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A Simulation-Optimisation Method for Targeting the Optimal Placement of Heat Pumps in Heat Exchanger Networks

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Heat pumps can enhance the utilization of low-grade thermal energy. Setting heat pumps correctly in a heat exchanger network can reduce the consumption of cold and hot utilities, achieving energy saving and pollution reduction. Therefore, targeting the optimal placement of heat pumps is of great interest in both the academia and industry. Focusing on the vapour compression heat pump, this work proposes a simulation-optimization method to identify the energy-optimal placement of heat pumps in heat exchanger networks. Based on the powerful fluid property database, the vapour compression heat pump system is first modelled in the Aspen HYSYS V10. Next, a mathematical model is built in the Matlab R2018b platform using the Grand Composite Curve of heat exchanger network as constraints for heat pump placement. The two platforms, Aspen HYSYS V10 and Matlab R2018b, are then coupled to realize the data transfer between the simulation and mathematical models. The genetic algorithm is used to target the energy-optimal placement of heat pump (evaporating temperature, condensing temperature, and working fluid flowrate) in the heat exchanger network. A case study is performed to illustrate the applicability of the proposed method. The proposed simulation-optimization method can be extended to other types of heat pumps.

1. Introduction

The increasing in energy consumption and the shortage of energy resources pose great challenges for energy supply, resource conversion and environmental protection. Supply, conversion and use of energy in the most efficient and environmentally-friendly way is significant and has been an active research area (Klemeš and Varbanov, 2018). Chemical processes usually cause great energy consumption and generate large amounts of low-grade heat. Heat exchanger network integration has been proven to efficiently reduce the energy consumption through maximizing the heat recovery (Čuček et al., 2019). At present, there are two main techniques for heat exchanger network integration: Pinch technology (Linnhoff and Flower, 1978) and mathematical programming (Yee et al., 1990).

Heat pumps can transform the low-temperature heat which cannot be directly used within the process into useful high-temperature heat. In this light, integrating heat pumps with heat exchanger networks reasonably could improve the low-grade heat utilization and further reduce energy consumption. Townsend and Linnhoff (1983) analysed three cases of heat pump placements in heat exchanger networks and conducted that only setting heat pumps across the Pinch can result in energy saving. Bagajewicz and Barbaro (2003) discussed the role of heat pumps in total site heat integration and proposed non-linear models to target the optimum pumping temperature levels. They obtained the optimal solution with heat pumps that do not cross the Pinch, contracting the analysis from Pinch Technology. However, this case was explained as setting the heat pump changes the Pinch location of the heat exchanger network (Yang et al., 2013). Besides, it was found that the change of Pinch location means there exists unreasonable heat integration with heat pumps. Later, Yang et al. (2016) proposed a systematic approach that using heat pumps to assist the Heat Integration of distillation column into the overall process. Due to the complexity of the heat pump system, these publications employs qualitative analysis or simple empirical formulas of heat pumps for easy solving. Kang and Liu (2015) proposed a multi-objective optimisation model for a heat exchanger network retrofit with a heat pump. In this work, polynomial regression of specific enthalpies of working fluid at the saturated gas and liquid states was used to model the heat pump system. The formulated model cannot describe the heat pump system accurately as the working fluid is usually

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at the superheated state after compression. As a result, the proven optimum may be suboptimal or even infeasible in the real world.

The main objective of this work is to propose a simulation-based optimisation model to target the energy-optimal placement of heat pump (evaporating temperature, condensing temperature, and working fluid flowrate) in the heat exchanger network. Aspen HYSYS V10 is employed for rigorous process and thermodynamic modelling of the heat pump system. Based on the Grand Composite Curve (GCC) of heat exchanger network, the simulation-based optimisation model is formulated and solved in the Matlab R2018b platform to minimize the energy consumption, identifying the optimal evaporating and condensing temperatures and working fluid flowrate. In the case study, a heat exchanger network with a heat pump is designed based on the results obtained by the proposed model.

