Chapter 4: The Grand Composite Curve

4.1 Introduction

After identifying the pinch temperature and the minimum heating- and cooling-utility duties, the next question is how to select appropriate utilities. For this, we construct the grand composite curve (Section 4.2) and place (or target) utilities according to it (Section 4.3). Essentially, the grand composite curve displays the net heat-flow characteristics of a process versus its temperature. This allows us to quickly identify regions where heating and cooling utilities are required. These utilities include heating utilities like high- and low-pressure steam. Cooling utilities include cooling water and refrigeration.

4.2 Grand Composite Curve

The grand composite curve is a graphical representation of the excess heat available to a process within each temperature interval. In intervals where a net heat surplus exists, we cascade that heat to lower temperature intervals. Once we have satisfied the demand for heat at lower temperature intervals, we apply cooling utilities to remove the remaining heat. In intervals where a net deficit of heat exists, we first use the excess heat from higher temperature intervals. Only after exhausting heat surpluses from higher temperature intervals, do we apply heating utilities.

4.2.1 Graphical Representation of the Heat Cascade

In this section, we return to Example 2.1 and investigate the flow of heat cascading down the temperature intervals. Tables 4.1 and 4.2 repeat the shifted stream data (ΔT_{min} = 20 °C) and the temperature-interval diagram (TID) for Example 2.1 first seen in Tables 2.2 and 2.9, respectively.

Table 4.1. Shifted stream data for Example 2.1. Temperatures shifted for a minimum approach temperature of 20 °C.

Stream **i**	$\mathbf{T^{supply}{}_i}$ **(°C)**	$\mathbf{T^{target}{}_i}$ **(°C)**	$\left(\dot{M}C_p\right)_i$ **(kW/°C)**	$\mathbf{DH_i}$ **(kW)**
H1	175	45	20	2600
H2	125	65	40	2400
C1	60	195	30	4050
C2	80	152	15	1080

Figure 2.1 illustrates the temperature intervals of Example 2.1. This figure shows the net heat deficits (i.e., a negative heat surplus) in temperature intervals 2, 5, 6 and 7. In contrast, intervals 1, 3, and 4 exhibit net heat surpluses, which are found in the "Net Heat Surplus" column of Table 4.2. Beginning with the highest temperature interval (T^*_8 = 195 °C to T^*_7 = 175 °C), we see a heat deficit. Because no net heat surplus exists in higher temperature intervals, we apply heating utilities (600 kW) to satisfy the net heat deficit within the interval. We see similar net heat deficits in the next two lower temperature interval (T^*_7 = 175 °C to T^*_6 = 152 °C, and T^*_6 = 152 °C to T^*_5 = 125 °C). Intervals 6 and 5 require heating utilities of 230 and 675 kW, respectively.

Table 4.2. TID for Example 2.1.

	Hot Streams				Cold Streams						
Shifted Temperature (°C)	**H1 20 kW/°C**	**H2 40 kW/°C**	**Heat Surplus (kW)**	**Cumulative Surplus (kW)**	**C1 30 kW/°C**	**C2 15 kW/°C**	**Heat Deficit (kW)**	**Cumulative Deficit (kW)**	**Net Heat Surplus (kW)**	**Cascaded Surplus (kW)**	**Adjusted Surplus (kW)**
45	▲			0				0		-130	1375
	│		300				0		300		
60	│			300	│			0		-430	1075
	│		100		│		150		-50		
65	│	▲		400	│			150		-380	1125
	│	│	900		│		450		450		
80	│	│		1300	│	│		600		-830	675
	│	│	2700		│	│	2025		675		
125	│	│		4000	│	│		2625		-1505	0
	│		540		│	│	1215		-675		
152	│			4540	│	▼		3840		-830	675
	│		460		│		690		-230		
175	│			5000	│			4530		-600	905
			0		│		600		-600		
195				5000	▼			5130		0	1505

