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Heat Exchanger Network Design Considering the Heat Pump Performance

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Setting heat pumps correctly in a heat exchanger network can reduce the consumption of cold and hot utilities simultaneously and further enhance the energy utilization efficiency. Based on the pinch technology, this paper proposes an experiential method for designing a heat exchanger network with heat pumps. Economy and feasible operation of heat pumps are taken as constraints for identifying its optimal placement scenario in the Grand Composite Curve (GCC). Based on the optimal scenario, the corresponding cold and hot streams which exchange heat with heat pumps are determined according the stream properties. A case is studied to illustrate the applicability of the proposed method and the corresponding design of the heat exchanger network.

1. Introduction

For the global shortage of energy resources and the increasingly serious pollution problems, energy saving and pollution reduction become an important topic. Pinch technology is a very powerful tool in optimization of the energy exchange networks to enhance the utilization of the energy resources (Matsuda et al., 2012a), as well as the mass exchange networks (Alves and Towler, 2002).

Heat pumps can transfer heat from a lower temperature level to a higher one and are widely used in daily life and industrial processes. Matsuda et al. (2012b) studied industrial heat pump for a petrochemical site using pinch technology. Modla and Lang (2013) focused on the reduction of energy demand of the batch distillation with heat pump. Nevertheless, the energy saving of a heat pump in a process system depends on its reasonable placement. In a heat exchanger network, the heat recovered by heat pumps is restricted by both the performances of heat pumps and the network. Based on Pinch Technology, Townsend and Linnhoff (1983a, b) discussed the possible placements of heat pumps in process systems and proposed the Across-Pinch Rule indicating that only heat pump placed across the pinch can save energy. Yang et al. (2013) analysed the dynamic changes of the GCC and the Pinch Point under different scenarios when placing heat pumps. They also gave the placements of heat pumps both across the original and new pinch points simultaneously but did not consider the performance of heat pumps effectively.

For the lack of the mathematical descriptions of a heat pump, it is difficult to optimize the heat exchanger network with considering the performance of a heat pump. The goal of this paper is to propose an experiential methodology for heat exchanger network design with heat pumps. In this work, the heat pump model is described by experiential formulas and combined with heat exchanger network based on pinch technology. Then the evaporating and condensing temperatures, the input and output heat of a heat pump are identified in the GCC. Finally, the heat exchanger network is designed.

2. Coefficient of performance of a heat pump

The vapour compression heat pump cycle is described in Figure 1. A heat pump can lift heat from a lower temperature source to a higher temperature sink with the help of some external energy. In general, the coefficient of performance (COP) of a heat pump can be defined as follows.

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$$\text{COP} = \frac{Q_E + W}{W} = \frac{Q_C}{W} \tag{1}$$

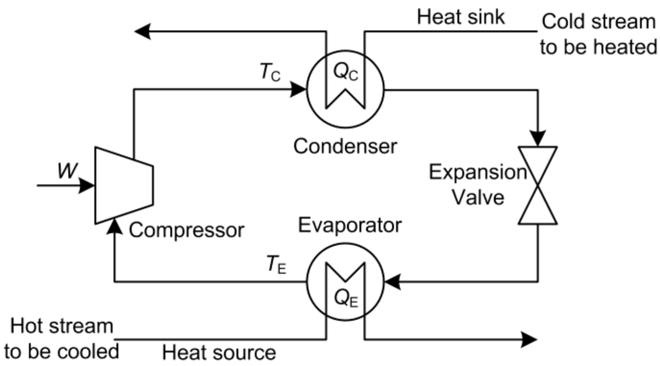

Figure 1: Schematic of vapor compression heat pump cycle

where Q_C is the heat output of a heat pump, Q_E is the heat input of a heat pump, and W is the external energy.
For reversed Carnot cycle between the evaporating temperature T_E and the condensing temperature T_C, the corresponding COP is

$$\text{COP}_\text{C} = \frac{T_C}{T_C - T_E} \tag{2}$$

The COP for a real cycle often can be expressed as follows.

$$\text{COP}=\eta_C \text{COP}_\text{C} = \eta_C \frac{T_C}{T_C - T_E} \tag{3}$$

where η_C is called the Carnot efficiency and often can be regarded as a constant with varying T_E and T_C in reasonable regions (RCG/Hagler Bailly Inc. et al., 1995).