2. Model formulation and solution strategy

The simulation-based optimisation model consists of two parts: (1) heat pump system simulation in Aspen HYSYS V10; (2) heat exchanger network model.

2.1 Simulation of heat pump system

Figure 1 shows the vapour compression heat pump system. It consists of four major devices: evaporator, condenser, compressor and expansion valve. The heat pump system is rigorous modelled in Aspen HYSYS V10. T_{Cond} and T_{Evap} are the condensing temperature and evaporating temperature of the working fluid; Q_{Cond} and Q_{Evap} are the heat delivered and received by the heat pump; W is the external power. According to the Across-Pinch Rule (Townsend and Linnhoff, 1983), the working fluid can be selected based on the Pinch temperature of the heat exchanger network. Note that a simplification is employed when combining the heat pump simulation model with the heat exchanger network model. Specifically, heat released from the superheated state to the saturated gas state is taken into account, but the temperature change between the two states is ignored.

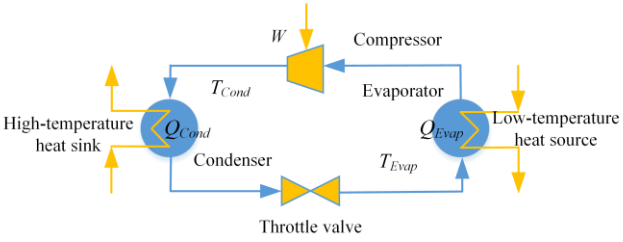

Figure 1: The heat pump model established in Aspen HYSYS V10

2.2 Heat exchanger network model

For a given heat exchanger network with the minimum temperature difference ΔT_{min} at the Pinch Point, the minimum consumption of hot and cold utilities can be identified by the problem table (Linnhoff and Flower, 1978). The GCC is generated based on the heat balance in each temperature interval, representing the ideal relationship between the heat deficit/surplus and the corresponding temperature. It is noteworthy that for the GCC with heat pockets, they can be left out when considering the utility requirements, as the local heat source and heat sink can be matched in the same heat pocket. The GCC is composed of multiple line segments, as shown in Figure 2. For a line segment, assuming that coordinates of the two endpoints are (Q_i, T_i) and (Q_{i+1}, T_{i+1}), this segment can be described as Eq(1). In this way, the GCC can be expressed as a piecewise linear function.

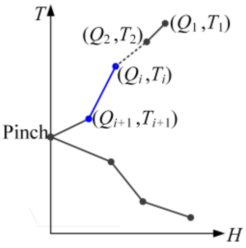

Figure 2: The GCC of a heat exchanger network

$$Q(T)=\frac{Q_{i+1}-Q_i}{T_{i+1}-T_i}\times T_i+(Q_i-\frac{Q_{i+1}-Q_i}{T_{i+1}-T_i}\times T_i),\quad T_i\le T\le T_{i+1} \tag{1}$$

To ensure all the heat received and delivered by the heat pump can be effectively used, the following two conditions should be satisfied simultaneously (Yang et al., 2013): (1) below the Pinch, the received heat cannot exceed the heat flux at temperature T_{Evap}^{GCC} on the GCC; (2) above the Pinch, the delivered heat cannot exceed the heat flux at temperature T_{Cond}^{GCC} on the GCC. These two conditions are expressed as Eq(2) and Eq(3):

$$Q_{Cond}\le Q_{Cond}^{GCC} \tag{2}$$

$$Q_{Evap}\le Q_{Evap}^{GCC} \tag{3}$$

The objective is to minimize the total energy consumption, which consists of hot utility, cold utility and power. The three items are measured by oil equivalent, and thus the objective function is given as Eq(4).

$$\text{Min } Obj=a\cdot Q_{hot}+b\cdot Q_{cold}+c\cdot W \tag{4}$$

where Q_{hot} and Q_{cold} represent the consumption of hot and cold utilities after setting heat pumps; a, b and c are the equivalent coefficients of hot utility, cold utility and power. According to the Chinese standard GB/T 50441-2016, a = 3.46X10^{-5} kg$_{oe}$·kJ^{-1}, b = 2.87X10^{-6} kg$_{oe}$·kJ^{-1}, and c = 6.11X10^{-5} kg$_{oe}$·kJ^{-1} (kg$_{oe}$ = kg of oil equivalent).

