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Heat Exchanger Network Retrofit Considering Heat Exchanger Types

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Heat exchanger network (HEN) retrofit has been widely studied to achieve energy savings. Different types of heat exchangers such as shell and tube, double-pipe, spiral plate, and spiral tube have their working temperature ranges and prices. However, considering the type of heat exchangers in the HEN retrofit process is rarely seen in previous publications. Selecting suitable types of heat exchangers according to their temperature ranges and prices is a crucial aspect in industrial implementation. The above-mentioned issue can be solved by the proposed Shifted Retrofit Thermodynamic Grid Diagram with the temperature range of heat exchangers (SRTGD-TR). The aim is to minimise the total cost, including utility cost and capital cost. The methodology is illustrated using a case study.

1. Introduction

Heat recovery has been regarded as a major measure to increase energy efficiency in process systems engineering. Heat exchanger network (HEN) retrofit is an effective way to utilise heat from process streams and to minimise the energy consumption (Klemeš et al., 2020). In the industrial application of HEN retrofit, different types of heat exchangers have their working temperature ranges and prices. Considering these aspects of the retrofit design process would make it more practical.

There are generally three methods for HEN retrofit, i.e., Pinch Analysis (PA), mathematical programming, and combined method (Klemeš and Kravanja, 2013). The PA-based graphical methods proposed for HEN retrofit such as Retrofit Thermodynamic Diagram (RTD) (Lakshmanan and Bañares-Alcántara, 1996), Stream Temperature vs Enthalpy Plot (STEP) (Wan Alwi and Manan, 2010), Temperature Driving Force (TDF) (Gadalla, 2015), and Energy Transfer Diagram (ETD) (Bonhivers et al., 2016) are widely used in the retrofit applications. Among them, RTD is a useful graphical visual tool. It can display the driving force around the heat exchanger and heat capacity flowrate graphically. Yong et al. (2014) modified the RTD and proposed a Shifted Retrofit Thermodynamic Diagram (SRTD). In SRTD, the hot streams are shifted by subtracting ΔT_{min}, and then the feasibility of implementing a heat exchanger can be visually seen by connecting both lower and higher temperature sides of hot and cold streams. If the slope of the connecting lines is negative, then it illustrates that the heat exchanger implementing plan violates the Pinch Rule. SRTD was later extended to Shifted Retrofit Thermodynamic Grid Diagram (SRTGD) by (Yong et al., 2015). It uses a dashed line to indicate the location of Process Pinch. By applying this diagram, Pinches can be detected, and the retrofit plan can be determined easier. Wang et al. (2020) developed a mathematical model based on the structure of the SRTGD and a two-stage method. In the first stage, the mathematical model was solved to obtain the topology of HEN with the aim of minimising utility and investment cost. While in the second stage, a particle swarm optimisation (PSO) algorithm was applied to adjust the inlet and outlet temperatures of each heat exchanger to achieve the goal of minimising payback period based on the obtained topology from the first stage. This method considers the price of utility and investment. It makes the retrofit design based on SRTGD more effective.

There are several advantages of using SRTGD in the HEN retrofit applications. It can identify the Process Pinch through the diagram. It is easy to check whether the retrofit plan violates the Pinch Rule, and to find if there is

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still potential for more heat recovery. It also shows the temperature range of each heat exchanger on hot and cold streams, which is a benefit that can be used in the heat exchanger type selection.
In the HEN retrofit process, achieving energy savings is one important task; another issue is to ensure the selected heat exchanger type can satisfy the heat transfer requirement between streams and has a relatively lower cost. Different types of heat exchangers such as shell and tube, double-pipe, spiral plate, and spiral tube have their working temperature ranges and capital costs. Soršak and Kravanja (2002) proposed an MINLP model for HEN synthesis and modelled the selection of heat exchanger types. Sun et al. (2013) presented the stream temperature vs enthalpy plot Supertargeting (STEPS) method to optimise the heat exchanger network cost. In their proposed step by step method, the heat exchanger types are considered, and the capital cost is calculated. As can be seen from the previous papers, the HEN retrofit with the consideration of heat exchanger types requires to be studied. Selecting suitable types of heat exchangers according to their temperature ranges and prices in the retrofit design is a crucial aspect in industrial implementation.

2. Methodology

There are several different variants of heat exchangers, the common types employed in the industry, including:

- Shell and tube heat exchangers
- Double pipe heat exchangers
- Spiral plate heat exchangers
- Spiral tube heat exchangers
- Scraped–wall heat exchangers

Besides them, compact plate heat exchangers are also widely used in the industrial application (Klemeš et al., 2015). This type of heat exchanger will be analysed in the next contribution.
The suitability of each heat exchanger type in transferring heat between streams is dependent on the specifications and requirements of the application. Table 1 lists several commonly used heat exchanger types, their temperature ranges, and normal area ranges. In the retrofit design process, these factors should be considered together with the aim of utility saving.

