CHAPTER IV

HEAT EXCHANGER NETWORK DESIGN

In chemical process industries, heat recovery from hot streams to preheat cold streams can save energy consumption. The hot streams usually refer to products or semi-products, and the cold streams usually refer to process feeds. Many heat exchanger used to recover heat are connected as a network, called a heat-exchanger network (HEN). *Pinch analysis* is a important tool to systematically design a HEN to achieve the minimum total cost. This includes capital and operating costs plus some consideration of flexibility and operability of the selected design [17]. The capital cost usually refers to a total cost of heat-exchanger. The operating cost is the cost of heating and cooling utilities for a HEN, minimized when a HEN can recover the maximum heat. For petroleum industry, the pinch analysis is used to improve the existing HEN to save energy about 30 % (payback period about 1 - 2 year) [18]. The minimum total cost usually is termed the HEN design target: a capital target for the capital cost and an energy target for the operating cost. To design the HEN, pinch analysis has three steps:

1. Determine the pinch position and the energy target.
2. Identify the capital target.
3. Design the complete HEN.

Determine the Pinch Position and the Energy Target

The pinch is the minimum temperature difference of heat transfer in the HEN. It usually ranges 10-20°C [17]. For HEN design, important properties of all hot and cold streams -- e.g., flowrate, initial and final temperatures, and heat capacity-- must be known first. The pinch position and the energy target can be determined by using either *composite curves* or *problem table algorithm*. The *composite curves* consist of hot and cold composite curves plotted the accumulative heat (x-axis) with temperature (y-axis). Consider a simple HEN problem which has two hot streams and two cold streams, shown in Table 4.1. The minimum temperature difference of this problem equates 10°C. In Figure 4.1, the hot composite curve is the accumulative heat in each temperature interval (divided by initial and final hot temperatures). In Figure 4.2, the cold composite curve is the accumulative heat in each temperature interval (divided by initial and final cold temperatures).

Table 4.1 Heat exchanger stream data[19]

Streams	Initial Temp.(°C)	Final temp.(°C)	ΔH (MW)	Heat Capacity Flowrate CP (MW/°C)
1) Hot	250	40	-31.5	0.15
2) Hot	200	80	-30.0	0.25
3) Cold	20	180	32.0	0.20
4) Cold	140	230	27.0	0.30

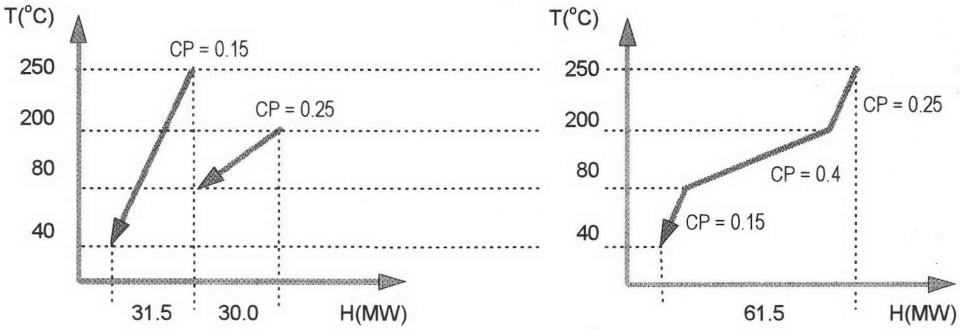


Figure 4.1 The hot streams can be combined to obtain a composite hot stream.