2.3 Solution strategy

In this work, the simulation-based optimisation model is formulated and solved using Aspen HYSYS V10 and Matlab R2018b. The genetic algorithm is employed as the global search method to obtain the optimal solution. It can be seen that the formulated model contains inequality constraints. For such models, penalty approaches are often used to handle the inequality constraints, which causes a risk of spending most of the computational effort in handling invalid solutions.

To enhance the computational efficiency, the simulation-based optimisation model is reformulated according to the influences of heat pump placements on heat exchanger networks. As shown in Figure 3a, the Pinch Temperature, evaporating temperature and condensing temperature divide the heat exchanger network into four intervals. It can be seen that only the two intervals (c and d) between the evaporating and condensing temperatures are affected by the heat pump. The required hot and cold utilities after setting the heat pump can be expressed as Eq(5) and Eq(6).

$$Q_{hot}{=}Q_{H,a}+dQ_H{=}\left(Q_{H,\min}-Q_{Cond}^{GCC}\right)+dQ_H \tag{5}$$

$$Q_{cold}{=}Q_{C,d}+dQ_C{=}\left(Q_{C,\min}-Q_{Evap}^{GCC}\right)+dQ_C \tag{6}$$

where $Q_{H,a}$ represents the heat deficit in the interval a; $Q_{C,d}$ represents the heat surplus in the interval d; dQ_H represents heat deficit in the interval b after setting the heat pump; and dQ_C represents heat surplus in the interval c after setting the heat pump.

It is noteworthy that the GCC shows the relationship between the temperature and deficit/surplus heat, which is determined as the total heat load of sources minus that of sinks in each interval. This means that the heat pump can receive more heat than the surplus on the GCC or deliver more heat than that the deficit on the GCC. According to the relationship between Q_{Cond} and Q_{Cond}^{GCC} and the relationship between Q_{Evap} and Q_{Evap}^{GCC}, dQ_H and dQ_C can be calculated based on five possible cases, as shown in Figures 3b to 3f.

Case 1: if $Q_{Cond}\le Q_{Cond}^{GCC}$ and $Q_{Evap}\le Q_{Evap}^{GCC}$, the GCC after setting heat pump is shown in Figure 3b as the dotted curve.

$$dQ_H=Q_{Cond}^{GCC}-Q_{Cond} \tag{7}$$

$$dQ_C=Q_{Evap}^{GCC}-Q_{Evap} \tag{8}$$

Case 2: if $Q_{Cond}\le Q_{Cond}^{GCC}$ and $Q_{Evap}>Q_{Evap}^{GCC}$, the new GCC is shown in Figure 3c.

$$dQ_H=Q_{Cond}^{GCC}-Q_{Cond}+Q_{Evap}-Q_{Evap}^{GCC} \tag{9}$$

$$dQ_C=0 \tag{10}$$

Case 3: if $Q_{Cond} > Q^{GCC}_{Cond}$ and $Q_{Evap} \le Q^{GCC}_{Evap}$, the new GCC is shown in Figure 3d.

$$dQ_H = 0 \tag{11}$$

$$dQ_C = Q^{GCC}_{Evap} - Q_{Evap} + Q_{Cond} - Q^{GCC}_{Cond} \tag{12}$$

Case 4: if $Q_{Cond} > Q^{GCC}_{Cond}$, $Q_{Evap} > Q^{GCC}_{Evap}$ and $Q_{Cond} - Q^{GCC}_{Cond} \le Q_{Evap} - Q^{GCC}_{Evap}$, the new GCC is shown in Figure 3e.