Table 1: Heat exchanger types and their temperature and area ranges (Sun et al., 2013)

Heat exchanger type	Max. Pressure (MPa)	Temp., approx. range (°C)	Normal area, approx. range (m^2)
Double–pipe (liq. and gas)	30	−100 to ~600	0.25 – 20
Shell and tube (liq. and gas)	30	−200 to 600+	3 – 1,000
Scraped–wall (liq.)	~0.01	Up to 200	2 – 20
Spiral plate (liq. and gas)	2	Up to 300	10 – 200
Spiral tube (liq. and gas)	50	Up to 350	1 –50

If the temperature of some potential heat recovery range pass through the temperature range boundary of some types of heat exchangers, or temperature ranges of some heat exchangers are in the range of more than one heat exchanger types, then focus should be given to this heat path. If the heat recovery range passes through the temperature range boundaries, then it should also consider whether to implement more than two heat exchangers on one heat path to achieve the minimum retrofit cost.
Besides the temperature and area ranges, the capital cost is another factor that is considered in designing and choosing a heat exchanger.
For the shell and tube heat exchanger with floating head, carbon steel for shell and Cr–Mo steel for tube, the capital cost calculation can be formulated as Eq(1) (Seider et al., 2010).

$$C^{s\&t} = [a + (\frac{A}{100})^b] \times [0.9803 + 0.018(\frac{P \times 145}{100}) + 0.0017(\frac{P \times 145}{100})^2] \times e^{11.667 - 0.8709\ln(A) + 0.09005[\ln(A)]^2} \quad (1)$$

where $C^{s\&t}$ is the capital cost of shell and tube heat exchanger; A is the heat transfer area in ft^2; P is the shell-side pressure in MPa; and parameters *a* and *b* are materials of construction factors when the shell is made of carbon steel, and the tube is made of Cr–Mo steel, the values of *a* and *b* are 1.55 and 0.05. It should be noted ft^2 is used in the calculation as formulated by (Seider et al., 2010), while m^2 is used in Tables in line with ISO SI, with the conversion rate of 1 m^2 = 10.76 ft^2.
For the double-pipe heat exchanger, the capital cost equation for an outer pipe of carbon steel and an inner pipe of stainless steel is formulated as Eq(2) (Seider et al., 2010).

$$C^{dp} = 2\times[0.8510+0.1292(\frac{P\times145}{100})+0.0198(\frac{P\times145}{100})^2]\times e^{7.1460+0.16\ln(A)} \quad (2)$$

where C^{dp} is the capital cost of the double-pipe heat exchanger.
The capital cost of the spiral plate can be calculated by Eq(3) (Seider et al., 2010).

$$C^{sp} = 6,200A^{0.42} \quad (3)$$

where C^{sp} is the capital cost of the spiral plate heat exchanger.
For the spiral tube, its capital cost can be calculated by Eq(4) (Seider et al., 2010).

$$C^{st} = e^{8.0757+0.4343\ln(A)+0.03812[\ln(A)]^2} \quad (4)$$

where C^{st} is the capital cost of the spiral tube heat exchanger.
The above equations for capital cost calculation are summarized in Table 2.

Table 2: Capital cost of different types of heat exchangers

Heat exchanger type	Capital cost ($)
Shell and tube	$C^{st} = [0.9803+0.018(\frac{P\times145}{100})+0.0017(\frac{P\times145}{100})^2]\times[a+(\frac{A}{100})^b]$ $\times e^{11.667-0.8709\ln(A)+0.09005[\ln(A)]^2}$
Double–pipe	$C^{dt} = 2\times[0.8510+0.1292(\frac{P\times145}{100})+0.0198(\frac{P\times145}{100})^2]\times e^{7.1460+0.16\ln(A)}$
Spiral plate	$C^{sp} = 6,200A^{0.42}$
Spiral tube	$C^{st} = e^{8.0757+0.4343\ln(A)+0.03812[\ln(A)]^2}$

Note: the unit for *A* (heat transfer area) in this table is ft^2.

In this paper, an extended version of the SRTGD is proposed, and it is called SRTGD with the temperature range of heat exchangers (SRTGD-TR). The basic method for drawing an SRTGD can be found in (Yong et al., 2015). In this version, the allowable temperature range of different heat exchanger types is coupled in the diagram. The area of hot and cold streams connecting by one heat exchanger should be in its temperature range. Also, when determining a retrofit plan, this diagram can help easily identify the boundary of the heat exchangers.

