Chapter 3: Heat-Exchanger Network Design

3.1 Introduction

In Chapter 2, we determined the minimum heating- and cooling-utility requirements for a heat-integration problem (Section 2.5), and compared it to the requirements for a similar system without heat integration (Section 2.4). Clearly, heat integration minimizes the use of heating and cooling utilities by maximizing heat transfer from hot streams to cold streams.

Now that we have the system requirements, we turn our attention to heat-exchanger network design and explain how to construct a network that will accomplish the necessary heat transfer and satisfy the stream data using the least amount of heating and cooling utilities and the fewest number of heat-exchange units.

Before developing heat-exchanger networks, this chapter first outlines some of the basic steps and key tools involved in designing any network (Section 3.2).

From there, we will turn to the heat-exchanger network. Constructing a network for this system is a two-step process:

1. Design a preliminary heat-exchanger network guaranteed to accomplish the heat transfer from hot streams to cold streams (Section 3.3).

2. Simplify the preliminary network to reduce the number of heat-exchange units (e.g., heat exchangers, steam heaters and water coolers) through an evolutionary process (Section 3.4).

3.2 Design Tools: Representing Heat-Exchanger Networks

We can represent a heat-exchanger network in a number of ways. Two common ones are grid diagram and the mass-content diagram. To illustrate these methods, let us look at a preliminary heat-exchanger network for Example 3.1 - a simple three-unit system consisting of one exchanger, one heater and one cooler.

3.2.1. The Grid Diagram

The most common representation scheme is the grid diagram, in which each heat-exchange unit is represented as a vertical line connecting two streams. In a grid diagram:

Solid horizontal lines at the top of the diagram represent hot streams. These streams flow from the left (hot side) to the right (cold side) of the diagram.

Solid horizontal lines at the bottom of the diagram represent cold streams. These streams flow from the right (cold side) to the left (hot side) of the diagram.

Dashed horizontal lines at the top of the diagram represent heating utilities (e.g., steam). Multiple lines can, for example, represent high-pressure and low-pressure steam supplies.

Dashed horizontal lines at the base of the diagram represent cooling utilities (e.g., cooling water or refrigerants).

Vertical lines represent heat-exchange unit. Each line can connect a hot and a cold stream, a hot stream and a cooling utility, or a cold stream and heating utility. We indicate the heat load of the unit (kW) within the circles connecting the lines, and also show the inlet and outlet temperatures of the hot and cold streams in each heat-exchange unit.

Bold vertical dashed line(s) indicate the position of any pinch points for the system.

Figure 3.1 shows the grid diagram for Example 3.1.

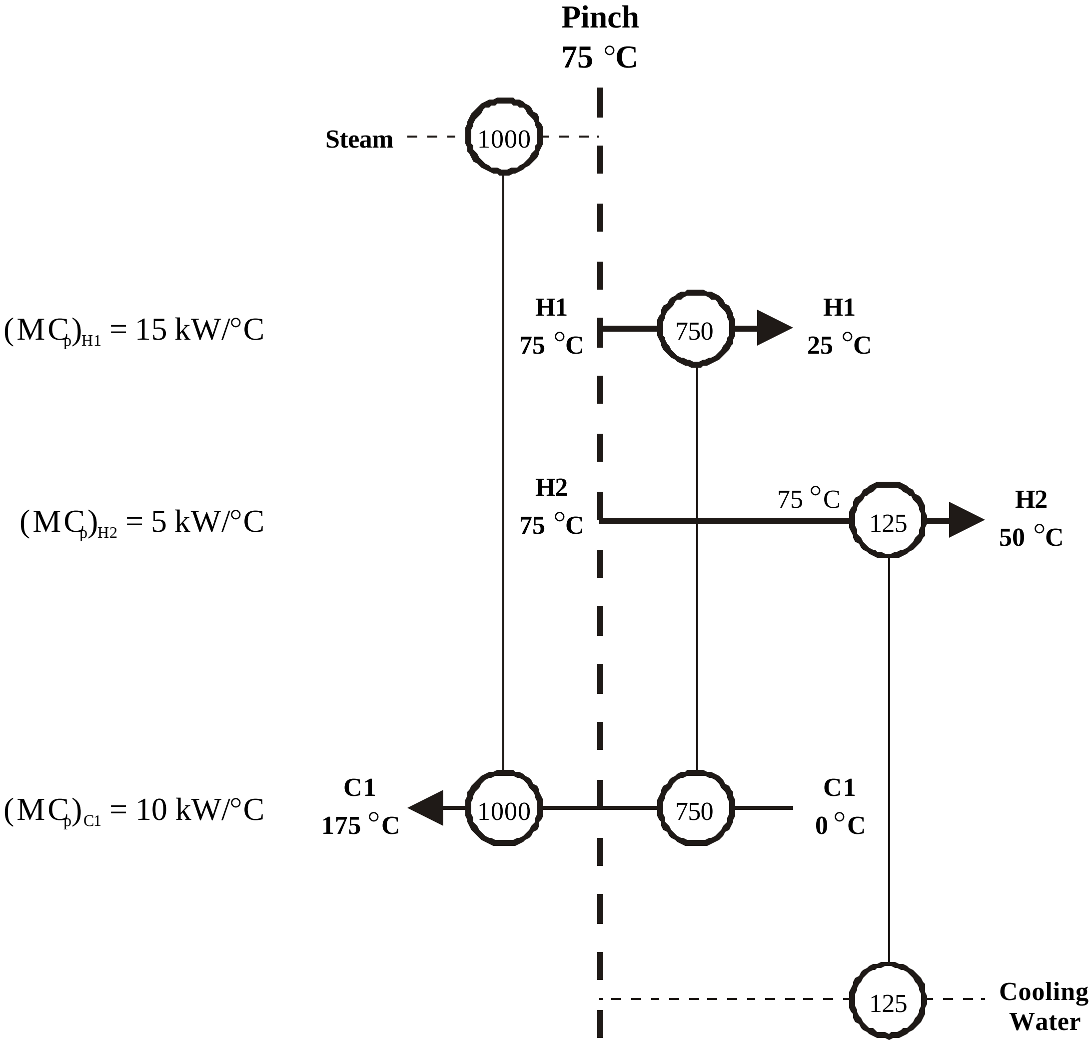


Figure 3.1. Grid diagram of a preliminary heat-exchanger network for a simple three-unit example. Heat duties in kW.

As the next section makes clear, grid diagrams are an invaluable tool for designing and representing networks for heat integration. We may divide the grid diagram into subproblems across the regions defined by the pinch points. Within these regions, we apply simple design rules to achieve the minimum heating- and cooling-utility duties as well as the minimum number of heat-exchange units.

3.2.2. The Heat-Content Diagram

Heat-content diagrams are yet another way to design and represent a heat-exchanger network (Nishida, et al., 1977). These diagrams provide an alternative to the grid diagrams and to give a visualization of each heat-exchange unit in the network. In a heat-content diagram:

> We represent each hot stream with a box on the hot side (above the x-axis), and each cold stream with a box on the cold side (below the x-axis). We label each corresponding pair of hot and cold boxes with the same letter.
>
> The top and bottom of a box on the hot side correspond to the supply and target temperatures of a hot stream, respectively. The width of the box, on the relative x-axis represents the heat-capacity flowrate of the hot stream. Therefore, the area of the box corresponds to the heat load of the hot stream.
>
> The bottom and top of a box on the cold side correspond to the supply and target temperatures of a cold stream, respectively. Once again, the width of the box, on the

relative x-axis represents the heat-capacity flowrate of the cold stream. Therefore, the area of the box corresponds to the heat load of the cold stream.

Figure 3.2 shows the heat-content diagram for Example 3.1.

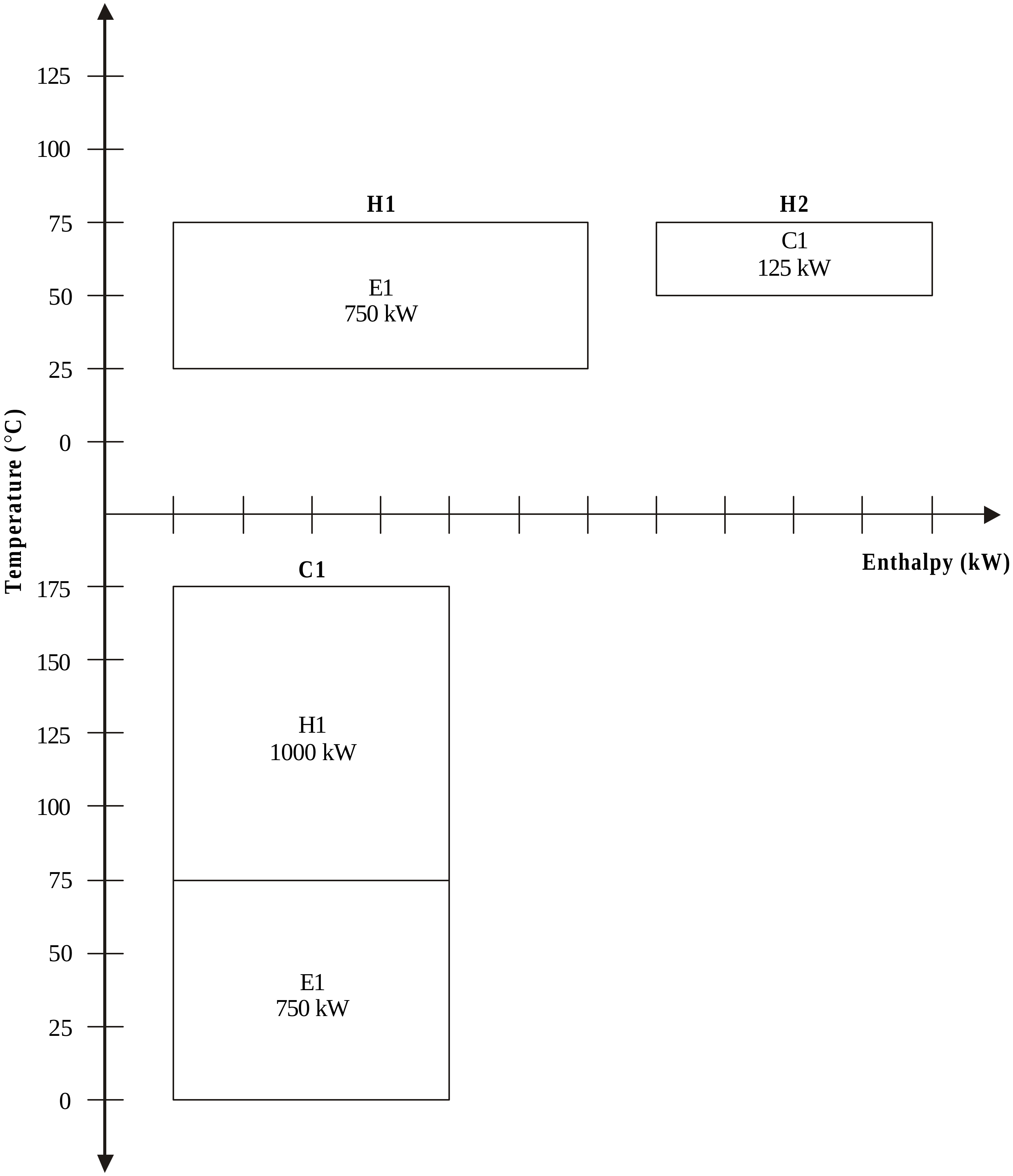


Figure 3.2. Heat-content diagram for Example 3.1.

3.3 Preliminary Heat-Exchanger Network Design

This section presents a method for designing preliminary heat-exchanger networks that guarantee to meet the minimum utility targets identified in Section 2.5. We examine the details of designing a preliminary heat-exchanger network for Example 2.1. In most cases, we first employ the shifted stream data to incorporate a minimum approach temperature into the design, and later adjust the temperatures to reflect the true approach temperatures within each heat-exchange unit.

We use Example 2.1 as a tutorial for designing preliminary heat-exchanger networks. Table 2.1 repeats the shifted stream data for Example 2.1. Through hot and cold composite curves (Figure 3.3) or a temperature-interval diagram (TID) (Table 3.2) we identify minimum heating- and cooling-utility duties of 1505 and 1375 kW, respectively.