The compressor can be driven by an electric motor, which is most frequently used. In China, electricity is mainly generated from fossil fuels with an efficiency of 30 - 40 %. In this way, a COP more than 3 is desired to acquire the primary energy efficiency and to achieve some economic return from the cost of the heat pump. In the work of Feng and Berntsson (1997), a general expression for critical COP has been derived based on the payback period, which can also be used in this work.

3. Integration of heat pumps in a heat exchanger network

3.1 Heat pump model in heat exchanger network

For a given heat exchanger network with the minimum temperature difference $\Delta T_{\min}$ at the pinch point, the GCC is easily established, which describes the relationship of the heat flux and the average temperature. Figure 2 shows the integration of heat pumps in the GCC referring to the Across-Pinch Rule. Heat pumps can be selected according to the pinch temperature. It is noteworthy that the temperature in the GCC is the average temperature. Assuming that the minimum temperature difference between streams and heat pumps also equals $\Delta T_{\min}$, so the real T_C is the T_C^G identified in the GCC plus $0.5\Delta T_{\min}$ and the real T_E is the T_E^G minus $0.5\Delta T_{\min}$. Hence, the temperature lift ($T_L = T_C - T_E$) equals T_L^G plus $\Delta T_{\min}$.
In practice, the allowable temperature lift of a heat pump is general small. Based on the across-pinch rule, the relationship of T_C, T_P and T_L can be expressed as Eq(4):

$$T_c = T_p + \gamma T_L \tag{4}$$

where γ is a ratio factor and ranges from 0 to 1.

Referring to Eq(3), the relationship of T_L and COP can be described as follows.

$$\text{COP}=\eta_C \frac{T_P + \gamma T_L}{T_L} \tag{5}$$

The COP value evaluates the economy of a heat pump. In this work, a desired COP (COP_D) is estimated or specified as a known constraint at first to make sure the integration of heat pump is cost-effective. For each COP_D, giving an initial value of γ, the corresponding temperature lift T_L can be calculated by Eq(6) derived from Eq(5).

$$T_L = \frac{T_P}{\frac{COP_D}{\eta_C} - \gamma} \tag{6}$$

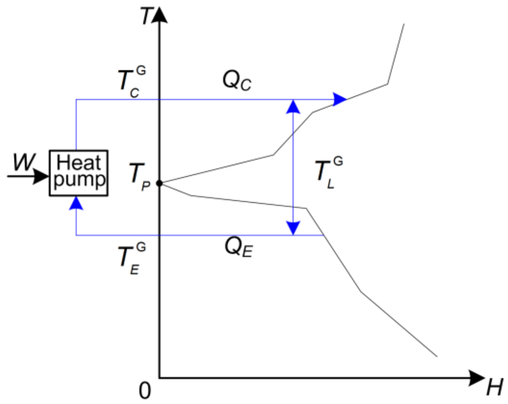

Figure 2: Integration of heat pumps in the GCC

3.2 Identification of the placements of heat pumps

The following step is to identify the placements of heat pumps in a heat exchanger network. From Eq(1), we can get the relationship of Q_C and Q_E as follow:

$$Q_C = \frac{COP_D}{COP_D - 1} Q_E \tag{7}$$

Figure 3(a) shows the relationship of Q_C and Q_E. For any point A, the corresponding Q_C and Q_E can be determined. For a Q_C or Q_E, the temperature at which the heat flux is larger than Q_C or Q_E can satisfy the demand of the heat pump. However, to minimize the temperature lift, the optimal T_C^G equals the temperature where the heat flux equals Q_C above the Pinch point in the GCC. And the similar to the optimal T_E^G, but below the pinch point, as shown in Figure 3(b).

