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Process Integration and Selection of Heat Pumps in Industrial Processes

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Waste heat recovery technologies holds great potential for cleaner production by improving energy efficiency, reducing energy usage and emissions of carbon dioxide. Mechanical heat pumps, absorption heat pumps and absorption heat transformers are attractive available technologies to upgrade low grade waste heat for energy conservation and sustainable development. However, there are few guidelines for the integration of proper heat pumps in industrial processes. Moreover, since heat upgraded by different heat pumps require energy of several types or grades (e.g. work, high or medium pressure steam), the coefficient of performance (COP) is not suitable to evaluate heat upgrading technologies. In this work, a novel criterion is proposed for the selection of heat pumps in industrial processes. The criterion (i.e. the coefficient of performance in exergy per total annual cost) measures the available energy performance of each type of heat pumps and includes economic impacts (i.e. economic investments). In addition, a systematic methodology for the integration of different heat pumps in an industrial process has been developed. It relies on Pinch Analysis of a given heat exchanger network. The process models of mechanical heat pumps, absorption heat pumps and absorption heat transformers are developed using Aspen Plus, and then proper heat sources and heat sinks are selected from the given streams for different heat pumps. Finally, an economic evaluation is performed according to the proposed novel criterion, calculated total annualized cost and payback time. The paper can provide a reference to choose a suitable waste heat recovery system for industrial processes.

1. Introduction

The energy consumption in industrial processes constitutes a significant portion of total energy consumption, and accounts for 58 % of total energy consumption in China (IEA, 2017), the majority of which is from combustion of fuels to produce heat and electricity. Because of the low energy efficiency, large amounts of low grade waste heat cannot be reused. Rising energy prices also has promoted the utilization of waste heat recovery technologies like heat pumps. In addition, the energy requirement of the industrial process can be reduced by process integration and heat pumps.

Process integration is an effective technique used for process optimization to improve energy efficiency in industry. The optimal integration and placement of an industrial heat pump can be achieved by Pinch Analysis, which has been an important and widespread method of process integration. Pinch Analysis allows to point out the heat recovery potential (Walmsley et al., 2016), and the integration of a proper heat pump can intensify energy savings. Also, an appropriate integration of heat pumps should consider the optimal heat pump type. Becker et al. (2011b) analysed heat pump integration for a cheese factory. However, the types of heat pumps are only limited to mechanical heat pump and vapour compression. Liew and Walmsley (2016) only considered vapour compression system.

There are several types of industrial heat pumps including mechanical heat pumps, absorption heat pumps and absorption heat transformers. Mechanical heat pumps (MHP) upgrade low temperature waste heat to a higher temperature with electrical power input. Absorption heat pumps (AHP) and heat transformers (AHT) are thermally driven, and the whole absorber/generator system has the same effect of the compressor in a MHP. Worthy to mention, an AHT can be considered as a reversed AHP, where the evaporator and absorber operate at a higher pressure than the condenser and generator (Zhang et al., 2016).

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When a heat pump is selected and integrated in an industrial process to recover low grade waste heat, various criteria have been attributed to heat pump systems. The coefficient of performance (COP) has been widely used to evaluate heat pump systems. However, it ignores interactions with different heat pump systems. Even though the COP for a MHP is higher than that for an AHP and an AHT (Abrahamsson et al., 1997), it requires electrical power, which is of higher grade than thermal energy required in an AHP and an AHT. Oluleye et al. (2016b) proposed a system-oriented criterion, the primary fuel recovery ratio (PRR), which can only measure the savings in primary fuel from heat upgraded. However, economical aspects were not considered. Bor and Ferreira (2013) defined an economic selection criterion but it cannot be associated with the thermal performance. It is believed that a sensible criterion can help industries with the selection and integration of heat pumps.

This work considers the real performance of different heat pumps by developing the process models of mechanical heat pumps, absorption heat pumps and absorption heat transformers using Aspen Plus. A novel criterion is proposed for the selection of heat pumps in industry processes. The criterion (the coefficient of performance in exergy per total annual cost) measures the available energy performance of each type of heat pumps and includes economic impacts (i.e. economic investments). Next, a pinch-based systematic methodology for the integration of different heat pumps in an industrial process has been developed. Meanwhile, the novel criterion, total annualized cost and payback time are used to do the economic evaluation.