$$dQ_H = 0 \tag{13}$$

$$dQ_C = (Q_{Cond} - Q^{GCC}_{Cond}) - (Q_{Evap} - Q^{GCC}_{Evap}) \tag{14}$$

Case 5: if $Q_{Cond} > Q^{GCC}_{Cond}$, $Q_{Evap} > Q^{GCC}_{Evap}$ and $Q_{Cond} - Q^{GCC}_{Cond} > Q_{Evap} - Q^{GCC}_{Evap}$, the new GCC is shown in Figure 3f.

$$dQ_H = (Q_{Evap} - Q^{GCC}_{Evap}) - (Q_{Cond} - Q^{GCC}_{Cond}) \tag{15}$$

$$dQ_C = 0 \tag{16}$$

The objective function can be expressed as Eq(17). The reformulated model does not contain the inequality constraints shown as Eq(2) and Eq(3), and it is fully equivalent to the original model with inequality constraints, effectively avoiding the risk of spending computational effort in handling invalid solutions.

$$\text{Min } Obj = a \cdot \left(Q_{H,a} + dQ_H\right) + b \cdot \left(Q_{C,d} + dQ_C\right) + c \cdot W \tag{17}$$

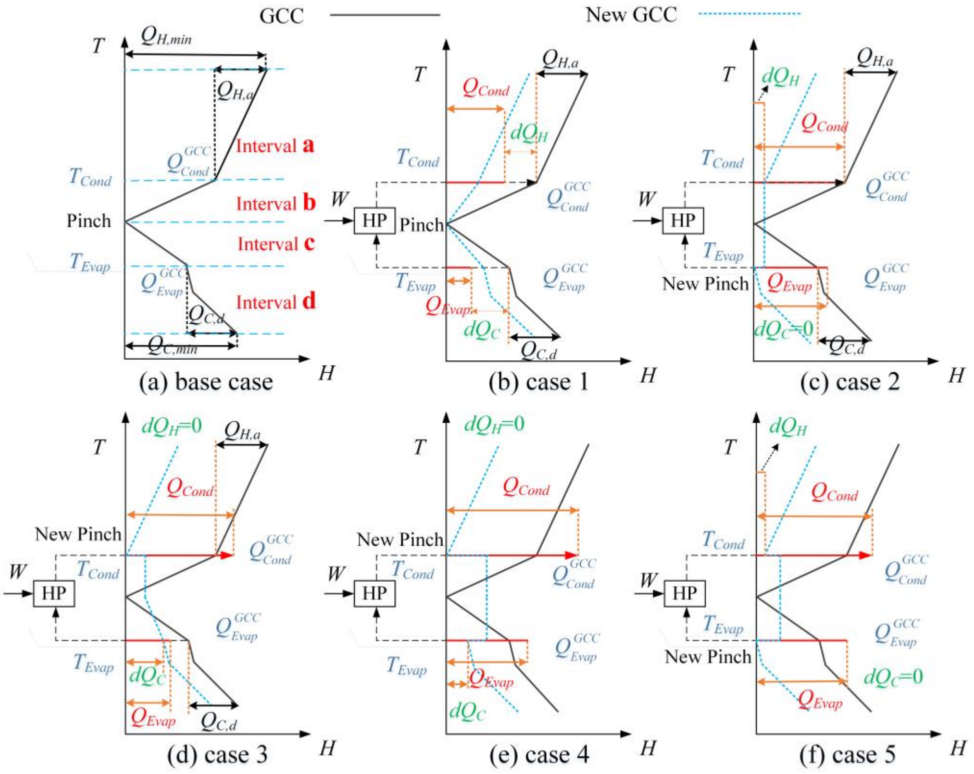

Figure 3: New Grand Composite Curve after setting up the heat pump (a) base case; (b) case 1; (c) case 2; (d) case 3; (e) case 4; (f) case 5

Theoretically, the optimal solution can be obtained with $Q_{Cond}=Q^{GCC}_{Cond}$ and $Q_{Evap}=Q^{GCC}_{Evap}$. If a solution is given as one of cases 1-5, the maximum number of generations of the genetic algorithm should be increased to find the optimal solution.