Moving the point A upwards along the line in Figure 3(a), Q_C and Q_E increase simultaneously. The T_L^G in Figure 3(b) will increase as well. Therefore, iteration is necessary to target the T_L calculated by Eq(6). When

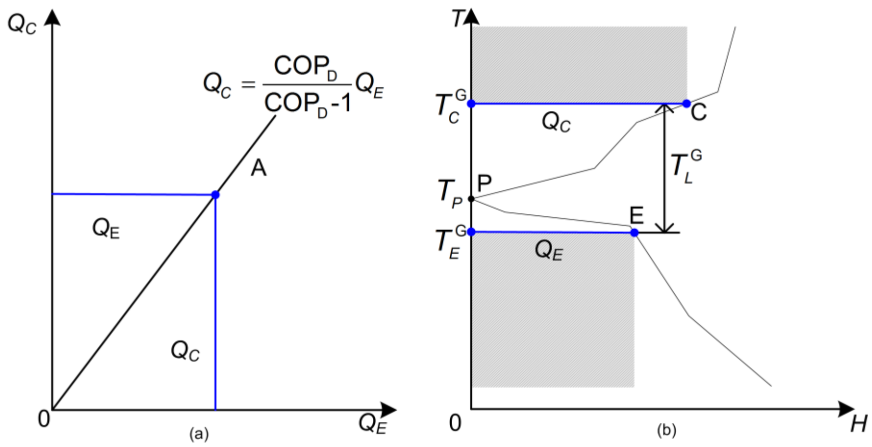

Figure 3: Identification of the placements of heat pumps: (a) relationship of Q_C and Q_E; (b) integration of heat pumps in a heat exchanger network

T_L is reached, Q_C and Q_E, T_C and T_E are determined respectively. Then a new γ can be acquired by Eq(8).

$$\gamma = \frac{T_C - T_P}{T_L} \tag{8}$$

If the difference of the new and initial γ is in an acceptable region, the final operation parameters of the heat pump are determined. Otherwise, take the value acquired from Eq(8) as the initial value of γ and repeat to do the identification procedure until the reasonable Q_C, Q_E, T_C and T_E are achieved. In this way, the maximum Q_C and Q_E are acquired for the specified COP_D.

3.3 Identification of the streams participating heat transfer in heat pumps

As shown in section 3.2, heat pumps are taken as a whole model. Although the placements of heat pumps are identified, multiple selections of cold and hot streams in the process participating heat transfer in heat pumps exist. For convenience, assume that there are an assumed cold stream and an assumed hot stream participating heat transfer in the whole heat pump model. Therefore, the assumed cold stream and the assumed hot stream satisfy Eqs(9) and (10).

$$CP_C^A = \frac{Q_C}{\left(T_C^G - 0.5\Delta T_{\min}\right) - \left(T_P - 0.5\Delta T_{\min}\right)} \tag{9}$$

$$CP_H^A = \frac{Q_E}{\left(T_P + 0.5\Delta T_{\min}\right) - \left(T_E^G + 0.5\Delta T_{\min}\right)} \tag{10}$$

where CP_C^A and CP_H^A represent the heat capacity flow rates of the assumed cold and assumed hot streams, respectively; $\left(T_P - 0.5\Delta T_{\min}\right)$ and $\left(T_C^G - 0.5\Delta T_{\min}\right)$ are the supply and the target temperatures of the assumed cold stream, respectively; while $\left(T_P + 0.5\Delta T_{\min}\right)$ and $\left(T_E^G + 0.5\Delta T_{\min}\right)$ are the supply and the target temperatures of the assumed hot stream.

