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Integration of Heat Exchanger Network Considering the Influence of the Reactor

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Integrating the Heat Exchanger Network (HEN) by Pinch Technology is an efficient method to decrease energy consumption. In a HEN, some source and sink streams, and their heating and cooling duties are dictated by the reactor. Hence, the reactor design affects the integration of HEN. There is the possibility to reduce the utility further by adjusting the reactor design parameters. To achieve this, it is necessary to consider the influence of reactor on the HEN integration.
In this work, a graphical method is proposed to analyze the effect of the reactor's uncertainty of VGO hydrotreating process. Since the variation of the reactor parameters affects the inlet and outlet streams' target and/or supply temperature, the temperature variation of the corresponding source and sink is accommodated by shifting the corresponding inflection point of the composite curve. Correspondingly, the part of the composite curve below or above the inflection point is shifted to target the heating and/or cooling utility. When the operating parameter of the reactor changes, whether the pinch will change or not can be identified by the proposed method, as well as the minimum heating and cooling utilities.

1. Introduction

In chemical process, the energy consumption can be reduced by integrating the Heat Exchanger Network (HEN) as a whole. The companies first used this technology had reported 30 % reduction in energy consumption in 1980s (Tovazhnyansky et al., 2005). Since then, Process Integration has been applied widely in many other fields (Souza et al., 2016).
The process integration was initially proposed by Linnhoff (1977), who developed the pinch analysis method for synthesizing an optimal HEN (Smith, 2000). The composite curves of graphical method by Hohmann (1971) and problem table algorithm by Linnhoff and Flower (1978) and bath algorithm by Townsend and Linnhoff (1984) were useful in preliminary estimate of energy consumption targets. A systematic method of the HEN using principles of pinch analysis to meet the minimum utilities was introduced by Linnhoff and Hindmarsh (1983). With high speed computing technology, mathematical modelling process were developed using the pinch analysis to minimize energy consumption as proposed in the work of Cerda et al.(1983) and Papoulias and Grossmann (1983). Then, a mathematical programming method using a superstructure was put forward (Yee et al., 1990).These superstructure models optimized the energy of exchangers to get economically feasible networks simultaneously (Klemeš et al., 2013).However, because of no physical meaning of a solver, the solution is mostly trapped near the local optima. Besides, the graphic pinch method is more efficient than modelling a superstructure with less data collected when optimizing preliminarily (Pouransari and Marechal, 2014).
In chemical process, HEN not only relative to streams and exchangers, but also other units, such as reactors and separators, which impact the inlet/ outlet temperature of streams. Of all, the reactor is the core of the whole process because of its high cost and inflexibility. For now, the integration of reactor is mainly focused on the integration of wastewater treatment (Klemeš, 2012) and energy recovery by using different type of digestion, catalyst or combining different reactors together, such as CSMER (continuous stirred microbial electrochemical reactor) and CSTR - continuous stirred tank reactor (Wang et al., 2015). However, there is no research about the integration between HEN and reactors with graphic pinch method. Adjusting the operating

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parameters of reactor influences the temperature of inlet feed or product of the reactor, which are the sinks or sources of HEN, as well as the integration of HEN. Moreover, the cooling and heating demands even the position of pinch point can be changed correspondingly.
The VGO hydrotreating process is a general process in refinery plant with difficult heat exchanger networks. Both cooling water and heating demands are consumed. It is essential to reduce their consumption to optimize in HEN.
In this work, a graphic method will be proposed to analyse the integration of HEN with the effect of reactor considered. The variation of the cold and heating utilities and the position of pinch point can be calculated by simple graphical conversion.

2. The sketch of a VGO hydrotreating process

The VGO hydrotreating process is aimed to remove impurities, such as Sulphur, nitrogen and metal, the simplified flowsheet is presented in Figure1.The feed of this process are VGO1, VGO2 and CGO from three different atmospheric and vacuum distillation units with processing abilitiesas 233,715 kg/h, 147,238 kg/h and 95,238 kg/h, respectively. VGO1, VGO2 and CGO from raw tank flow into stabilization tank (D102) and the bottom product is pumped by P102 and preheated by heat exchangers E104, E102 and E101, before entering reactor R101. The makeup hydrogen is compressed by compressor K101 at the top of tank D109 and is mixed with the recycled hydrogen, which is compressed by compressor K102, and is then split into three sub-streams: the first is mixed with feed oil before entering E102; the second is heated in heat exchangers E106 and E103 and furnace F101 before being inlet to R101; the last one is introduced into the reactor directly as quench gas. The product from R101 is cooled in exchangers E101, E102, E103 and E104, and is separated in hot high pressure separator D103. Then the top product is sent to cold high pressure separator D105 after being cooled in heat exchangers E106, E107 and cooler A101, while the bottom is sent to hot low pressure separator D104. The top product from D105 is separated in separator D108, and the top product is sent to K102. The product from top of D104 is cooled in A102, and then is separated in cold low pressure separator, D106, as well as the oil from D105 and D108. The bottom products of D106 and D104 flow out to further fractionation, respectively, and the gas part goes to steam stripping.