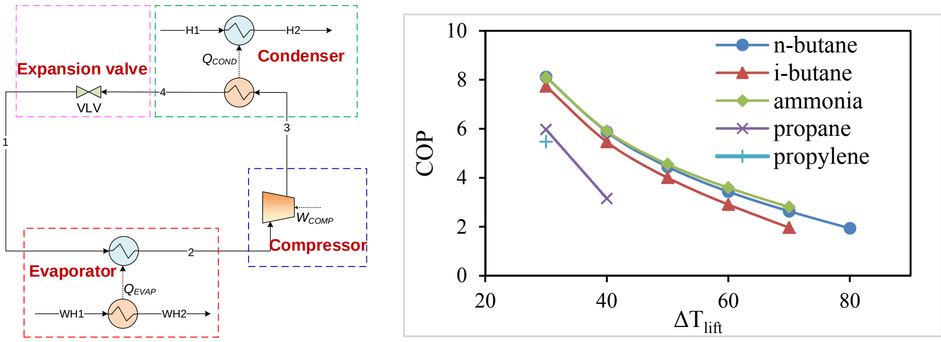
2. Methodology

2.1 Models of heat pumps

The ideal performance of heat pumps has been used to evaluate heat pump systems. However, this method ignores the inefficiencies of the cycle and non-ideal behaviour of working fluid. To obtain more accurate results, the process models of mechanical heat pumps, absorption heat pumps and absorption heat transformers are developed using Aspen Plus.

(1) Mechanical heat pumps (MHP)

For closed loop systems, the working fluid takes in low grade waste heat in the evaporator and releases higher grade heat in the condenser consuming electrical power in the compressor. Figure 1a shows the schematic diagram of mechanical heat pump. The COP can be determined by Eq(1).



(a) (b)

Figure 1: (a) Schematic diagram of a MHP. (b) Working fluid selection for a MHP using the real COP

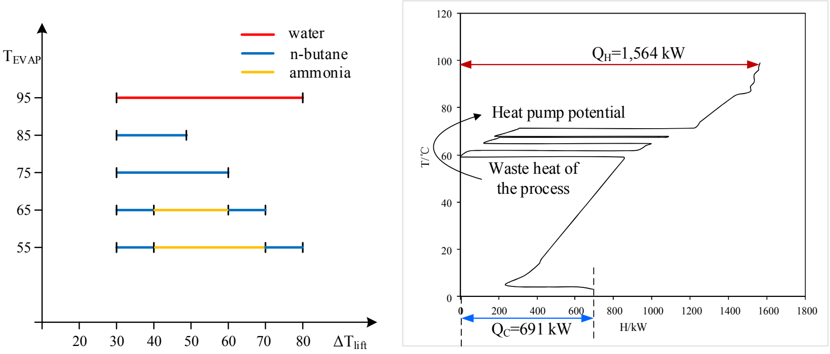
$$COP_{MHP} = \frac{Q_{COND}}{W_{COMP}} \tag{1}$$

$$\Delta T_{lift} = T_{COND} - T_{EVAP} \tag{2}$$

Note: the temperature difference ΔT_{min} is set as 5 °C.

Preselected working fluids considered in this work are n-butane, i-butane, ammonia, propane, propylene and water. Due to the high specific volumes of water steam in the corresponding temperature range, water is applicable for higher evaporation temperature. The real COP can be used to determine the best working fluid considering evaporation and condensation temperatures. Similarly, at the same evaporation temperature of 55

°C, the best working fluid can be determined for different temperature lifts defined in Eq(2), as shown in Figure 1b. For different cycle evaporation temperatures, working fluids with the highest COP are shown in Figure 2a.



