CHAPTER NINE

HEAT INTEGRATION

Up to this chapter, attention has been given to mass integration. As mentioned in Chapter One, there are two main commodities handled in the process: mass and energy. Both contribute to the overall performance of the process and both affect the capital and operating costs of the process. Heat is one of the most important energy forms in the process. The current chapter provides an overview of heat integration. First, the problem of synthesizing networks of heat exchangers is discussed while highlighting the analogy with synthesizing networks of mass exchangers. Next, targeting procedures are presented with the objective of minimizing heating and cooling utilities while maximizing heat exchange among the process streams.

9.1. SYNTHESIS OF HEAT-EXCHANGE NETWORKS (HENs)

In a typical 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. Indeed, 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.

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 (flowrate x specific heat) of each process hot stream, $FC_{P,u}$; its supply (inlet) temperature, T_u^s; and its target (outlet) temperature, T_u^t, where u = 1,2,...,N_H. In addition, the heat capacity, $fc_{P,v}$, supply and target temperatures, t_v^s and t_v^t, 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. Figure 9.1 is a schematic representation of the HEN problem statement.

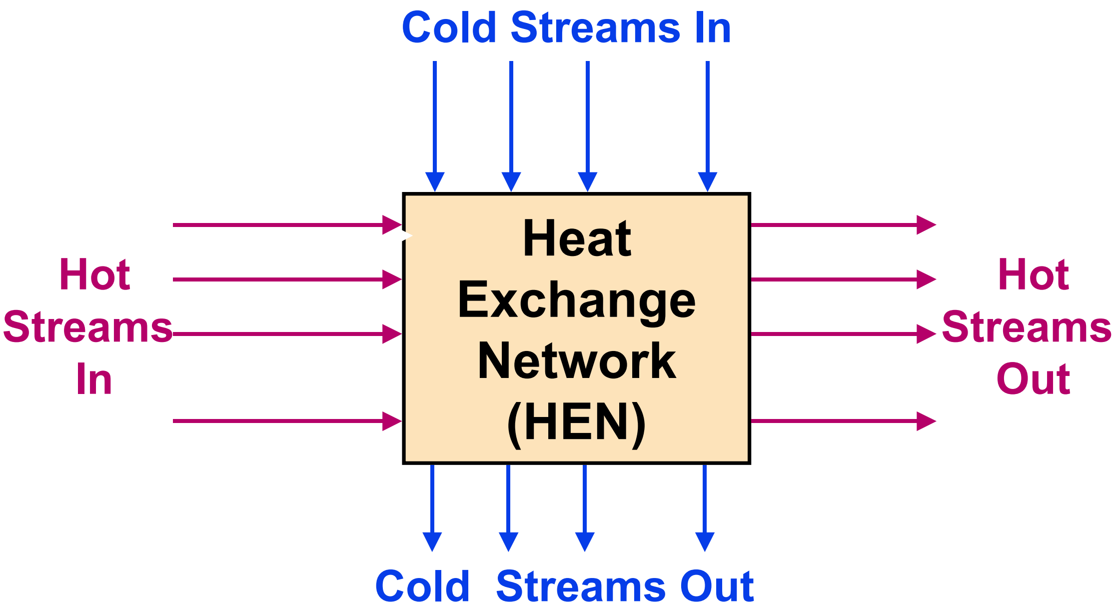

Fig. 9.1. Synthesis of HENs.

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 ?) ?

Numerous methods have been developed for the synthesis of HENs. These methods have been reviewed by Shenoy (1995), Linnhoff (1993), Gundersen and Naess (1988) and Douglas (1988). One of the key advances in synthesizing HENs is the identification of minimum utility targets ahead of designing the network using the thermal pinch analysis. This technique is presented in the following section.

9.2. HEAT-EXCHANGE PINCH DIAGRAM

Let us 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

$$T = t \tag{9.1}$$

By employing a minimum heat-exchange driving force of $\Delta T^{\min}$, 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.

$$T = t + \Delta T^{\min} \tag{9.2}$$

This expression ensures that the heat-transfer considerations of the second law of thermodynamics are satisfied. 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. It is worth noting the analogy between Eqs. (9.2) and (4.16). Thermal equilibrium is a special case of mass-exchange equilibrium with T, t, and $\Delta T^{\min}$ corresponding to y_i, x_j and ε_j, respectively, while the values of m_j and b_j are one and zero, respectively. Table 9.1 summarizes the analogous terms in MENs and HENs. Similar to the role of ε_j in cost optimization, $\Delta T^{\min}$ can be used to trade off capital versus operating costs as shown in Fig. 9.2.

Table 9.1. 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: $\Delta T^{\min}$

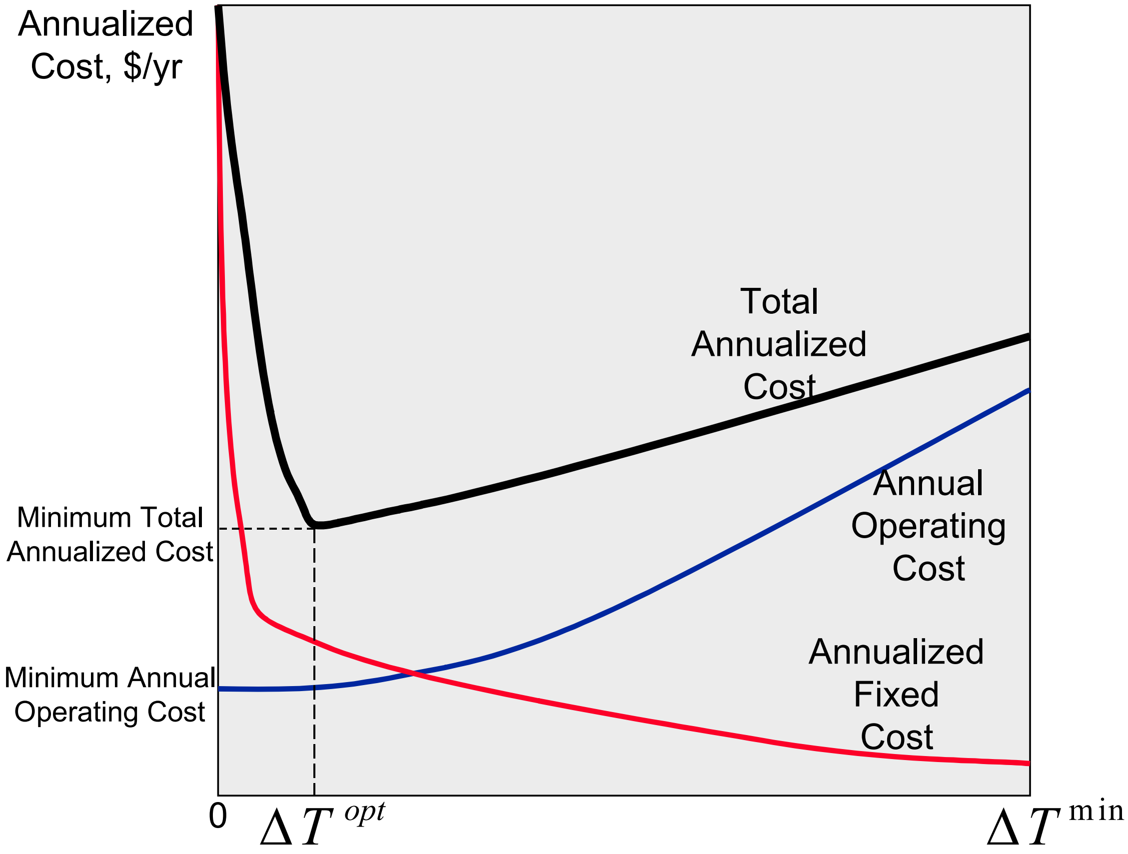

Fig. 9.2. Role of Minimum Approach Temperature

in Trading Off Capital versus Operating Costs

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." This technique is primarily based on the work of Linnhoff and co-workers (e.g. Linnhoff and Hindmarsh, 1983), Umeda *et al.* (1979), and Hohmann (1971). 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.[1] Hence, a hot stream losing sensible heat[2] is represented as an arrow whose tail 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 $F_uC_{P,u}$. 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 *u*th hot stream $HH_u = F_u C_{p,u}(T_u^s - T_u^t)$,

where

$$u = 1,2,..,N_H. \tag{9.3}$$

Note that 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 Chapter Four, one can create a hot composite stream using the diagonal rule. Figure 9.3 illustrates this concept for two hot streams.

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[1] In most HEN literature, the temperature is plotted versus the enthalpy. However, in this chapter enthalpy is plotted versus temperature in order to draw the analogy with MEN synthesis. Furthermore, when there is a strong interaction between mass and energy objectives the enthalpy expressions become nonlinear functions of temperature. In such cases, it is easier to represent enthalpy as a function of temperature.

[2] Whenever there is a change in phase, the latent heat should also be included.

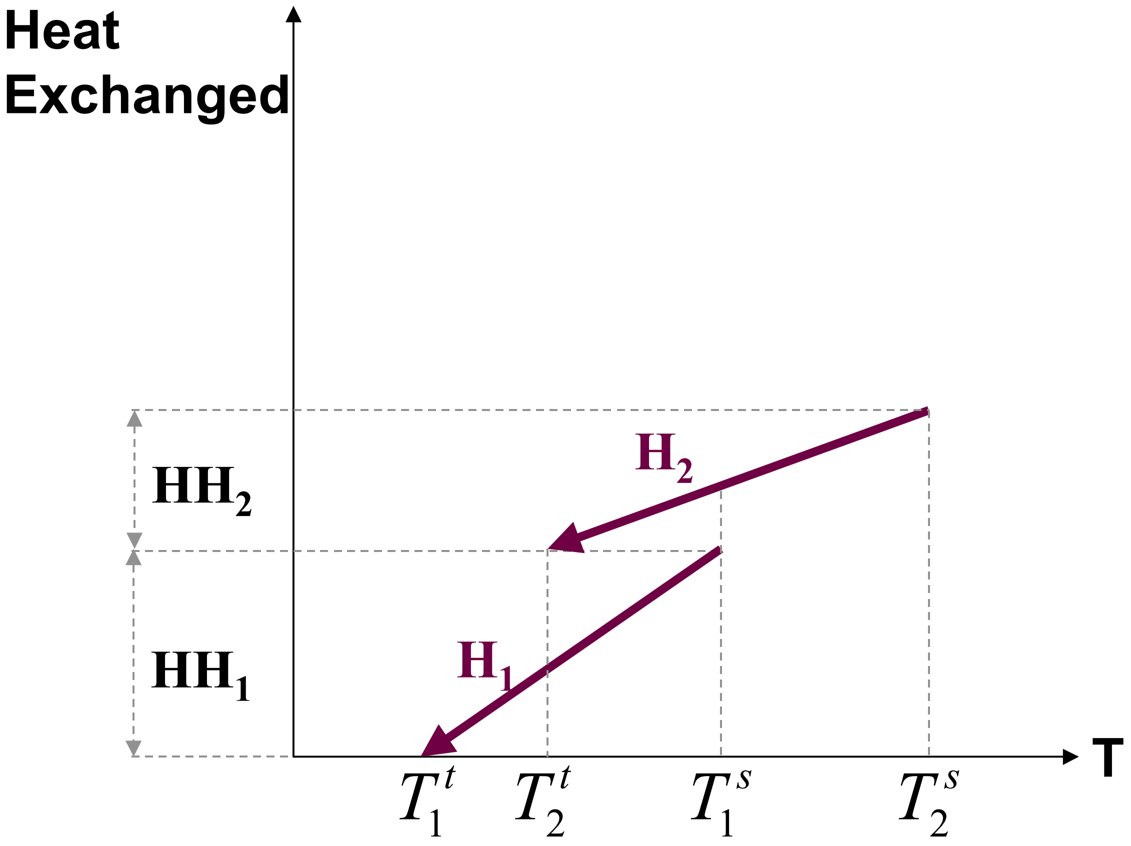

Fig. 9.3a. Representing hot streams

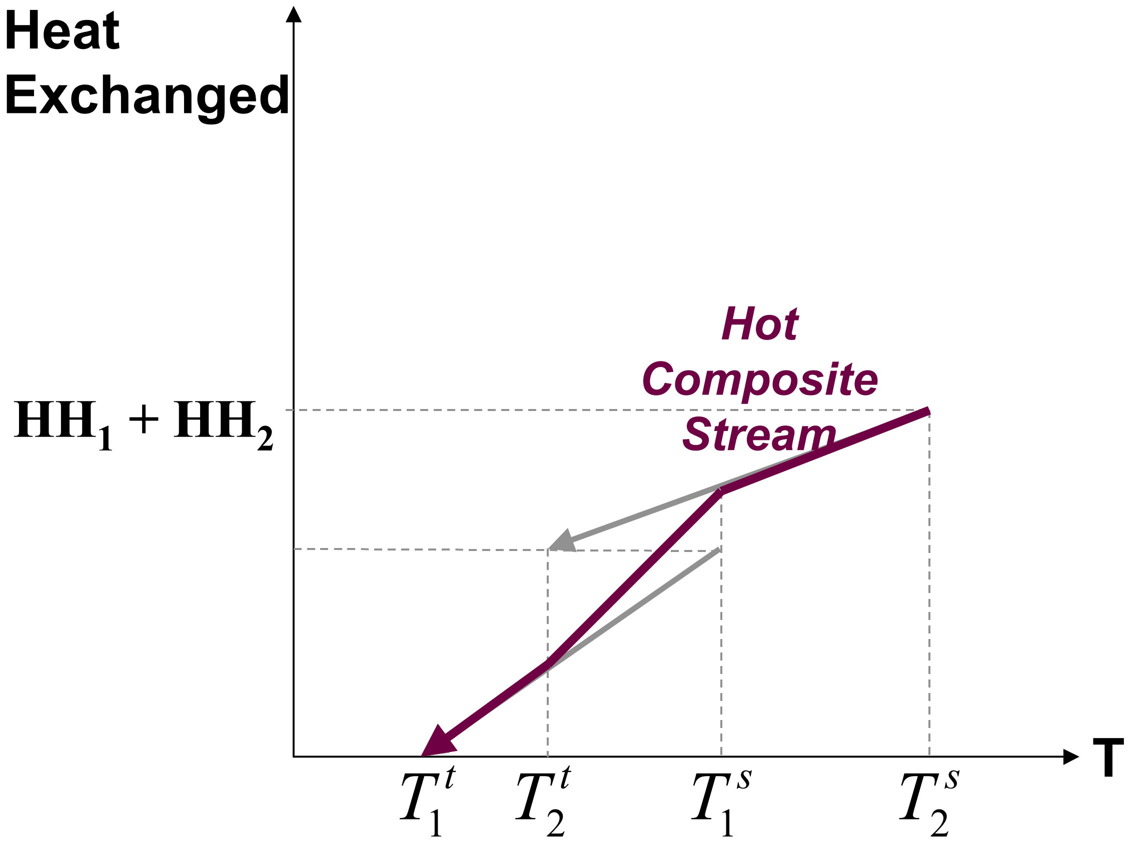

Fig. 9.3b. Constructing a hot composite stream using superposition

(dashed line represents composite line).