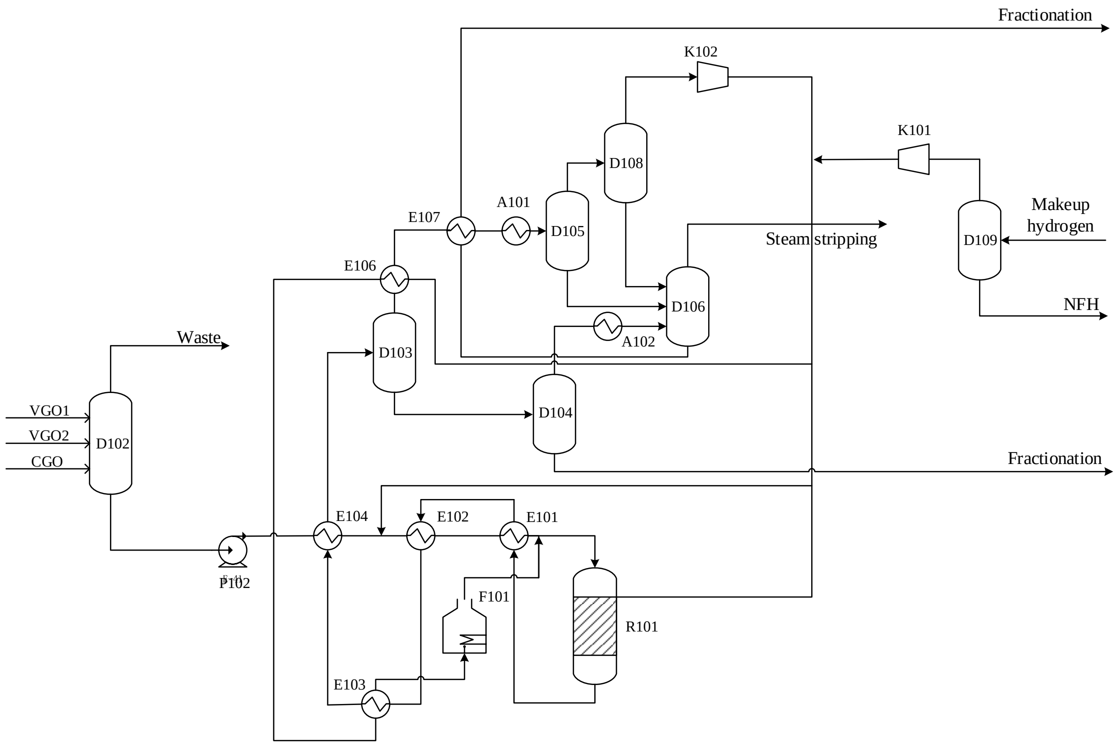

Figure 1: Process flowsheet of VGO hydrotreating process

3. Optimization of HEN

There are 3 cold streams and 3 hot streams in the heat exchanger network of this VGO process, and the data of each stream are listed in Table 1. Since the CP of each stream varies significantly, each stream is divided into multiple temperature intervals, and the CP of each temperature interval is taken as a constant.

With the approach temperature taken as 10 °C, the composite curve is plotted, as shown in Figure 2. It is identified that the minimum hot and cold utility consumptions and the pinch temperature are 2,186.04 kW, 17,176.9 kW and 358 °C.

In this process, the temperature of the feed mixture of hydrotreating reactor is 358°C, and is influenced by several uncertain parameters, such as catalyst, operating pressure or the amount of makeup hydrogen. Adjusting these factors may change the inlet temperature of reactor. Thus, the shape of composite curve will change, as well as the cooling and heating demands, and the position of Pinch Point.