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

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

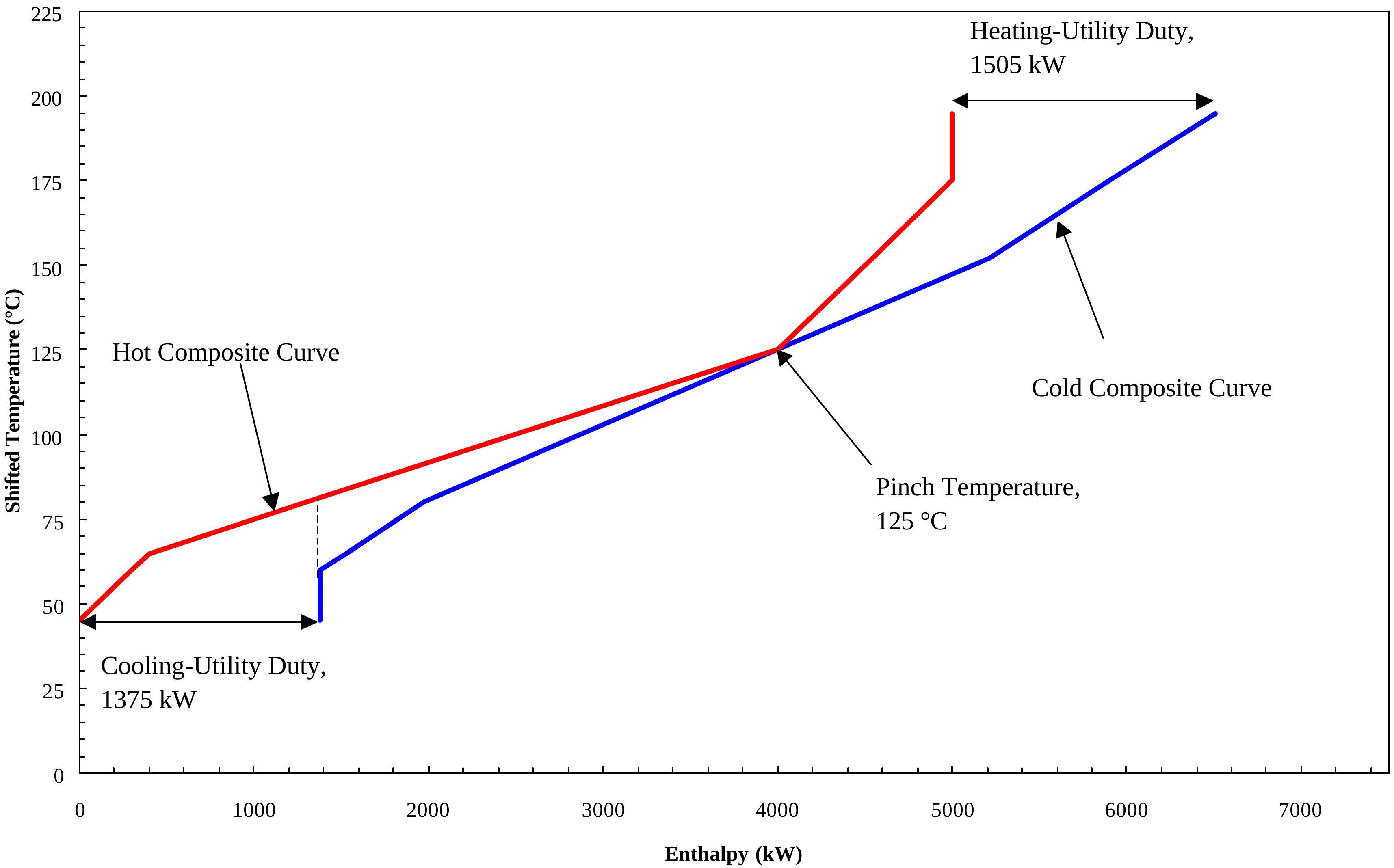


Figure 3.3. Hot and cold composite curves for Example 2.1. Temperatures shifted for a minimum approach temperature of 20 °C.

Table 3.2. TID for Example 2.1. Temperatures shifted for a minimum approach temperature of 20 °C.

	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*

3.2.1 Pinch Subnetworks

The nature of the pinch allows us to divide the design problem into subnetworks defined by the pinch temperature(s). Recall that no heat should be transferred across the pinch and that heating and cooling utilities should not be employed above and below the pinch, respectively. Beginning at the pinch and working away form the pinch, we select matches according to the design rules presented in Sections 3.3.2 and 3.3.4 to satisfy the stream data.

Figure 3.4 is a grid diagram for Example 2.1. At this point, we have not identified heat-exchange units. However, the problem is divided into two subnetworks – above and below the pinch at a shifted temperature of 125 °C.

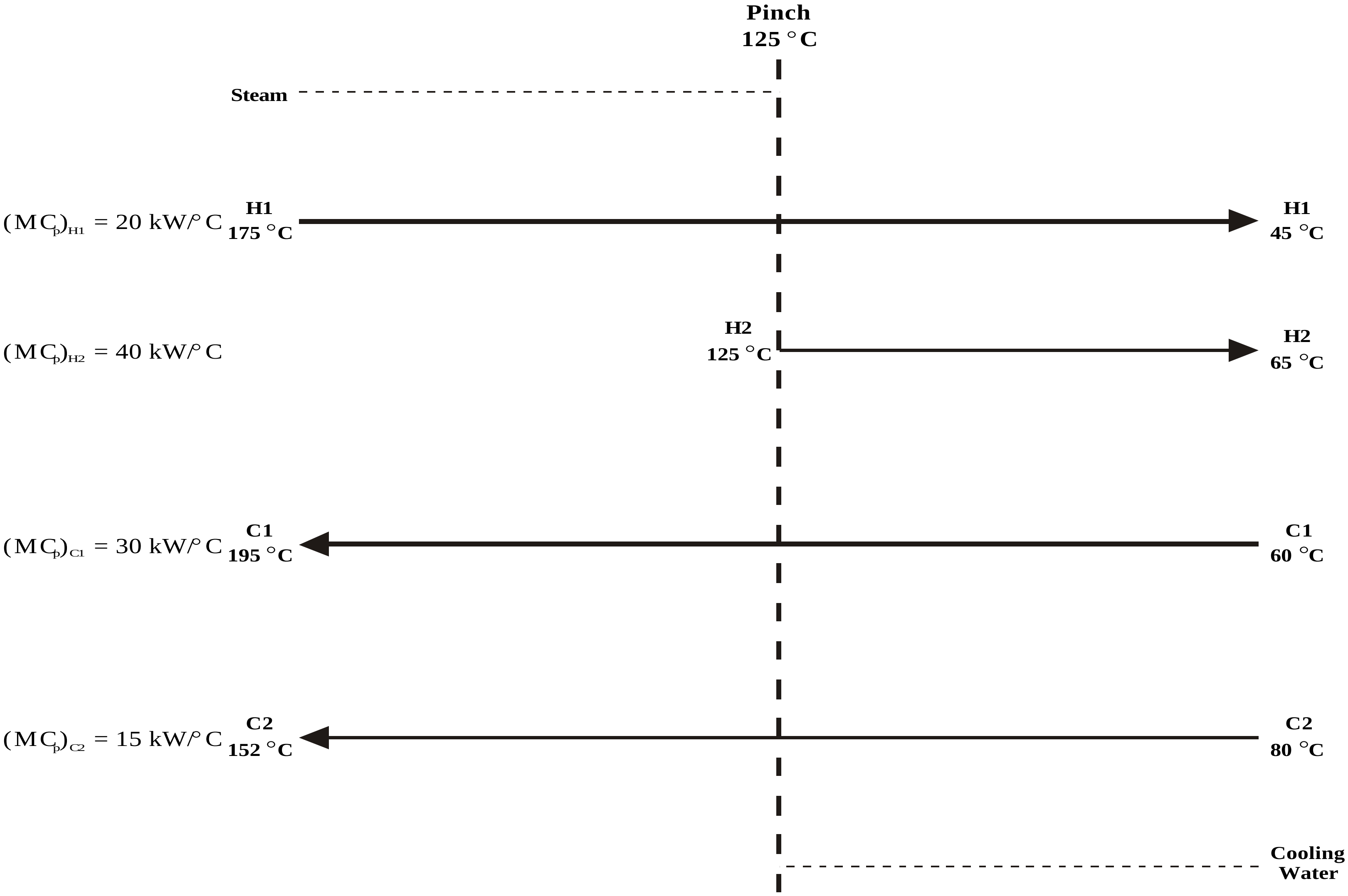


Figure 3.4. Grid diagram for designing a preliminary heat-exchanger network for Example 2.1 divided into two subnetworks above and below the pinch temperature. Temperatures shifted for a minimum approach temperature of 20 °C.

3.3.2 Minimum Number of Heat-Exchange Units

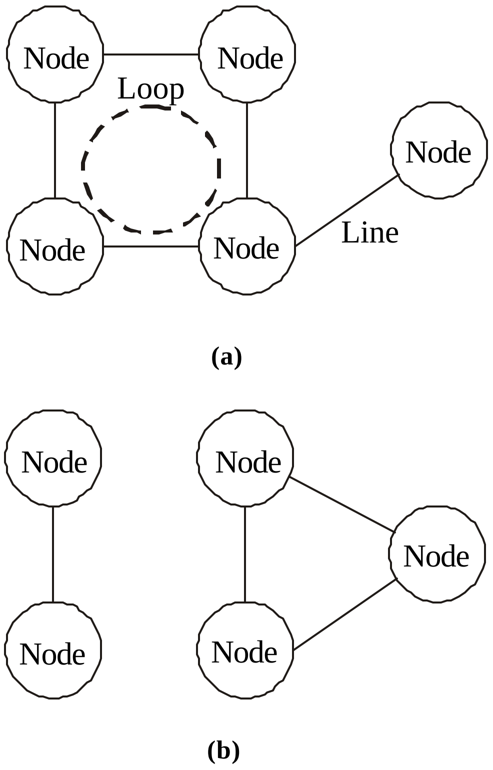
This section briefly presents Euler's graph theory for identifying the theoretical minimum number of heat-exchanger units from the number of process streams and utilities. Euler's graph theory gives us tools to evaluate heat-exchanger networks. Figure 3.5 illustrates simple diagrams with interconnected nodes (streams) linked with lines (heat-exchange units). In Figure 3.5a, five nodes are connected to each other through 5 lines. Here, four lines form *a loop* (ABCD). In contrast to Figure 3.5a, Figure 3.5b illustrates how five nodes can be connected via lines to form two *independent components.*

Euler's graph theory relates the number of lines (units) to the number of nodes (streams), loops and independent components. In terms of heat-exchanger networks:

$$N_{units} = S + L - C \qquad (3.1)$$

where N_{units} is the number of heat-exchanger units, S is the number of streams (including utilities), L is the number of loops and C is the number of independent components. Except in rare cases, loops can be eliminated (Section 3.4.2) and the number of independent components is one. Equation 3.6 becomes:

$$N_{units} = S - 1 \qquad (3.2)$$



(a)

(b)

Figure 3.5. Illustration of Euler's graph theory applied to heat-exchanger networks.

For systems where the pinch divides the design in to two separate components (see Section 3.3.2), the number of units is:

$$N_{units} = \left(N_H + H_C + N_{HU} - 1\right)_{\text{Abovethe Pinch}} + \left(N_H + H_C + N_{CU} - 1\right)_{\text{Below the Pinch}} \qquad (3.3)$$

where N_H and N_C are the number of hot and cold process streams, respectively, and N^{HU} and N_{CU} are the number of hot utilities above the pinch and cold utilities below the pinch, respectively.

For the four process streams and two utilities of Example 2.1, Equation 3.3 gives the minimum number of units as:

$$\begin{aligned} N_{units} &= \left(N_H + H_C + N_{HU} - 1\right)_{\text{Abovethe Pinch}} + \left(N_H + H_C + N_{CU} - 1\right)_{\text{Below the Pinch}} \\ &= \left(1 + 2 + 1 - 1\right)_{\text{Abovethe Pinch}} + \left(2 + 2 + 1 - 1\right)_{\text{Below the Pinch}} \\ &= 7 \end{aligned} \qquad (3.4)$$

3.3.3 Maximize Exchanger-Heat Loads

To minimize the number of heat-exchange units, we maximize the heat transferred in each exchanger by first identifying the total heat available from the hot stream and the heat required by the cold stream. Second, we choose the lesser of the two to maximize the heat transferred in the unit. Equations 3.3 and 3.4 modify Equations 3.1 and 3.2 to give the heat load available and required by hot and cold streams, respectively, above the pinch. Here, T^*_{pinch} is the pinch temperature.

$$Q_{Hi}^{available}(kW) = \left(\dot{M}C_p\right)_{Hi}\left(\frac{kW}{°C}\right)\left[T_{Hi}^{supply} - T_{pinch}^{*}\right](°C) \tag{3.3}$$

$$Q_{Ci}^{required}(kW) = \left(\dot{M}C_p\right)_{Ci}\left(\frac{kW}{°C}\right)\left[T_{Ci}^{target} - T_{pinch}^{*}\right](°C) \tag{3.4}$$

Similarly, Equations 3.5 and 3.6 give these heat loads below the pinch temperature.

$$Q_{Hi}^{available}(kW) = \left(\dot{M}C_p\right)_{Hi}\left(\frac{kW}{°C}\right)\left[T_{pinch}^{*} - T_{Hi}^{target}\right](°C) \tag{3.5}$$

$$Q_{Ci}^{required}(kW) = \left(\dot{M}C_p\right)_{Ci}\left(\frac{kW}{°C}\right)\left[T_{pinch}^{*} - T_{Ci}^{supply}\right](°C) \tag{3.6}$$

Figures 3.6 and 3.7 illustrate the two possible matches between hot and cold streams above the pinch for Example 2.1 (hot steam 1 to cold stream 1, and hot stream 1 to cold stream 2, respectively). In the figures, 500 kW are available from hot stream 1, while 1400 and 405 kW are required by cold streams 1 and 2, respectively. Figure 3.6 shows that to maximize the heat load of each unit, 500 kW are transferred from hot stream 1 to cold stream 1 (hot stream 1 limiting because 500 kW < 1400 kW). Figure 3.7 illustrates that only 405 kW are transferred from hot stream 1 to cold stream 2 (cold stream 2 limiting because 405 kW < 500 kW).