Next, a cold-temperature scale, *t*, is created in one-to-one correspondence with the hot temperature scale, *T*, using Eq. (9.2). The enthalpy of each cold stream is plotted versus the cold temperature scale, *t*. The vertical distance between the arrow head and tail for a cold stream is given by

$$\text{Heat gained by the } v\text{th cold stream } HC_v = f_v c_{p,v}(t_v^t - t_v^s),$$

$$\text{where} \quad v = 1,2,.,N_C. \tag{9.4}$$

In a similar manner to constructing the hot-composite line, a cold composite stream is plotted (see Fig. 9.4 for a two-cold-stream example).

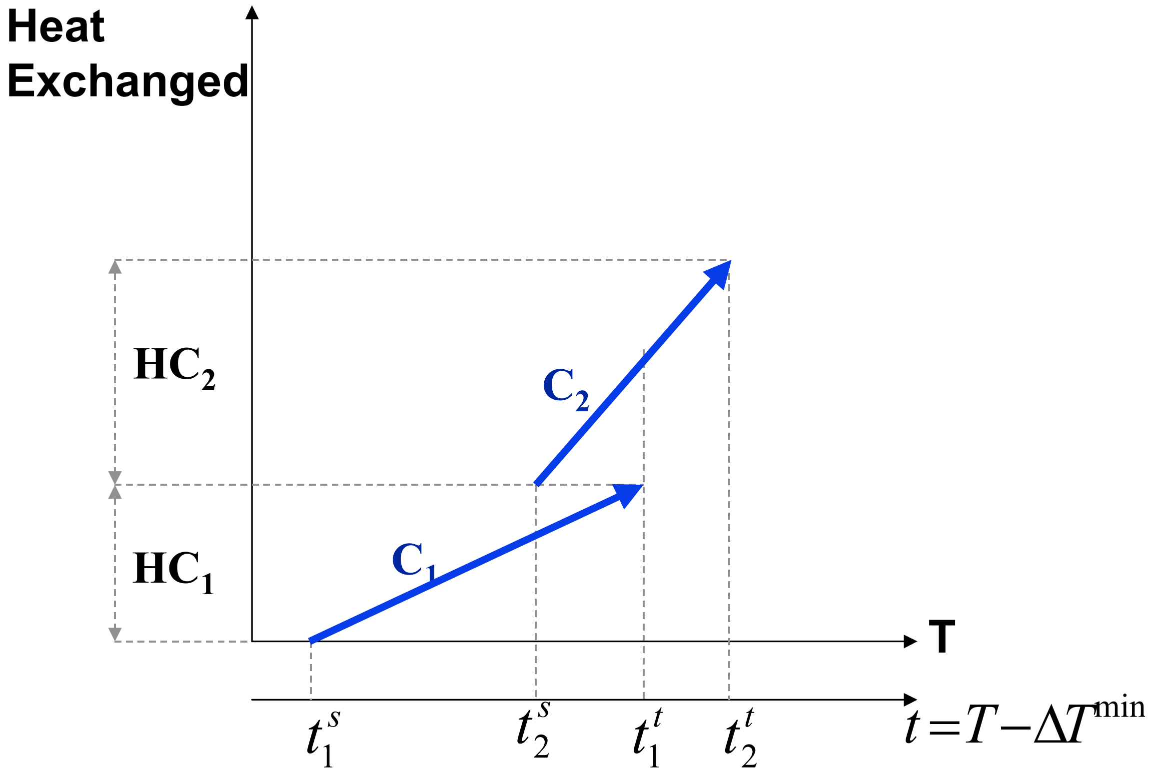

Fig. 9.4a. Representing cold streams

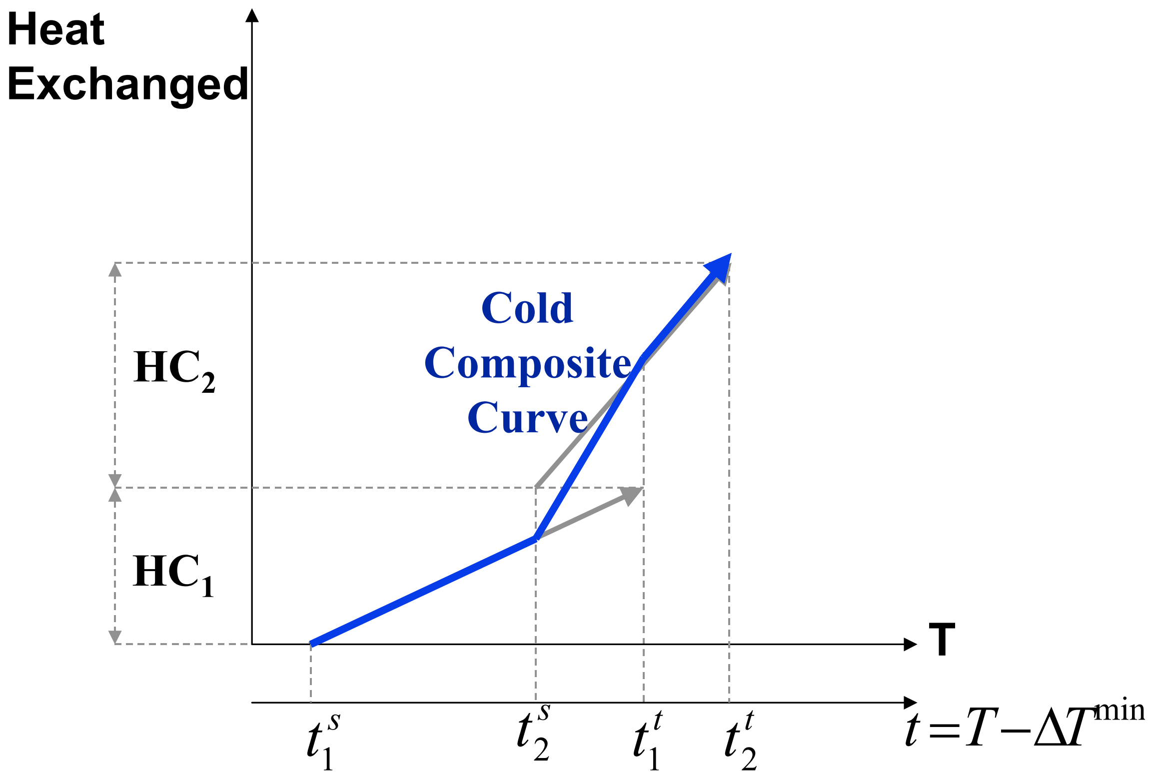

Fig. 9.4b. Constructing a cold composite stream using superposition (dashed line represents composite line).

Next, both composite streams are plotted on the same diagram (Fig. 9.5). 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 than 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.

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 as seen in Fig. 9.5. When the cold composite stream is moved downwards so as to provide some horizontal overlap, some integrated heat exchange can be achieved (Fig. 9.6). 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 (Fig. 9.7). 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." As Fig. 9.8. shows, 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 Fig. 9.9. 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.