3. Case study

The process data for a heat exchanger network is shown in Table 1. It contains 3 hot streams and 3 cold streams. The minimum Pinch temperature difference ΔT_{min} is assumed as 10.0 °C. The average Pinch temperature is calculated as 85.0 °C through problem table method, that is, the cold side temperature at the Pinch point is 80.0 °C and the hot side is 90.0 °C. The GCC of the network as shown in Figure 4a: it contains two heat pockets (ABCDE and FGI) and the GCC excluding heat pockets is represented by the curve AEPFI. The minimum hot and cold utilities required for this system are determined as 600.0 kW and 300.0 kW. The total annual energy consumption of the process is equal to 6.23×10^5 kg_{oe}.

Table 1: Hot and cold stream data of the process

Stream	CP/kW·°C $^{-1}$	T_s /°C	T_t /°C	Heat load / kW
Hot 1	30.0	170.0	60.0	3,300.0
Hot 2	15.0	150.0	30.0	1,800.0
Hot 3	10.0	60.0	30.0	300.0
Cold 1	40.0	80.0	150.0	2,800.0
Cold 2	20.0	20.0	135.0	2,300.0
Cold 3	10.0	20.0	80.0	600.0

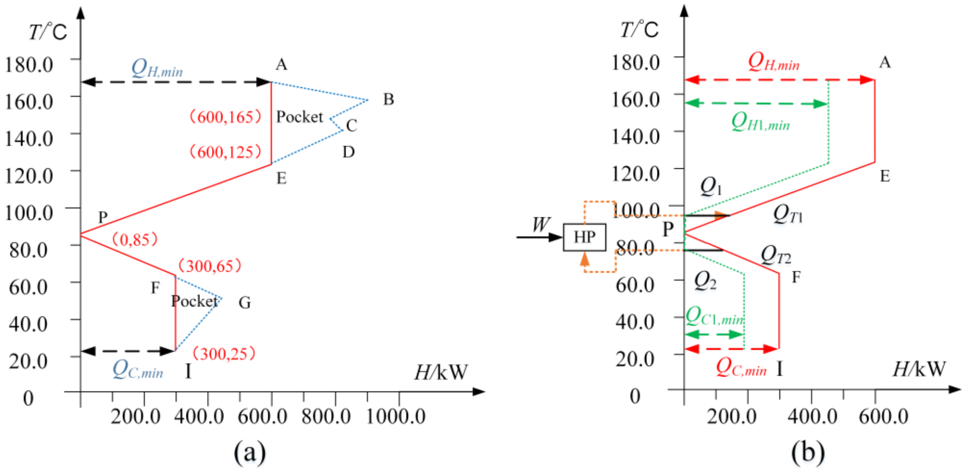

Figure 4(a): The initial Grand Composite Curve of the case (b): The new Grand Composite Curve of the case after setting up the heat pump

