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Strategy for Total Energy System Retrofit of a Chemical Plant

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A total energy system of a chemical plant includes reactors, separators, a heat exchanger network (HEN), and a utility system. For the retrofit to save energy, reactors normally are unchanged. Based on the “onion model”, the total energy system is divided into three subsystems, separation, heat exchange, and utility subsystems. The strategy for total energy system retrofit is proposed in this paper, which considers Heat Integration within each subsystem and coordination between each two subsystems. The first step is to find out the Pinch temperature of the HEN. According to the relative position of the endothermic and exothermic temperatures with the Pinch temperature, different retrofit strategies for separators will be used. For separators above or below the Pinch, Heat Integration between separators and between separators and the HEN should considered. The utility subsystem will be adjusted to fit the other subsystems, and heat engines and heat pumps are involved under economic consideration. To make coordination between each two subsystems, cycling calculation is needed. A caprolactam plant is used as the case study to show the proposed strategy.

1. Introduction

To enable the energy system with effective energy utilization, the integration between total sites are considered (Chen and Lin, 2011). The total site energy system is aiming at studying the Heat Integration of a whole chemical process system. A chemical process system is prettily complex, so it is better to divide it into subsystems when it is analyzed and optimized. A total energy system of a chemical plant includes reactors, separators, a HEN, and a utility subsystem. The hierarchy of a chemical process system can be represented by the “onion model” (Linnhoff et al, 1982).
Chemical Process Integration includes both Heat Integration within each subsystem and coordination between each two subsystems. Each layer of the “onion model” does not exist independently, but interrelates and affects one another.
There are two cases for the integration of the total site energy system, new design and retrofit. In this paper, the latter one is considered. For the retrofit to save energy, reactors normally are unchanged. Then the total system is divided into a HEN subsystem, a separation subsystem and a utility subsystem. At first each subsystem independent retrofit is considered, and then coordination between subsystems is considered.

2. Retrofit for subsystem

2.1 Heat exchanger network (HEN) subsystem

Based on Pinch Technology, the temperature - enthalpy diagram is used to analyze the HEN retrofit. The retrofit of an existing HEN is different from a new design. The structure of the current network should be fully taken into account. Fewer changes are preferred. For the retrofit, the three principles of Pinch Technology should be obeyed (Linnhoff et al, 1982):

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i) No heat transfer across the Pinch)
ii) No cold utility used above the Pinch,
ii) Nno hot utility used below the Pinch,

2.2 Separation subsystem

Energy saving in a separation subsystem includes two aspects, technique for a separator itself and Heat Integration between separators. Here we take distillation columns as an example.

(1) Single column

To describe the thermal characteristics of a distillation column, the condensing and reboiling process are assumed to occur at a constant temperature like a simple “box” (Mishra et al., 2005). For a column, the shorter the width of the rectangle, the less consumption of utility is (Nie et al., 2012). The Column Grand Composite Curve can be used to analyze how to get the best energy performance through the retrofit of the column.

The energy saving methods for a single column include reducing the reflux ratio, preheating the feed, adding middle condensers and reboilers, multi-efficient distillation, distillation with heat pump and so on (Feng, 2009).

(2) Heat Integration between columns

In a distillation column system, an overhead stream in one column can supply heat to a bottom stream in another column, so that the utilities can decrease.

If there is no suitable temperature difference between the integrated reboilier and condenser, direct Heat Integration cannot be performed. Adjusting pressure may be considered for the reboiler and/or the condenser to make the integration feasible (Yao, 2009).

2.3 Utility subsystem

The heating duties and cooling duties not serviced by heat recovery will be provided by utilities. The most common hot utility is steam. Cold utilities may be cooling water, refrigeration etc.

The Grand Composite Curve (GCC) is used to decide the duty of the utility at each level. According to the steam demand at each pressure level, heat engines can be considered to reduce the use of external fuel (Klemeš et al., 1997).

3. Coordination between subsystem

3.1 Coordination between separation subsystem and HEN subsystem

There are significant interactions between the separation subsystem and the HEN (Smith et al., 2010). The GCC of the background process (which does not include the reboilers and condensers) is used to consider the Heat Integration of columns.

(1) Columns not across the Pinch

For a column above the pinch, the reboiler can be serviced directly from the hot utility with the condenser integrated above the Pinch. And for a column below the Pinch, the condenser can be serviced directly by cold utility with the reboiler integrated below the Pinch (Cuthrell and Biegler, 1987). In this way, the utilities can be obviously reduced.