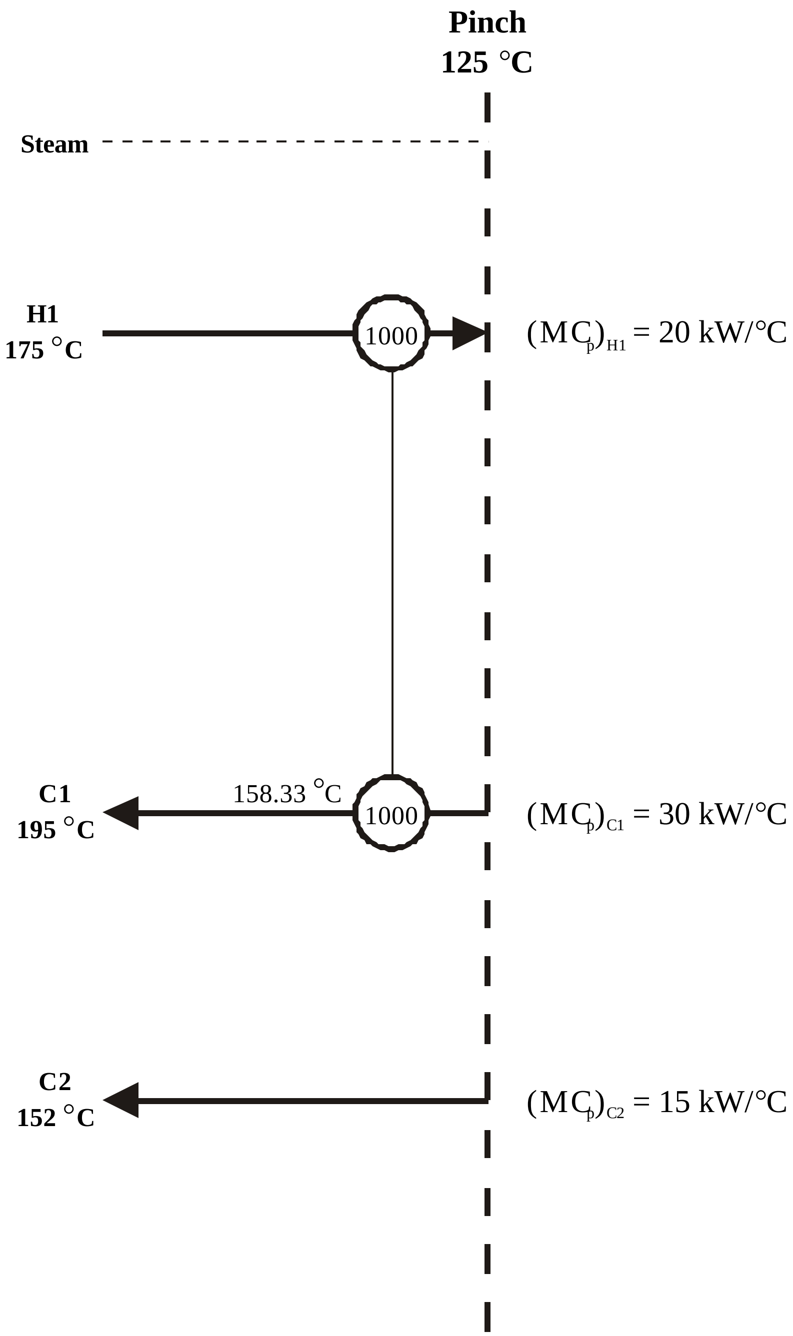


Figure 3.6. Grid diagram of a match between hot stream 1 and cold stream 1 for Example 2.1 above the pinch. Temperatures shifted for a minimum approach temperature of 20 °C. Heat duties in kW.

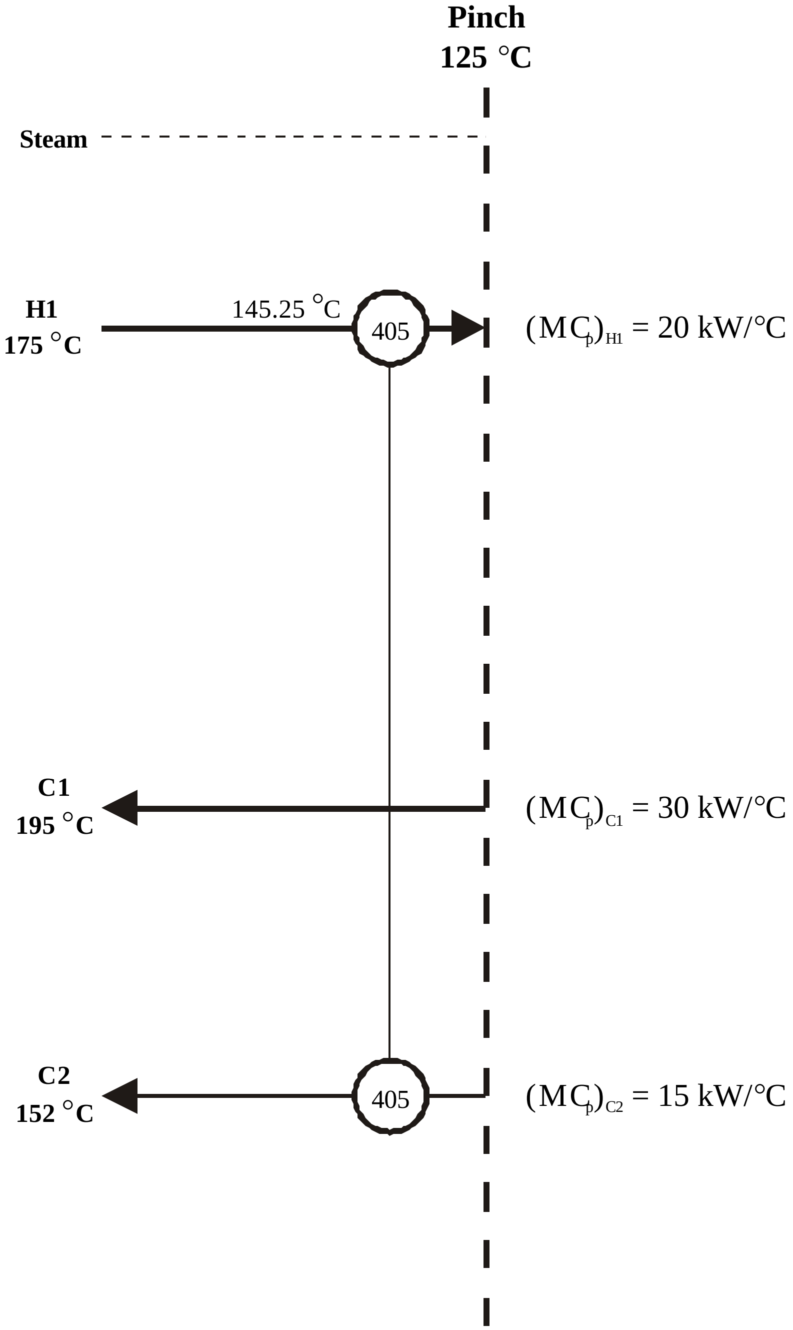


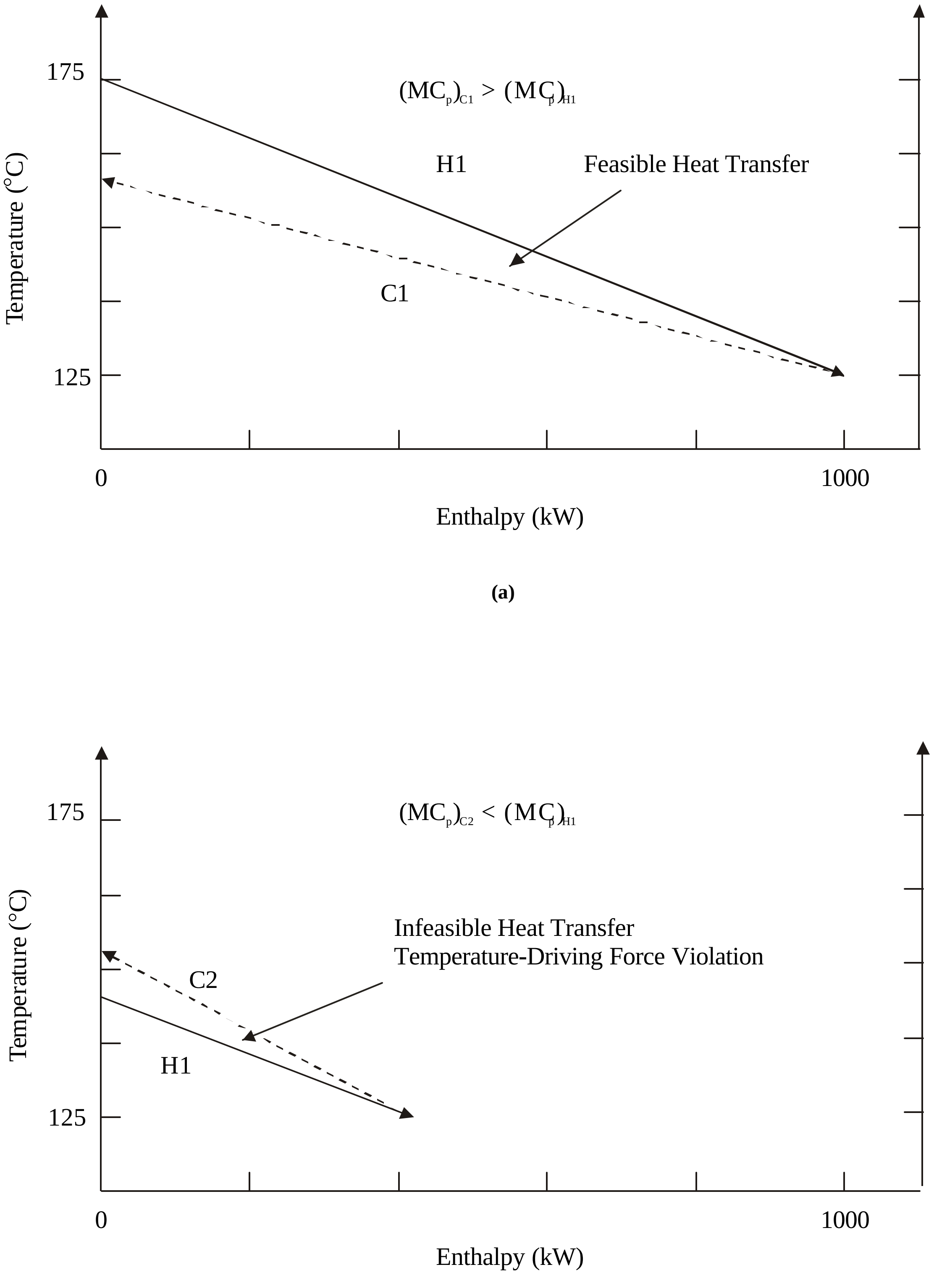
Figure 3.7. Grid diagram of a match between hot stream 1 and cold stream 2 for Example 2.1 above the pinch. Temperatures shifted for a minimum approach temperature of 20 °C. Heat duties in kW.

3.3.4 Capacity-Flowrate Rule for Match Feasibility

With more than one possible match between a hot stream and a cold stream available, we select stream matches according to their capacity flowrates. A general rule for matching a hot stream to a cold stream is that *the capacity flowrates of streams leaving the pinch temperature (i.e., hot streams above the pinch temperature or cold streams below the pinch temperature) must be greater than or equal to the capacity flowrate of streams approaching the pinch temperature (i.e., cold streams above the pinch temperature or hot streams below the pinch temperature)*. In other words, for matches at the pinch temperature:

$$\left(\dot{M}C_p\right)_{out} \geq \left(\dot{M}C_p\right)_{in} \tag{3.7}$$

For Example 2.1, Figure 3.8 illustrates the capacity flowrate rule. In the figure, the solid lines represent hot stream 1, and the dashed lines represent cold streams 1 and 2 in Figures 3.8a and b, respectively. In this case, we have drawn the streams in opposite directions (i.e., the hot-side inlet is to the right and the outlet is to the left, while the cold-side inlet is to the left and the outlet is to the right) to better agree with the format of the grid diagram. Figure 3.8a illustrates the case where the capacity flowrate of the cold stream is greater than that of the hot stream (i.e., in agreement with the capacity-flowrate rule). Here, the streams diverge from right to left and heat transfer between the streams is always feasible. Recall that the capacity flowrate is equal to the slope of the stream on a T-Q diagram. However, in the case of Figure 3.8b, the capacity flowrate of the cold stream is less than that of the hot stream (i.e., against the capacity flowrate rule). Now, we see that the cold stream is always above the hot stream on the T-Q diagram and heat transfer is infeasible.



(a)

(b)

Figure 3.8. T-Q diagram for matches between (a) hot stream 1 and cold stream 1 and (b) hot stream 1 and cold stream 2.

A simple and effective technique for identify matches with respect to the capacity flowrates of streams entering and leaving the pinch is *the tick-off table*. Table 3.3 lists the capacity flowrates of the four streams of Example 2.1 above (left) and below (right) the pinch temperature. In the table, we match streams above the pinch by drawing lines from a cold stream to a hot stream (i.e. right to left) such that the line always points to a hot stream with a lower capacity flowrate. Conversely, below the pinch, we draw lines to identify matches from a hot stream to a cold stream (i.e., from left to right), such that the line always points to a cold stream with a lower capacity flowrate.

Table 3.3. Tick-off table for Example 2.1.

	Above the pinch		**Below the Pinch**	
Stream i	**$(MC_p)_{Hi}$ (kW/°C)**	**$(MC_p)_{Ci}$ (kW/°C)**	**$(MC_p)_{Hi}$ (kW/°C)**	**$(MC_p)_{Ci}$ (kW/°C)**
1	20 ←	30	20 ↘	30
2	-	15	40 ↗	15

3.3.5 Matches Away from the Pinch

Once we have identified the matches between hot and cold streams near the pinch temperature, the design problem is relaxed. In other words, away from the pinch temperature, we have greater latitude in selecting stream matches. It is at this point where we are likely to generate alternative designs for heat-exchanger networks. Here, we may consider other factors like physical location, and stream compatibility to reduce network complexity or operational hazards.

