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Shifted Retrofit Thermodynamic Diagram: A Modified Tool for Retrofitting Heat Exchanger Networks

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Chemical industries are constantly looking for ways to improve the plants' energy efficiencies due to increasing energy price. One of the ways is to perform retrofit on heat exchanger networks. Over the decades, much research has been performed in this area and can be generally classified into insight-based methods and optimisation-based methods. In this paper, Shifted Retrofit Thermodynamic Diagram (SRTD) is introduced, which is a modification from Retrofit Thermodynamic Diagram (RTD) is found in literature. SRTD has the features of RTD and incorporates thermodynamic feasibility representation as well as minimum allowed temperature difference. This paper also includes an illustrative case study.

1. Introduction

Over the years, high energy prices (BP, 2013) have driven the chemical industries to look for ways of increasing the energy efficiency of their plants. The plants had also undergone modifications to increase their product yield to cope with the ever increasing market demand. Because of that and energy are more expensive over the last decades, which was when the time the plant was built on, investors are looking for retrofit options on heat exchanger networks (HENs) to reduce the energy usage by investing changes to the plant. The chemical industries include, but not limited to, pulp industries (Nordman and Berntsson, 2006), crude oil distillation (Ochoa-Estopier et al., 2013) and even further extended to total sites (Liew et al., 2014). The retrofits done on HENs include purchasing new heat exchangers (van Reisen et al., 1995), additional of heat transfer area, performing heat transfer enhancement (Pan et al., 2013) and making changes to piping. Different methods have been used in retrofitting HENs, which can generally group into insight-based methods and optimisation-based methods. Insight-based methods utilise graphical representation and involvement of engineering judgement into calculating the energy targets (Nordman and Berntsson, 2009). Optimisation-based methods use mathematical programing to maximise or minimise certain objective functions, such as total annual cost, payback period and energy usage (Smith et al., 2010). While both of the methods have their own advantages and disadvantages, insight-based methods could not carry out cost optimisation at diagnosis stage simultaneously, optimisation-base method is complex in terms of structure and coding, while it does not guarantee global optimum. In 1996, a graphical visual tool was developed by Lakshmanan and Bañares-Alcántara (1996) called Retrofit Thermodynamic Diagram (RTD). As the conventional grid diagram is mostly not drawn according to the streams temperature, the driving force around the heat exchanger is not explicitly displayed. Also The conventional grid diagram does not visually highlight the significance of heat capacity flowrate. Therefore RTD is a modification of the conventional grid diagram which graphically shows the driving force and heat capacity flowrate. The stream is replaced by boxes representing heat exchangers. The width of the box is the stream temperature range while the height is proportional to the heat capacity flowrate. Lakshmanan and Bañares-Alcántara (1998) further discussed some other retrofit guideline using RTD. The work is then further extended to include Constraint Logic Programming (Abbas et al., 1999). However, RTD does not show thermodynamic feasibility clearly. This is important as to ensure that heat exchanging is feasible, the cold stream should have lower temperature than hot stream at both ends of a heat exchanger. RTD does not incorporate minimum allowed temperature difference (ΔT_{min}) as well. In this paper, RTD is modified to include all the features mentioned and is called Shifted Retrofit Thermodynamic Diagram (SRTD).

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In SRTD, the hot streams are shifted to include the analysis of ΔT_{min}. The ends of both streams of a heat exchanger are connected to show the thermodynamic feasibility. This will create either positive slant lines or vertical lines. The vertical lines show the locations of the Pinches. The presence of a negative slant line this indicates that the cold stream has higher temperature than the hot streams, which should be determined as an error in data collection. The tendency for a line to become a Pinch can be seen from its horizontal gap, which is the temperature difference between the hot stream and cold stream. Line that has smaller temperature difference has higher tendency to become the next Pinch. This paper also discusses about the Pinches, particularly Network Pinch (Asante and Zhu, 1997), its effect on SRTD and how to deal with them. The SRTD and its analysis are further demonstrated with an illustrative case study.