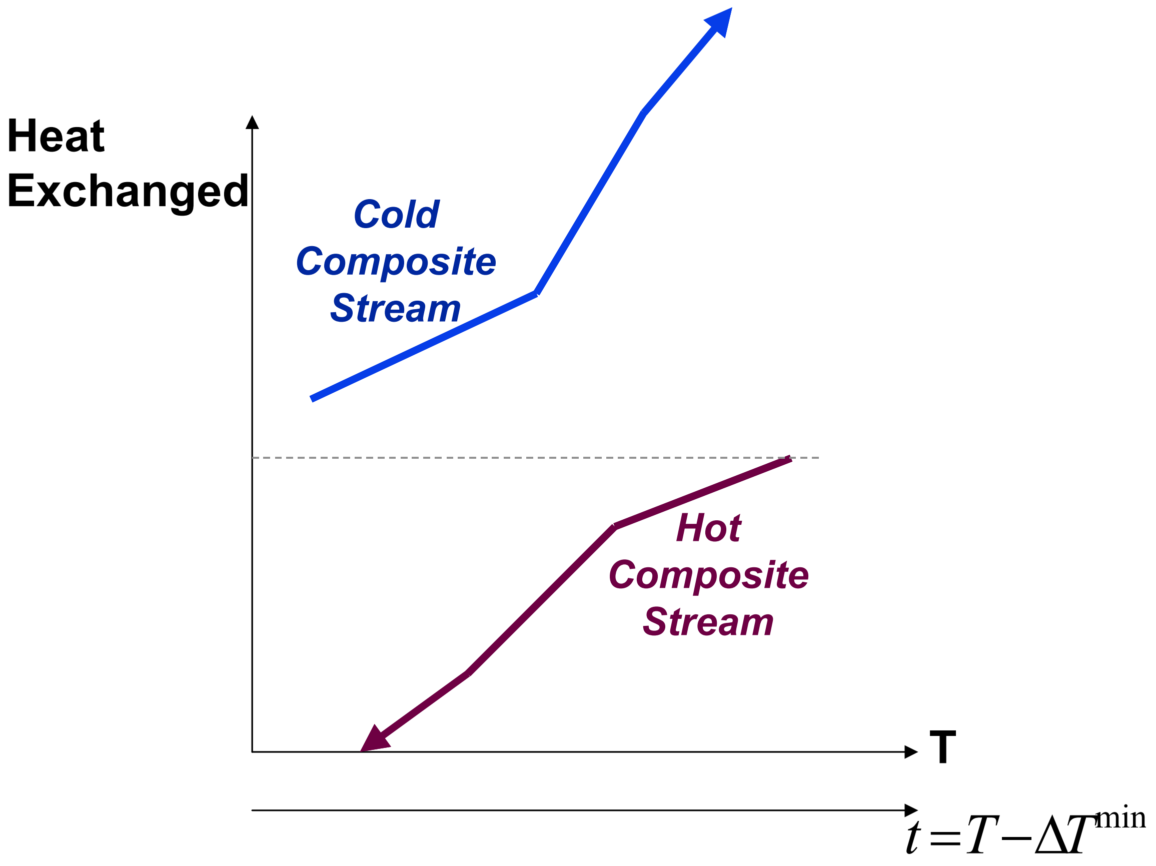

Fig. 9.5 Placement of Composite Streams with No Heat Integration

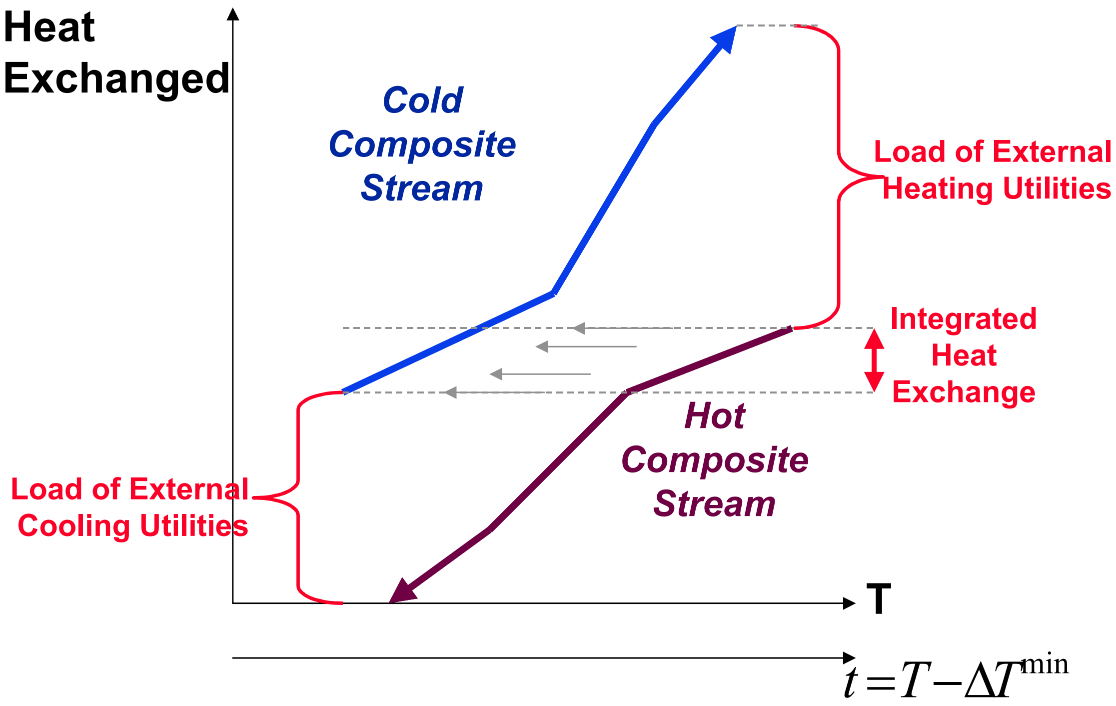

Fig. 9.6. Partial Heat Integration

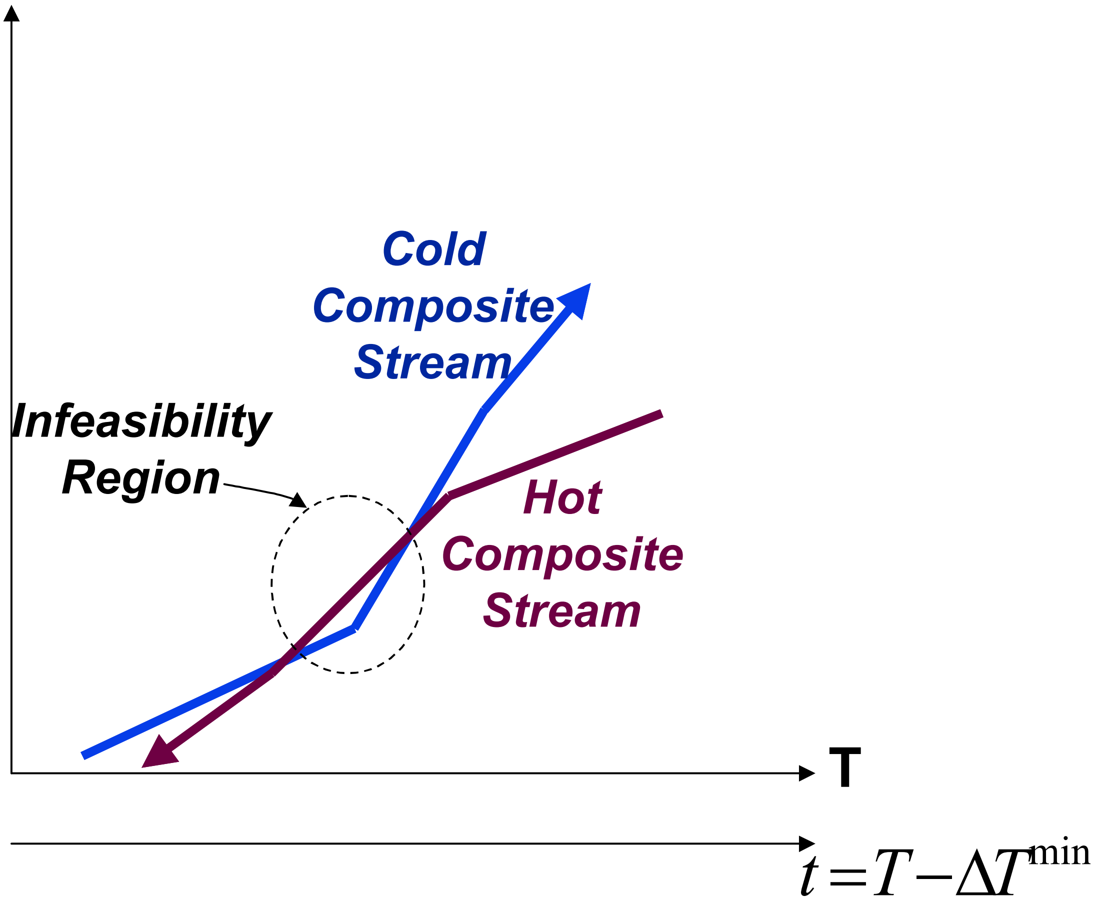

Fig. 9.7. Infeasible Heat Integration

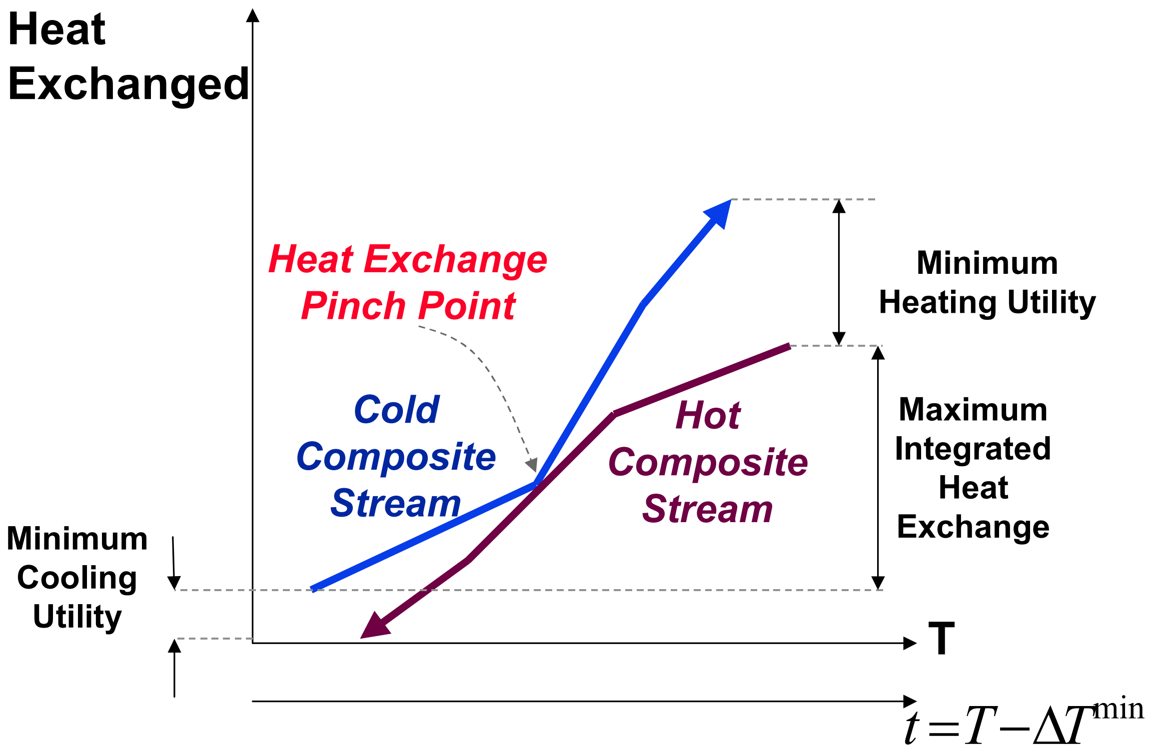

Fig. 9.8. Thermal pinch diagram.

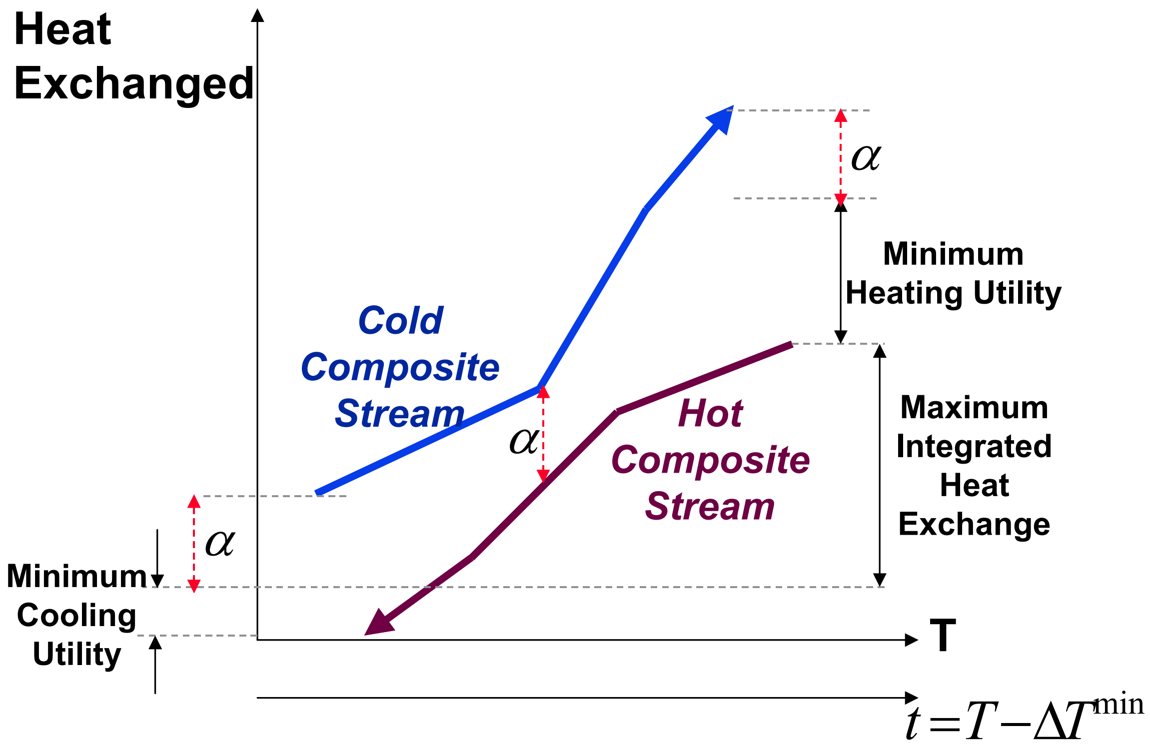

Fig. 9.9. Penalties Associated with Passing Heat through the Pinch

EXAMPLE 9.1. UTILITY MINIMIZATION IN A CHEMICAL PLANT

Consider the chemical processing facility illustrated in Fig. 9.10. The process has two adiabatic reactors. The intermediate product leaving the first reactor (C_1) is heated from 420 to 490 K before being fed to the second reactor. The off-gases leaving the reactor (H_1) at 460 K are cooled to 350 K 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 (H_2) is cooled from 400 to 300 prior to sales. A byproduct stream (C_2) is heated from 320 to 390 K before being fed to a flash column. Stream data are given in Table 9.1.

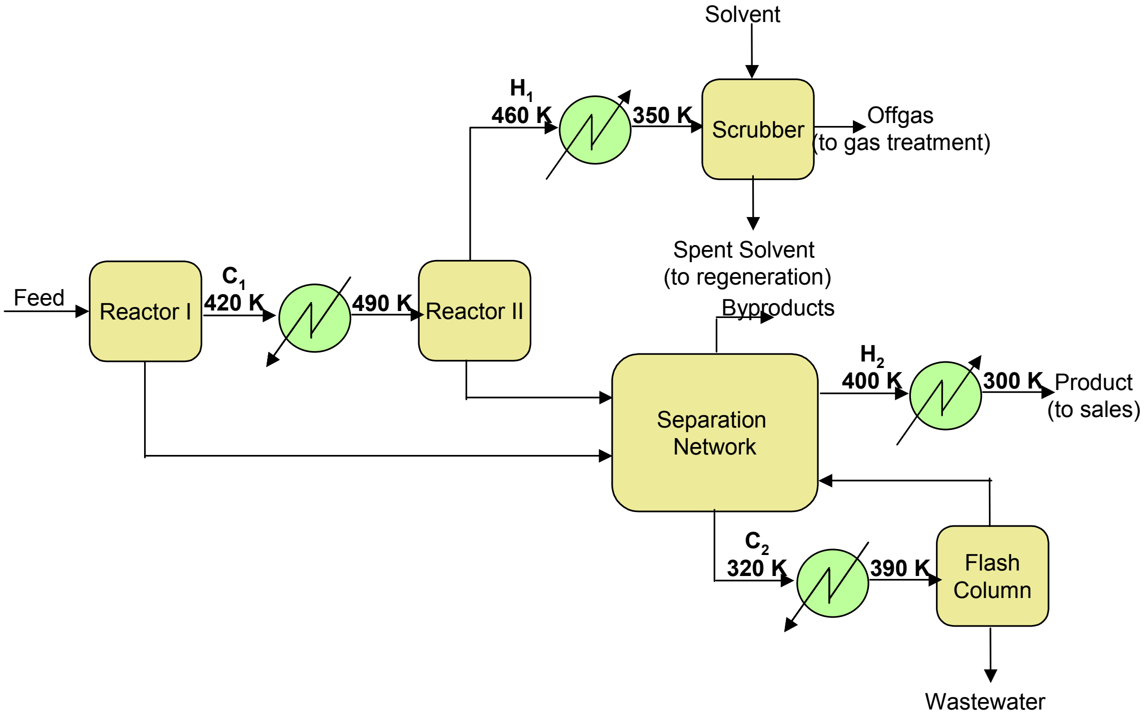

Fig. 9.10. Simplified Flowsheet for the Chemical Processing Facility.

Table 9.2. Stream Data for the Chemical Process

Stream	Flowrate x 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

Figures 9.11 – 9.13 illustrate the hot composite stream, the cold composite stream and the pinch diagram, respectively. As can be seen from Fig. 9.13, 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:

$$\text{Target for percentage savings in heating utility} = \frac{56{,}000 - 33{,}000}{56{,}000} x100\% = 41\% \qquad (9.5)$$

$$\text{Target for percentage savings in cooling utility} = \frac{83{,}000 - 60{,}000}{83{,}000} x100\% = 28\% \qquad (9.6)$$

Once the minimum operating cost is determined, a network of heat exchangers can be synthesized.[3] The trade-off between capital and operating costs can be established by iteratively varying $\Delta T^{\min}$ until the minimum total annualized cost is attained.

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[3] Constructing the HEN with minimum number of units and minimum heat-transfer area is analogous to constructing a MEN. The design starts from the pinch following two matching criteria relating number of streams and heat capacities. A detailed discussion on this issue can be found in Linnhoff and Hindmarsh (1983), Douglas (1988) Shenoy (1995), and Smith (1995).