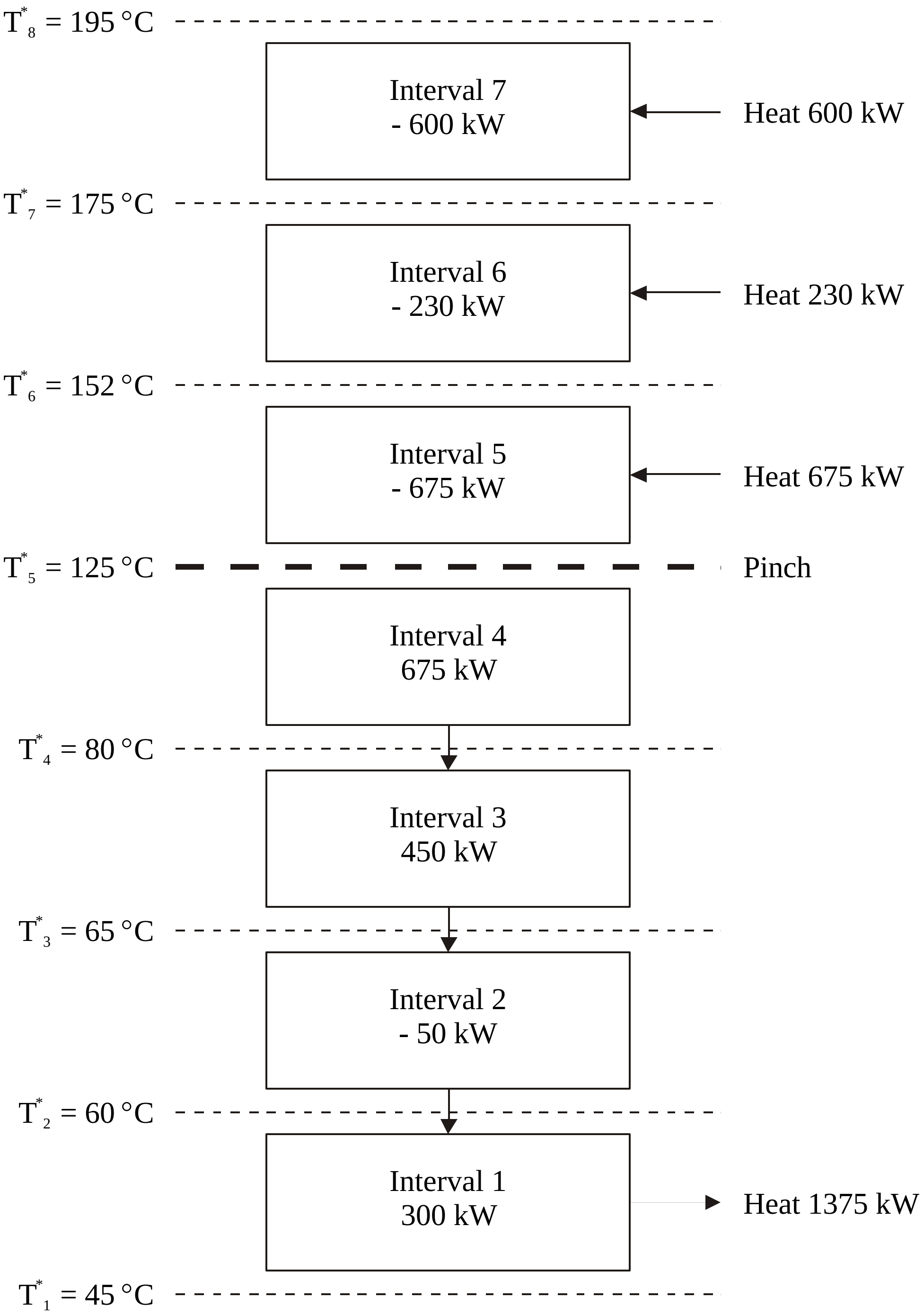


Figure 4.1. Cascaded heat for the temperature intervals of Example 2.1. Temperatures shifted for a minimum approach temperature of 20 °C.

Interval 4 (T^*_5 = 125 °C to T^*_4 = 80 °C) shows the first net surplus of heat (675 kW). In the long run, we cannot determine if this heat will satisfy heat deficits at lower temperature intervals or if cooling utilities will be needed to remove it. For now, we reserve this heat for lower temperature intervals. Continuing down through the temperature intervals, we accumulate net heat surpluses and apply them in intervals that exhibit net heat deficits.