The assumed hot and cold streams represent all the process streams participating heat transfer in heat pumps. Process streams need to meet the heat duty, supply and target temperatures of the assumed streams. Thus, the assumed hot stream may consist of one or more hot streams in the process and several scenarios may exist. To simplify the heat exchanger network and reduce the number of heat pumps, the assumed streams consist of less process streams is the best scenario. To reach the calculated Q_C and Q_E, stream splitting may be necessary. For a single heat pump, if its heat load is small, whether this heat pump is cost-effective or not should be considered.

4. Case study

Table 1 shows streams data of a process. With a $\Delta T_{\min}$ of 20 °C, the results calculated by the Pinch technology show that the pinch temperature is 80 °C (90 °C for hot streams and 70 °C for cold streams), and the minimum hot and cold utility are 107.5 kW and 110 kW.

Table 1: Process data for the case study

Stream	Supply temperature (°C)	Target temperature (°C)	Heat capacity flow rate (kW/°C)
1(hot)	150	60	2.0
2(hot)	90	60	8.0
3(cold)	30	125	2.5
4(cold)	40	100	3.0

Figure 4 shows the corresponding GCC of this process. Specifying the COP_D=5 and taking η_C =0.6 and the initial value of γ as 0.5. It can be calculated that Q_C=1.25Q_E from Eq(7). To make sure the accuracy of the results, the difference of the new and initial γ is specified less than 0.05. Following the identification procedures in Section 3, the identification results are shown in Table 2 and Figure 4. The dotted curve is the GCC after introducing heat pumps, which indicates that a pinch interval exists. It can be seen that the identified maximum Q_E=44.5 kW and Q_C=55.7 kW, and the real T_E=60.1 °C and T_C=105.9 °C.

Table 2: Results of the identification process

Step	initial γ	T_L	T_L^G	T_C^G	T_E^G	Q_C	Q_E	new γ	γ difference
1	0.50	45.1	25.1	95.5	70.4	54.2	43.3	0.616	0.116
2	0.62	45.8	25.8	95.9	70.1	55.7	44.5	0.616	0