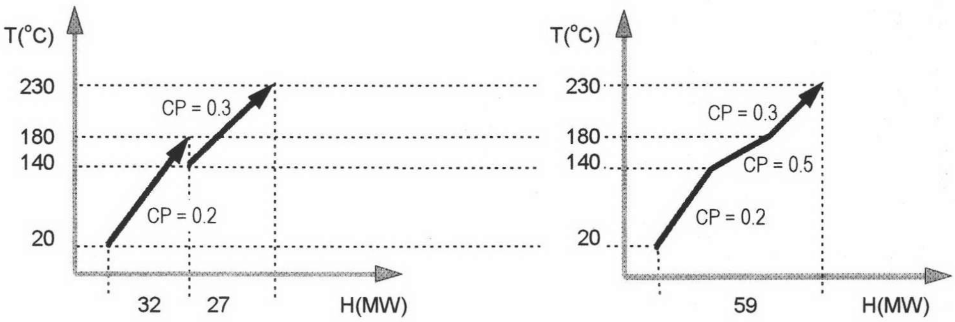


Figure 4.2 The cold streams can be combined to obtain a composite cold stream.

Plotting hot and cold composite curves together shown in Figure 4.3, the maximum possible heat recovery is the overlap of two composite curves. The minimum utility requirements are the overshoots of them; left is the minimum cooling and right is the minimum heating. ΔT_{min} is the pinch. An overview of composite curves is shown in Figure 4.4.

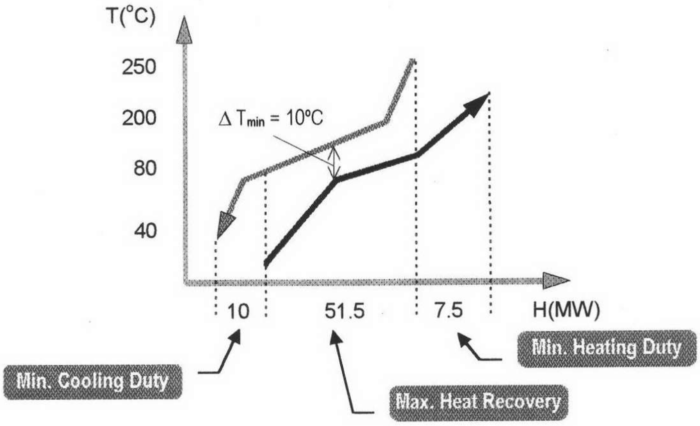


Figure 4.3 Plotting hot and cold composite curves together

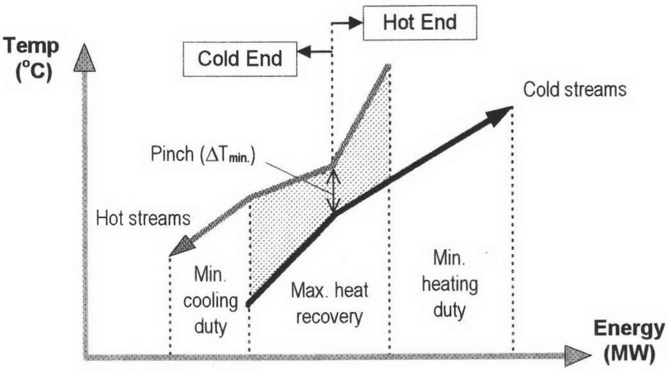
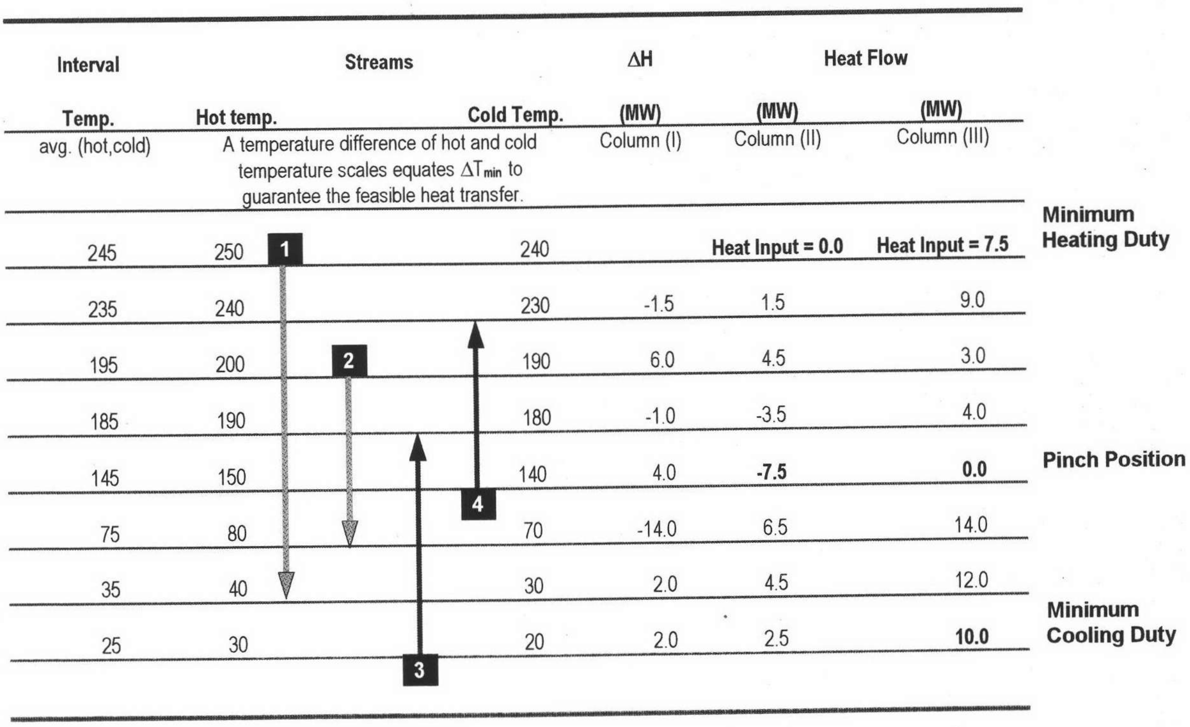