Figure 4.1 shows that the net heat deficit within temperature interval 2 (T^*_3 = 65 °C to T^*_2 = 60 °C) consumes 50 kW of the net surplus of interval 3. The remaining 1375 kW of heat from intervals 1, 3 and 4 must be removed with cooling utilities.

4.2.2 Tabular Construction: Temperature-Interval Diagram (TID)

The graphical representation of cascaded heats is fairly involved and difficult to visualize. An alternative approach is to use results already present on the temperature-interval diagram (TID) to quickly generate the grand composite curve. Here, we repeat the procedure for generating the data contained in the last two columns of the TID to justify the steps presented in Section 2.5.3.2. Refer to Table 4.2 for the net heat surplus available within each temperature interval.

Cascade the net heat surplus starting with zero at the highest temperature-interval boundary (bottom) in the “Cascaded Surplus” column. This reflects the flow of excess heat from higher temperature intervals to lower temperature intervals (Section 4.2.1).

Place the negative of the minimum (most negative) value from the cascaded heat surplus column at the bottom temperature-interval boundary in the final column of the TID. Once again, cascade the net heat surplus starting with that value at the highest temperature-interval boundary (bottom right). We locate the pinch temperature(s) at the temperatures where zeros are found in this column, and find the minimum cooling and heating duties at the top (1375 kW) and bottom (1505 kW) of the last column, respectively.

Figure 4.2 is constructed by plotting the first versus last columns of the TID in Table 4.2. In the figure, pinch-point temperature(s) are identified where the curve touches the y-axis (i.e., a value of zero in the last column of Table 4.2). The regions labeled with heating and cooling utilities require external utilities. Recall that the first and last row of the “Adjusted Surplus” column in a TID give the minimum cooling- and heating-utility requirements of the process.

The slope of the curve in each region reflects how the process acts. Where the curve has a positive slope, the process is acting as a net heat sink. Conversely, a negative slope suggests that the process is acting as a net heat source.

Pockets in the curve represent regions where process-to-process heat exchange is sufficient (i.e., where a net heat deficit is satisfied by cascaded heat from higher temperature intervals). Note that process-to-process heat transfer is not limited to these pockets. They simply reflect where process-to-process heat transfer occurs between streams in different temperature intervals.