2. Methodology of Constructing and Analysing using Shifted Retrofit Thermodynamic Diagram

The methodology of constructing and analysing using SRTD is as follow:

1. Gather all the data for all heat exchangers, coolers and heaters. The data includes the inlet temperatures, outlet temperatures and heat capacity flowrates for both cold and hot streams.
2. Shift all the temperatures of hot streams by subtraction with the magnitude of ΔT_{min}. This is to ensure that ΔT_{min} is observed and not violated at all times during the design.
3. Construct the SRTD with boxes representing heat exchangers. Temperature spam will be the width of the box and heat capacity flowrate (CP) will be the height. Then match the colds inlet with hot outlets as well as cold outlet with hot inlet for all heat exchangers using connecting lines.
4. Check for potential heat recovery from the coolers. When potential heat saving is found, trace the heat path from the cooler to a heater. For retrofit to be possible, Pinches that appear along the heat path should be removed. Relocate that section of cold streams that causes the Pinches backwards to create positive slant lines. Ensure that by doing so it will not create another Pinches or even negative slant lines along the heat path.
5. Along the heat path, determine the next potential Pinch that has the smallest temperature difference. The maximum allowable heat for recovery without violating ΔT_{min} is depending on where is the potential Pinch located. Proceed to step 5a if the potential Pinch is connected to the inlet of the cooler, otherwise proceed to step 5b.

5a. The maximum allowable heat for recovery without violating ΔT_{min} is then calculated to be the product of temperature difference of that potential Pinch and heat capacity flow of the hot stream.

5b. The maximum allowable heat for recovery without violating ΔT_{min} is then calculated to be the product of temperature difference of that potential Pinch and heat capacity flow of the cold stream.

6. Depending on the amount of heat available for recovery in the cooler, the cooler can be removed if the heat available is equal or less than the maximum allowable heat for recovery. Otherwise, the remaining heat duty has to be performed by that cooler.
7. Repeat steps 4 to 6 until no further retrofit can be done.

3. Illustrative Case Study

3.1 Original Plant Data and Layout

An illustrative case study is used to demonstrate the methodology. A part of a chemical process plant is considered, where a stream is preheated by exchanging heat with six other streams before it is heated to desired temperature. The plant was initially design according to Pinch Analysis with ΔT_{min} = 10 °C, the Pinch was previously identified at 330 °C/340 °C for Hot Pinch and Cold Pinch. Over the years, the plant had gone through modifications due to increase in demand while still keeping the old Pinch temperatures. In recent of the increase in energy price, the investors of the chemical plant would like to have retrofit on the plant so that the plant uses less energy in terms of utility.

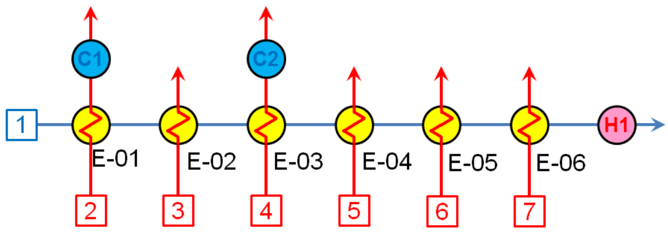

Figure 1: Schematic diagram showing part of a chemical process plant

Table 1: Stream properties for the illustrative case study

Steam Name	Supply Temperature (°C)	Target Temperature (°C)	Heat Capacity Flow (kW/°C)	Heat Flow (kW)
1	30	600	5	2,850
2	185	20	4	660
3	250	170	5	400
4	570	320	3	750
5	410	340	2	140
6	468	368	3	300
7	560	525	10	350

