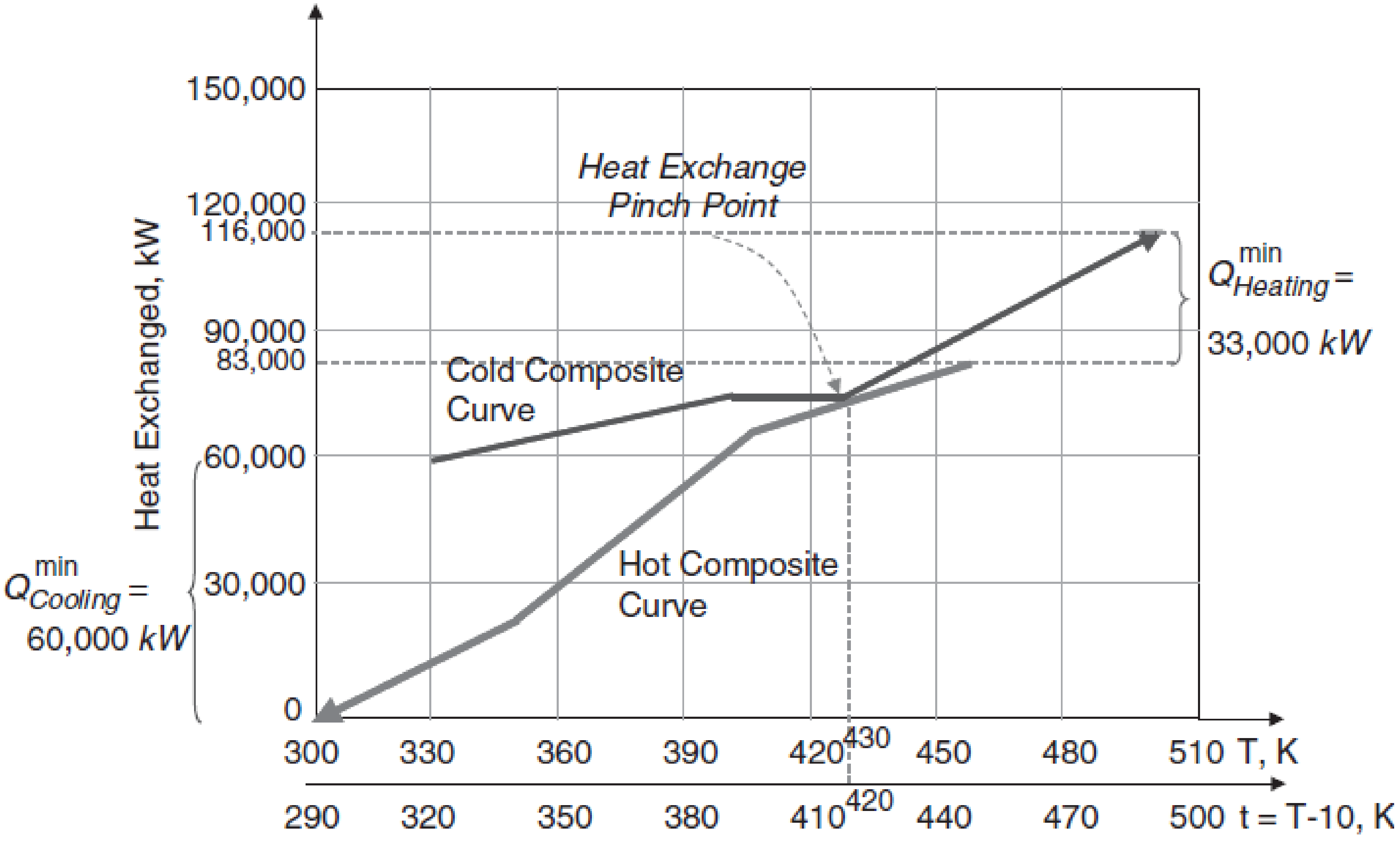
HOT COMPOSITE STREAM



REPRESENTING THE COLD STREAMS



COLD COMPOSITE STREAM



THERMAL PINCH DIAGRAM

- As can be seen from pinch diagram, the two composite streams touch at 430 K on the hot scale (420 K on the cold scale).

- This designates the location of the heat exchange pinch point. The minimum heating and cooling utilities are 33,000 and 60,000 kW, respectively. Therefore, the potential reduction in utilities can be calculated as follows:

$$\text{Target for percentage savings in heating utility} = \frac{56{,}000 - 33{,}000}{56{,}000} \times 100\% = 41\%$$

$$\text{Target for percentage savings in cooling utility} = \frac{83{,}000 - 60{,}000}{83{,}000} \times 100\% = 28\%$$

- Once the minimum operating cost is determined, a network of heat exchangers can be synthesized. The trade off between capital and operating costs can be established by iteratively varying ∆Tmin **until the minimum total annualized cost is attained**.