3.3.6 Heaters and Coolers

Figure 3.9 shows a preliminary heat-exchanger network for Example 2.1 where we have made all possible stream matches according to the design rules of Sections 3.2.1 to 3.3.5. Now, the remainder of the heat transfer must be accomplished through heating and cooling utilities. In Figure 3.10, we add 900 and 405 kW of heat to cold streams 1 and 2, respectively, with steam heaters above the pinch. In Figure 3.11, we remove 1100 and 125 kW of heat from hot streams 1 and 2, respectively, with water coolers below the pinch. Note that the total heating utility (900 kW + 405 kW = 1305 kW) and cooling utility (1100 kW + 125 kW = 1225 kW) agree with those determined through hot and cold composite curves (Figure 2.17) and a TID (Table 3.9).

Figures 3.12 and 3.13 illustrate the complete heat-exchanger network for Example 2.1 on grid and heat-content diagrams, respectively.

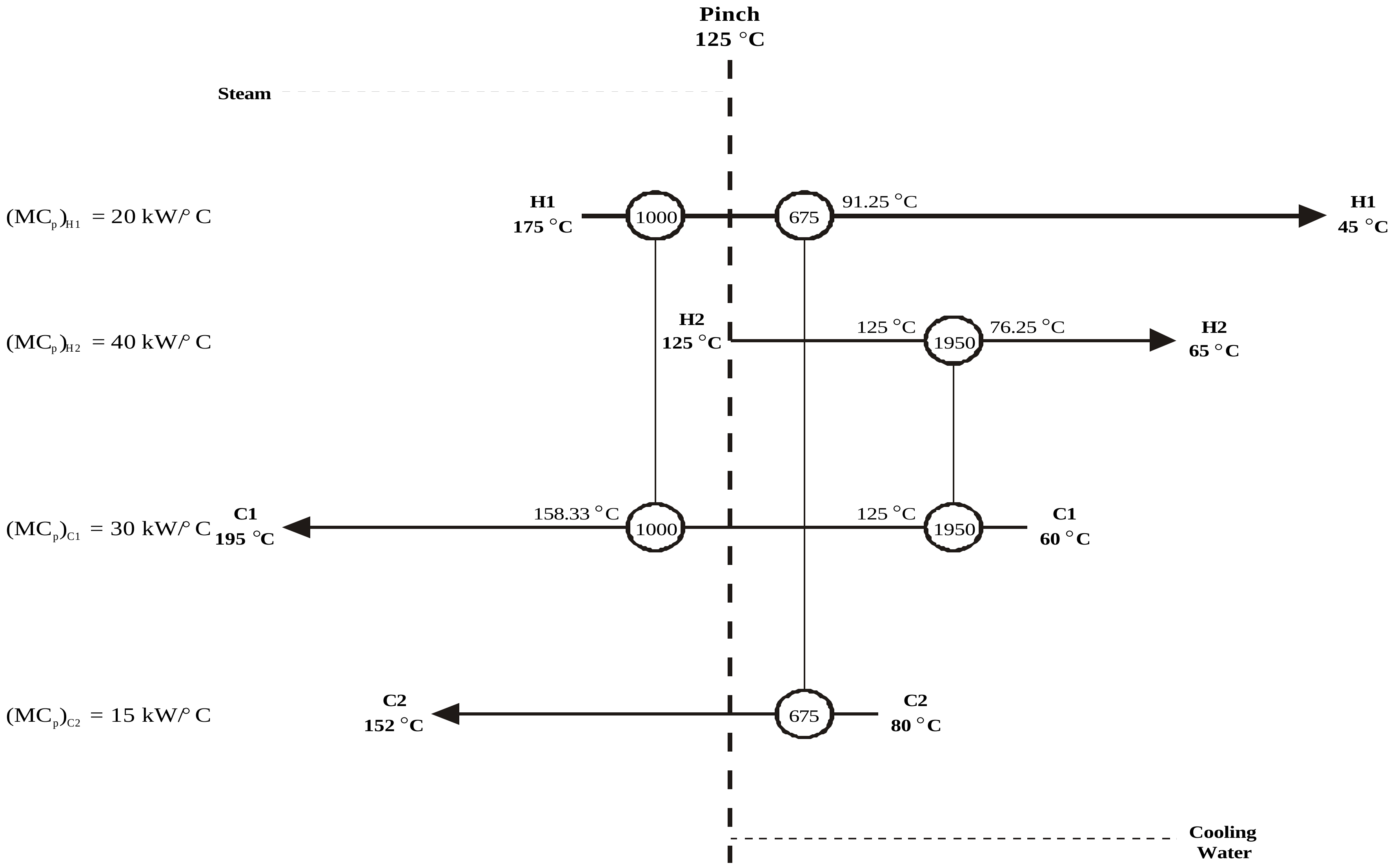


Figure 3.9. Grid diagram of a preliminary heat-exchanger network for Example 2.1 with all possible hot stream to cold stream matches. Temperatures shifted for a minimum approach temperature of 20 °C. Heat duties in kW.

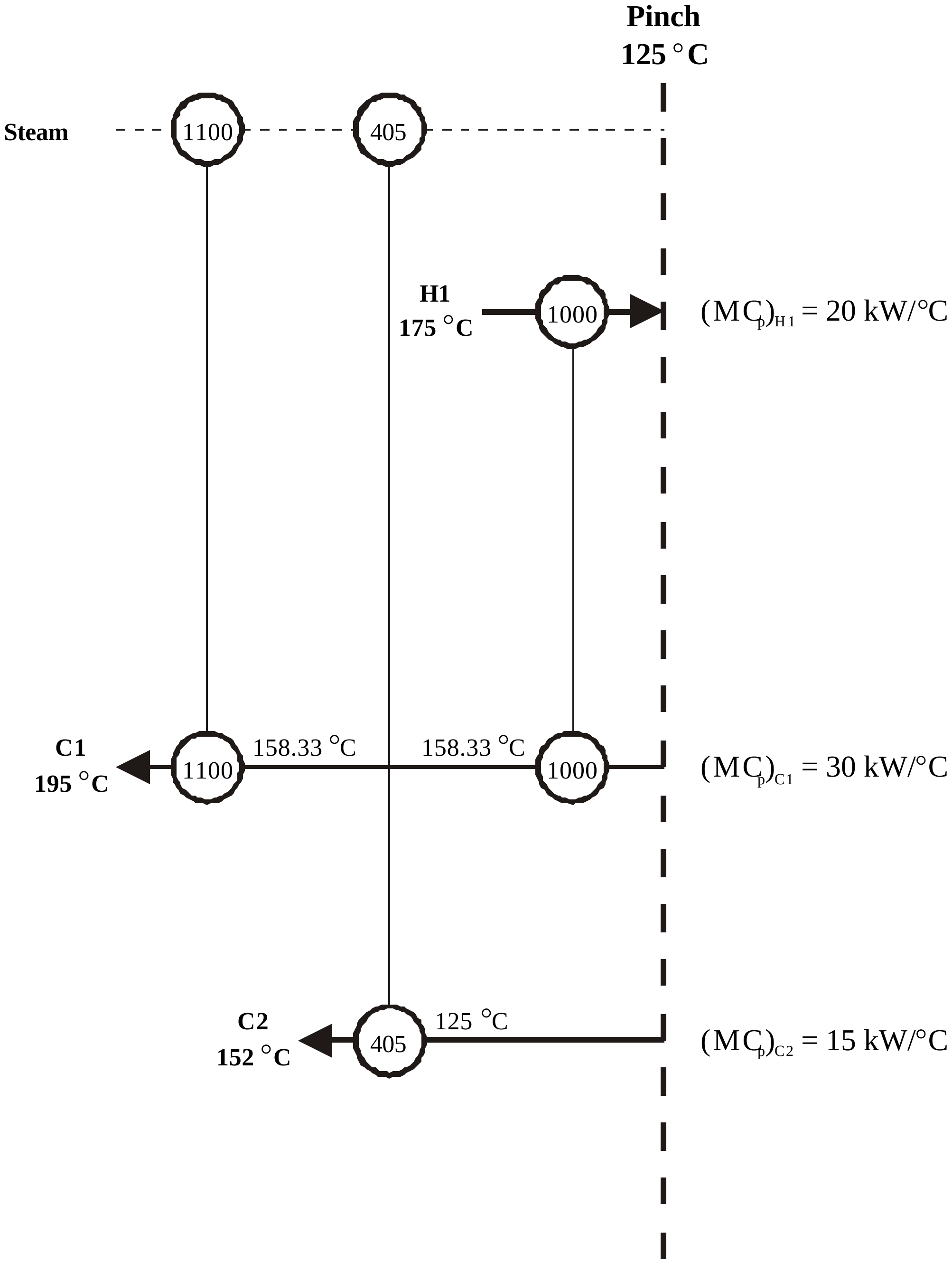


Figure 3.10. Grid diagram of a preliminary heat-exchanger network for Example 2.1 above the pinch with two heaters. Temperatures shifted for a minimum approach temperature of 20 °C. Heat duties in kW.

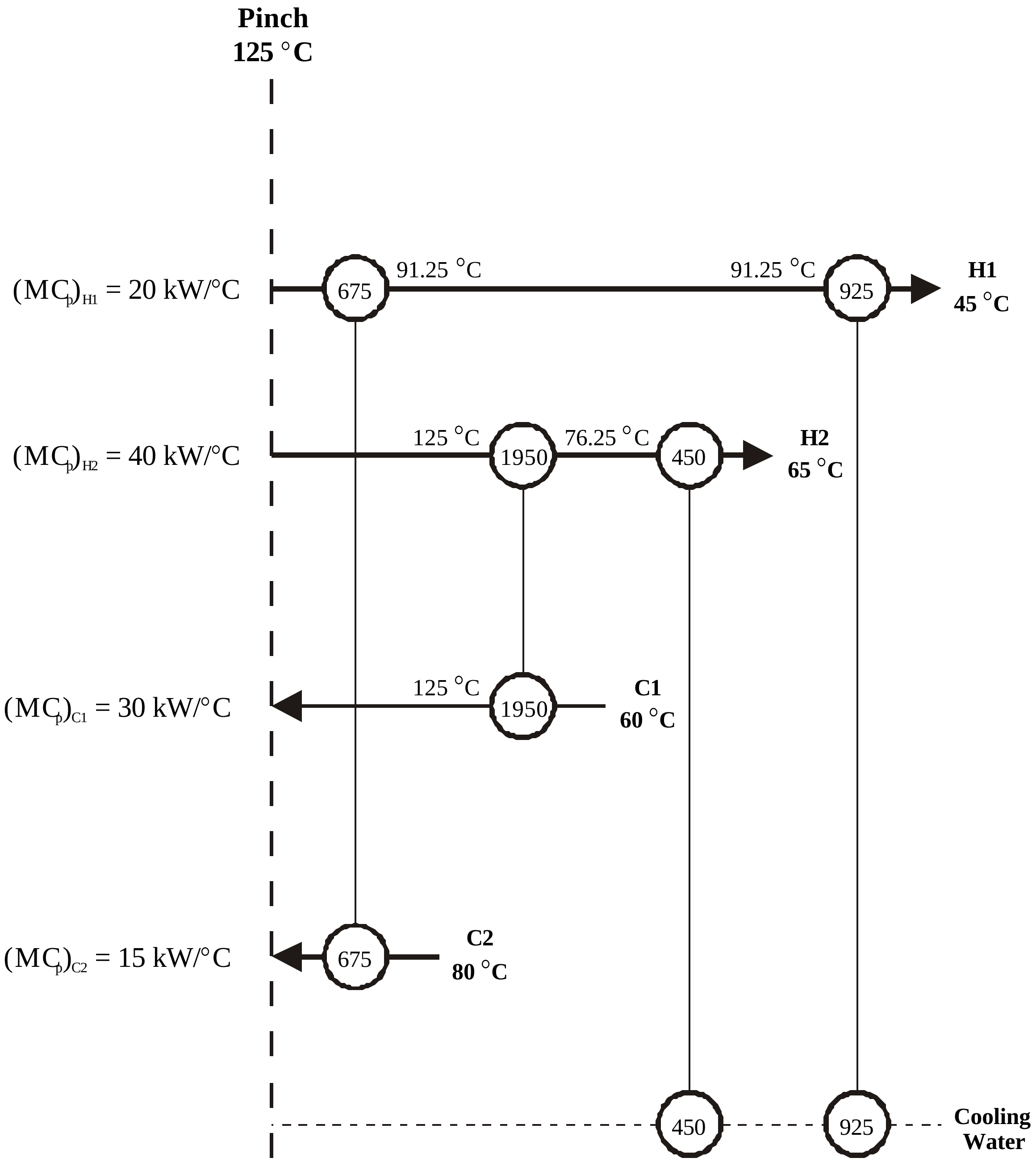


Figure 3.11. Grid diagram of a preliminary heat-exchanger network for Example 2.1 below the pinch with two coolers. Temperatures shifted for a minimum approach temperature of 20 °C. Heat duties in kW.