For a column across the Pinch, if changing its pressure is allowable, the column can be shifted above or below the Pinch. Once the column’s pressure changes, the feed preheat and product cooling status will change accordingly, which will affect the thermal feature of the background process and even the Pinch position.

Sometimes, the separation subsystem cannot be completely integrated with the background process. In this case, the energy saving technique described for signal column can be considered to reduce the heat duty of the reboiler and condenser.

So coordination between the separation and HEN subsystems is needed.

(2) Columns across the Pinch

Not all columns across the Pinch can be shifted above or below the Pinch. For example, increasing pressure is not good for separation, especially for heat-sensitive material. Along with the temperature reduction of a column, the gas density in the column is decreased and so does the processing capacity of the column.

If a distillation column cannot be shifted the relative position with the Pinch, it can be treated as a stand-alone column. The energy saving technique described for signal column can be considered.

3.2 Coordination between separation subsystem and utility subsystem

Adopting energy saving techniques in the separation subsystem will influence the utility demands to the utility subsystem. In addition, it should be analyzed whether a column uses a higher level utility than should be. In industries, a column uses a higher level utility is a common case.

3.3 Coordination between HEN subsystem and utility subsystem

The GCC is used to analyze the relationship between the HEN subsystem and utility subsystem. Figure1 shows the usage of steam in the GCC under current operating conditions. It is obvious that the high pressure steam (HPS) that located on the extension portion of the left side can be partly replaced by the medium pressure steam (MPS), while the MPS can also be partly replaced by the low pressure steam (LPS). Then the LPS and MPS curves arrive at the GCC, forming the Pinch Point of the utility subsystem. In this way, the usage of high quality steam decreases and the usage of low quality steam increases, as shown in Figure 2.

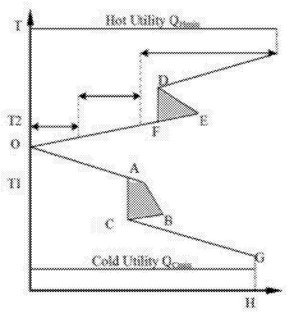

Figure1: Current steam usage in the GCC

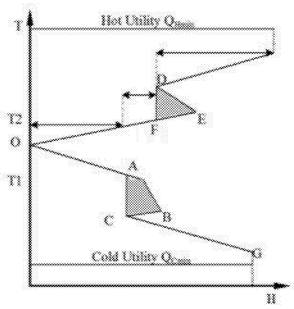

Figure2: Steam usage in the GCC after retrofit

Similarly, for the cold utility below the Pinch, the utility subsystem can be analyzed in the same way, that is cooling water is used to replace chilled water and chilled water with higher temperature is used to replace the one with lower temperature.

4. Procedure of Energy Integration for Total Site System Retrofit

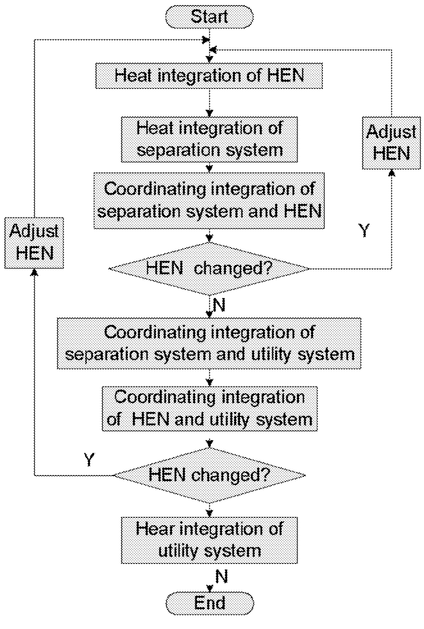

Figure 3: Procedure of energy integration for total site system retrofit

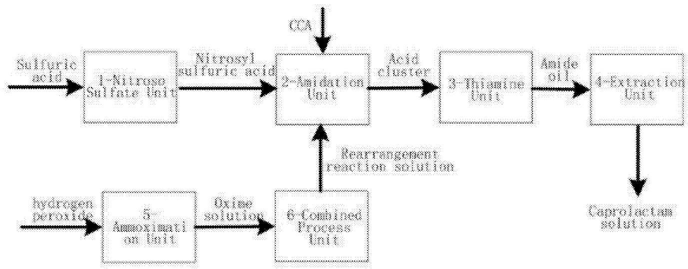

Figure 4: Caprolactam production process diagram

Energy integration for total site system retrofit is not simply Heat Integration from one subsystem to another, because each step of the retrofit may affect the other subsystem. So in the retrofit process, cycle analysis and calculation are needed to achieve the eventual balance.