Figure 4.4 Composite curves of the heat exchanger network.

The composite curves are useful in providing conceptual understanding of the process. However, they are inconvenient to calculate energy targets because they are based on a graphic construction. To overcome this problem, the *problem table algorithm* is used. It can calculate energy targets directly without the need for graphic construction. The process is first divided into temperature intervals (or subnetworks). In each interval, the upper and lower limits are identified by hot or cold temperatures or both. The difference of hot and cold temperature scales equates ΔT_{min} to guarantee the feasible heat transfer from hot streams to cold streams, shown in Figure 4.5. In column I of Figure 4.5, the net heat of each interval can calculate from a simple energy balance (ΔH) of hot streams and cold streams; a deficit is positive and a surplus is negative. Higher interval heat can shift to lower, called heat flow [20,21] in process. If the top interval has no heating duty input (column II), the heat flow from the top to bottom interval may be negative. For feasible design, heat flow must not be negative; thus, the heating duty must be added at the top interval (column III). Clearly, the minimum required heat equates the maximum negative heat-flow (-7.5 MW). Adding this duty at the top interval (7.5 MW in column III), the zero heat-flow interval is the pinch position, and the net heat at bottom-interval is the minimum cooling duty (10 MW).



Interval	**Streams**			**ΔH**	**Heat Flow**		
Temp. avg. (hot,cold)	**Hot temp.**	A temperature difference of hot and cold temperature scales equates ΔT_{min} to guarantee the feasible heat transfer.	**Cold Temp.**	**(MW)** Column (I)	**(MW)** Column (II)	**(MW)** Column (III)	
245	250	1	240		**Heat Input = 0.0**	**Heat Input = 7.5**	**Minimum Heating Duty**
235	240		230	-1.5	1.5	9.0	
195	200	2	190	6.0	4.5	3.0	
185	190		180	-1.0	-3.5	4.0	
145	150		140	4.0	**-7.5**	**0.0**	**Pinch Position**
75	80	4	70	-14.0	6.5	14.0	
35	40		30	2.0	4.5	12.0	
25	30	3	20	2.0	2.5	**10.0**	**Minimum Cooling Duty**

Figure 4.5 Problem table algorithm of HEN (stream data from Table 4.1)[19]

Identify the Capital Target

Capital target usually refers to area and units of heat exchanger. Minimum units is the function of the number of process streams and utilities, expressed in the simple relationship

$$U_{min} = N - 1 \tag{4.1}$$

where U_{min} = the minimum number of units; N = the number of process streams and utilities[19,21].