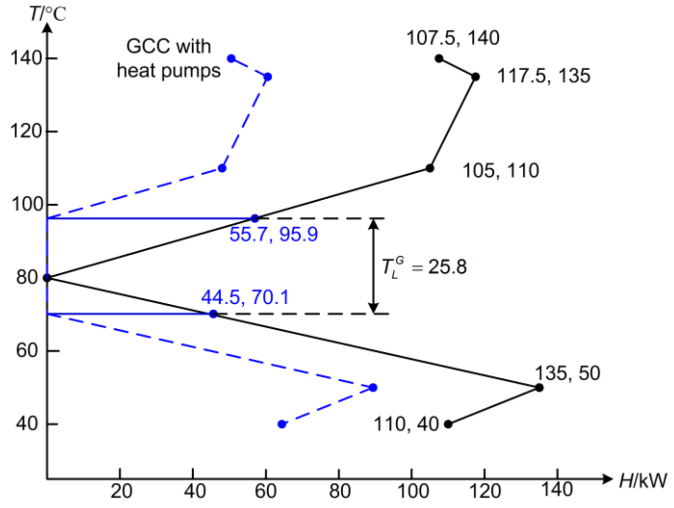

Figure 4: The GCC of the case study

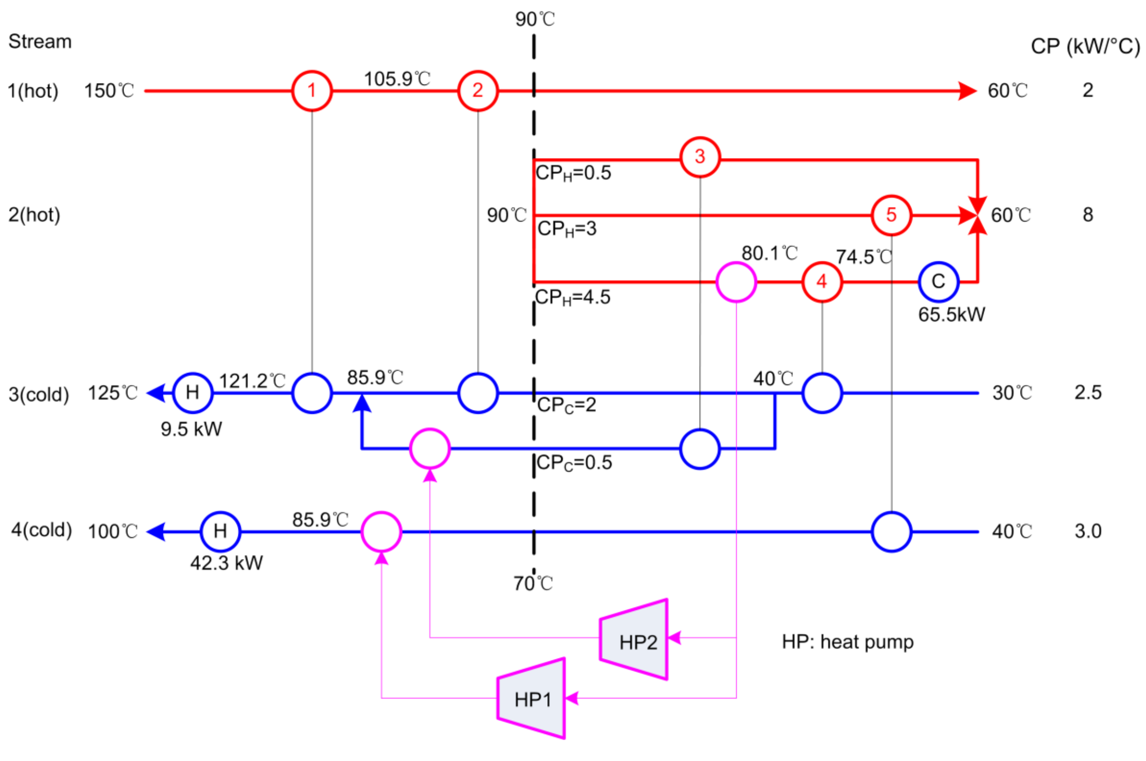

Figure 5: Heat exchanger network design with heat pumps

From Eqs(9) and (10), we can get that:

$$CP_C^A = \frac{Q_C}{\left(T_C^G - 0.5\Delta T_{\min}\right) - \left(T_P - 0.5\Delta T_{\min}\right)} = \frac{55.7}{85.9 - 70} \approx 3.5$$

$$CP_H^A = \frac{Q_E}{\left(T_P + 0.5\Delta T_{\min}\right) - \left(T_E^G + 0.5\Delta T_{\min}\right)} = \frac{44.5}{90 - 80.1} \approx 4.5$$

Referring to the process data in Table 1, stream splitting is necessary to meet the need of both the heat exchanger network and the heat pumps. Based on the Pinch Aanalysis results, the heat exchanger network with heat pumps is designed as shown in Figure 5. The hot and cold utility consumptions are 51.8 kW and 65.5 kW, reducing 55.7 kW and 44.5 kW by heat pumps, respectively. Heat pump 1 reduces 47.7 kW of hot utility and 38.1 kW of cold utility. Heat pump 2 reduces 8.0 kW of hot utility and 6.4 kW of cold utility. The total electrical energy for heat pumps is 11.2 kW. It is noted that for the heat pumps change the original Pinch Point, so the heat exchanger 2 in Figure 5 placing across the original pinch also obeys the Pinch Rule.

5. Conclusion

This work presents a pinch-based method for heat exchanger network design with heat pumps to reduce the hot and cold utility consumptions. Industrial experience is easily integrated into this method. The condensing and evaporating temperatures, the heat input and output of heat pumps can be identified based on the GCC simultaneously. The results of the case study show that heat pumps can further reduce the consumptions of hot and cold utility. Finally, this proposed method gives an initial design of a heat exchanger network with heat pumps. However, due to the limitation of the pinch method, this work does not analyse the economy of the whole heat exchanger network, which will be considered in the future work.

Acknowledgement

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