(a) (b)

Figure 2: (a) Selected working fluid at different evaporation temperatures. (b) Process Grand Composite Curve

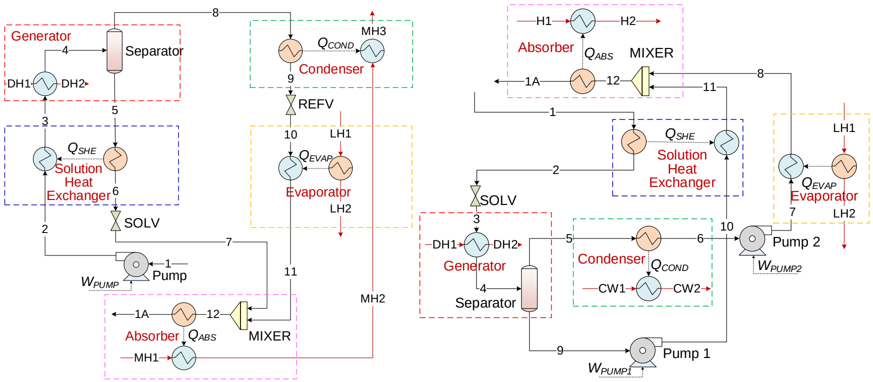
(2) Absorption heat pumps (AHP)

In the process of an AHP, generator pressure is higher than that in the absorber, so dilute solution is pressurized in a pump and brought to the generator again and a cycle is done. The whole cycle is divided into a solution cycle and a refrigeration fluid cycle. The schematic diagram of an AHP is illustrated in Figure 3a. The COP can be calculated in Eq(3), where the work of the pump can be negligible. Because LiBr-H_2O belongs to electrolytes, the property method ELECNRTL is selected for the process simulation in Aspen Plus.

$$COP_{AHP} = \frac{Q_{ABS} + Q_{COND}}{Q_{GEN}} \tag{3}$$

$$COP_{AHT} = \frac{Q_{ABS}}{Q_{EVAP} + Q_{GEN}} \tag{4}$$

(3) Absorption heat transformers (AHT)



(a) AHP (b) AHT

Figure 3. Schematic diagram of (a) an AHP and (b) an AHT

Figure 3b shows the schematic diagram of an AHT. Note that an AHT has the same components as an AHP but requires driving heat sources of different grades. The COP can be calculated by Eq(4). The work of the pump is ignored.

To simplify the calculation, appropriate assumptions are given as follows.

(1) Pressure loss due to the friction and heat loss in heat exchangers and connecting pipes are negligible. (2) For an AHP, refrigeration solution in the solution pump is saturated liquid. (3) Liquid in the condenser and vapour in the evaporator are saturated. (4) The difference of condensation temperature (evaporation temperature/generation temperature) and cooling water outlet temperature (waste heat outlet temperature/driving heat temperature) is 5 °C (generally 2~5 °C); Condensation temperature in the AHT is set

at 30 °C. (5) Compressor isentropic efficiency is assumed to be 80 %. (6) Solution heat exchange efficiency is specified as 0.64 (Somers et al., 2011).

2.2 Novel criterion for the evaluation of thermodynamic and economical performances

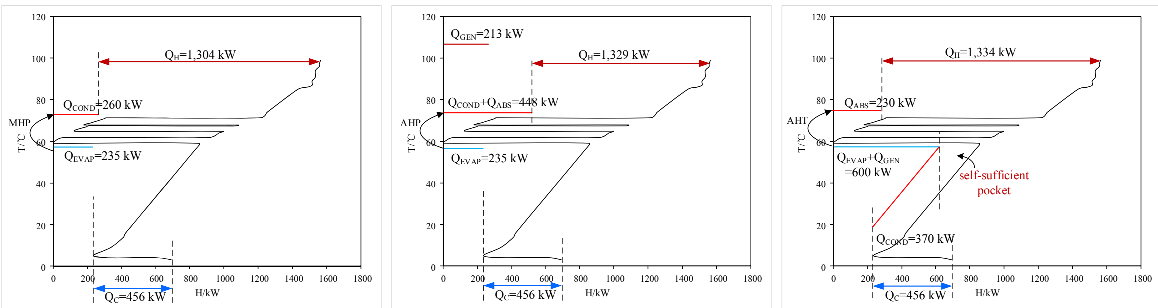
Because heat upgraded by different heat pumps require energy of several types or grades (e.g. work, high or medium pressure steam), the COP is not suitable to evaluate heat upgrading systems. Exergy is typically used for the comparisons of energy with different grades, i.e. thermal energy, work. Associated with exergy analysis, a novel criterion that is defined as the coefficient of performance in exergy per total annual cost (EPC) is introduced, which is given by Eq(5). The novel criterion allows thermal and economic comparison of different types of heat pumps.