The area target is the accumulative heat-exchanger area of all temperature intervals (expressed in equation 4.2), based on the constant heat-transfer coefficients and the vertical heat transfer in the composite curve[22].

$$A = \sum_{i}^{\text{int ervals}} \frac{1}{\Delta T_{LM_i}} \left[\sum_{j}^{\text{streams}} \left(\frac{q_j}{h_j} \right) \right]_i \tag{4.2}$$

where, interval i, there are j streams (hot and cold) with their individual heat load, q_j and their respective stream film and fouling, h_j. ΔT_{LM_i} is the log-mean temperature difference in interval i. This equation provides a useful estimate of minimum overall heat-exchanger area. It is usually accurate to within 10%[34]. When the pinch position and energy and capital targets are known, the complete HEN design is the final step.

Design the Complete HEN

A important method for HEN design is the *grid diagram*. In grid diagram (Figure 4.6)[19], hot streams are grouped together at the top and run left to right from their initial (or supply) to final (or target) temperature. But, cold stream beneath run countercurrent. Matches (or exchangers) are represented by vertical lines and circles on the streams matched. At the pinch, the HEN problem is separated into separate problems (hot end and cold end).

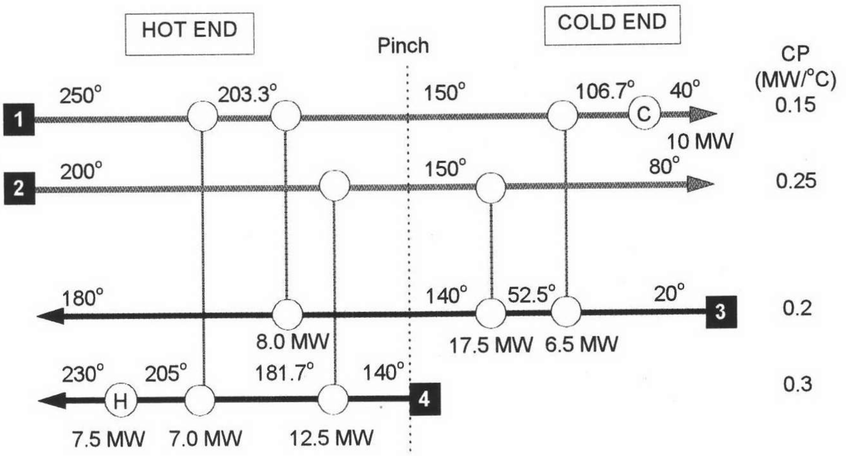


Figure 4.6 Grid Diagram for the data from Table 4.1

Start to design each end at the pinch and move away, because two ends designs can easy combine to a complete design. The HEN design must be satisfied three following rules to achieve the energy targets (set by the composite curves or by the problem table algorithm)[19,21]:

1. No cold utility above the pinch (hot end)
2. No heat utility below the pinch (cold end)
3. No process heat recovery across the pinch

To achieve first rule, above the pinch, cold streams must cool all hot streams to pinch temperature with one-to-one matching. Thus, they should not be less than hot streams. If they are less than hot streams, they must split into parallel branches to increase streams to match all hot streams, shown in Figure 4.7a. Therefore, a *stream number criterion* above the pinch [19,21] can be expressed as