Table 1: The data of stream

Streams	Description	T_S,°C	T_T,°C	ΔH, kW	CP, kW·°C $^{-1}$
C1	Raw material	115	230	36,090	313.83
		224.1	310	31,060	361.58
		310	358	18,610	385.71
C2	Makeup hydrogen	77	144	3,244	48.42
		144	270	6,149	48.80
		270	358	4,356	49.50
C3	Bottom product of D106	41	100	4,686	79.42
H1	Reaction product	363	333.7	18,610	635.15
		333.7	282.9	31,060	611.42
		282.9	272.5	6,149	591.25
		272.5	209.4	36,090	571.95
H2	Top product of D103	209.4	187	3,244	144.82
		187	165	4,686	213.00
		165	40	18,890	151.12
H3	Top product of D104	215.8	40	456.9	2.60

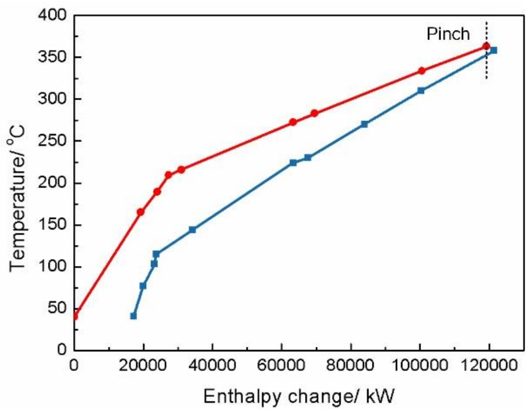

Figure 2: The Composite Curves

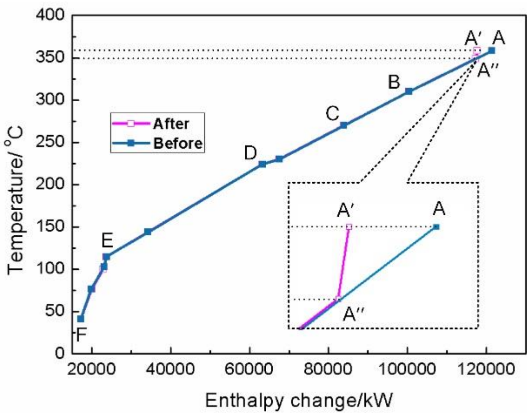

Figure 3: The change of Sink Composite Curve

With the catalyst of the reactor changed, the inlet temperature of R101 can be decreased from 358 °C to 350 °C. Since this stream is the mixture of the feed oil and hydrogen, and the temperature of the hydrogen, which flows out of furnace F101, can be kept unchanged, the target temperature of C2 will decrease to 349 °C. By simulation, it can be identified that both the target temperature of H1 and the supply temperature of H2 will increase to 212.3 °C, and the supply temperature of H3 will increase to 218 °C. The data of these streams are shown in Table 2.

To illustrate the variation of composite curve clearly, the sink composite curve shown in Figure 2 is plotted in Figure 3 and the main inflection points are marked with letters. The target temperature of C1 corresponds to point A and this sink only exists in the temperature interval between point A and B. When the target temperature of C1 decreases to 349 °C, the energy demanded by C1 will decrease by 3,560 kW. Point A″

corresponds the new supply temperature of C1, and lies on AB. Hence, C1 only appear in A"B, and will not appear in the temperature interval between point A and A″. Consequently, there is one sink less than before and it leads to a decrement of CP of in the temperature interval corresponding AA″. Point A will move leftward, and the decrement of enthalpy change equals the decrement of the energy demand of C1.The curve A′A″BCDEF is the new sink composite curve after the catalyst of reactor R101 is changed.

Table 2: The data of changed stream

Streams	T_S,°C	T_T, °C	Exchanger	ΔH, kW	CP, kW·°C $^{-1}$
C1	115	230	E104	36,090	313.83
	224.1	310	E102	31,060	361.58
	310	349	E101	15,050	385.90
H1	363	338.9	E101	15,050	624.48
	338.9	287.2	E102	31,060	600.77
	287.2	276.6	E103	6,149	580.09
	276.6	212.3	E104	36,090	561.28
H2	212.3	189	E106	3,244	139.23
	189	165	E107	4,686	195.25
	165	40	A101	18,890	151.12
H3	218	40	A102	478.7	2.69

Similarly, the source composite curve shown in Figure 2 is plotted in Figure 4 and all inflection points are marked with letters, as shown in Figure 4. Since both the supply temperature of H2 and the target temperature of H1 are increased to 212.3 °C, a horizontal line is plotted corresponding this temperature and intersects source composite curve at point F'. This means that the point corresponding to this temperature will shift from point F to point F’. As well, the point corresponds the target temperature of H3 will shift from point E to point E’ when it increases to 218 °C. The sources in the segments below point F do not change, and the CP in these segments do not change. Plot the horizontal line across F, and it intersects with the extending line of FG at point O. Shifting segment OGHI rightward until O coincides with F’, G, H and I will shift to G', H' and I'. AE′F′G'H'I′ is the new source composite curve. II′ stands for the decrement of cooling utility requirement, and equals 3,538.2 kW.