$$EPC = \frac{E_{UH}/E_{DH}}{TAC} \tag{5}$$

where E_{UH} refers to the exergy of the upgraded heat, E_{DH} denotes the exergy of the driving heat, which is mechnical work for a MHP, high grade heat sources used in an AHP and medium/low grade heat sources used in an AHT, respectively, and *TAC* represents the total annualized cost of heat pump system.

2.3 Heat pump integration and Pinch Analysis

Heat pump integration considers both the process streams and diverse types of heat pumps. Before applying heat pumps into industrial processes, Pinch Analysis is required to determine the energy and cost targets. Given a temperature difference (ΔT_{min}), the grand composite curve (GCC) in Pinch Analysis can show the minimum hot and cold utility. Then the benefit of heat pump integration can be evaluated. Townsend and Linnhoff (1983) first introduced the correct and incorrect placement of heat pumps in the process. Bakhtiari et al. (2010) illustrated a simple case of the correct placement of diverse types of heat pumps. Generally, the proper placement of a heat pump is below the Pinch point where the heat pump can upgrade waste heat to a higher temperature level (Townsend and Linnhoff, 1983).



(a) MHP (b) AHP (c) AHT

Figure 4: Appropriate placement of a MHP, an AHP and an AHT in GCC

Figure 4 illustrates the appropriate placement of a MHP, an AHP and an AHT, and the GCC graphically represents the feasible cascade of net heat flow needed at specific temperature intervals shifted for a given ΔT_{min} to ensure a necessary temperature driving force in the heat transfer process (Wallin and Berntsson, 1994). It is convenient to show the temperature of the evaporator, condenser, generator and absorber in Figure 4. As the driving forces in heat pumps are different, the reduction in both hot and cold utility and the COP of different heat pumps cannot simply determine a proper heat pump for an industrial process, it is critical to perform a suitable evaluation based on a novel criterion, total annualized cost and payback time.
The procedure for heat pumps integration into process systems can be summarized by the following steps:
(1) Perform Pinch Analysis of a given industry process.
(2) Select proper process streams recovered by diverse types of heat pumps.
(3) Select corresponding heat sinks.
(4) Determine the operating parameters for different heat pumps.
(5) Calculate and compare different heat pumps based on different criteria.
(6) Heat exchanger network (HEN) reconfigurations (if required).

3. Case study

The proposed method for the selection of heat pumps in industrial processes is applied to a typical dairy process, where milk is transformed to produce concentrated milk, pasteurized milk and cream, yoghurts and desserts. This case is taken from Becker et al. (2011a), and the process stream data can be found in the literature. At first, given the temperature difference, Pinch Analysis for the heat exchanger network is conducted, and the corresponding minimum hot and cold utility are determined as 691 kW and 1,564 kW. The GCC of the process is shown in Figure 2b, and the Pinch temperature is about 59 °C. Based on the above rules of heat pump placement, a heat pump can be integrated to upgrade heat from below the Pinch for use above the Pinch. In the second and third step, the temperature of evaporator and condenser are estimated. Considering the temperature of the heat source stream (58 °C), which is determined by the Pinch temperature and ΔT_{min} (gas) = 2 °C, and ΔT_{min} (liquids) = 5 °C, the maximum evaporator temperature should be 53 °C. The minimum condenser temperature is estimated as 77 °C. In the case study, three types of heat pumps, a MHP, an AHP and an AHT are considered. The working fluid of a MHP is selected based on Figure 2a. Then the models of the MHP, AHP and AHT are simulated. The operating parameters of these three heat pumps can be shown in Figure 4. To calculate the novel criterion in Eq(5), the total annual cost of different heat pump systems is given in Eq(9), Eq(10) and Eq(11).