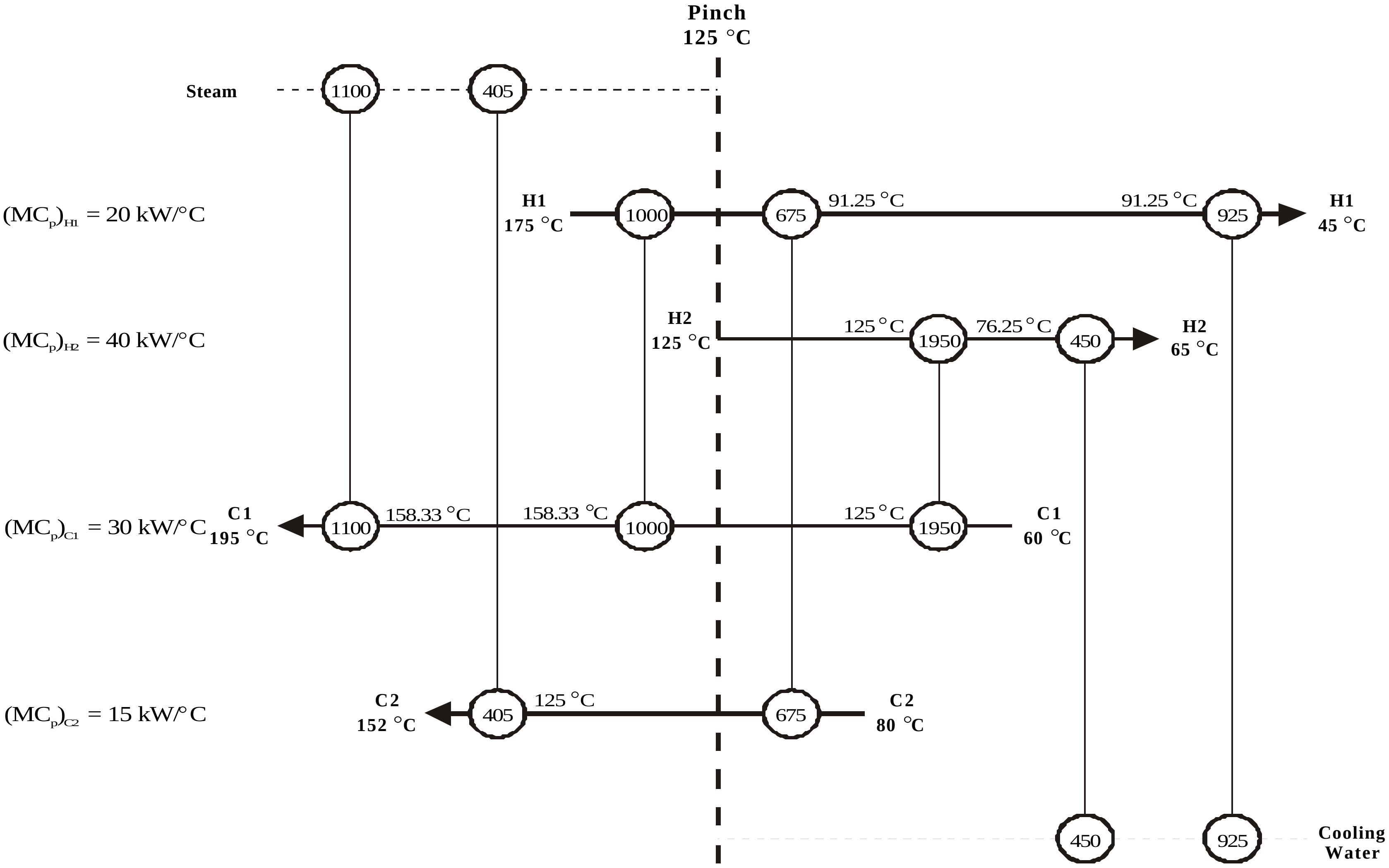


Figure 3.12. Grid diagram of a complete preliminary heat-exchanger network for Example 2.1. Temperatures shifted for a minimum approach temperature of 20 °C. Heat duties in kW.

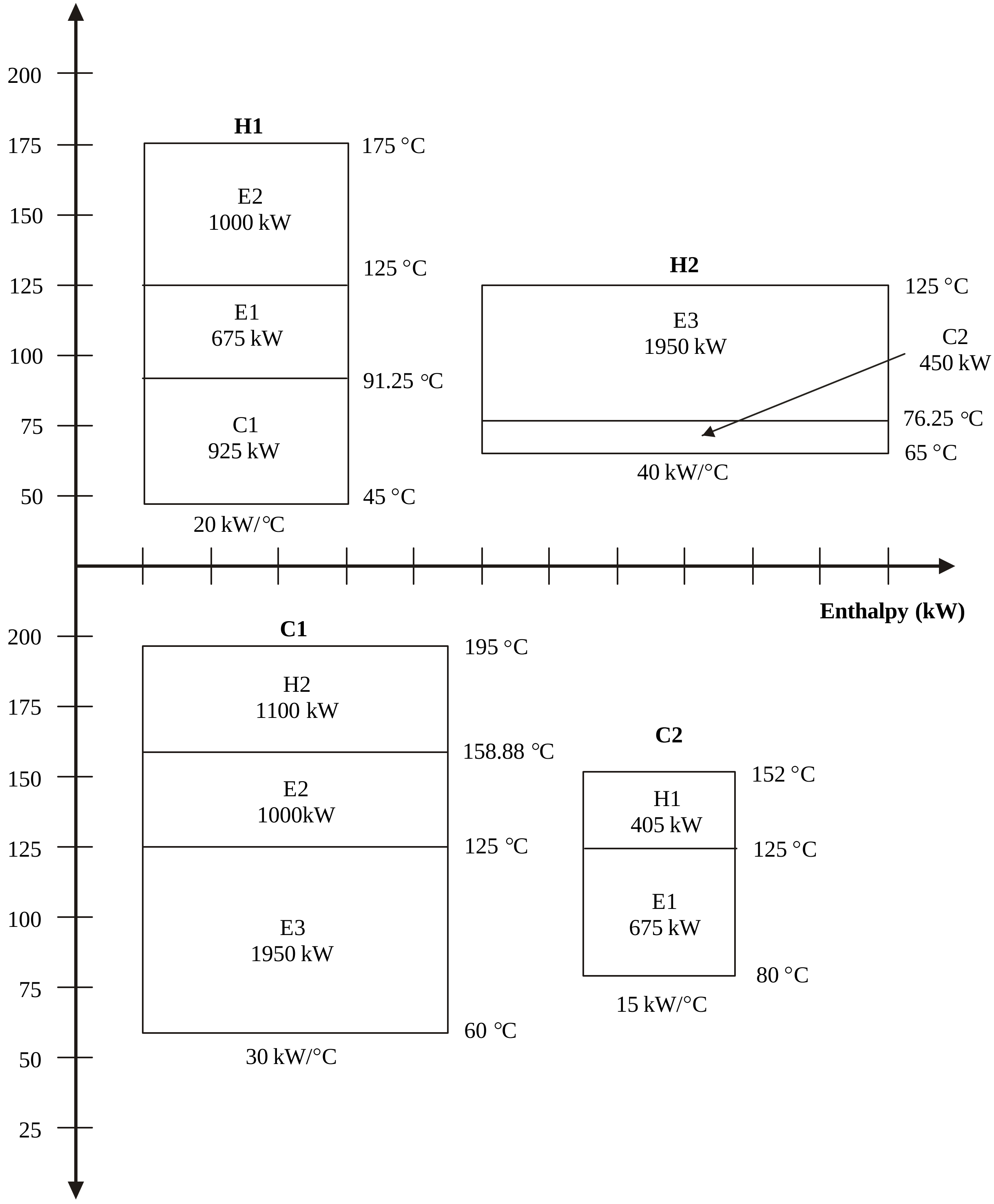


Figure 3.13. Heat-content diagram of a preliminary heat-exchanger network for Example 2.1. Temperatures shifted for a minimum approach temperature of 20 °C. Heat duties in kW.

3.3.7 Stream Splitting

For some problems, we may not be able to strictly follow the capacity-flowrate rule (Section 3.3.3) for stream matching. To illustrate this situation, we introduce Example 3.2. Here, we modify Example 2.1 so that we cannot follow the capacity flowrate rule for stream matching below the pinch. Tables 3.4 and 3.5 list the stream data and the shifted stream data, respectively, for Example 3.2 with a minimum approach temperature of 20 °C.

Table 3.4. Stream data for Example 3.2.

Stream i	$\mathbf{T^{supply}_i}$ **(°C)**	$\mathbf{T^{target}_i}$ **(°C)**	$\left(\dot{M}C_p\right)_i$ **(kW/°C)**
H1	165	35	10
H2	115	55	40
C1	165	30	20
C2	122	50	15

Table 3.5. Shifted stream data for Example 3.2 with a minimum approach temperature, DT_{min} = 20 °C.

Stream i	T^{supply}_i (°C)	T^{target}_i (°C)	$(\dot{M}C_p)_i$ (kW/°C)
H1	155	25	10
H2	105	45	40
C1	175	40	20
C2	132	60	15

Figure 3.14 and Table 3.6 are the composite curves and TID for Example 3.2, respectively. From either the figure or the table, we recognize that the pinch point remains at a shifted temperature of 125 °C, while the minimum heating- and cooling-utility duties are increased to 1225 and 1305 kW, respectively.

Figure 3.15 shows the streams and their capacity flowrates for Example 3.2. Table 3.7 lists the capacity flowrates of streams above and below the pinch for Example 3.2 for the tick-off matching procedure. We notice that above the pinch, there are two feasible matches - hot stream 1 to cold stream 2, or hot stream 1 to cold stream 2 (both 20 and 15 kW/°C are greater than 10 kW/°C). However, we are not so fortunate below the pinch. Table 3.7 shows that a match between hot stream 1 and cold stream 2 is infeasible (10 kW/°C is less than 15 kW/°C).

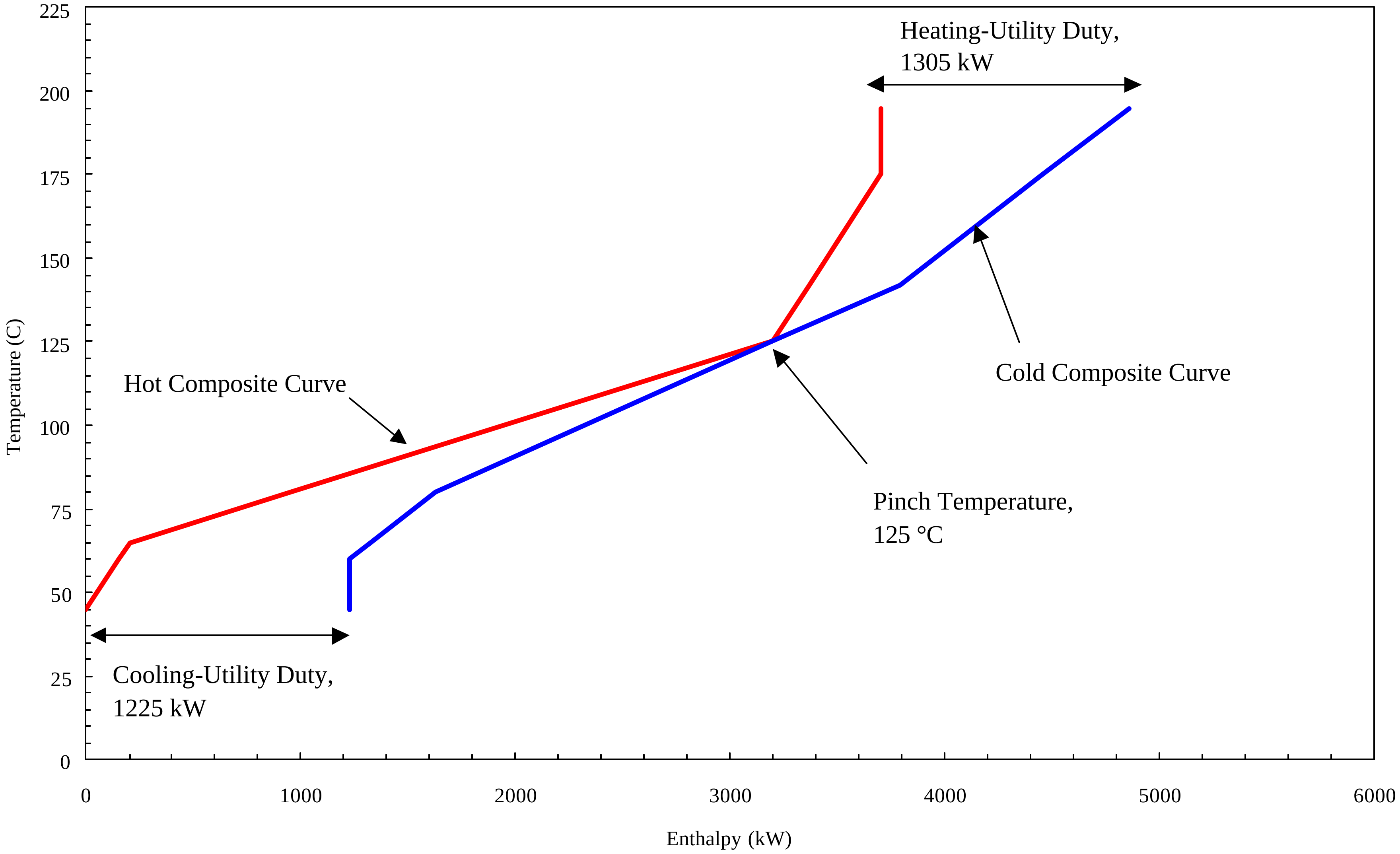


Figure 3.14. Hot and cold composite curves for Example 3.2. Temperatures shifted for a minimum approach temperature of 20 °C

Table 3.6. TID for Example 3.2. Temperatures shifted for a minimum approach temperature of 20 °C.