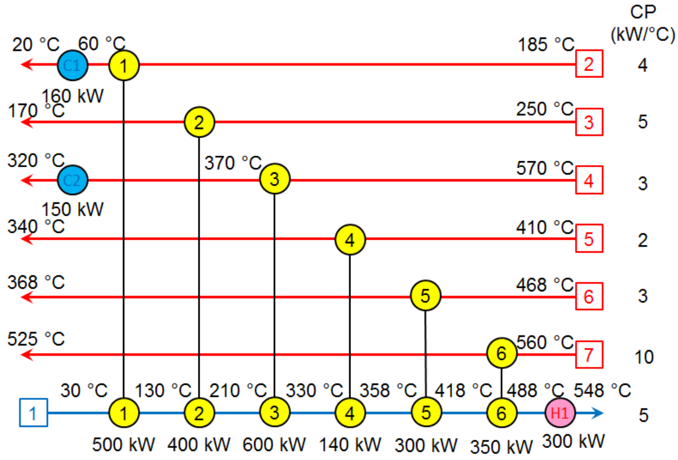

Figure 2: Conventional heat exchanger network Grid diagram of the current chemical process plant

The detailed but conventional heat exchanger network Grid diagram is shown in Figure 2. As mention in the previous section, conventional grid diagram seldom takes visually highlight the significance of stream's temperature and heat capacity flowrate. The Pinch, particularly Network Pinch, is hard to be detected as well from the conventional grid diagram. This will further increase the difficulty to retrofit the plant.

4. Application of the Shifted Retrofit Thermodynamic Diagram on the Case Study

The data is first reorganised according to step 1 found in Section 2. The next step is to shift all the temperatures of hot streams by subtracting with ΔT_{min}. In this case study, it is decided that ΔT_{min} is 10 °C. The temperatures for cold streams remained unchanged. The conventional grid diagram is then redrawn using the methodology explained according to step 3 in section 2, which is shown in Figure 3. The SRTD is drawn according to temperature and heat capacity flow scale. It is then can be seen clearly that the Pinches exist not only at HEX-04 (as previously mention it is maintained as Process Pinch) but at HEX-05 as well. The Pinch at HEX-05 is considered as Network Pinch, which is only noticeable during the design of heat exchanger network.

Table 2: Reorganised data showing the details of each heat exchangers, heater and coolers

Heat Exchanger Name	Duty (kW)	Hot Stream				Cold Stream			
		Name	CP (kW/°C)	TS (°C)	TT (°C)	Name	CP (kW/°C)	TS (°C)	TT (°C)
HEX - 01	500	2	4	185	60	1	5	30	130
HEX - 02	400	3	5	250	170	1	5	130	210
HEX - 03	600	4	3	570	370	1	5	210	330
HEX - 04	140	5	2	410	340	1	5	330	358
HEX - 05	300	6	3	468	368	1	5	358	418
HEX - 06	350	7	10	560	525	1	5	418	488
H1	560					1	5	488	600
C1	160	2	4	60	20				
C2	150	4	3	370	320				

Table 3: Data showing the details of each heat exchangers, heater and coolers with shifted hot temperatures

Heat Exchanger Name	Duty (kW)	Hot Stream Name	CP (kW/°C)	TS* (°C)	TT* (°C)	Cold Stream Name	CP (kW/°C)	TS (°C)	TT (°C)
HEX - 01	500	2	4	175	50	1	5	30	130
HEX - 02	400	3	5	240	160	1	5	130	210
HEX - 03	600	4	3	560	360	1	5	210	330
HEX - 04	140	5	2	400	330	1	5	330	358
HEX - 05	300	6	3	458	358	1	5	358	418
HEX - 06	350	7	10	550	515	1	5	418	488
H1	560					1	5	488	600
C1	160	2	4	50	10				
C2	150	4	3	360	310				

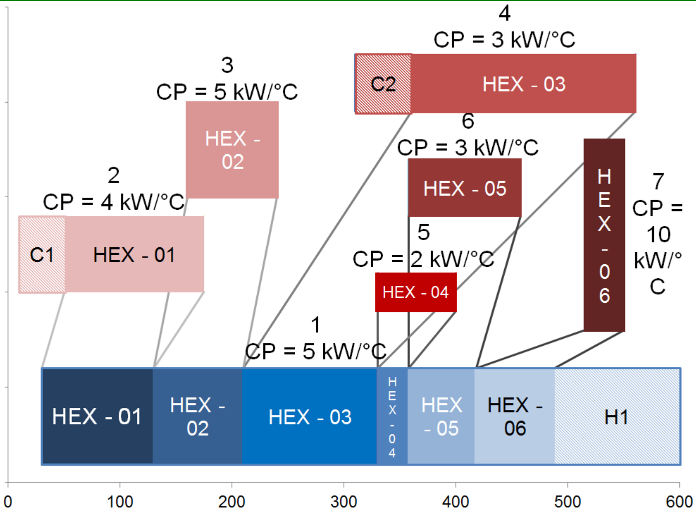

Figure 3: SRTD of the current chemical process plant. The shaded area shows the amount of hot utility and cold utilities used.