Total site system retrofit energy integration analysis starts from the Heat Integration of each subsystem, especially the HEN, and then the coordination between subsystems is considered. The concrete steps are shown in Figure 3. The Pinch position of the HEN is determined first, because the subsequent analysis and optimization is based on the Pinch position. Then the separation system is considered, including single columns and the column system. After that the coordination between the separation subsystem and the HEN subsystem is considered. The retrofit of the separation subsystem will affect the HEN subsystem, causing a change of the HEN's matches, so that new Heat Integration for the HEN may be needed. Next is the coordination between the separation subsystem and the HEN subsystem with utility subsystem separately. And the coordination between HEN subsystem and the utility subsystem can also have impacts on the HEN, so that the Heat Integration of the HEN is considered again. After all the retrofit, the supply and demand of different levels of steam are fixed, and so the last one analyzed is the Heat Integration of utility subsystem.

5. Case study

In this paper, the complex Heat Integration in a chemical company is chosen as a case study. The chemical company mainly produces caprolactam solution. The process has six units, whose relationship is shown in Figure 4.

5.1 HEN subsystem integration

The temperature of the hot streams at Pinch Point is 105.7 °C and that of the cold ones is 95.7 °C (ΔT_{min} = 10 °C). The energy saving potential is 6,885 kW. The Composite Curve and the Grand Composite Curve are shown in Figure 5 and Figure 6.

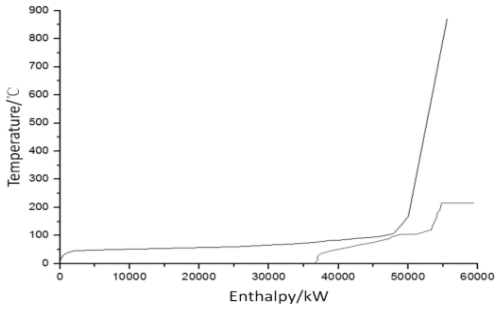

Figure 5: *The Composite Curve of the HEN*

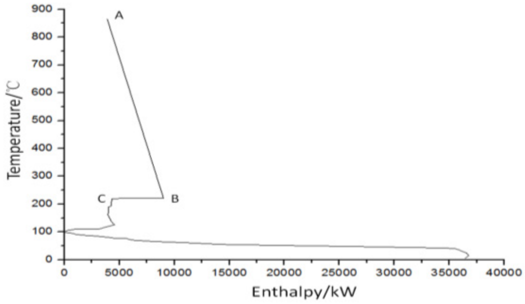

Figure 6: *The GCC of the HEN*

After an initial retrofit (complying with the three principle of Pinch Technology), six heat exchangers are added and 4,946 kW hot and cold utility are saved.

5.2 Separation subsystem integration and its coordination with HEN subsystem

Five distillation columns are discussed in the separation subsystem. Their positions with Pinch Point are shown in Table 1. So T-401, T-501 and T-502 crossing the Pinch Point are chosen to be adjusted to the position above or below the Pinch Point.

After simulation for pressure adjusting, only T-401 can be moved above the Pinch Point. While T-501 and T-502 still cross the Pinch as they cannot be adjusted above or below Pinch Point. So decreasing the reflux ratio is chosen to reduce the energy consumption of the two columns.

After the pressure adjusting, finally there are two columns above the Pinch and one below it. However, the heat duty released by the condensers of T-503 and T-401 is more than the demand of the HEN subsystem. So reducing their reflux ratio is considered. Then the columns' position on the GCC are shown in Figure 7

The heat duty released by the condensers is still greater than the demand above the Pinch point. So, the extra part (B-C) can be applied to T-101, through which there is no need to change some heat exchanger matches below the Pinch.

Then the condensers of T-503 and T-401 and the reboiler of T-101 are considered into the HEN. After a new match process, nine new heat exchangers are added and the energy saving of the hot and cold utilities is both 10341kW, which is more than 5,381 kW compared to the former retrofit.

5.3 Coordination of HEN subsystem and utility subsystem

In Fig.6, there is a huge "heat pocket" (A-B-C) in the curve, which exists in unit 1.The heat is recovered to generate HP steam (225 °C, 1.7 MPa) currently, shown in Fig.8. However, some SHP steam (386 °C, 3.5 MPa) can be generated by using the heat between 436 °C and 870 °C at the minimum temperature difference as 50 °C, and at the same time, the yield of the high pressure steam will be reduced, as shown in Fig.9. In this way, the SHP steam increases 5.9 t/h and the HP steam decreases from 8.6 t/h to 2.4 t/h.