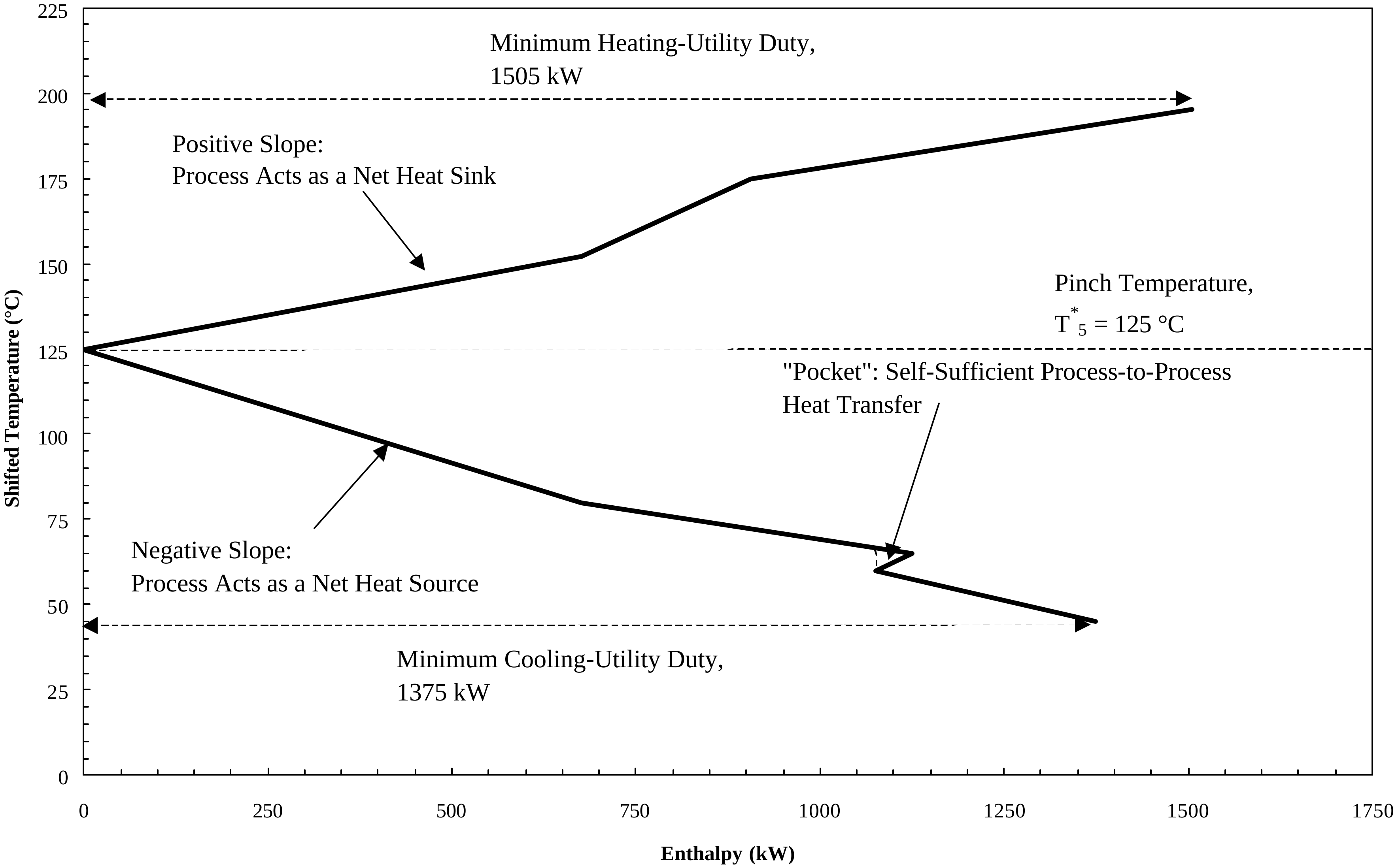


Figure 4.2. Grand composite curve for Example 2.1.

4.3 Utility Placement: Grand Composite Curve

A key question in chemical process design and retrofit is how to optimally place (integrate) utility systems (e.g., a steam boiler) into a process flowsheet. To answer this question, we model the heating and cooling requirements of the process through the hot and cold composite curves and the grand composite curve. The remaining task is to develop models for those heating and cooling utilities and to place them with respect to the grand composite curve.

4.3.1 Modeling Heating and Cooling Utilities

In general, we can categorize most heating and cooling utilities as either constant-temperature (e.g., condensing steam) or variable-temperature (e.g., cooling water) utilities. The representation of these two types of utilities on the grand composite curve is simple.

Figure 4.3 is the grand composite curve for Example 2.1. Horizontal lines represent constant-temperature utilities. In the figure, a horizontal line represents high-pressure steam (condensing at a shifted temperature of 210 °C) on the hot side of the grand composite curve. In this case, the entire heating needs of the process are satisfied by high-pressure steam. Latter, we shall see that it is often more thermodynamically efficient to satisfy the heating-utility requirements by multiple levels of heating utilities (i.e., high- and low-pressure steams).