4.1 First Retrofit

The first retrofit is done on increasing the heat exchange duty of HEX-03 to reduce utilities used, as heat can be recovered from cooler C2. The heat path is traced from cooler C2 to heater H1, which involves stream 1 and stream 4. Along the heat path, there are Pinches at HEX-04 and HEX-05 as indicated by two straight vertical lines. Therefore, step 4a is carried out by re-piping and shifting these two heat exchangers after HEX-02 and before HEX-03. It will increase the inlet temperature of cold stream of HEX-03 from 210 °C to 298 °C. The heat exchange for HEX-03 is still feasible as indicated by the positive slant lines connecting stream 1 and stream 4. According to the methodology, the match with smallest temperature difference along the heat path should be given attention as it has the potential to become the next Pinch. It is found to be the match connecting the cold inlet and hot outlet of HEX-03, and has temperature difference of 62 °C. This potential Pinch is connected to the inlet of a cooler, therefore step 5a is carried out whereby the heat capacity flowrate of the cold stream (i. e. stream 4) will be used in calculating the maximum allowable heat for recovery. The maximum allowable heat for recovery is then calculated to be 186 kW. However, the cooler C2 has only 150 kW of heat available for exchange. The HEX-03 will then has its duty increased by 150 kW and cooler C2 can be removed from the design. This will increase all the temperatures of stream 1 along the heat path. The amount of hot utility is reduced from 560 kW to 410 kW. The removal of cooler C2 also reduce the amount of cold utility used to be 160 kW. The result is shown in Figure 4.

4.2 Second Retrofit

Further retrofit is possible to be done after the first retrofit. Following off from the first retrofit, there is heat potential to be recovered in cooler C1. The heat path is then traced from cooler C1 to heater H1. Along the heat path, there is no Pinch and therefore re-piping of heat exchangers is not needed. The potential Pinch is found again the match between connecting the cold inlet and hot outlet of HEX-03, and has temperature