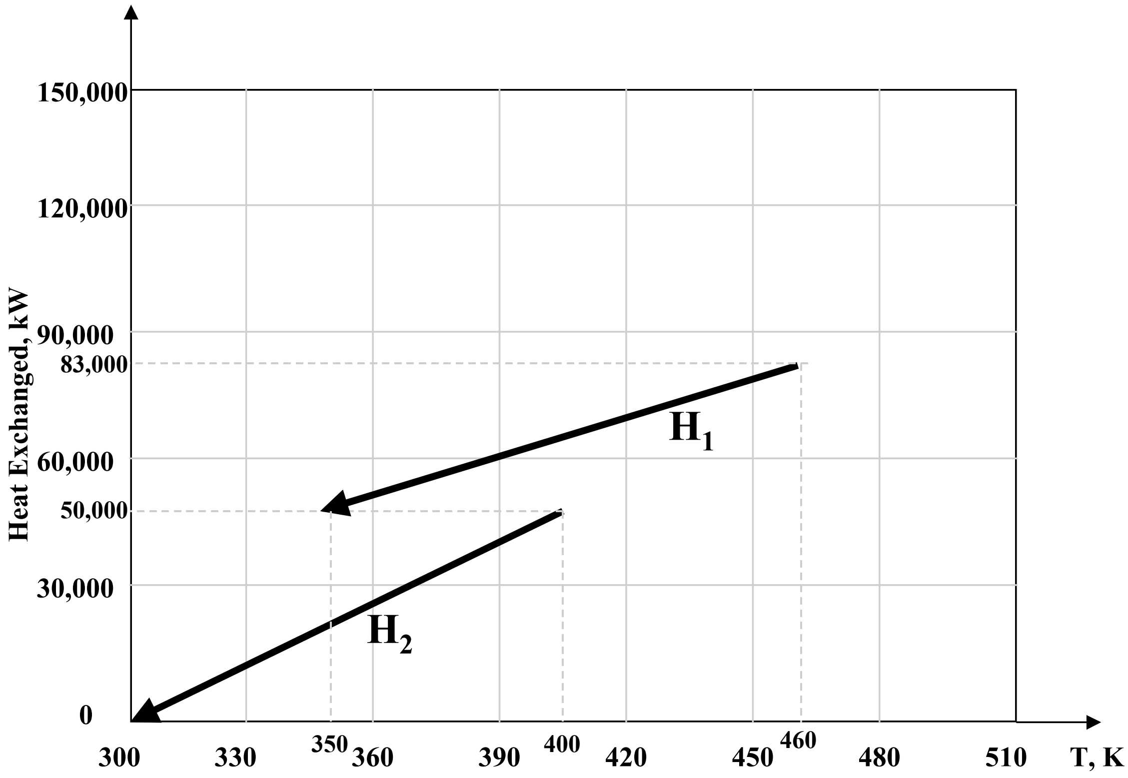


Fig. 9.11a. Hot Streams Example 10.1.

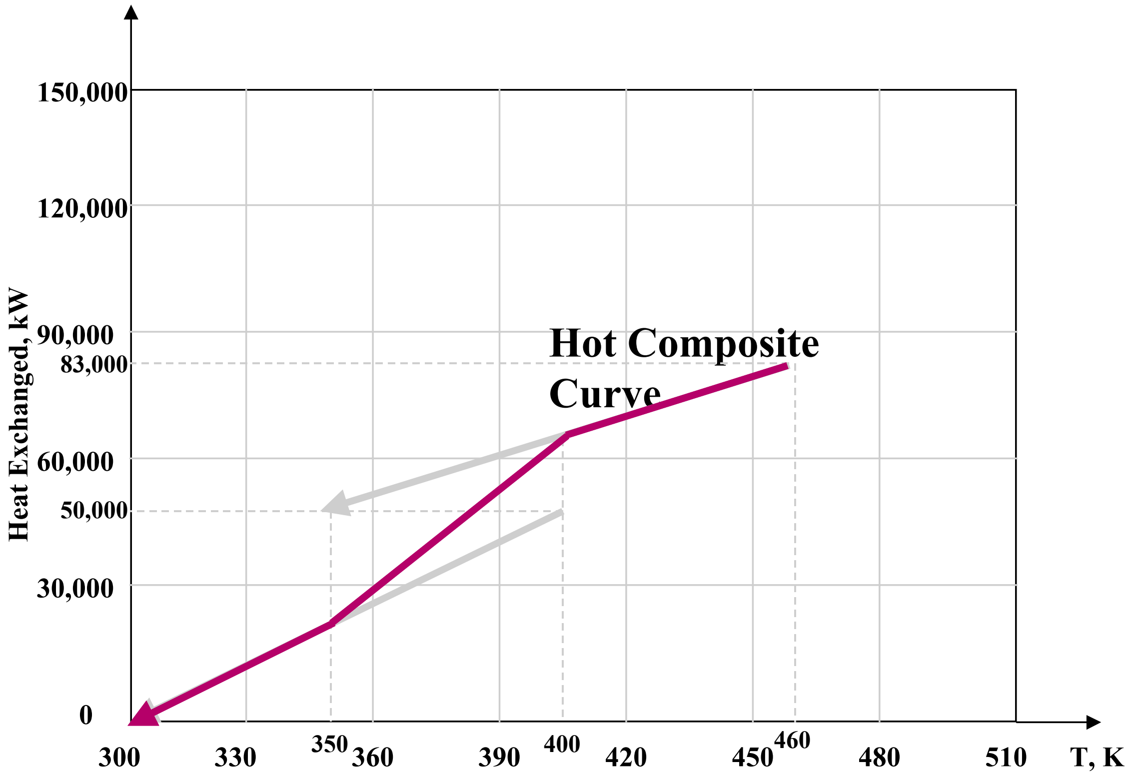


Fig. 9.11b. Hot Composite Stream Example 10.1.

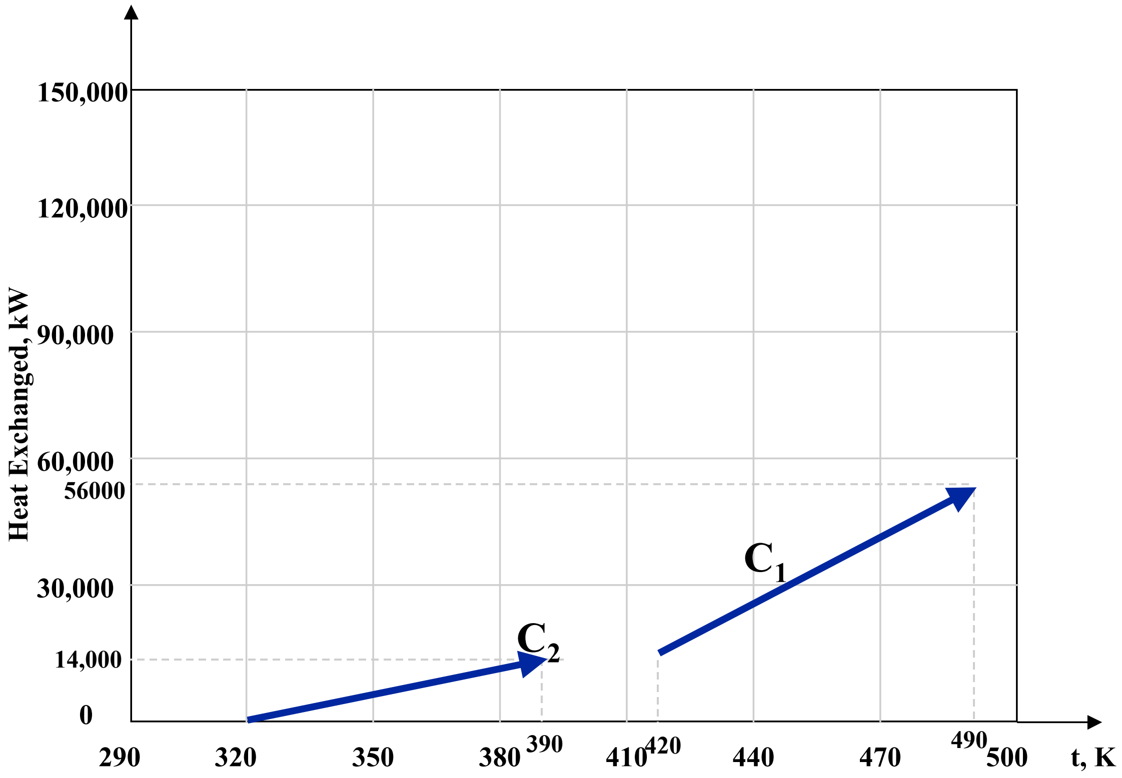


Fig. 9.12a Representing the Cold Streams for Example 9.1

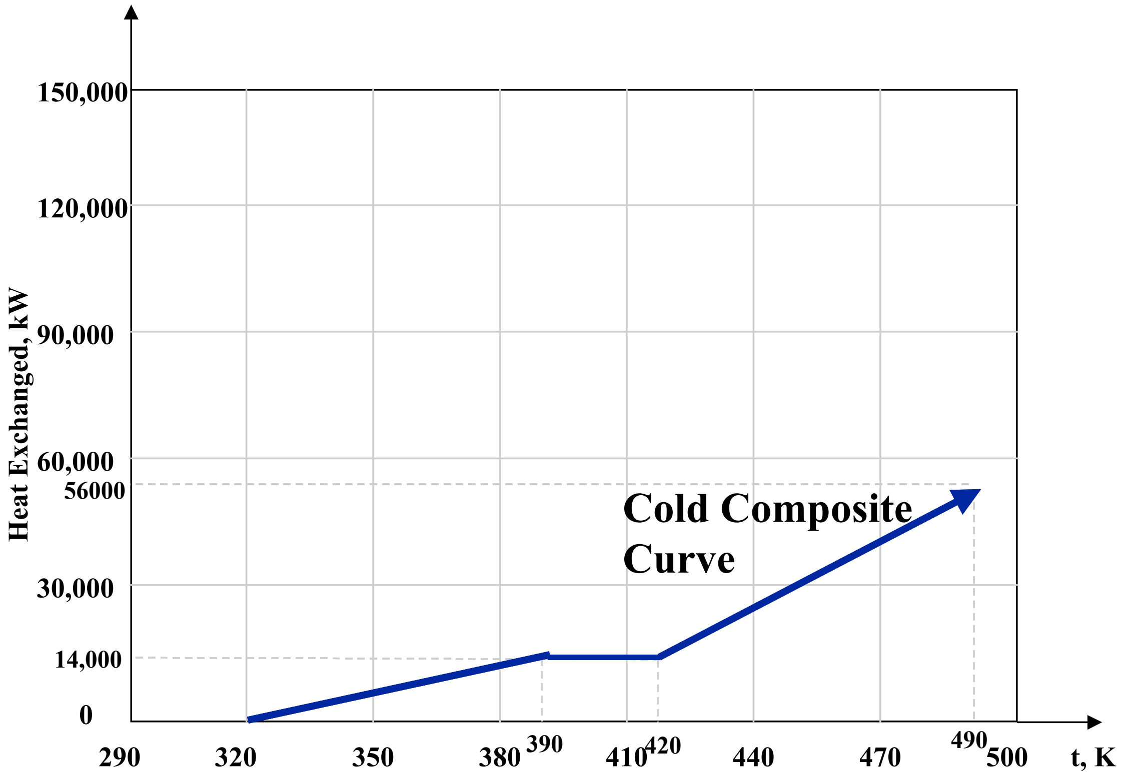


Fig. 9.12b. Cold Composite Stream for Example 9.1.

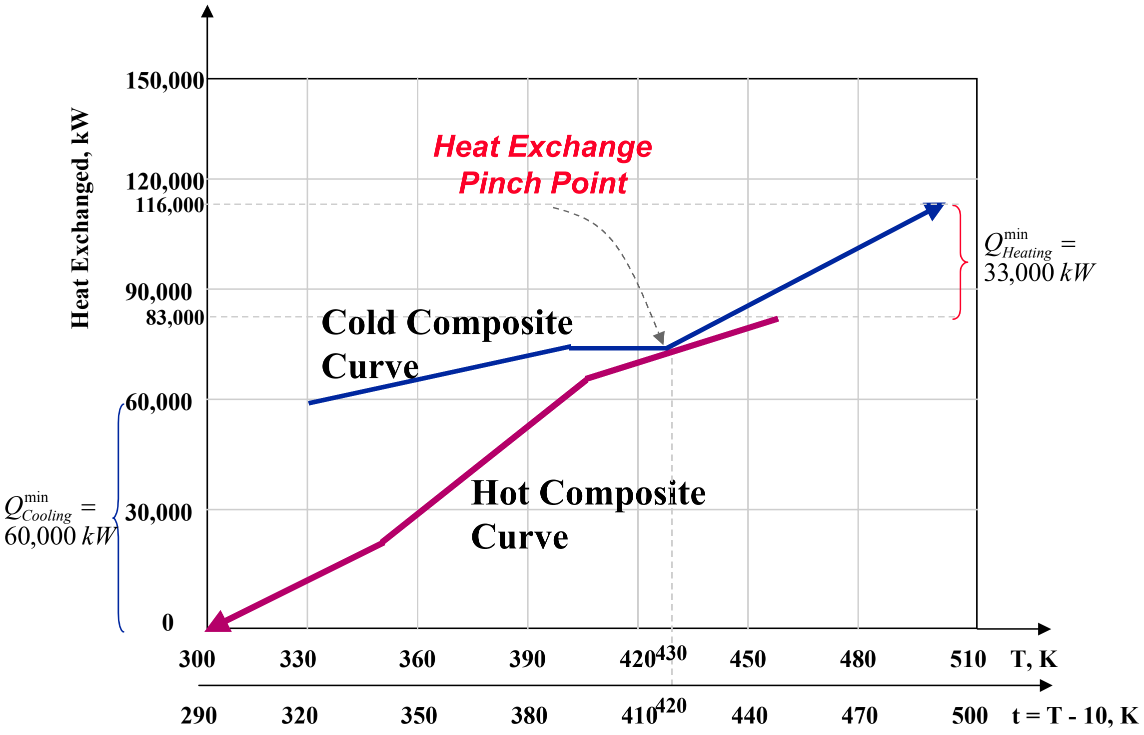


Fig. 9.13a. Thermal Pinch Diagram for Example 9.1.