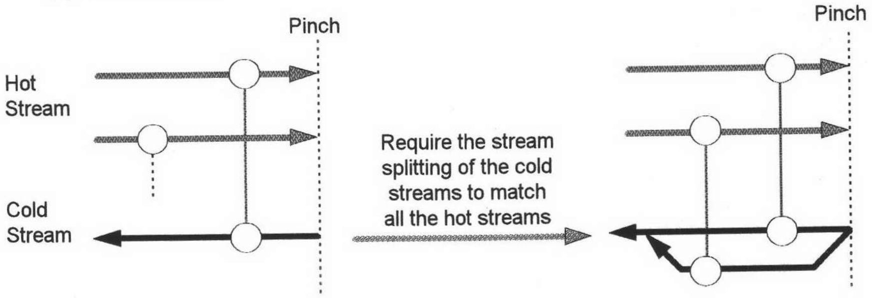
$$S_H \leq S_C \qquad \text{(above pinch)} \qquad (4.3)$$

where, S_H = number of hot streams at the pinch (including branches)
S_C = number of cold streams at the pinch (including branches)

For second rule, below the pinch, hot streams must heat all cold streams to pinch temperature by one-to-one matching. Thus, they should not be less than cold streams. If they are less than cold streams, they must split into branches to increase streams to match all cold streams, shown in Figure 4.7b. Therefore, a stream number criterion below the pinch [19,21] can be expressed as

$$S_H \geq S_C \qquad \text{(below pinch)} \qquad (4.3)$$

(a) ABOVE PINCH



(b) BELOW PINCH

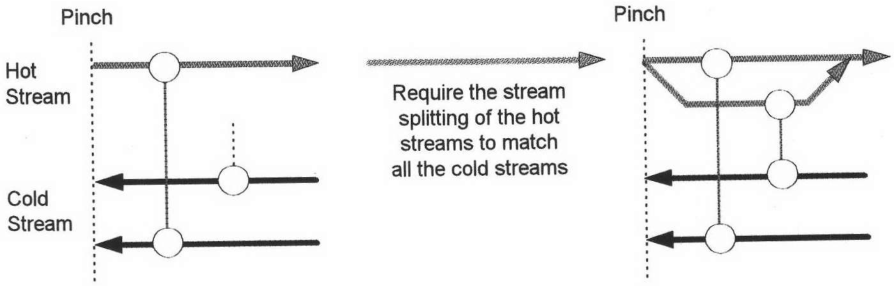


Figure 4.7 Splitting streams to obey the stream number criterion.

In the third rule, heat across the pinch must be zero to achieve the minimum utility targets. Because heat across the pinch is the excessive heat from hot utilities, it must be removed at the cool utilities. Thus, it lead to increase hot and cold utilities, avoiding the energy targets.

The pinch is the minimum temperature difference (ΔT_{min}), meaning that no individual exchanger should have a temperature difference smaller than ΔT_{min}. All pinch matches must have larger the temperature difference than ΔT_{min} when they move away from the pinch. A method used to check temperature difference criteria is the *CP inequality for individual matches.* CP is heat capacity flowrate (MW/°C). Above the pinch, Figure 4.8a shows the temperature difference criteria for pinch matches. To obey this criteria, a hot stream must match with a cold stream which has a higher CP(a less steep slope). Below the pinch, Figure 4.8b shows the temperature difference criteria for pinch matches. To obey CP inequalities, a hot stream must match with a cold stream which has a smaller CP (a more steep slope). The CP inequality for individual matches [19,21] can be expressed as