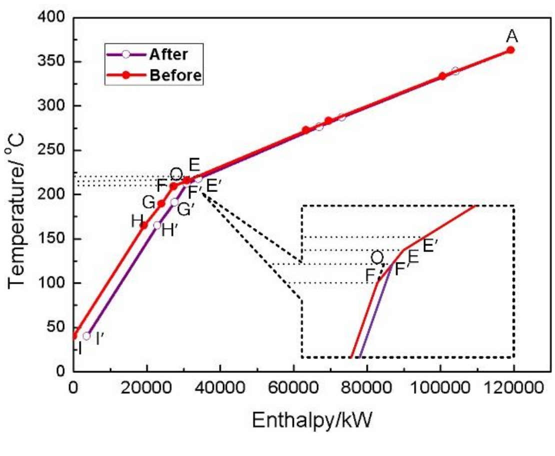

Figure 4: The Source Composite Curve

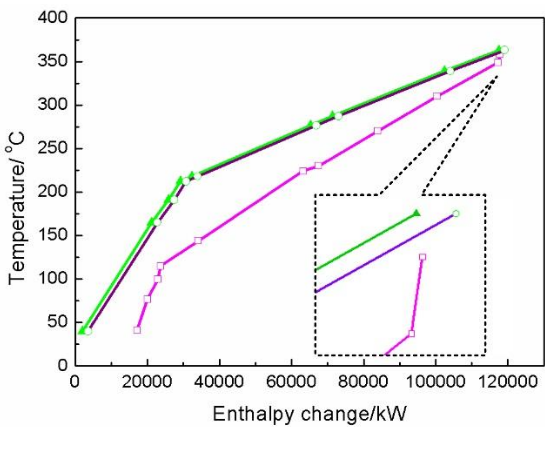

Figure 5: New Composite Curves diagram

With the new Source and Sink Composite Curves plotted together in Figure 5, it can be identified that the temperature approach at the top endpoint of the Sink Composite Curve is less than 10 °C. To meet the minimum temperature approach, the Source Composite Curve should be shifted leftwards or the Sink Composite Curve shifted rightward by 1,621.5 kW, as shown in Figure 5. The Pinch still appears at the top endpoint of the Source Composite Curve, and its average temperature is 358 °C. The minimum cooling and heating demands are 15,260.2 kW and 247.5 kW. Compared with the case before adjusting parameters, the decrement of cold and hot utilities are 1,916.7 kW and 1,938.54 kW.
According to Table 1 and Table 2, the Composite Curves can be plotted by the original Pinch Method, as shown by Figure 6. It can be identified that the cooling and heating demands and Pinch Point are in good agreement with those identified by the graphic method proposed above.

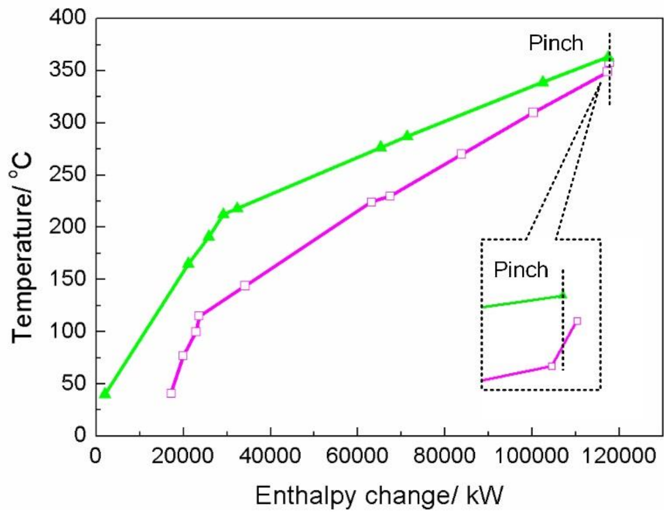

Figure 6: The Composite Curve plotted by the original Pinch Method

4. Conclusion

A graphical method is proposed and applied to analyze the influence of the reactor on the HEN integration of VGO hydrotreating process. By this method, the variation of heating and cooling utility and pinch point can be easily identified by shifting the corresponding section of composite curve below or above the inflection point. In the studied VGO hydrotreating process, when the inlet temperature of the reactor decreases, the heating utility consumption will decrease by 1,938 kW, accounts for 88.67 % of the heating utility consumption, while the cooling utility consumption decreased by 1,917 kW, accounting for 11.16 %. The variation of cold and hot utilities equals the difference of the decrement of energy supplied by the source that of energy demand of the sink, and the shifted distance.

The proposed method can be extended to analyse the influence of the operating parameters of reactor and other uncertainties on the HEN integration and derive the general rules. This will be studied in the further work.

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