As mentioned before, there are several techniques for configuring the actual network of heat exchangers that satisfies that utility targets. One technique is to match streams that lie at the same temperature level by transferring heat horizontally. Figure 9.13b is an illustration of this approach with the dotted boxes representing the horizontal heat transfers. Each box may represent an actual heat exchanger or more (in case of multiple streams in the box). It is worth noting that the first and the last two boxes involve the use of heating and cooling utilities, respectively.

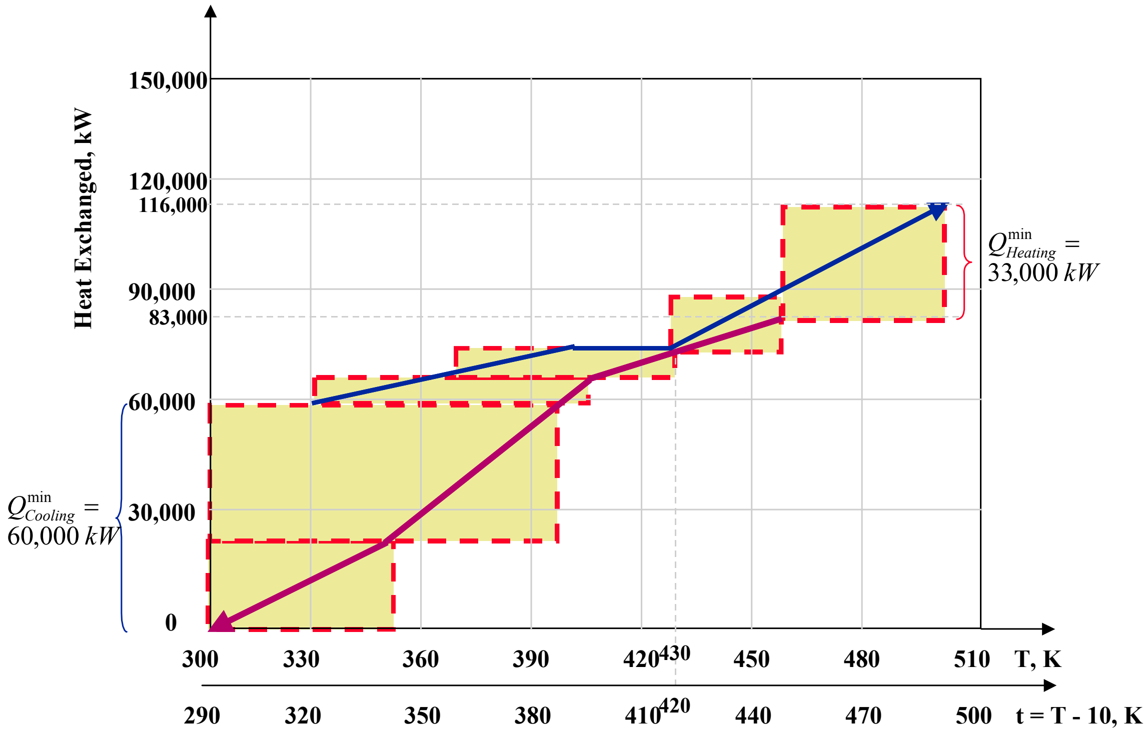


Fig. 9.13b Matching of Hot and Cold Streams

9.3. MINIMUM UTILITY TARGETING THROUGH AN ALGEBRAIC PROCEDURE

The temperature-interval diagram (TID) is a useful tool for ensuring thermodynamic feasibility of heat exchange. It is a special case of the CID described in Chapter Seven in which only two corresponding temperature scales are generated: hot and cold. The scale correspondence is determined using Eq. (9.2). Each stream is represented as a vertical arrow whose tail corresponds to its supply temperature, while its head represents its target temperature. Next, horizontal lines are drawn at the heads and tails of the arrows. These horizontal lines define a series of temperature intervals $z = 1,2, ., n_{\text{int}}$. Within any interval, it is thermodynamically feasible to transfer heat from the hot streams to the cold streams. It is also feasible to transfer heat from a hot stream in an interval z to any cold stream which lies in an interval below it

Next, we construct a table of exchangeable heat loads (TEHL) to determine the heat-exchange loads of the process streams in each temperature interval. The exchangeable load of the uth hot stream (losing sensible heat) which passes through the z th interval is defined as

$$\mathrm{HH}_{u,z} = F_u \, \mathrm{C}_{\mathrm{p,u}} \, (\mathrm{T}_{\mathrm{z-1}} - \mathrm{T}_{\mathrm{z}}), \tag{9.7}$$

where $T_{z\text{-}1}$ and T_z are the hot-scale temperatures at the top and the bottom lines defining the zth interval. On the other hand, the exchangeable capacity of the vth cold stream (gaining sensible heat) which passes through the zth interval is computed through

$$\mathrm{H}C_{v,z} = f_v \, c_{p,v} \, (t_{z-1} - t_z), \tag{9.8}$$

where $\mathrm{t}_{\mathrm{z-1}}$ and t_z are the cold-scale temperatures at the top and the bottom lines defining the zth interval.

Having determined the individual heating loads and cooling capacities of all process streams for all temperature intervals, one can also obtain the collective loads (capacities) of the hot (cold) process streams. The collective load of hot process streams within the zth interval is calculated by summing up the individual loads of the hot process streams that pass through that interval, i.e.,

$$HH_z^{Total} = \sum_{\substack{u \text{ passes through interval } z \\ \text{where } \mathrm{u}=1,\, 2,\, \ldots\ldots,\, \mathrm{N}_\mathrm{H}}} HH_{u,z}. \tag{9.9}$$

Similarly, the collective cooling capacity of the cold process streams within the zth interval is evaluated as follows:

$$HC_z^{Total} = \sum_{\substack{v \text{ passes through interval } z \\ \text{and } v=1,2,\ldots.,N_C}} HC_{v,z} \tag{9.10}$$

As has been mentioned earlier, within each temperature interval, it is thermodynamically as well as technically feasible to transfer heat from a hot process stream to a cold process stream. Moreover, it is feasible to pass heat from a hot process stream in an interval to any cold process stream in a lower interval. Hence, for the *z*th temperature interval, one can write the following heat-balance equation:

$$r_z = HH_z^{Total} - HC_z^{Total} + r_{z-1} \tag{9.11}$$

where r_{z-1} and r_z are the residual heats entering and leaving the *z*th interval. Figure 9.14 illustrates the heat balance around the *z*th temperature interval.

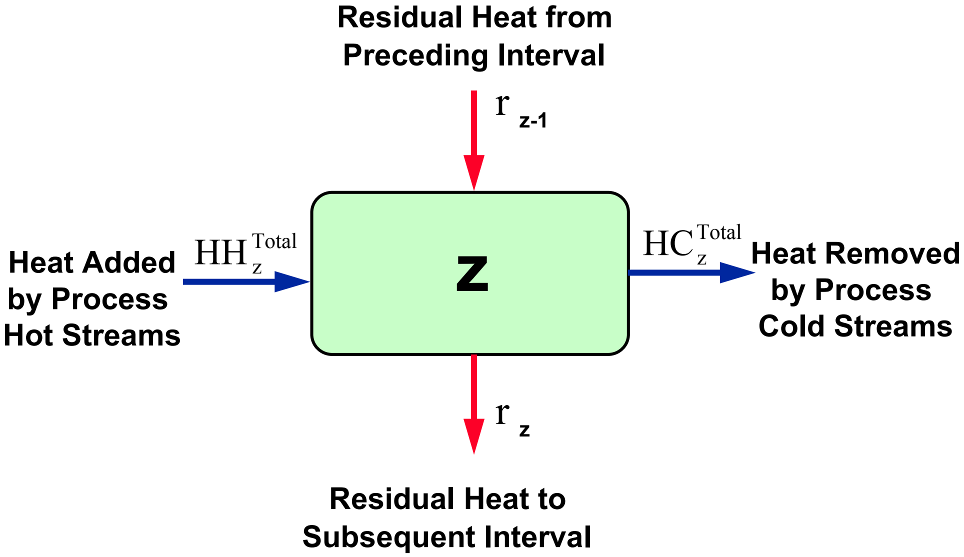


Fig. 9.14. Heat balance around temperature interval.

r_0 is zero, since no process streams exist above the first interval. In addition, thermodynamic feasibility is ensured when all the r_z's are nonnegative. Hence, a negative r_z indicates that residual heat is flowing upwards, which is thermodynamically infeasible . All negative residual heats can be made non negative if a hot load equal to the most negative r_z is added to the problem. This load is referred to as the minimum heating utility requirement, $Q_{Heating}^{\min}$. Once this hot load is added, the cascade diagram is revised. A zero residual heat designates the thermal-pinch location. The load leaving the last temperature interval is the minimum cooling utility requirement, $Q_{Cooling}^{\min}$.

9.4. CASE STUDY REVISITED USING THE ALGEBRAIC PROCEDURE

We now solve the pharmaceutical case study described earlier using the algebraic cascade diagram. The first step is the construction of the TID (Fig. 9.15). Next, the TEHLs for the process hot and cold streams are developed (Tables 9.3 and 10.4). Figures 9.16 and 9.17 show the cascade-diagram calculations. The results obtained from the revised cascade diagram are identical to those obtained using the graphical pinch approach.

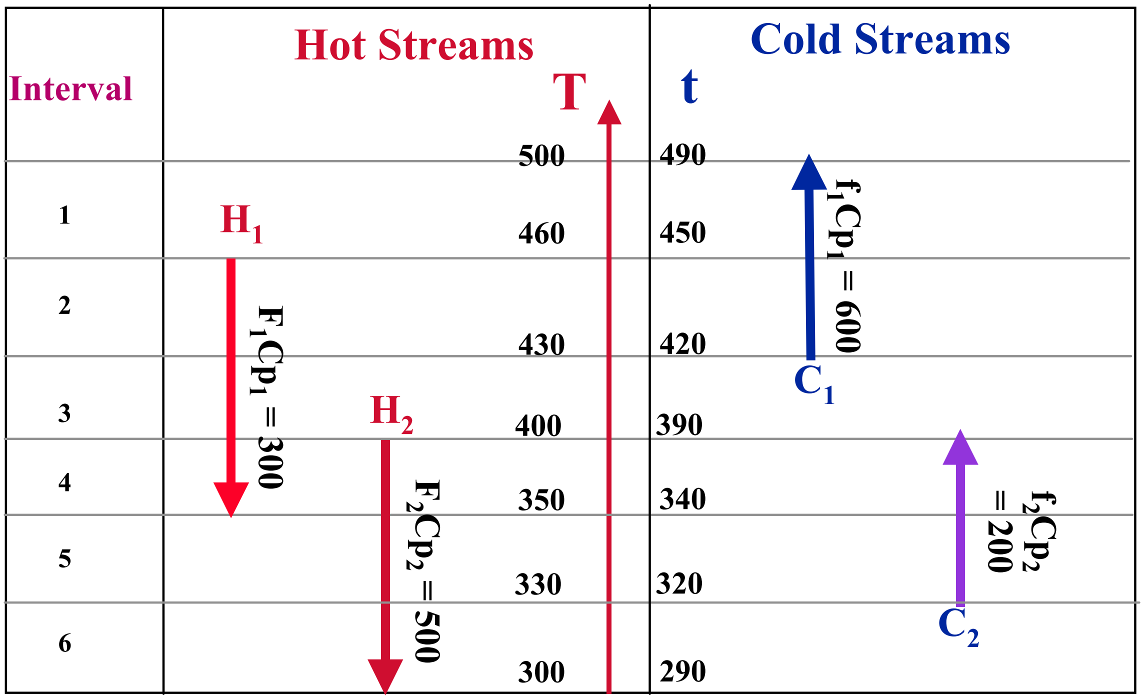


Fig. 9.15. Temperature Interval Diagram for Example 9.1.