	Hot Streams				Cold Streams						
Shifted Temperature (°C)	H1 10 kW/°C	H2 40 kW/°C	Heat Surplus (kW)	Cumulative Surplus (kW)	C1 20 kW/°C	C2 15 kW/°C	Heat Deficit (kW)	Cumulative Deficit (kW)	Net Heat Surplus (kW)	Cascaded Surplus (kW)	Adjusted Surplus (kW)
25	↑			0				0		-80	1225
	│		150				0		150		
40	│			150	│			0		-230	1075
	│		50		│		100		-50		
45	│	↑		200	│			100		-180	1125
	│	│	750		│		300		450		
60	│	│		950	│	│		400		-630	675
	│	│	2250		│	│	1575		675		
105	│	│		3200	│	│		1975		-1305	0
	│		270		│	│	945		-675		
132	│			3470	│	↓		2920		-630	675
	│		230		│		460		-230		
155	│			3700	│			3380		-400	905
			0		│		400		-400		
175				3700	↓			3780		0	1305

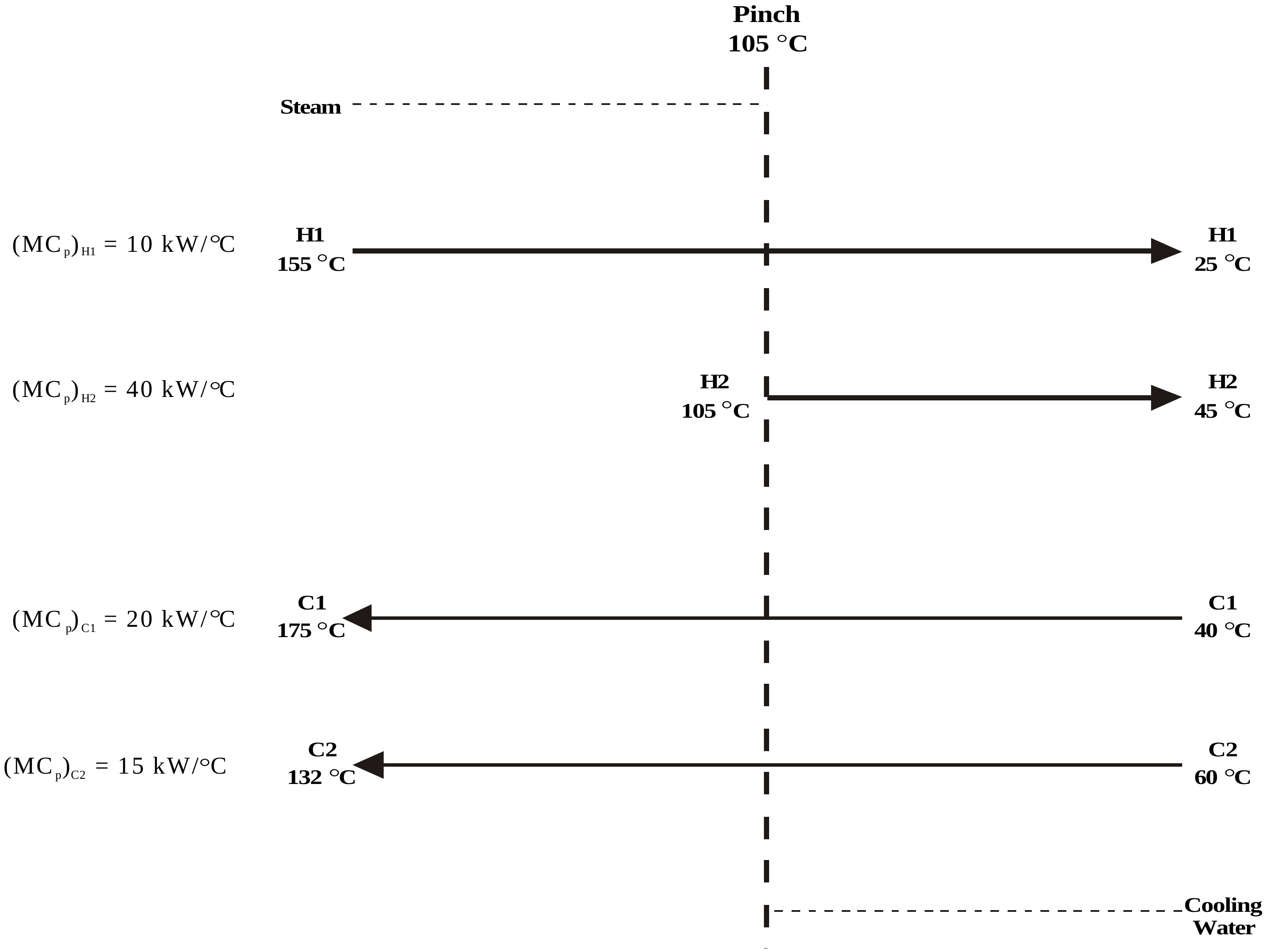


Figure 3.15. Grid diagram of hot and cold streams for Example 3.2. Temperatures shifted for a minimum approach temperature of 20 °C.

Table 3.7. Tick-off table for Example 3.2.

	Above the pinch		**Below the Pinch**	
Stream	**$(MC_p)_{Hi}$**	**$(MC_p)_{Ci}$**	**$(MC_p)_{Hi}$**	**$(MC_p)_{Ci}$**
i	**(kW/°C)**	**(kW/°C)**	**(kW/°C)**	**(kW/°C)**
1	10 ←	20	10	20
2	-	15	40 ↗	15

How do we supply the necessary heat to cold streams below the pinch? We have one hot stream available near the pinch (hot stream 2) and cannot use heaters below the pinch. We *split* the available hot stream and use a portion of its capacity flowrate to heat each cold stream. Figure 3.16 illustrates one method for splitting hot stream 2 to accomplish the heating of cold streams below the pinch. We supply a total of 1975 kW of heat to cold stream 1 (1300 kW) and cold stream 2 (675 kW) to raise the temperature of both to 125 °C. We distribute the capacity flowrate of hot stream 2 to the cold streams in proportion to the heat loads of each unit:

$$\left(MC_p\right)_{H2\rightarrow C1} = \left(MC_p\right)_{H2}\left(\frac{1300\text{kW}}{1300\text{kW}+675\text{kW}}\right) = 26.33\frac{\text{kW}}{^\circ\text{C}}$$

$$\left(MC_p\right)_{H2\rightarrow C2} = \left(MC_p\right)_{H2}\left(\frac{675\text{kW}}{1300\text{kW}+675\text{kW}}\right) = 13.67\frac{\text{kW}}{^\circ\text{C}}$$

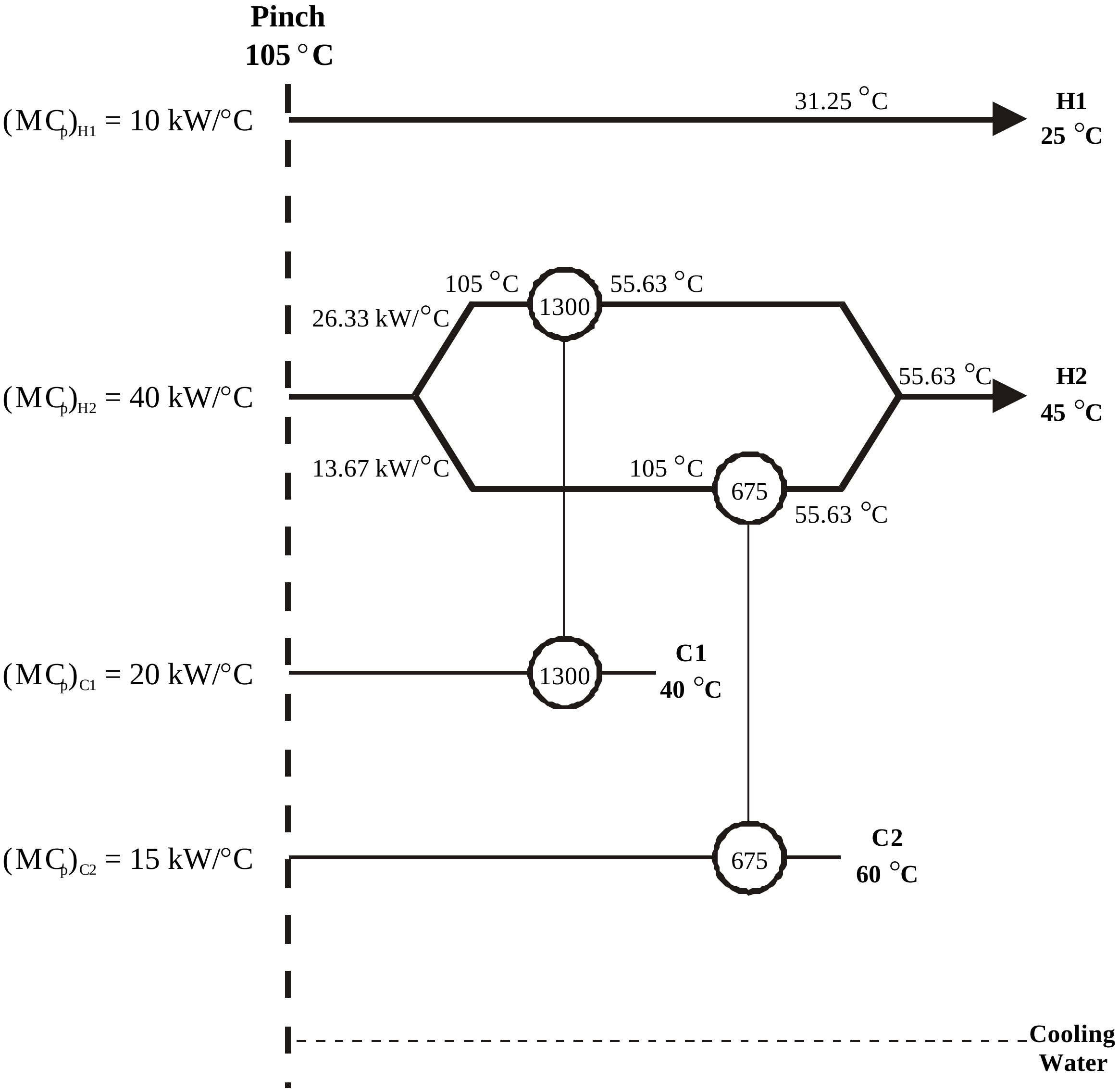


Figure 3.16. Grid diagram of a preliminary heat-exchanger network for Example 3.2 below the pinch featuring stream splitting. Temperatures shifted for a minimum approach temperature of 20 °C. Heat duties in kW.

In the figure, we split hot stream 2 and supply 26.33 and 13.67 kW/°C of its capacity flowrate to heat cold streams 1 and 2 from 40 to 105 °C and from 60 to 125 °C, respectively. The outlet temperatures from the two units are:

$$\begin{aligned} T^{out}_{H2\to C1} &= T^{in}_{H2\to C1} - \frac{Q_{H2\to C1}(kW)}{(MC_p)_{H2\to C1}\left(\frac{kW}{^\circ C}\right)} \\ &= 105^\circ C - \frac{1300kW}{26.33\frac{kW}{^\circ C}} \\ &= 55.63^\circ C \end{aligned}$$

$$\begin{aligned} T^{out}_{H2\to C2} &= T^{in}_{H2\to C2} - \frac{Q_{H2\to C2}(kW)}{(MC_p)_{H2\to C2}\left(\frac{kW}{^\circ C}\right)} \\ &= 105^\circ C - \frac{675kW}{13.67\frac{kW}{^\circ C}} \\ &= 55.63^\circ C \end{aligned}$$

The outlet temperatures for both units are equal because we distributed the capacity flowrate of hot streams 2 proportional to the heat duties of each unit.

Figures 3.17 and 3.18 depict the entire preliminary heat-exchanger network for Example 3.2 including heating and cooling utilities on gird and heat-content diagrams, respectively. In Figure 3.18, we represent stream splitting with vertical lines.