$$CP_H \leq CP_C \quad \text{(above pinch)} \qquad (4.4)$$

$$CP_H \geq CP_C \quad \text{(below pinch)} \qquad (4.5)$$

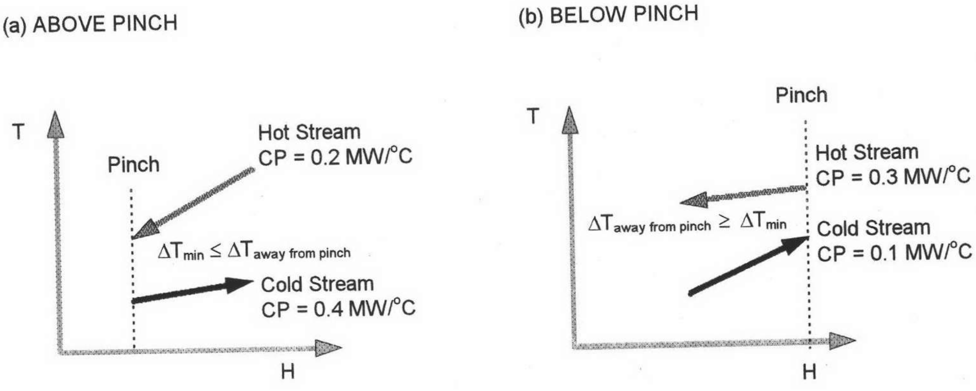


Figure 4.8 CP criteria for pinch matches.

Note that the CP inequalities given by Equations (4.4) and (4.5) apply only the pinch when both ends of the match are at pinch conditions. Away from the pinch, temperature difference increase, and it is no longer essential to obey the CP inequalities [19]. Occasionally, the pinch matches violate the CP inequalities, the stream splitting can solve this problem, reducing CP. Pinch design procedure obeying with two criterions (the stream number and the CP inequalities) is shown in Figure 4.9 [19,20,21]. The pinch design usually yield many feasible solutions. To reduce those solutions, process constraints must be imposed such as start-up, operation flexibility, safety etc. [17,19,23] Moreover, the heat-exchanger units (or matches) can be reduced by loop and path method [19,20,21,22]. A loop is a closed connection through streams and exchangers, i.e., it starts and ends on the same point on the grid (Figure 4.10a). A path is a connection through streams and exchangers between two utilities (Figure 4.11a). Heat can be shifted around the loop (Figure 4.10b) and along the path (Figure 4.11b). Once, the shifted duty equates duty of any match (Figure 4.10c and 4.11c), this match is removed from the design because duty becomes zero (Figure 4.10d and 4.11d). Loop and path method may violate the third rule because the heat across the pinch occur. However, a slight violation can be allowed in an actual design [19,23].

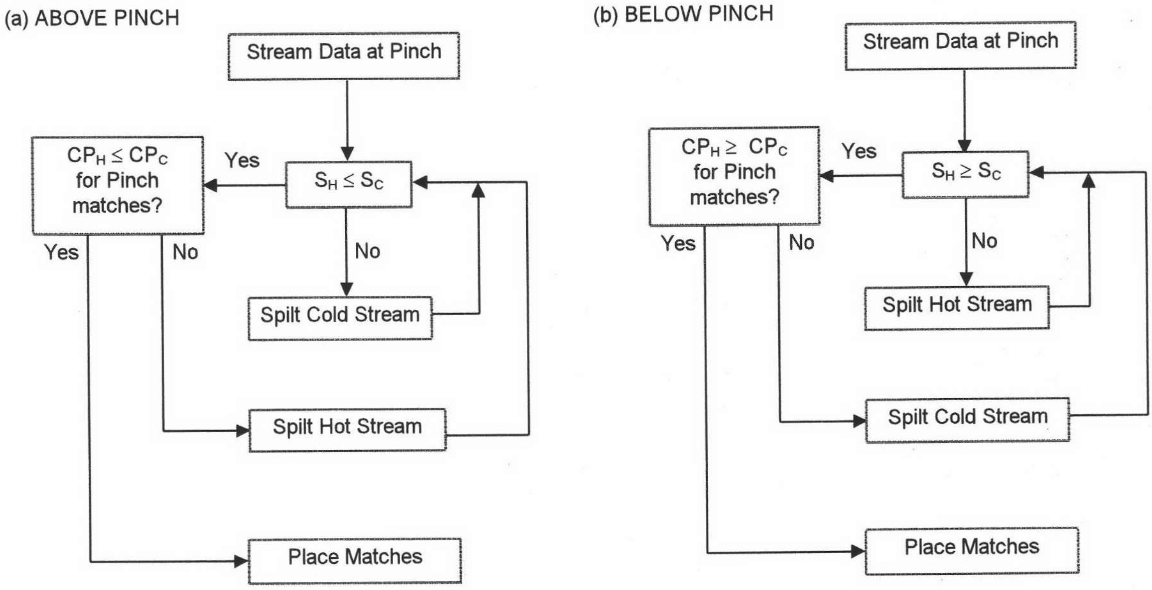
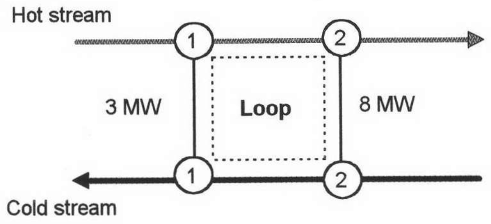
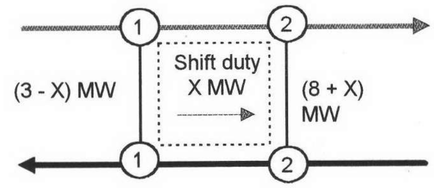