Table 9.3. TEHL for Process Hot Streams

Interval	Load of H_1 (kW)	Load of H_2 (kW)	Total Load (kW)
1	-	-	-
2	9,000	-	9,000
3	9,000	-	9,000
4	15,000	25,000	40,000
5	-	10,000	10,000
6	-	15,000	15,000

Table 9.4. TEHL for Process Cold Streams

Interval	Capacity of C_1 (kW)	Capacity of C_2 (kW)	Total capacity (kW)
1	24,000	-	24,000
2	18,000	-	18,000
3	-	-	-
4	-	10,000	10,000
5	-	4,000	4,000
6	-	-	-

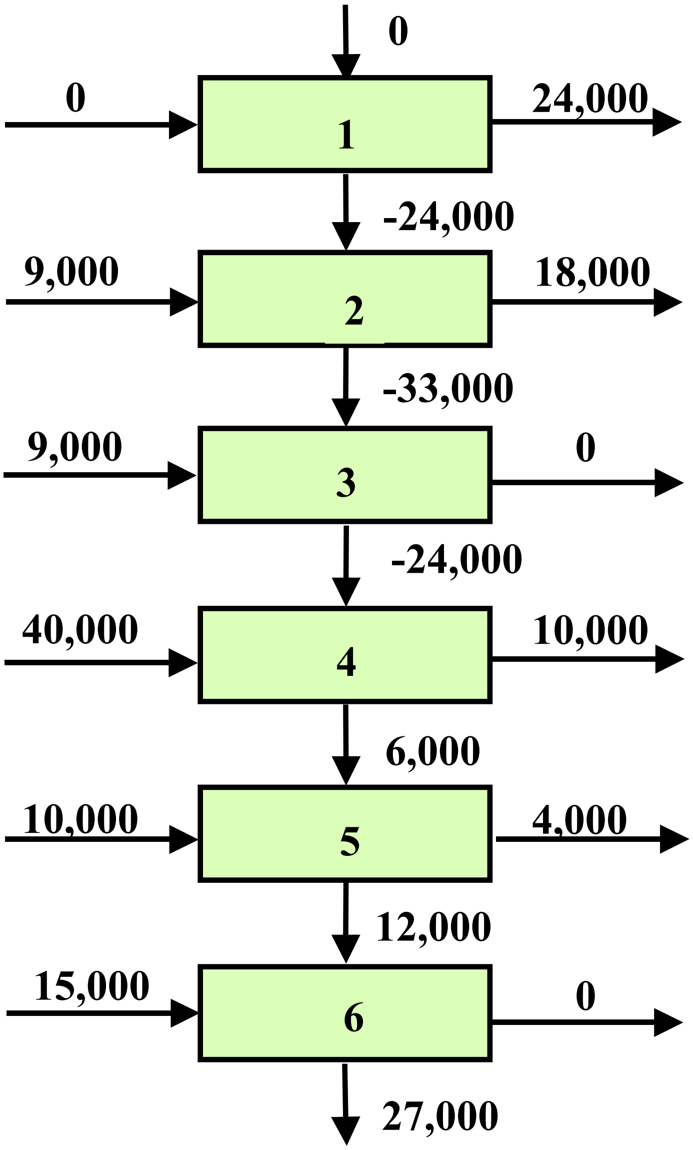


Fig. 9.16. Cascade Diagram for Example 9.1

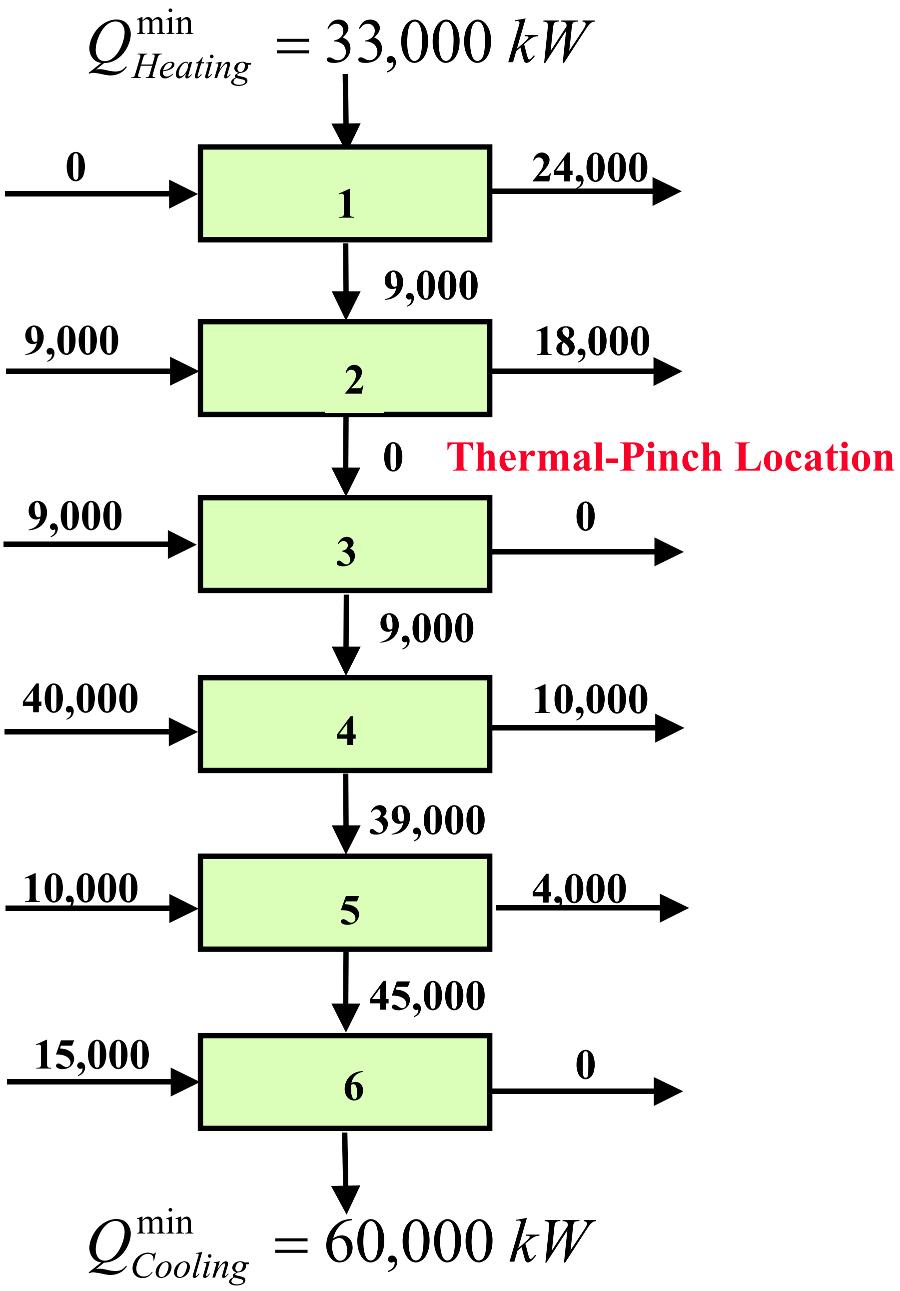


Fig. 9.17 Revised Cascade Diagram for Example 9.1

As mentioned earlier, for minimum utility usage no heat should be passed through the pinch. Let us illustrate this point using the cascade diagram. Suppose that we use $Q_{Heating}^{extra}$ kW more than the minimum heating utility. As can be seen from Fig. 9.18, this additional heating utility passes down through the cascade diagram in the form of an increased residual heat load. At the pinch, the residual load becomes $Q_{Heating}^{extra}$. The net effect is not only an increase in the heating utility load, but also an equivalent increase in the cooling utility load.

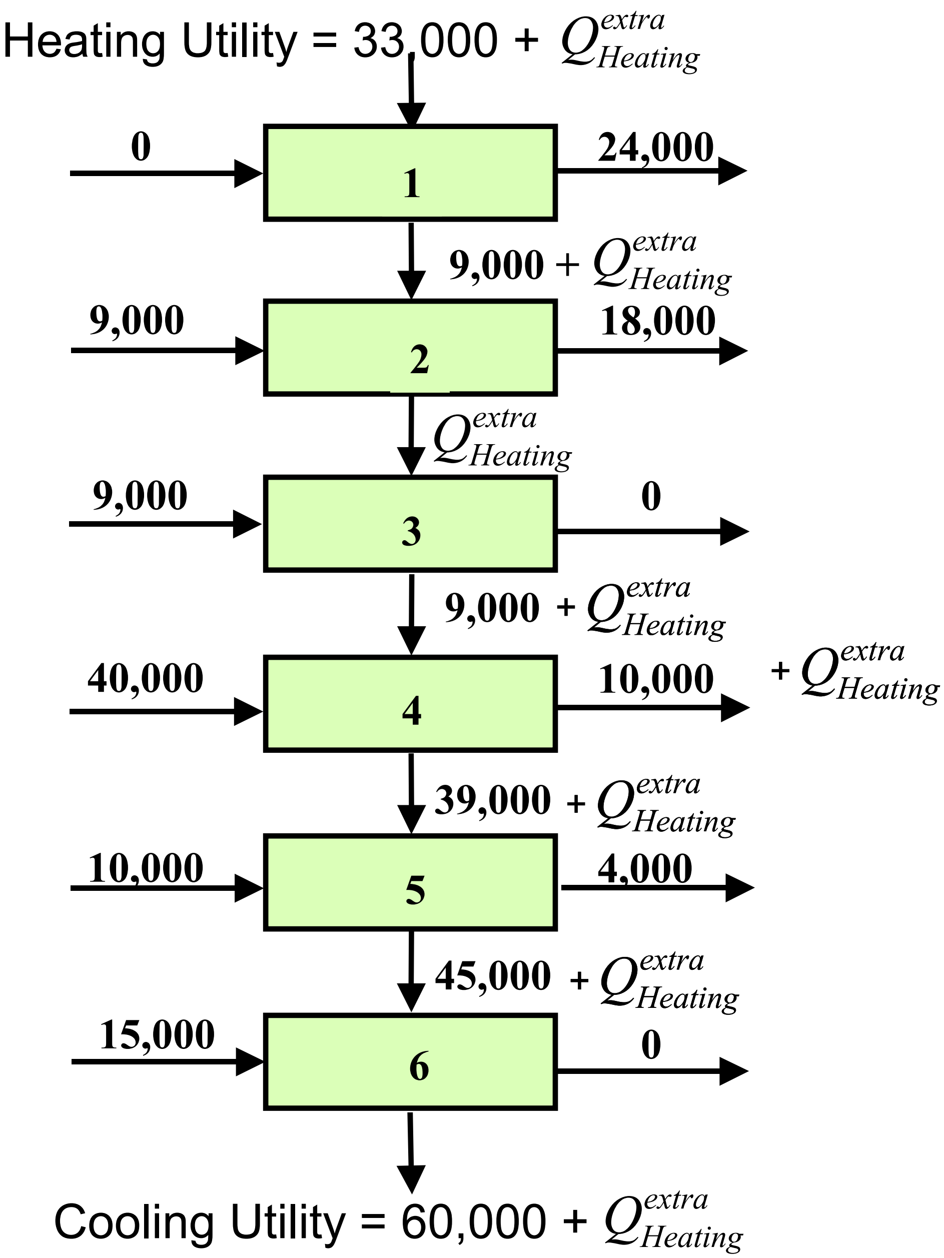


Fig. 9.18. Consequences of Passing Heat Across the Pinch.

9.5. SCREENING OF MULTIPLE UTILITIES USING THE GRAND COMPOSITE REPRESENTATION

So far, construction of the heat-exchange pinch diagram started by maximizing the heat exchange among the process hot and cold streams and minimizing the external heating and cooling utilities. In many cases, multiple utilizes are available for service. These utilities must be screened so as to determine which one(s) should be used and the task of each utility. In order to minimize the cost of utilities, it may be necessary to stage the use of utilities such that at each level the use of the cheapest utility ($/kJ) is maximized while insuring its feasibility. A convenient way of screening multiple utilities is the ***grand composite curve (GCC)***.

The GCC may be directly constructed from the cascade diagram. To illustrate the procedure for constructing the GCC, let us consider the cascade diagram shown in Fig. 9.19a. The residual heat loads are shown leaving the temperature intervals. Suppose that r_4 is the most negative residual. As mentioned before, this infeasibility and all other infeasibilities are removed by adding the absolute value of r_4 to the top of the cascade diagram. This value is also the minimum heating utility. The residual loads are re-calculated with the load leaving the last temperature interval being the minimum cold utility.

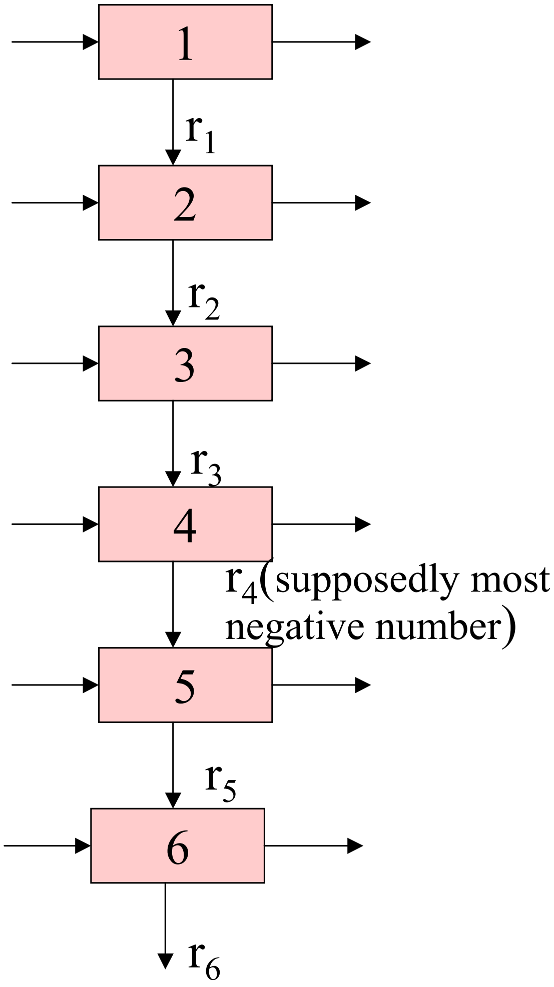


Fig. 9.19a Cascade Diagram

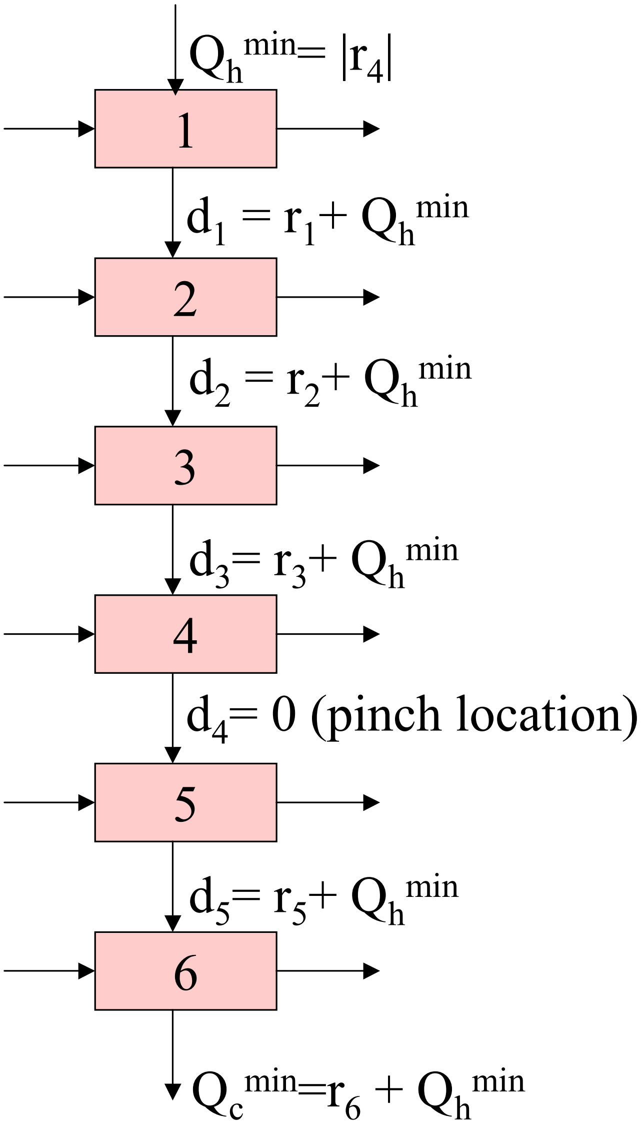


Fig. 9.19b Revised Cascade Diagram

Each residual heat corresponds to a hot temperature and a cold temperature. In order to have a single-temperature representation, we use an adjusted temperature scale which is calculated as the arithmetic average of the hot and the cold temperature, i.e.