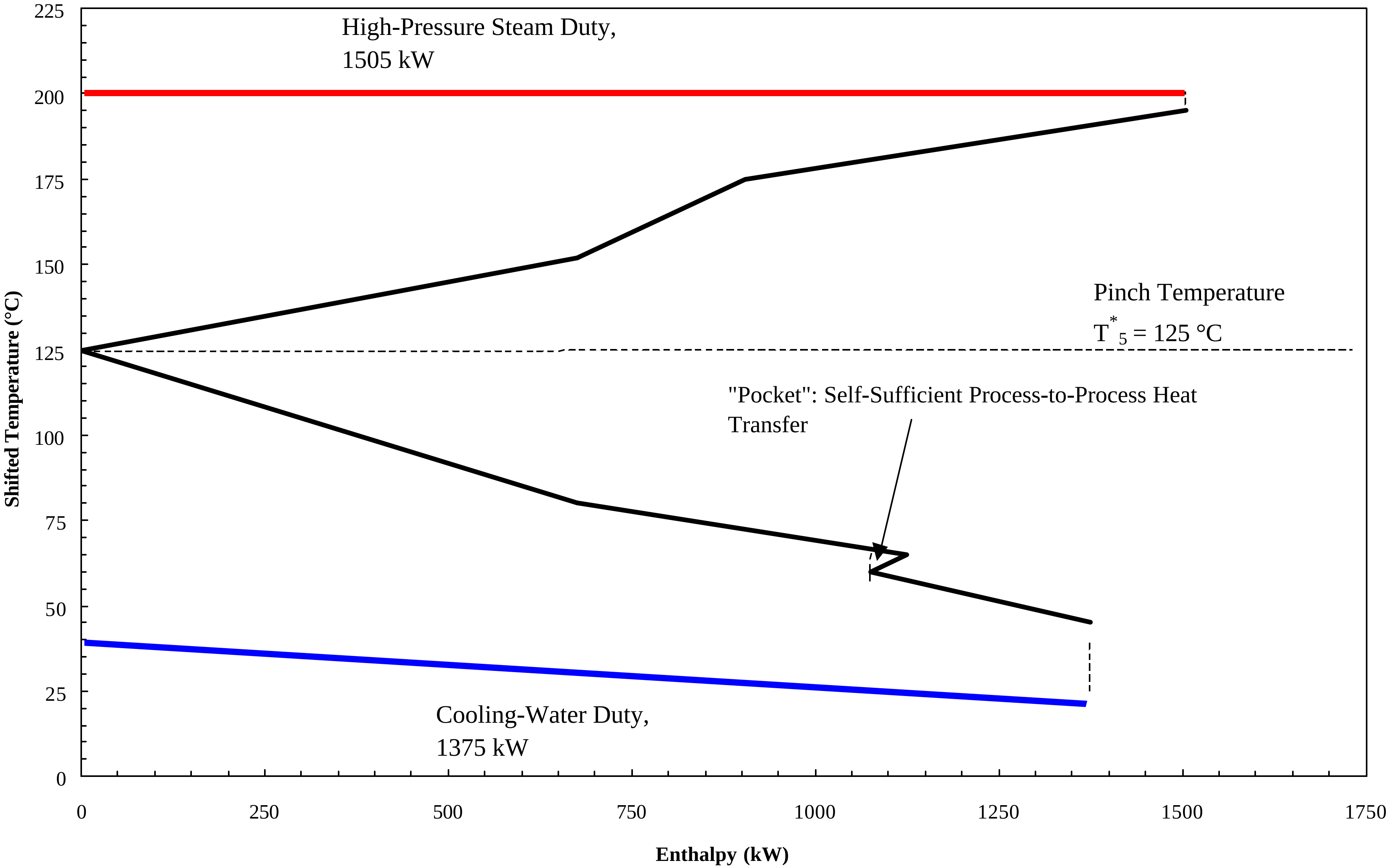


Figure 4.3. Grand composite curve for Example 2.1 with heating and cooling utilities.

Sloped lines represent variable-temperature utilities on the grand composite curve. On the cold side of Figure 4.3, a sloped line represents cooling water. We draw this line from the shifted cooling-water-supply temperature of 30 °C to the shifted cooling-water-return temperature of 40 °C. The slope of the line is inversely proportional to the capacity flowrate of cooling water:

$$\left[\dot{M}C_p\right]_{CW}\left(\frac{kW}{°C}\right)=\frac{Q_{CW}\,(kW)}{\left[T_{CW}^{target}-T_{CW}^{supply}\right](°C)} \qquad (4.1)$$

where Q_{CW} is the cooling-water duty, and $T^{target}{}_{CW}$ and $T^{supply}{}_{CW}$ are the cooling-water supply and target temperatures, respectively. Equation 4.2 gives the mass flowrate of cooling water:

$$\dot{M}_{CW}\left(\frac{kg}{s}\right)=\frac{Q_{CW}\,(kW)}{C_{p,CW}\left(\frac{kJ}{kg}\right)\left[T_{CW}^{target}-T_{CW}^{supply}\right](°C)} \qquad (4.2)$$

Note that the cooling utility does not lie within the pocket region of the grand composite curve. Heat transfer in these regions is accomplished through process-to-process heat exchange.