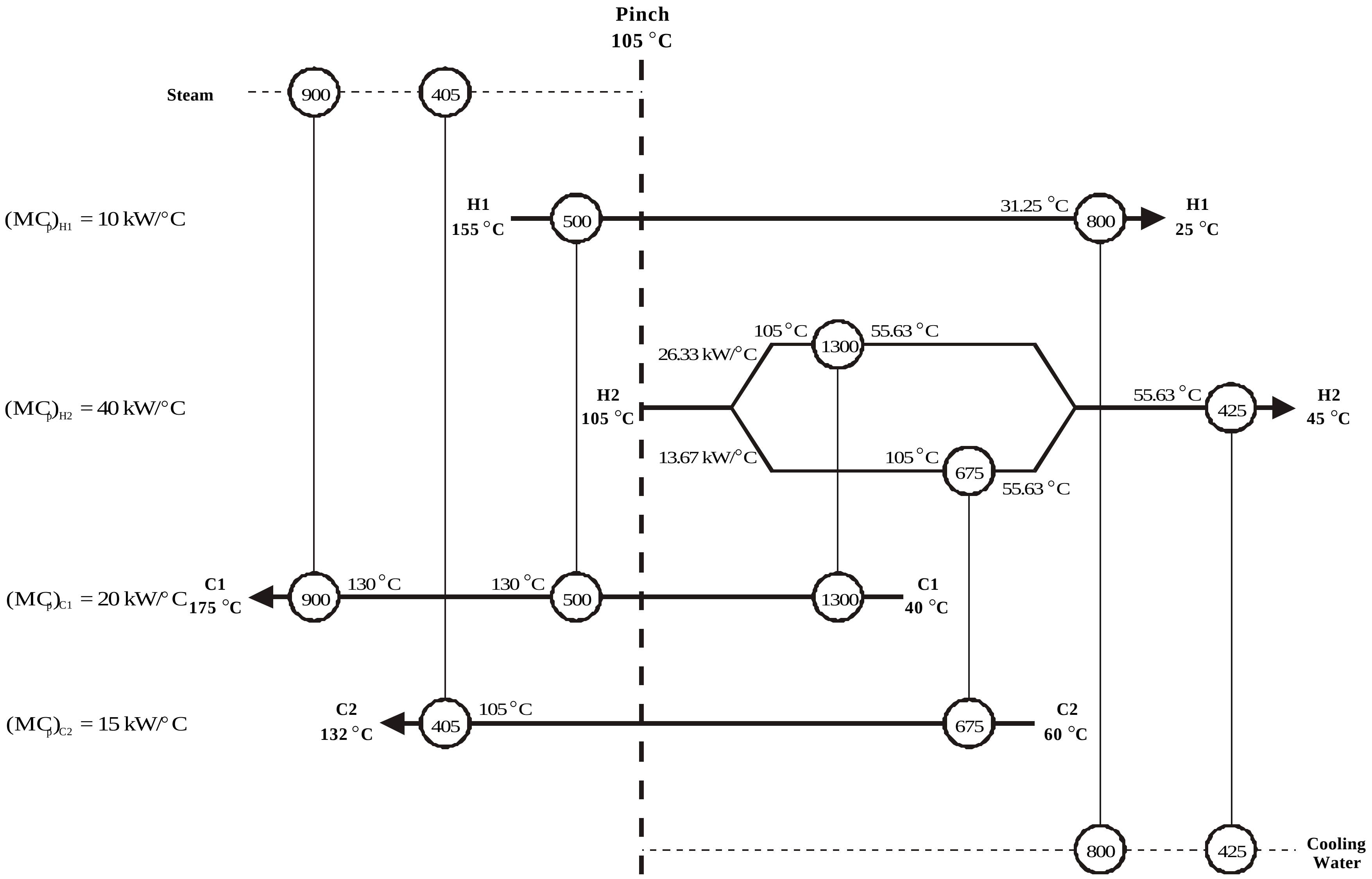


Figure 3.17. Grid diagram of a complete preliminary heat-exchanger network for Example 3.2. Temperatures shifted for a minimum approach temperature of 20 °C. Heat duties in kW.

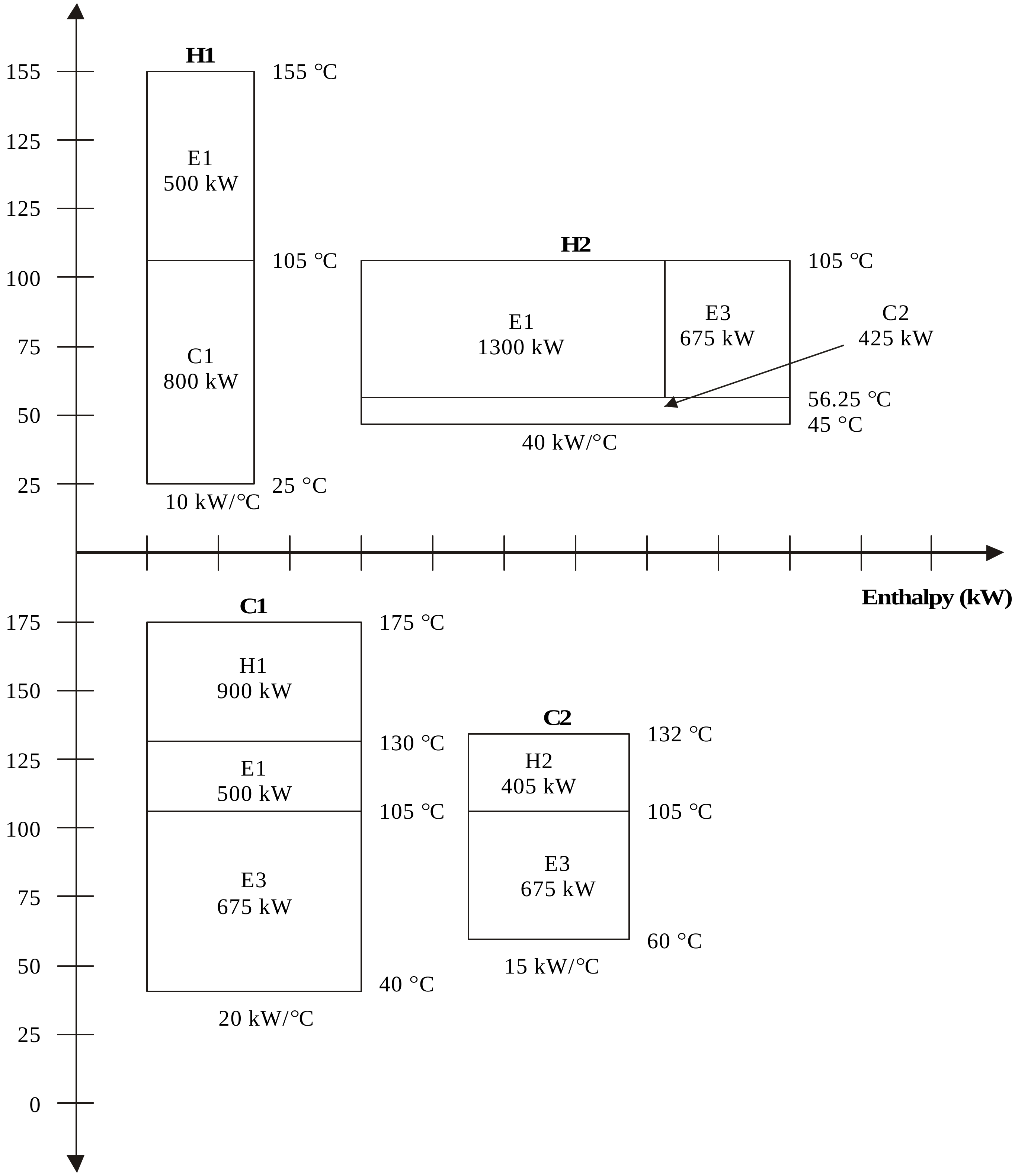


Figure 3.18. Heat-content diagram of a preliminary heat-exchanger network for Example 3.2. Temperatures shifted for a minimum approach temperature of 20 °C. Heat duties in kW.

3.4 Network Evolution

In this section, we present guidelines for optimizing preliminary heat-exchanger networks by identify loops and paths within preliminary designs and shifting heat loads away from small, inefficient heat-exchange units to create fewer, larger, more cost-effective units. We begin by relaxing the restrictions imposed on preliminary heat-exchanger networks and allowing individual exchangers to operate below minimum approach temperatures and/or transfer heat across the pinch.

3.4.1 Shifting Heat Loads around Network Loops

Figure 3.19 shows a grid diagram for a new example with a loop (bold dashed line) between heat-exchange units. To identify the loop, we begin at unit C and proceed toward the bottom of the diagram to cold stream 1. Following, the line representing cold stream 1, we reach unit F and follow the unit toward the top of the diagram to hot stream 1. Finally, we return to unit C along the line representing cold stream 1.

In Figure 3.19, we shift a heat load, ΔH, across exchangers to optimize the network design constrained only by feasible heat transfer (i.e., positive driving forces) and other practical guidelines (e.g., minimum and maximum exchanger areas). By doing so, we leave the heat balance over each stream, and the minimum heating- and cooling-utility duties, unchanged while opening a degree of freedom in the final network design. The shifting of heat loads across units within the loop can continue until the smallest unit in the loop is eliminated (unit F, 400 kW). Figure 3.20 shows a simplified heat-exchanger network for Example 3.3 after eliminating unit F (0 kW). Note that unit C exhibits a MAT violation but he transfer remains feasible.

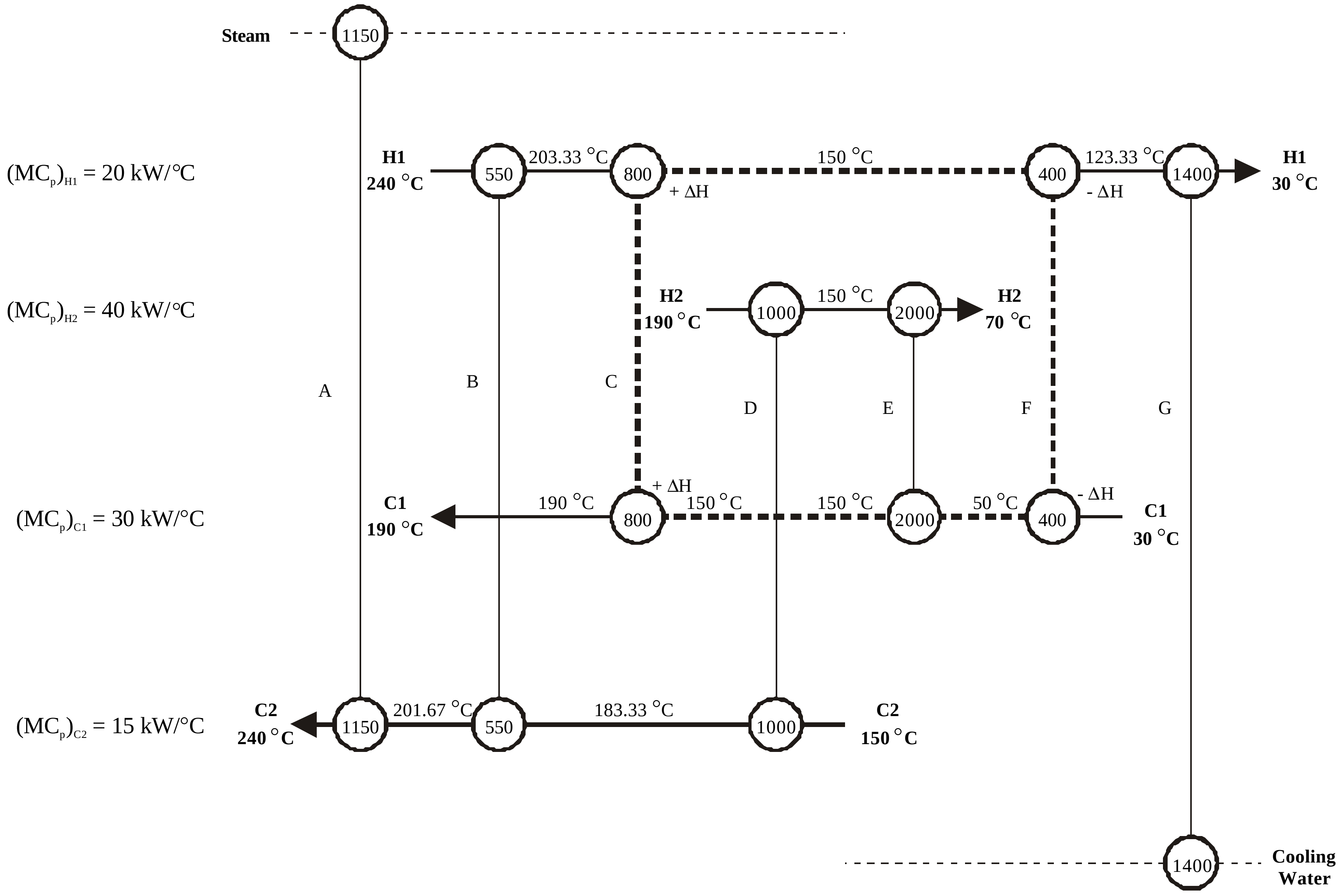


Figure 3.19. Grid diagram of a preliminary heat-exchanger network for Example 3.3 with a network loop. Temperatures shifted for a minimum approach temperature of 20 °C. Heat duties in kW.

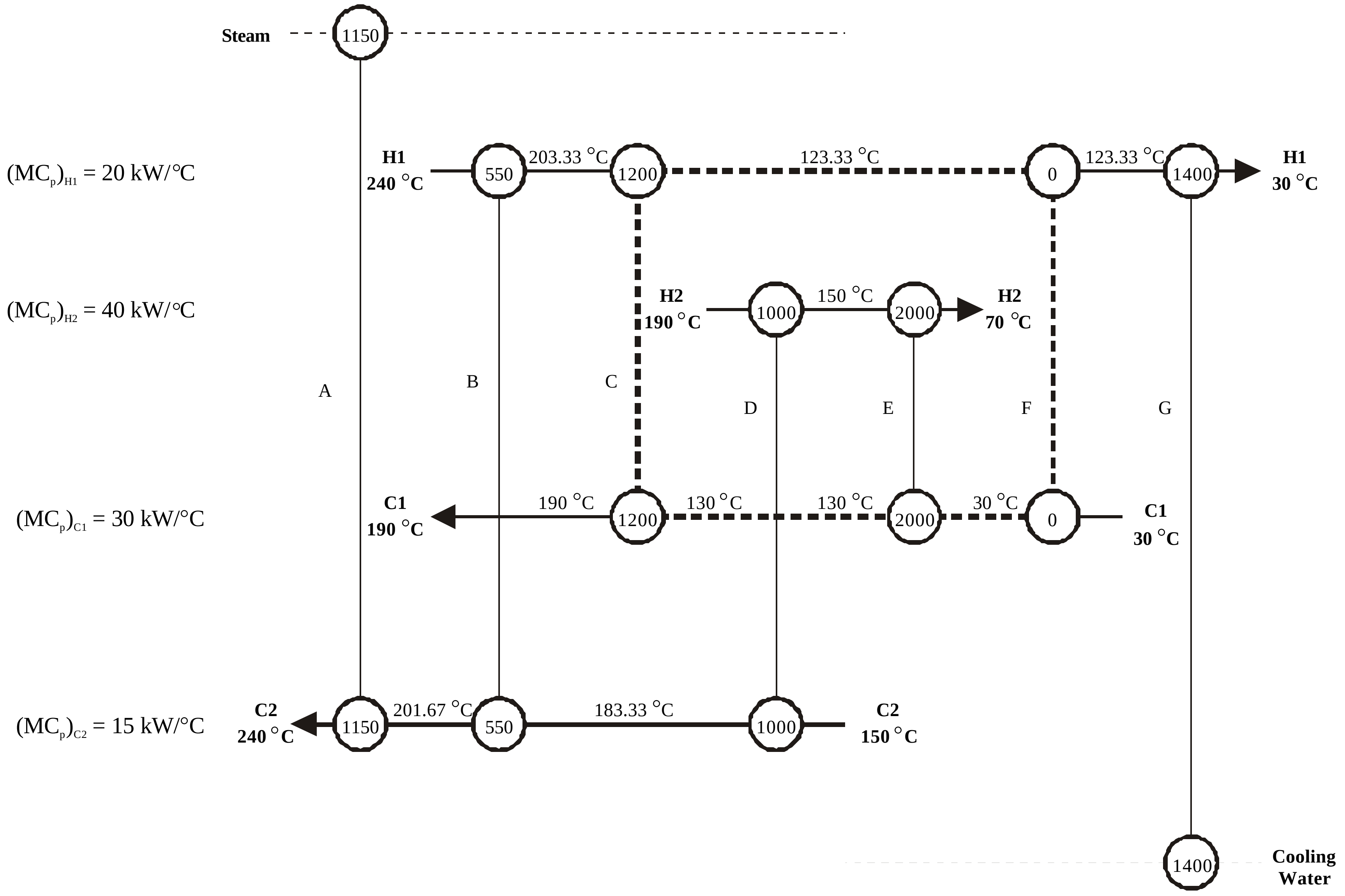


Figure 3.20. Simplified grid diagram for Example 3.3 first shown in Figure 3.19 after eliminating unit D within a network loop. Temperatures shifted for a minimum approach temperature of 20 °C. Heat duties in kW.