Figure 4.9 Pinch design procedure obeying with two criterions: (1) the stream number and (2) the CP inequalities.

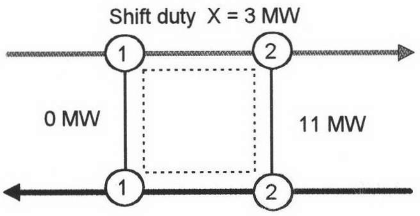
(a) A loop is a closed connection through streams and exchangers (or matches), shown dash line.



(b) Shift duty (X MW) around the loop.



(c) The shifted duty equates the duty of the match No.1.



(d) Match No. 1 is removed from the design because duty becomes zero.

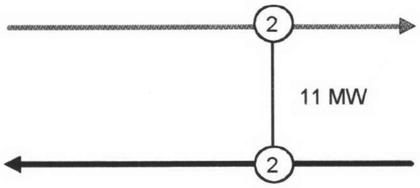
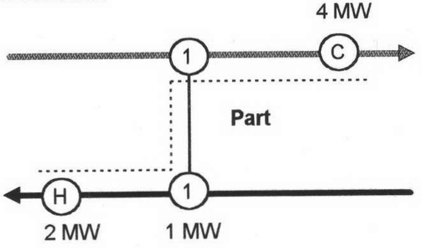
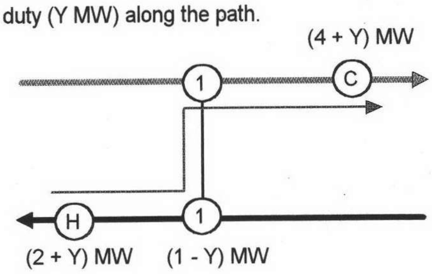


Figure 4.10 A Loop and reducing a match with shifted duty

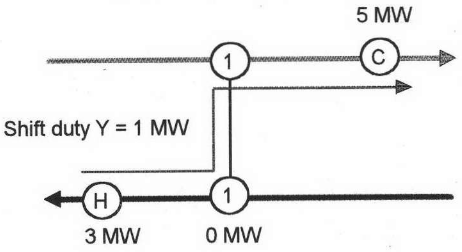
(a) A path is a connection through streams and exchangers (or matches) between two utilities, shown dash line.



(b) Shift duty (Y MW) along the path.



(c) The shifted duty equates the duty of the match No.1.



(d) Match No. 1 is removed from the design because duty becomes zero.

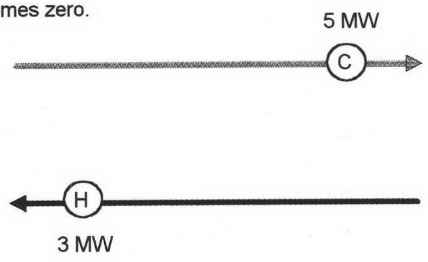


Figure 4.11 A path and reducing a match with shifted duty