4.3.2 Optimal Utility Placement: Profile Matching

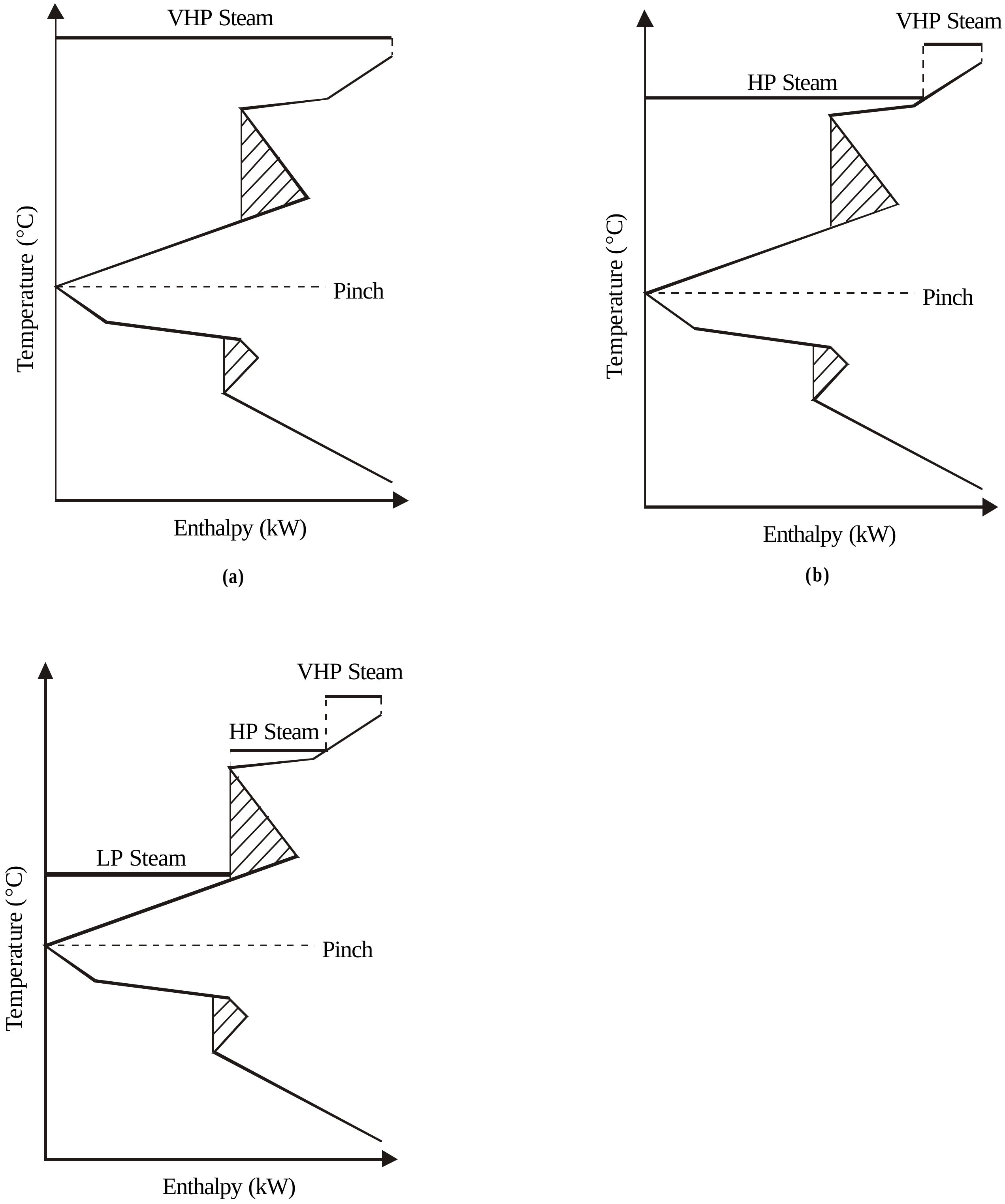
In this section, we apply the grand composite curve to answer questions like:

- When multiple steam levels are available, how do we optimize their use in a process?