3. Illustrative Case Study

An illustrative case study of how to use this method for HEN retrofit considering heat exchanger types is explained in this section.
Three streams are selected from a chemical process plant, and an existing heat exchanger is connecting between stream 1 and 3 for heat recovery. The data for these three streams are shown in Table 3, and the corresponding SRTGD-TR is shown in Figure 1. In this case, ΔT_{min} is set as 20 °C. It can be seen that this HEN still has great potential for heat recovery.
The notation of the heat transfer used in this work includes for all topology diagrams are shown as the following:

- H[number]: utility heater
- C[number]: utility cooler
- E[number]: recovery heat exchanger

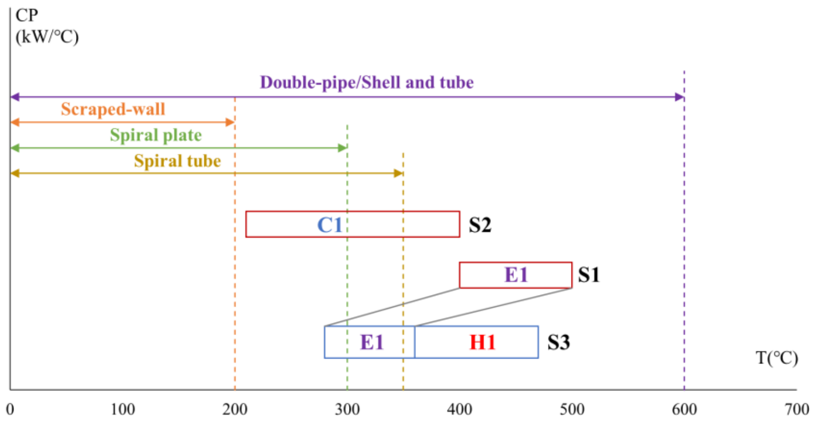

Figure 1: SRTGD-TR of the existing HEN

Table 3: Stream data for case study

Stream	T_S (°C)	T_T (°C)	*CP* (kW/°C)	*h* (kW/m²·°C)
1	520	420	4	0.85
2	420	230	4	0.85
3	280	470	5	0.80

Note: T_S is the supply temperature, (°C); T_T is the target temperature, (°C); *CP* is the heat-capacity flow rate, (kW/°C), and *h* is the heat transfer coefficient, (kW/m²·°C).

To fully utilize the heat from the hot stream, four retrofit plans are proposed based on SRTGD-TR. The first retrofit plan shown in Figure 2 uses one new heat exchanger between streams 2 and 3.
As can be observed from Figure 2, some parts of the temperature range of the new heat exchanger are higher than 350 °C, which is higher than the upper bound of the spiral tube heat exchanger, only double-pipe or shell and tube heat exchanger can be used. To not violate the Pinch Rule, stream 2 use E2 and C1 to reach the target temperature. The vertical line indicates the Process Pinch.

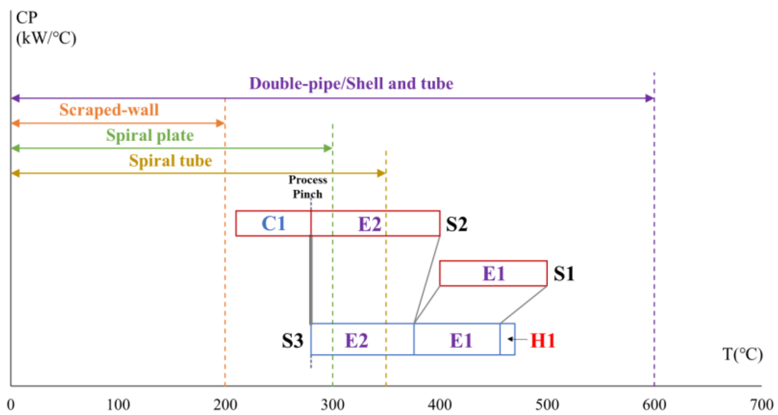

Figure 2: SRTGD-TR of the first retrofit plan

The second retrofit plan (Figure 3) considers implementing a spiral tube heat exchanger for this HEN. It is easy to identify the retrofit plan based on the SRTGD-TR. To implement a spiral tube heat exchanger to this HEN, the highest temperature on both hot and cold streams could not higher than 350 °C, which is also marked on the diagram. For heat exchanger E3, considering the hot stream S2 has a relatively lower heat capacity flowrate than the cold stream, the shifted inlet temperature on the hot stream should not higher than the upper bound of implementing a spiral tube heat exchanger. It should be noted that the temperature of hot streams is shifted. So the inlet shifted temperature of E3 on this diagram should be the upper temperature bound minus ΔT_{min}. Then the inlet and outlet temperature of heat exchanger E2 as well as E3 can be determined.