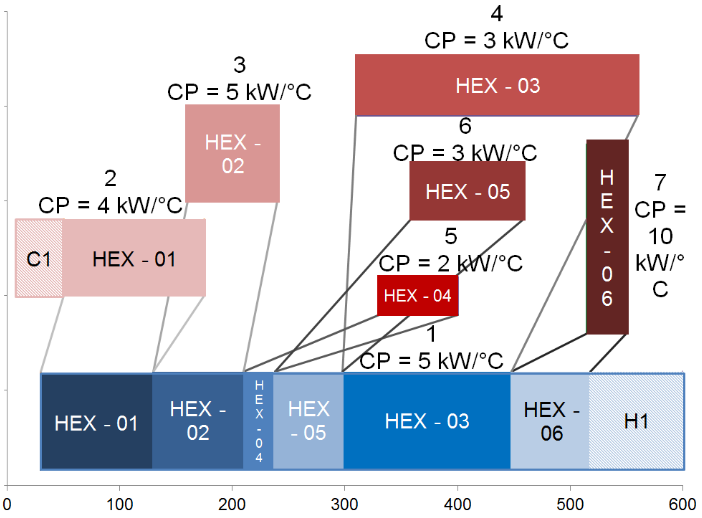

Figure 4: SRTD for the first retrofit

difference of 12 °C. In this second retrofit, the potential Pinch is not connected with the inlet of cooler C1, therefore step 5b is carried out. The heat capacity flowrate of stream 1 will be used, resulting in the maximum allowable heat for recovery calculated to be 60 kW. It should be noted that not all heat can be recovered from stream 2 in cooler C1. To avoid violating the ΔT_{min}, temperature of hot stream outlet of HEX-01 should not be lower than 40 °C, which only has 80 kW of heat available to be recovered. Nevertheless, the maximum allowable heat for recovery is lower than the heat available to be recovered. Therefore following step 6, the 60 kW of heat will be used for heat recovery while the remaining 20 kW of heat will still cooled by cooler C1. After the second retrofit, both hot and cold utilities are further reduced by 60 kW, with the required hot and cold utilities are found to be 100 kW and 350 kW. Figure 5 shows the result after performing the second retrofit. Further retrofit is not possible. Although as mentioned previously there are still 20 kW of heat available for recovery at cooler C1, the Pinch at HEX-03 could not be relocated due to its high temperature span. To further recover the 20 kW of heat, the heat exchanger network might have to redesign, which is economically infeasible.

5. Analysis of the Retrofits

For comparison purpose, Pinch Analysis is performed on the chemical plant by first assuming that the plant does not have any heat integration. The results of all three type of retrofit are shown in Table 4. Chemical plant before retrofit is used as the base case. By just relocating Pinches and modify HEX – 03,

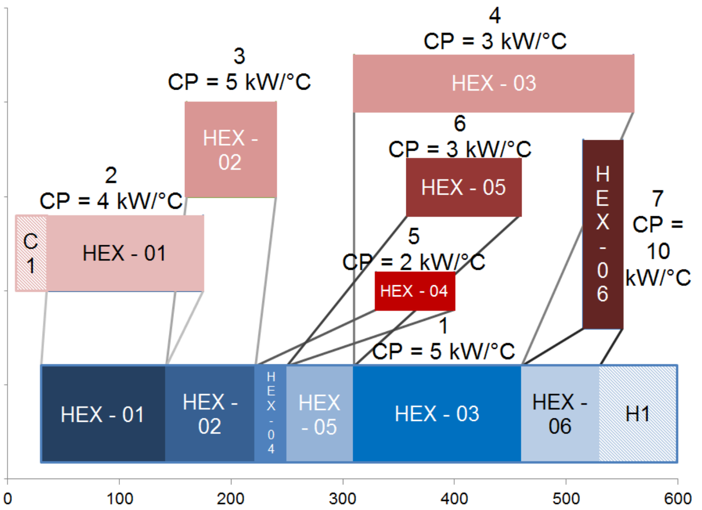

Figure 5: SRTD for the second retrofit

Table 4: Comparisons on utilities used and heat recovered between base case (chemical plant before retrofit), Retrofit 1, Retrofit 2 and New Design according to Pinch Analysis

Case	Base Case	Retrofit 1	Retrofit 2	New Design
Hot Utility (kW)	560	410	350	330
Cold Utility (kW)	310	160	100	80
Heat Recovered (kW)	2,290	2,440	2,500	2,520

Retrofit 1 is able to further recover 150 kW (6.55 %) of heat. Retrofit 2 is done by modifying HEX – 01 and it further recovers 210 kW (9.17 %) of heat. It is worth mentioning that Retrofit 2 is only 20 kW less than newly designed heat exchanger network using Pinch Analysis. The preliminary designed heat exchanger network according to Pinch Analysis is also more complex than Retrofit 2.

6. Conclusions and Further Work

By using the SRTD, the Pinches are easier to be detected and retrofits are easier to be done. More heat can be recovered and more utilities can be saved by following the methodology that is described in this paper. An illustrative case study is made as an example on how to apply the methodology and the potential of heat can be recovered and utilities can be saved. The case study showed around 9 % of heat can be recovered more if the chemical plant undergoes the retrofits. The final retrofit is also just uses 20 kW of utilities more when compared to minimum hot and cold utilities required calculated using Pinch Analysis. For further work, this paper will be extended to the effect of split stream on Pinch and retrofit, flexibility of a heat exchanger network design using RSTD, and the cost of retrofit associated with mainly the additional heat exchanger area needed due to the change of duty and log mean temperature difference. RSTD will be research into total site as well.

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