According to the Pinch Temperature, R718 is selected as the working fluid in this study (Arpagaus et al., 2018). In the simulation, the Peng-Robinson package is chosen for the heat pump system. The Centrifugal Compressor is used to model the vapour compression heat pump, and it is assumed to have the default adiabatic efficiency of 0.75. The optimal setting parameters of the heat pump are targeted using the proposed simulation-based optimisation model, as shown in Table 2. The new GCC after setting the heat pump is represented by the dotted line in Figure 4b. It can be found that the received heat (Q_{Evap}) below the Pinch of equals the heat flux (Q_{Evap}^{GCC}) at the evaporating temperature (T_{Evap}), and the delivered heat (Q_{Cond}) above the Pinch is equal to the heat flux (Q_{Cond}^{GCC}) at the condensing temperature (T_{Cond}). The heat exchanger network with a heat pump is designed as shown in Figure 5. As a result, the hot utility consumption is reduced to 430.3 kW by 169.7 kW, the cold utility is reduced to 150.6 kW by 149.4 kW, and the external power (W) consumed by the heat pump is 20.3 kW. The energy consumption of the whole heat exchanger network is 4.77×10^5 kg_{oe}/y ($a \cdot Q_{hot} = 4.29 \times 10^5$ kg_{oe}/y, $b \cdot Q_{cold} = 1.24 \times 10^4$ kg_{oe}/y, and $c \cdot W = 1.24 \times 10^4$ kg_{oe}/y). Compared with the original heat exchanger network, the placement of heat pump results in an energy saving of 23.4 %.

Table 2: The optimal setting parameters of the case study

T_{Cond} / °C	T_{Evap} / °C	Q_{Cond} / kW	Q_{Evap} / kW	W / kW	F / kg·h^{-1}
101.3	70.1	169.7	149.4	20.3	242.6

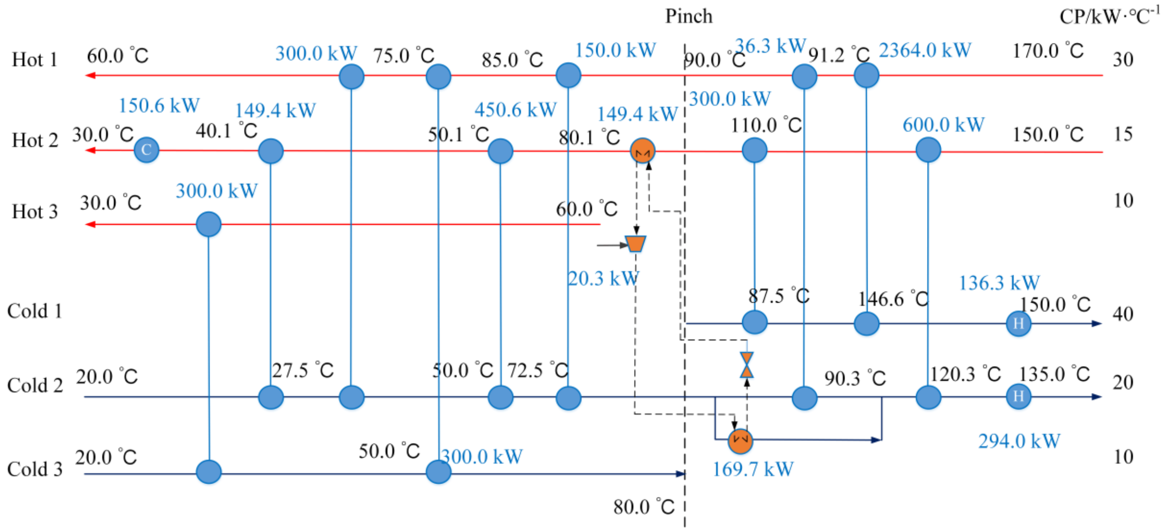

Figure 5: The heat exchanger network after setting up the heat pump

4. Conclusions

In this work, the Pinch technology is combined with Aspen HYSYS V10 modelling and simulation to target the energy-optimal placement of heat pump into heat exchanger network. A simulation-based optimisation model was proposed and a solution strategy was developed to enhance the computational efficiency based on characteristics of the heat exchanger network. In the case study, it was found that the proposed model determined the heat received and delivered by the heat pump equalling the heat surplus and deficit on the GCC at the evaporating and condensing temperatures. The received and delivered heat were all used to save energy, reducing the energy consumption by 23.4 %. The proposed simulation-based optimisation model can also be applied to other types of heat pumps.

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