At the same time, there are some improper usages of hot and cold utility in the HEN. In the retrofit process, the low-quality utilities are preferred to replace the ones with high-quality.

Table1: The position between column and Pinch Point

Column No.	Condenser Temperature	Reboiler Temperature	The Relationship Between a Column and Pinch Point
T-101	65	85	Below the Pinch
T-401	97.5	104.3	Cross the Pinch
T-501	75	118	Cross the Pinch
T-502	54	124	Cross the Pinch
T-503	115	159	Above the Pinch

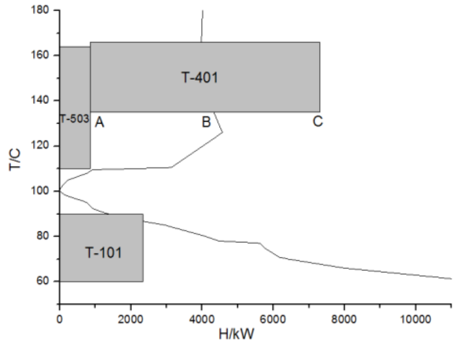

Figure 7: Columns' position on the GCC

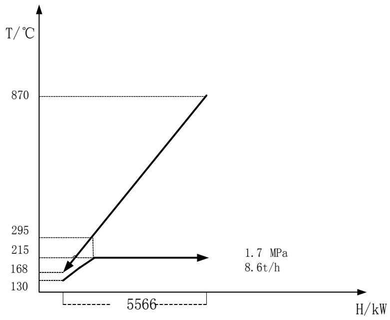

Figure 8 The current heat recovery situation of unit 1

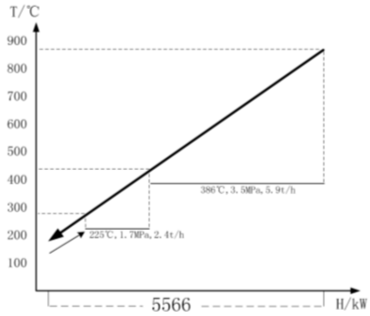

Figure 9 Heat recovery situation of unit 1 after retrofit

5.4 Steam subsystem retrofit

Through the above retrofit, the heat duty changes of different utilities are shown in Table 2, which obviously affect the conversion between different levels of steam. Currently flowrate changes steam at different pressure level are performed by valves to reduce the pressure and temperature, as shown in Table 3, which causes 13,854 MJ/h of exergy lose.

Table 2: Changes of different utilities

Utility	Change
SHPS	Production increased by 5.9 t/h
HPS	Production decreased by 6.2 t/h, usage decreased by 1.65 t/h
IPS	usage increased by 15.76 t/h
MPS	usage decreased by 6.9 t/h
LPS	usage decreased by 29.66 t/h
Cooling Water	usage decreased by 492.49 t/h
Chilled Water	usage decreased by 128.45 t/h

Table 3: Flowrate through valves

Pressure levels	Flowrate before retrofit (t/h)	Flowrate after retrofit (t/h)	Exergy loss after retrofit (MJ/h)
SHPS→HPS	32.3	34.21	8535
HPS→MPS	18.4	0	
HPS→IPS	28.5	44.26	4339
MPS→LPS	20.6	9.1	980

Table4: New turbines

Turbine	Level change	Flow rate (t/h)	Work (kW)
T-1	SHP→HP	34.21	1,324
T-2	HP→IP	44.26	1,076
T-3	MP→LP	9.1	336
T-4	LP	18.16	1,944

In order to decrease the exergy loss, the cogeneration of power and heat strategy is adopted. In this case, four steam turbines are added as shown in Table 4, in which the last one is a condensing steam turbine, and the others are back pressure turbines. The total turbine work output is 4,680 kW.
After a new balance of the steam subsystem, as a total, 3.99 t/h SHP steam can be saved and 4,680 kW power can be generated.

Conclusion

In this paper, the strategy for total energy system retrofit is proposed. The procedure is based on the “onion model”. The first step is to find out the Pinch temperature of the HEN. According to the Pinch position, initial retrofit for HEN and separation subsystems is considered. Coordination between subsystems is needed. Adjusting the utility subsystem will be the last step to fit the other subsystems.
A caprolactam plant is used as the case study to show the proposed strategy. The retrofit decreases 3.99 t/h SHP steam, 482.49 t/h cooling water and 128.45 t/h chilled water, and increases 4,680 kW power.

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