$$C_{MHP} = 0.00462W^{0.9} \tag{6}$$

$$C_{AHP} = 0.000394(Q_{ABS} + Q_{COND}) \tag{7}$$

$$C_{AHT} = 0.000535Q_{ABS} \tag{8}$$

$$TAC_{MHP} = k_F C_{MHP} + H_Y (C_{ELECT}W + C_{LP}Q_H + C_{CU}Q_C) \tag{9}$$

$$TAC_{AHP} = k_F C_{AHP} + H_Y (C_{LP}Q_{GE} + C_{LP}Q_H + C_{CU}Q_C) \tag{10}$$

$$TAC_{AHT} = k_F C_{AHT} + H_Y (C_{LP}Q_H + C_{CU}Q_C) \tag{11}$$

$$k_F = 0.16,\ H_Y:\ 8{,}000\ \mathrm{h},\ C_{ELECT}:\ 26{,}300\ \mathrm{M\$/MJ},\ C_{LP}:\ 8{,}300\ \mathrm{M\$/MJ},\ C_{CU}:\ 27{,}170\ \mathrm{M\$/t}$$

where k_F, H_Y, C_{ELECT}, C_{LP} and C_{CU} represent annualized factor, annual operating time, unit cost of electrical power, unit cost of low pressure steam and unit cost of cooling utility , respectively. C_{MHP} denotes capital cost of the MHP (Wallerand et al., 2017). C_{AHP} and C_{AHT} represent capital cost of the AHP and the AHT, respectively (Oluleye et al., 2016a).

4. Results and discussion

Table 1 shows the thermodynamic parameters of different heat pumps and the economic feasibility of those three heat pumps was evaluated based on the novel criterion, total annualized cost and payback time, which are presented in Table 2.

Table 1: Thermodynamic parameters of different heat pumps

Type	Working fluid	COP	Q_{EVAP} (kW)	Q_{COND} (kW)	W (kW)	Q_{ABS} (kW)	Q_{GEN} (kW)	T_G (°C)	Q_H (kW)	Q_C (kW)
No heat pump	-	-	-	-	-	-	-	-	1,564	691
MHP	n-Butane	10.40	235	260	25	-	-	-	1,304	456
AHP	LiBr-H_2O	2.10	235	250	-	198	213	132	1,329	456
AHT	LiBr-H_2O	0.38	368	370	-	230	232	60	1,334	456

As shown in Table 1, the COP of the MHP is the highest, and the COP of the AHT is not competitive compared with the MHP and AHP. However, comparison results are different based on other criteria in Table 2. Based on the novel criterion, the EPC of the MHP and AHT are not much different, which are both higher than that of the AHP. It indicates that the integration of an AHT into the process can also utilise the waste heat efficiently under the same investment. In addition, the TAC and payback time of the AHP are the highest and it indicates that the AHP is not proper for the process, resulting in low EPC. In Figure 4c, the condensation heat in the AHT can be removed by the process streams instead of cooling water and then the self-sufficient pocket of the GCC becomes small, which can improve heat exchange efficiency. Therefore, an AHT is selected to recover waste heat of the process.

Table 2: Economic evaluation of different types of heat pumps

Type	MHP	AHP	AHT
EPC	3.87	2.50	3.75
TAC (M$)	0.37	0.42	0.36
Payback time	1.53	10.53	1.85

5. Conclusions

In this work, a novel criterion EPC (i.e. the coefficient of performance in exergy per total annual cost) is proposed for selecting heat pumps, modelling diverse types of heat pumps for operating conditions. The novel criterion can both evaluate the thermodynamic and economical performances of heat pumps, which can be more suitable for heat upgrading technologies. In addition, a guideline for heat pump integration is introduced. One literature case study is analysed to show the applicability of the proposed methodology. The results show that the AHT is the best choice to recover waste heat of the process. The EPC is 3.75, payback time is 1.85 and the heat exchange efficiency of the process is much better than the other two heat pumps

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