$$\text{Adjusted temperature} = \frac{T+t}{2} \tag{9.12}$$

Given the relationship between the hot and cold temperature (described by Eq. 10.2), we get:

$$\text{Adjusted temperature} = T - \frac{\Delta T^{\min}}{2} \tag{9.13a}$$

$$= t + \frac{\Delta T^{\min}}{2} \quad (9.13b)$$

Next, we represent the adjusted temperature versus the residual enthalpy as shown in Fig. 9.20a. This representation is the GCC. The pinch point corresponds to the zero-residual point. Additionally, the top and bottom residuals represent the minimum heating and cooling utilities. The question is how to distribute these loads over the multiple utilities? Any time, the enthalpy representation is given by a line drawn from left to right, it corresponds to a surplus of heat in that interval. Conversely, when an enthalpy line is drawn from right to left, it corresponds to deficiency in heat in that interval. A heat surplus may be used to satisfy a heat residual below it. Therefore, the shaded regions (referred to as ***"pockets"***) shown in Fig. 9.20b are fully integrated by transferring heat from process hot streams to process cold streams. Then, we represent each utility based on its temperature. The adjusted temperature of a heating utility is given by Eq. 9.13a while that for a cooling utility is given by Eq. 9.13b. We start with the cheapest utility and maximize its use by filling the enthalpy gap (deficiency) at that level. Then, we move up for heating utilities and down for cooling utilities and continue to fill the enthalpy gaps by the cheapest utility at that level. Figure 9.20b is an illustration of this concept by screening low-and high-pressure steam where the low-pressure steam is cheaper ($/kJ) than the high-pressure steam. It is worth noting that the sum of the heating loads of the low- and high-pressure steams is equal to the minimum heating utility (the value of the top heat residual).

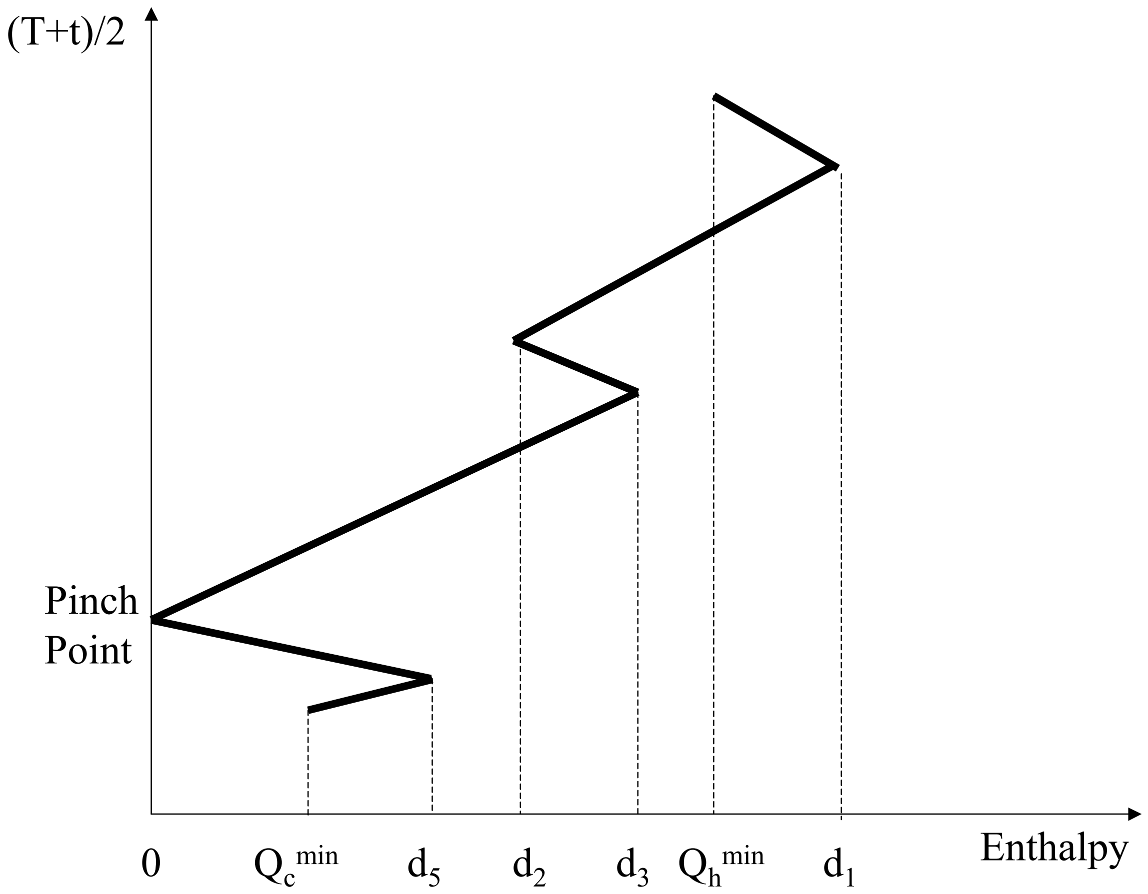


Fig. 9.20a Construction of the GCC

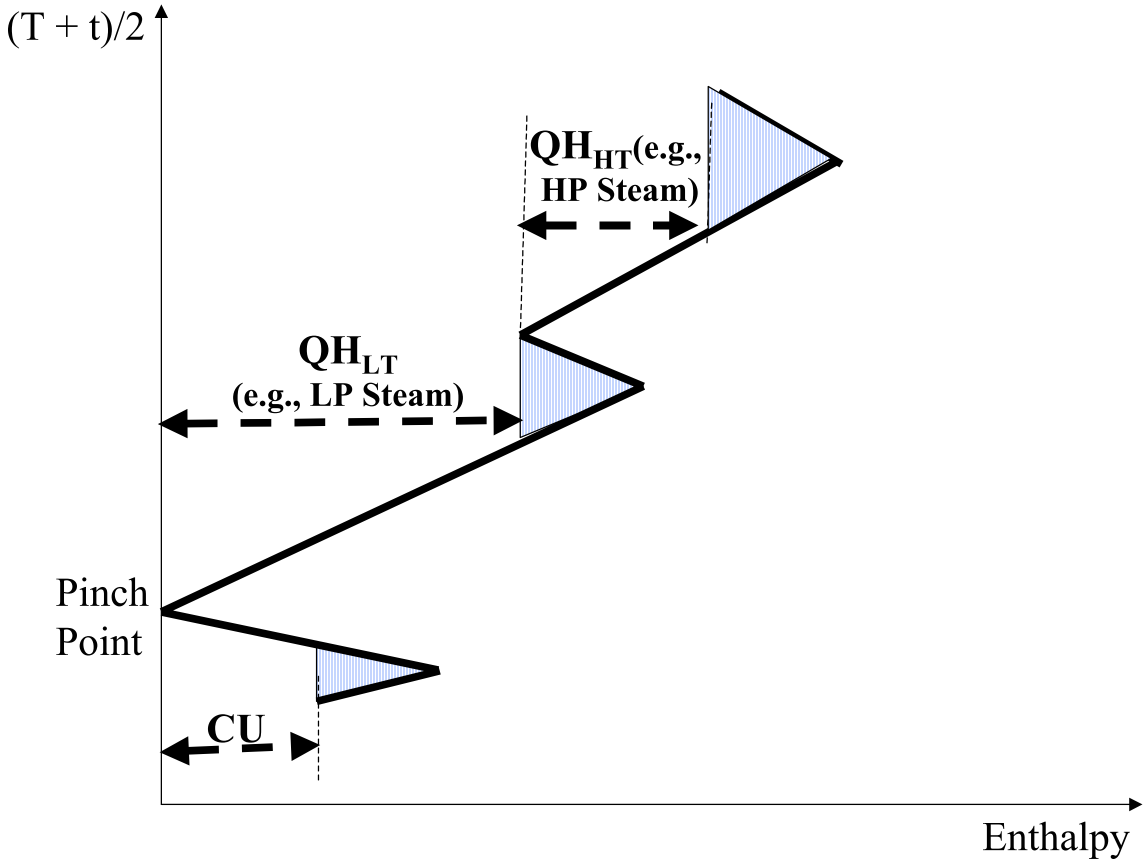


Fig. 9.20b Representation of the GCC with Integrated Pockets and Optimal Placement of Utilities

EXAMPLE 9.2. UTILITY SELECTION

Consider the stream data given in Table 9.5. Available for service two heating utilities: a high pressure (HP) steam and a very high pressure (VHP) steam whose temperatures are 450 and 660 ^{o}F, respectively. The VHP steam is more expensive than the HP. Also available for service is a cooling utility whose temperature is 100 ^{o}F. The minimum approach temperature is taken as 10 ^{o}F. Figures 9.21 – 9.23 represent the temperature-interval diagram, cascade diagram, and the GCC. As can be seen from Fig. 9.22, the minimum heating requirement is 90 MM Btu/hr. In order to maximize the use of the HP steam, we represent the HP on the GCC (a horizontal line at $450 - \frac{10}{2} = 445$ ^{o}F). The deficit below this line is 50 MM Bru/hr. Therefore, the duty of the HP steam is 50 MM Btu/hr and the rest of the heating requirement (40 MM Btu/hr) will be provided by the VHP steam.

Table 9.5. Stream Data for Example 10.2

Stream	Flowrate x Specific Heat MMBtu/(hr . °F)	Supply temperature, °F	Target temperature, °F	Enthalpy change MMBtu/hr
H_1	0.5	650	150	250.0
H_2	2.0	550	500	100.0
C_1	0.9	490	640	-135.0
C_2	1.5	360	490	-195.0

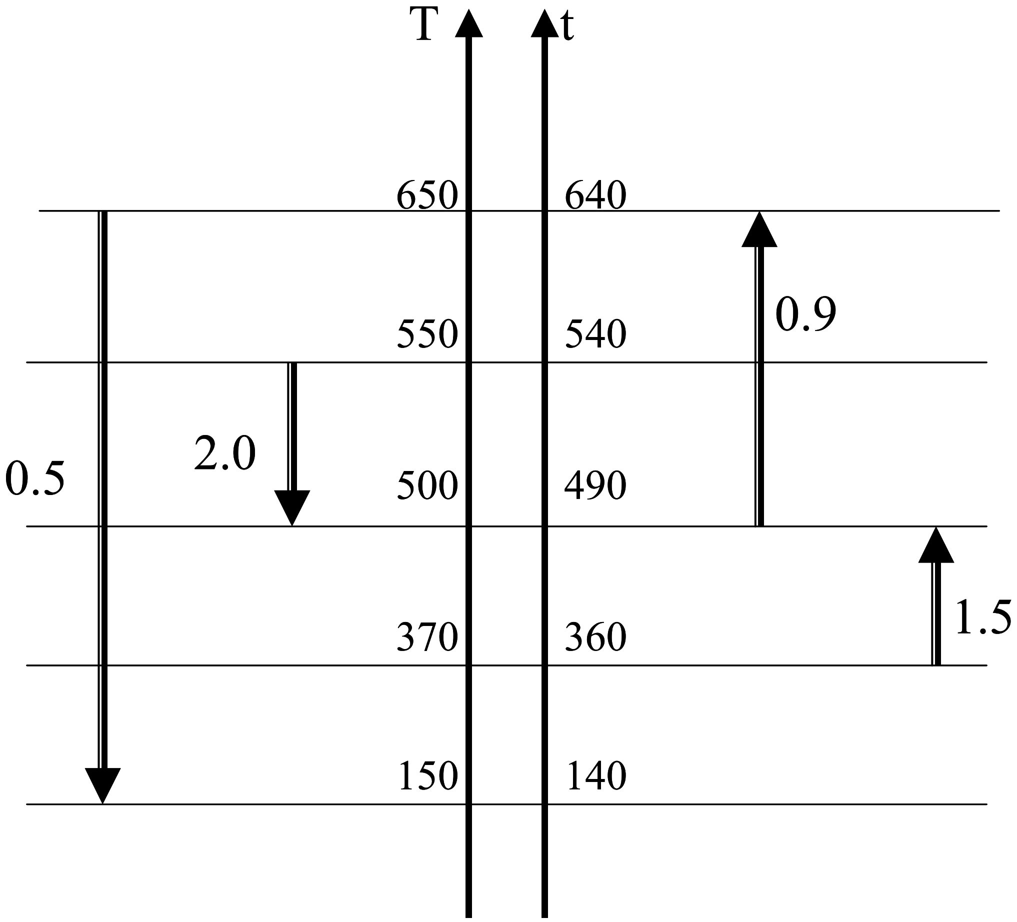
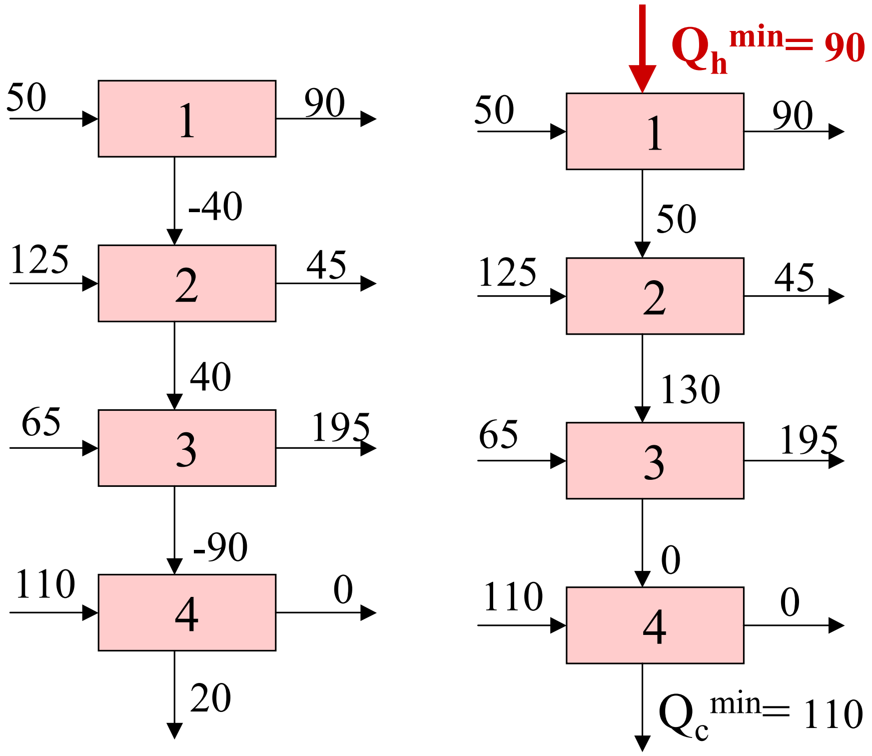