- Can the process generate very-low pressure steam? How can the process be applied as a preheat for this steam?

4.3.2.1 Optimizing Steam-Pressure Levels

Figure 4.4 illustrates a grand composite curve as an example of utility selection according to the following “profile matching” heuristic. We choose the utility levels such that their placement matches the grand composite curve as closely as possible. We prefer to use heating utilities at the lowest temperature levels, and cooling utilities at the highest temperature levels. In the figure, steam is available at three levels: 180, 200 and 230 °C (shifted temperatures). First, Figure 4.4a ignores our heuristic and accomplishes the total heating requirements of the process with very-high-pressure steam. This arrangement is certainly the least complex method for heating the process, however, we may wish to reduce operating costs (i.e., use less expensive high-pressure and low-pressure steam where applicable) at the expense of greater capital costs (i.e., an increase in complexity). Figure 4.4b illustrates the case where both very-high-pressure (VHP) and high-pressure (HP) steam are employed. Finally, in Figure 4.4c, we follow our heuristic by utilizing the greatest amount of steam at the lowest temperature available, 180 °C. Note that the hashed region represents self-sufficient process-to-process heat exchange, and does not require steam. Continuing up the grand composite curve, we apply steam at 200 °C and finally at 230 °C.



(a)

(b)

(c)

Figure 4.4. Grand composite curves with three degrees of profile matching. Operating costs decrease and capital costs increase from (a) to (c).

4.3.2.2 Raising Steam from Boiler Feedwater

In contrast to the previous section, *we raise steam from boiler feedwater at the highest possible temperature*. Figure 4.5 illustrates the same grand composite curve.

We may utilize the surplus heat of the process to raise low-pressure steam from boiler feedwater. Figure 4.5 displays two line segments. The first segment (sloped) represents the sensible heat used for preheating the boiler feedwater. The capacity flowrate of the boiler feedwater is related to the inverse of the slope of this segment through Equation 4.3.

$$\left[\dot{M}C_p\right]_{BF}\left(\frac{kW}{°C}\right) = \frac{Q_{BF}(kW)}{\left[T_{BF}^{target} - T_{BF}^{supply}\right](°C)} \tag{4.3}$$

where Q_{BF} is the heat absorbed as sensible heating of the boiler feedwater, and $T^{target}{}_{BF}$ and $T^{supply}{}_{BF}$ are the target and supply temperatures of the boiler feedwater, respectively. The mass flowrate of the boiler feedwater consumed or the steam produced is, $\dot{M}_{BF}$:

$$\dot{M}_{BF}\left(\frac{kg}{s}\right) = \dot{M}_{LP}\left(\frac{kg}{s}\right) = \frac{Q_{BF}(kW)}{C_{p,BF}\left(\frac{kJ}{kg}\right)\left[T_{BF}^{target} - T_{BF}^{supply}\right](°C)} \tag{4.4}$$