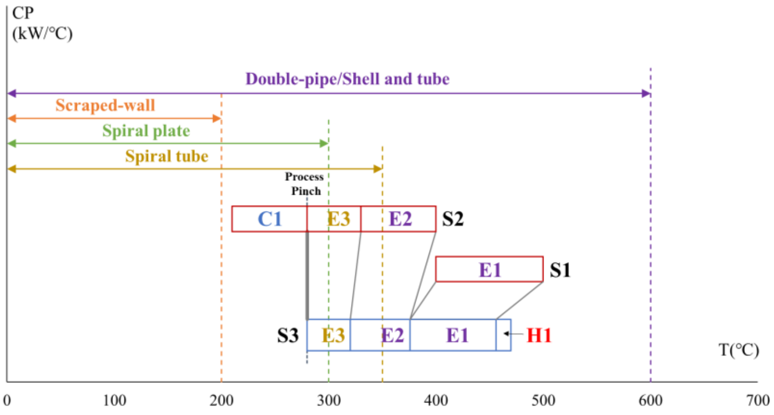

Figure 3: SRTGD-TR of the second retrofit plan

The third retrofit plan considers using a spiral plate. However, the upper-temperature boundary of spiral plate heat exchanger minus the ΔT_{min} equals to the inlet temperature of stream S3. It is not feasible to use a spiral plate heat exchanger; the retrofit plan of this consideration is the same as the first retrofit plan (Figure 2); one heat exchanger is implemented.

There is another potential option for implementing two double-pipe heat exchangers since its capital cost is much cheaper. The Pinch Point is still 280 °C. The range of the normal area of the double-pipe is 0.25 – 20 m^2. By adjusting the inlet and outlet temperatures of heat exchanger E3 and E2, the retrofit plan of implementing two double-pipe heat exchangers is shown in Figure 4.

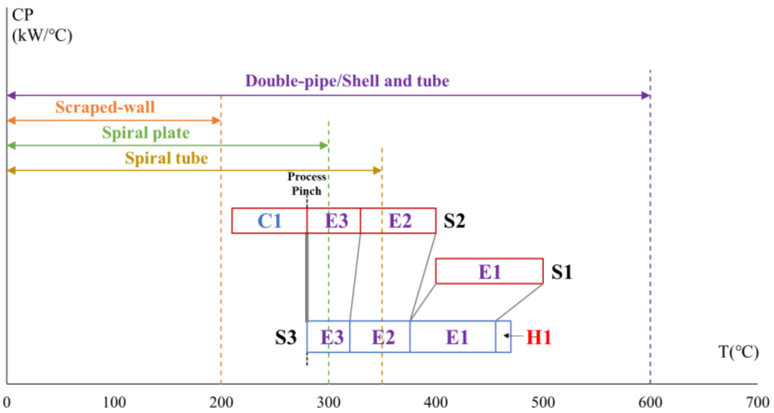

Figure 4: SRTGD-TR of the third retrofit plan

Table 4: Comparison of the results

Solutions	Solution 1			Solution 2			Solution 3		
Items	Type	Area (m^2)	Cost (k$)	Type	Area (m^2)	Cost (k$)	Type	Area (m^2)	Cost (k$)
HE1	D-P	18.2	10.4	D-P	18.2	10.4	D-P	18.2	10.4
HE2	S&T	38.3	46.0	D-P	12.5	9.8	D-P	18.6	10.4
HE3				S-T	25.8	123.5	D-P	19.7	10.5
Sum			56.4			143.7			31.3

Note: S&T refers to the shell-and-tube heat exchanger, D-P refers to the double-pipe heat exchanger, S-T refers to the spiral tube heat exchanger, S-P refers to the spiral plate heat exchanger.

As can be observed from Figure 2 to Figure 4, the utility cost of all these three retrofit plans is the same. They can recover 480 kW of heat. The difference among these plans is the selection of heat exchanger types and their capital costs. The comparison of the capital cost for all the retrofit plans is shown in Table 4. The total capital cost for the third retrofit plan is the cheapest. Two new double-pipe heat exchangers are selected. Another feasible plan is solution 1. One shell-and-tube heat exchanger should be implemented. For Solution 2, the capital cost for the spiral tube heat exchanger is too high. Although it has a higher maximum bearing pressure, in this case, there is no need to use this type of heat exchanger.

4. Conclusions

By using the novel SRTGD-TR, the retrofit plan can be easily determined. This method can help engineers to identify potential HEN retrofit plans with different types of heat exchangers, and illustrate these plans visually. The case study shows that an extra 480 kW of heat can be recovered. The right selection of heat exchanger types can help to achieve a relatively lower capital cost.

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