Fig. 9.21. The Temperature Interval Diagram for Example 9.2



Original Cascade Diagram (with -ive residulas)

Adding Heating Utility at the Highest Level

Fig. 9.22. The Cascade and Revised Cascade Diagrams for Example 9.2

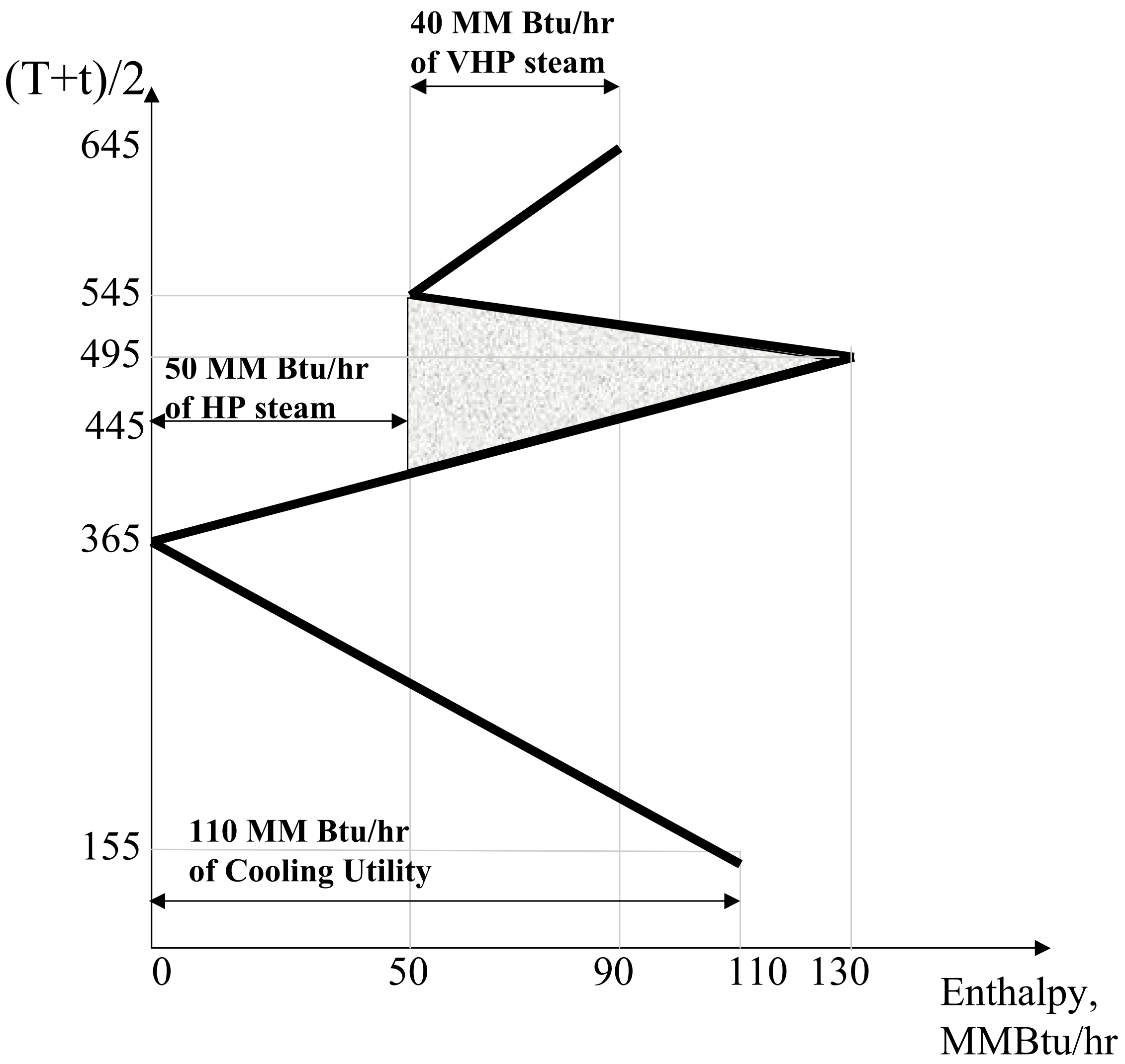


Fig. 9.23. The GCC for Example 9.2

PROBLEMS

9.1. A plant has two process hot streams (H_1 and H_2), two process cold streams (C_1 and C_2), a heating utility (HU_1), and a cooling utility (CU_1). The problem data are given in Table 9.6. A value of $\Delta T^{\min} = 10$ °F is used. Using graphical and algebraic techniques, determine the minimum heating and cooling requirements for the problem.

Table 9.6. Stream Data for Problem 10.1 (Douglas, 1988)

Stream	Flowrate x specific heat (Btu/hr °F)	Supply temperature (°F)	Target temperature (°F)	Enthalpy change (10^3 Btu/hr)
H_1	1000	250	120	130
H_2	4000	200	100	400
HU_1	?	280	250	?
C_1	3000	90	150	-180
C_2	6000	130	190	-360
CU_1	?	60	80	?

9.2. Consider a process that has two process hot streams (H_1 and H_2), two process cold streams (C_1 and C_2), a heating utility (HU_1, which is a saturated vapor that loses its latent heat of condensation), and a cooling utility (CU_1). The problem data are given in Table 9.7. The cost of the heating utility is \$4/10^6 kJ added, and the cost of the coolant is \$7/10^6 kJ. A value of $\Delta T^{\min} =$

10 K is used. Employ graphical, algebraic, and optimization techniques to determine the minimum heating and cooling requirements for the process.

Table 9.7. Stream Data for Problem 9.2 (Papoulias and Grossmann, 1983)

Stream	Flowrate x Specific Heat (kW/ ^oC)	Supply temperature (^oC)	Target temperature, (^oC)
H_1	10.55	249	138
H_2	8.79	160	93
HU_1	?	270	270
C_1	7.62	60	160
C_2	6.08	116	260
CU_1	?	38	82

9.3. Consider the pharmaceutical processing facility illustrated in Fig. 9.24 (El-Halwagi, 1997). The feed mixture (C_1) is first heated to 550 K, then fed to an adiabatic reactor where an endothermic reaction takes place. The off-gases leaving the reactor (H_1) at 520 K are cooled to 330 K prior to being forwarded to the recovery unit. The mixture leaving the bottom of the reactor is separated into a vapor fraction and a slurry fraction. The vapor fraction (H_2) exits the separation unit at 380 K and is to be cooled to 300 prior to storage. The slurry fraction is washed with a hot immiscible liquid at 380 K. The wash liquid is purified and recycled to the washing unit. During purification, the temperature drops to 320 K. Therefore, the recycled liquid (C_2) is heated to 380 K. Two utilities are available for service; HU_1 and CU_1. The cost of the heating and cooling utilities ($\$/10^6$ kJ) are 3 and 5, respectively. Stream data are given in Table 9.8.

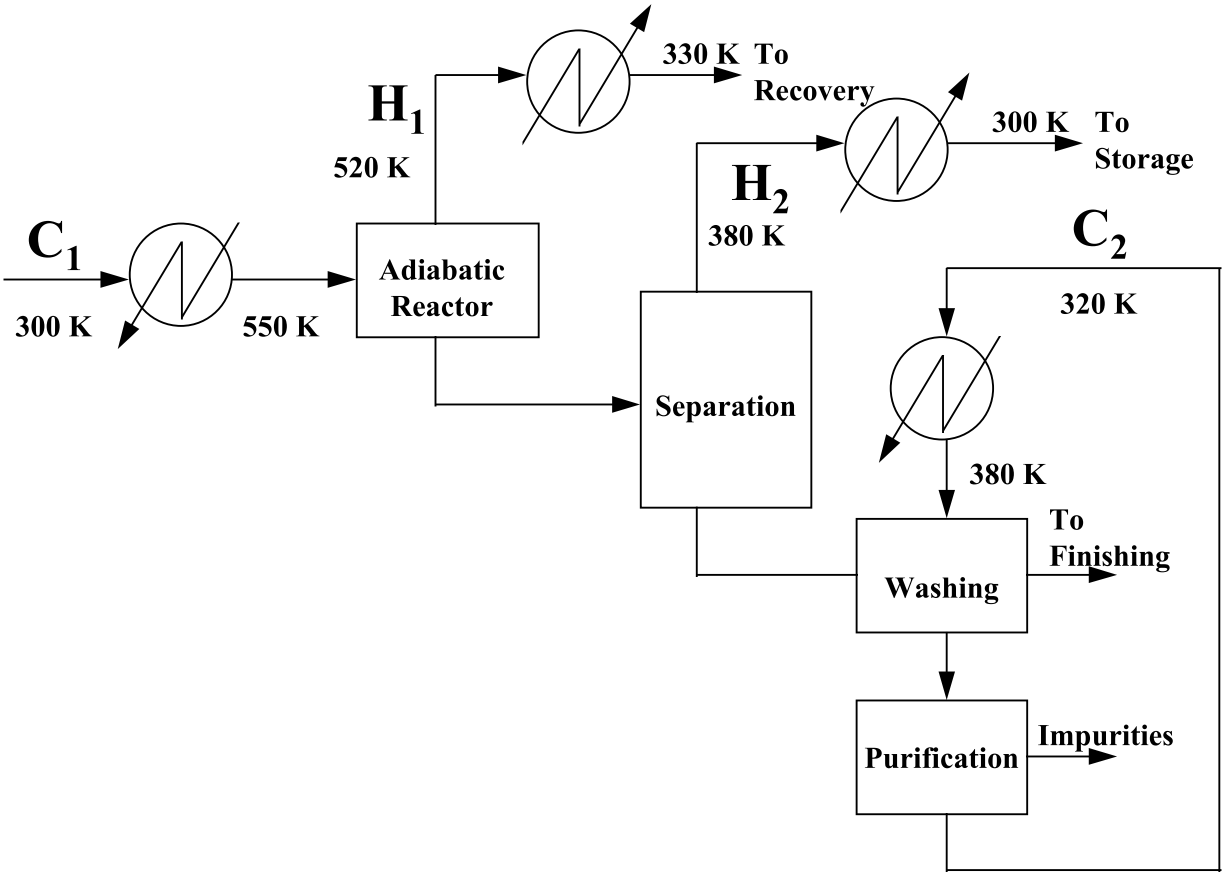


Fig. 9.5. Simplified flowsheet for pharmaceutical process (El-Halwagi, 1997)

Table 9.8. Stream Data for Pharmaceutical Process (El-Halwagi, 1997)

Stream	Flowrate x specific heat kW/^oC	Supply temperature, K	Target temperature, K	Enthalpy change kW
H_1	10	520	330	1900
H_2	5	380	300	400
HU_1	?	560	520	?
C_1	19	300	550	-4750
C_2	2	320	380	-120
CU_1	?	290	300	?

A value of $\Delta T^{min} = 10$ K is used. Using the pinch analysis, determine the minimum heating and cooling utilities for the process.

Symbols

$C_{P,u}$	Specif heat of hot stream u [kJ/(kg K)]
$c_{P,v}$	Specif heat of cold stream v [kJ/(kg K)]
f	flowrate of cold stream (kg/s)
F	flowrate of hot stream (kg/s)
$HC_{v,z}$	cold load in interval *z*
$HH_{u,z}$	hot load in interval *z*
N_C	number of process cold streams
N_{CU}	number of cooling utilities
N_H	number of process hot streams
N_{HU}	number of process cold streams
r_z	residual heat leaving interval z
t	temperature of cold stream (K)
t_v^s	supply temperature of cold stream v (K)
t_v^t	target temperature of cold streamv (K)
T_u^s	supply temperature of hot stream u (K)
T_u^t	target temperature of hot stream u (K)
T	temperature of hot stream (K)
u	index for hot streams
v	index for cold streams
z	temperature interval

Greek

$\Delta T^{\min}$	minimum approach temperature (K)

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