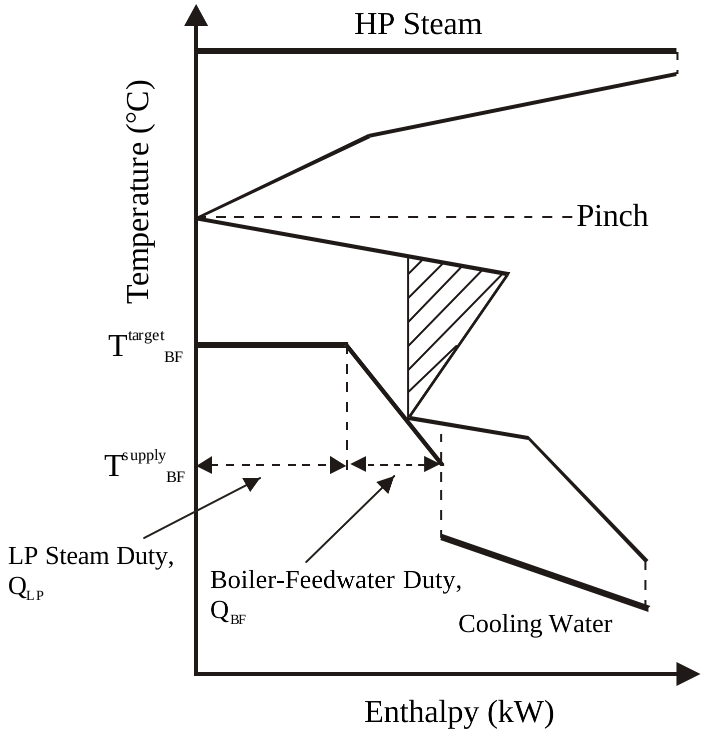


Figure 4.5. Grand composite curves where two qualities of very-low-pressure steam are generated.

where $C_{p,BF}$ is the heat capacity of the boiler feedwater. The second segment (horizontal) corresponds to the latent heat of vaporization of the boiler feedwater. We relate the length of this segment to the flowrate of the boiler feedwater consumed or the steam produced) through Equation 4.5:

$$Q_{LP}(\mathrm{kW}) = \dot{M}_{LP}\left(\frac{\mathrm{kg}}{\mathrm{s}}\right)\Delta H_{BF}^{VAP}\left(\frac{\mathrm{kJ}}{\mathrm{kg}}\right) \tag{4.5}$$

where ΔH^{vap}_{BF} is the latent heat of vaporization of boiler feedwater at the temperature and pressure we are generating steam. In this case, the remaining surplus heat of the process is rejected to cooling water (see Section 4.3.2.3).

4.4 Summary

- To select appropriate utilities, we construct the grand composite curve (Section 4.2) and place (or target) utilities according to it (Section 4.3). Utilities include heating utilities like high- and low-pressure steams and cooling utilities such as cooling water and refrigeration.

- The grand composite curve displays the net heat-flow characteristics of a process versus its temperature. This allows us to quickly identify regions where heating and cooling utilities are required.

- We construct the grand composite curve by plotting the first versus last columns of the temperature-interval diagram (TID). In the figure, pinch-point temperature(s) are identified where the curve touches the y-axis (i.e., a value of zero in the last column of the TID).

- Heating and cooling utilities can be categorized as either constant-temperature (e.g., condensing steam) or variable-temperature (e.g., cooling water) utilities. We represent constant- and variable-temperature utilities as horizontal and sloped lines, respectively.

- Utilities do not lie within the pocket regions of the grand composite curve. Heat transfer in these regions is accomplished through process-to-process heat exchange without external utilities.

- Generally, we use heating and cooling utilities at the lowest and highest temperature levels possible, respectively.

Nomenclature

Q_{BF}	Boiler-feedwater (preheat) duty, kW
Q_{CU}	Minimum cooling-utility duty, kW
Q_{CW}	Cooling-water duty, kW
Q_{LP}	Low-pressure steam duty, kW
Q_{HP}	High-pressure steam duty, kW
Q_{HU}	Minimum heating-utility duty, kW
$T^{supply}{}_{BF}$	Supply temperature of boiler feedwater, °C
$T^{supply}{}_{CW}$	Supply temperature of cooling water, °C
$T^{supply}{}_{i}$	Supply temperature of process stream i, °C
$T^{target}{}_{BF}$	Supply temperature of boiler feedwater, °C
$T^{target}{}_{CW}$	Supply temperature of cooling water, °C
$T^{target}{}_{i}$	Supply temperature of process stream i, °C
$T^{*}{}_{k}$	Shifted temperature of temperature-interval boundary k, °C
ΔH_i	Duty of process stream i, kW
$\Delta H^{vap}{}_{BF}$	Latent heat of vaporization of boiler feedwater, kJ/kg

References

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