3.4.2 Shifting Heat Loads along Network Paths

Figure 3.21 shows a grid diagram for Example 3.4 with a path (bold dashed line) between heating steam and cooling water. To identify the path, we start at a heating utility (heater labeled unit A) and proceed toward the line representing cold stream 1. Following this line, we reach exchanger E. Continuing toward the top of the diagram, we reach hot stream 2. Traveling along hot stream 2, we reach a cooler, unit F, and finally stop at a cooling utility (cooling water).

We use network paths to eliminate small, less cost-effective exchangers, heaters and coolers. In Figure 3.21, we again shift a heat load, ΔH, along the network to optimize the network design constrained only by feasible heat transfer and other practical guidelines. However, we cannot shift heat loads along a network path and leave the heat balance over each stream, and the minimum heating- and cooling-utility duties, unchanged. For network paths, opening a degree of freedom always results in a change in the minimum heating- and cooling-utility duties. In this case, Figure 3.22 shows that we can eliminate heater F and reduce heating- and cooling-utility duties by 50 kW. However, we see a minimum approach-temperature violation in unit E. Note, heat transfer remains feasible as we have incorporated a minimum approach temperature of 20 °C into the temperatures shown in Figure 3.22.

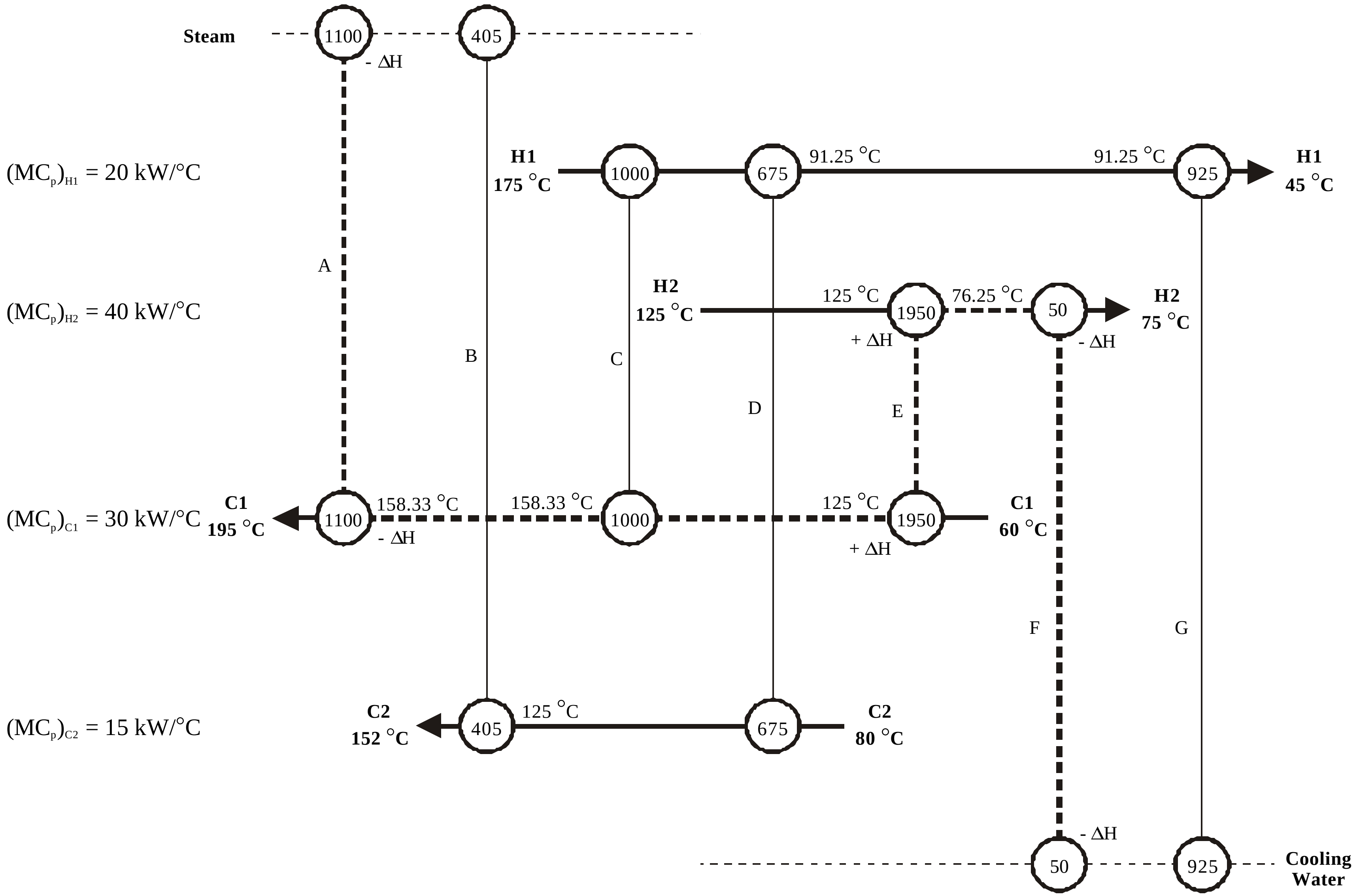


Figure 3.21. Grid diagram of a preliminary heat-exchanger network for Example 3.4 with a network path. Temperatures shifted for a minimum approach temperature of 20 °C. Heat duties in kW.

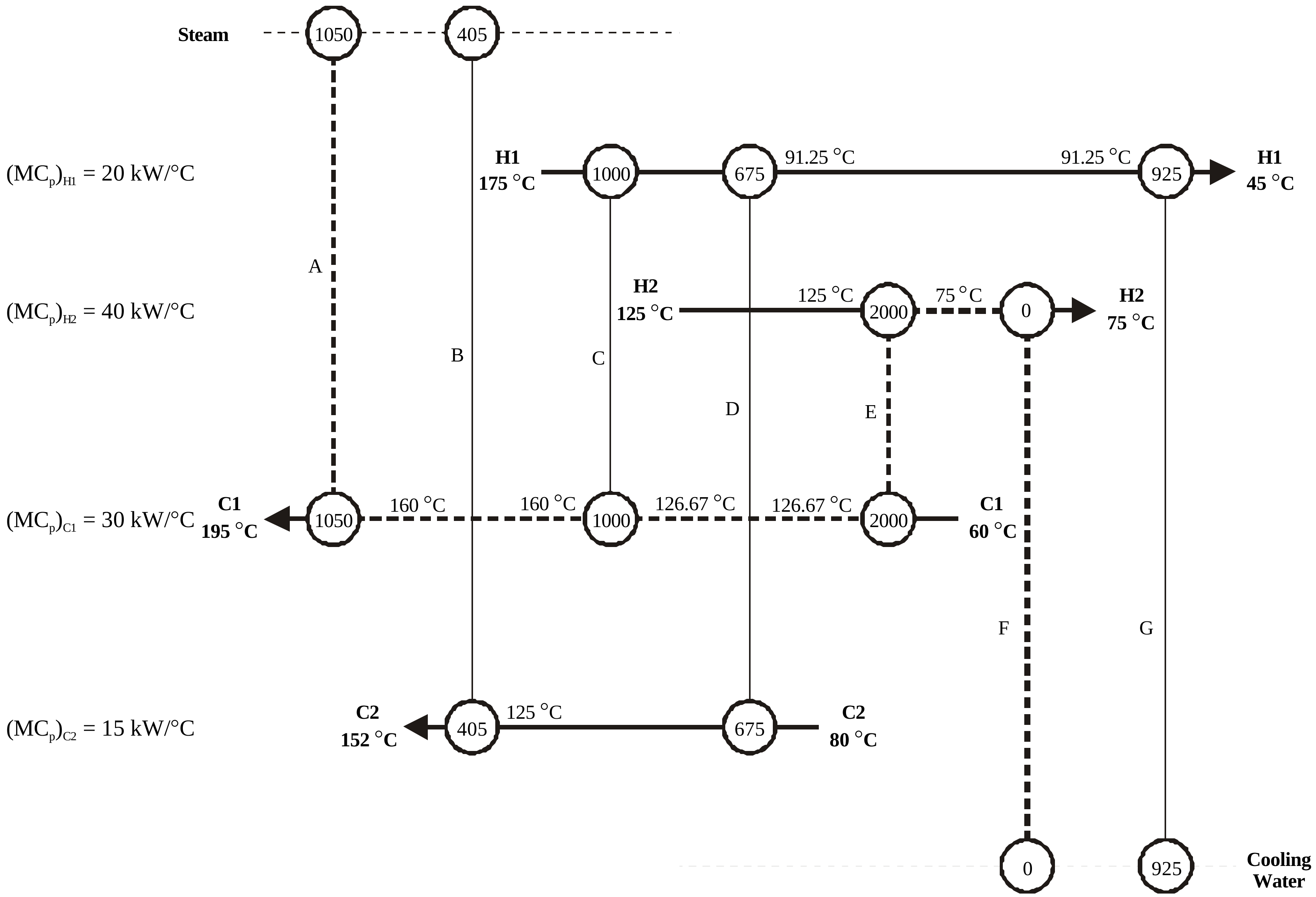


Figure 3.22. Simplified grid diagram for Example 3.4 first shown in Figure 3.21 after eliminating heater F along a network path. Temperatures shifted for a minimum approach temperature of 20Ê°C. Heat duties in kW.

3.5 Summary

- After targeting minimum heat- and cooling-utility duties, we design heat-exchanger networks that accomplish the necessary heat transfer and satisfy the stream data using the least amount of heating and cooling utilities and the fewest number of heat-exchange units.

- First, we design a preliminary heat-exchanger network guaranteed to accomplish the heat transfer from hot streams to cold streams (Section 3.3).

- Second, we simplify the preliminary network to reduce the number of heat-exchange units (e.g., heat exchangers, steam heaters and water coolers) through an evolutionary process (Section 3.4).

- The pinch divides the problem into subnetworks defined by the pinch temperature(s). No heat should be transferred across the pinch and that heating and cooling utilities should not be employed above and below the pinch, respectively.

- Beginning at the pinch and working away form the pinch, we select matches according to the design rules presented in Sections 3.3.2 and 3.3.4 to satisfy the stream data.

- Euler's graph theory gives us tools to evaluate heat-exchanger networks and identify the minimum number of heat-exchange units above and below the pinch temperature from the number of process and utility streams.

- A general rule for matching a hot stream to a cold stream is that the capacity flowrates of streams leaving the pinch temperature (i.e., hot streams above the pinch temperature or cold streams below the pinch temperature) must be greater than or equal to the capacity flowrate of streams approaching the pinch temperature (i.e., cold streams above the pinch temperature or hot streams below the pinch temperature).

- When we can not strictly follow the capacity-flowrate rule for stream matching, we split streams into segments with capacity flowrates such that we can follow the capacity-flowrate rule for stream matching.

- We optimize preliminary heat-exchanger networks by relaxing the restrictions on preliminary networks and allowing individual exchangers to operate below minimum approach temperatures and/or transfer heat across the pinch.

- We shift heat within network loops to eliminate small exchangers, heaters and coolers without changing the heat balance on streams or the heating- and cooling-utility duties.

- We shift heat along network paths to eliminate small exchangers, heaters and coolers. This can change the heating- and cooling-utility duties.

References

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Nomenclature

C	Number of independent components
L	Number of loops
$\left(MC_p\right)_i$	Capacity flowrate of stream i, kW/°C
N_C	Number of cold process streams
N_{CU}	Number of cooling utilities below the pinch temperature
N_H	Number of hot process streams
N_{HU}	Number of heating utilities above the pinch temperature
N_{units}	Minimum number of units
S	Number of units