Chapter 2
Reaction Section

Abstract The naphtha hydrodesulfurization (HDS) process in the refinery has a reaction section which is a heating and cooling thermal process consisting of a feed-effluent heat exchanger and a fired heater. Energy savings are fundamentally made as a result of the maximized heat recovery in the heat exchanger and the reduced heat duty of the fired heater. To achieve further energy saving in the process, "self-heat recuperation technology" (SHRT) was adopted by a naphtha HDS process with the capacity of 18,000 barrel per stream day (BPSD). A compressor was introduced in this technology. The suction side of the compressor needed lower pressure so that the feed stream could evaporate more easily. The discharged side of the compressor satisfied the operating conditions of both pressure and temperature at the inlet of the reactor. And the reactor effluent stream was able to be used completely to preheat and vaporize the feed stream. All the heat in the process stream was recirculated without the necessity of a fired heater. It was confirmed that despite there being no more energy saving potential in the conventional process that makes use of a fired heater, the advanced process based on SHR can reduce the energy consumption significantly by using the recuperated heat of the feed stream.

Keywords Self-heat recuperation technology · Reactor · Naphtha · Hydro desulfurization · Compressor · Minimum temperature difference

2.1 Introduction

The naphtha hydrodesulfurization (HDS) process, a well-known process adopted by refineries, uses a fired heater in the reaction section to heat the process streams. The reaction section of such process is a heating and cooling thermal process

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consisting of a feed-effluent heat exchanger and a fired heater. The fired heater consumes not only a large amount of energy but also a large amount of exergy during combustion due to the large temperature difference in the fired heater between fuel combustion (over 800 °C) and process condition (around 300 °C) for the reactor.

Energy savings are fundamentally made as a result of the maximized heat recovery in the heat exchanger and the reduced heat duty of the fired heater. In order to reduce energy consumption in the fired heater, pinch technology has been widely applied for heat recovery to save energy in a plant or a complex of plants. To achieve further energy saving in the process, "self-heat recuperation technology" (SHRT) was adopted (Matsuda et al. 2010).

2.2 Process Flow Description

Figure 2.1 shows the naphtha HDS process (conventional case). Liquid naphtha is pumped and mixed with compressed hydrogen and then the mixed stream of naphtha and hydrogen gas, which has a vapor/liquid mixed phase, is heated in a heat exchanger. The stream is further heated by a fired heater to the required condition (300 °C) for the reactor. Because of the temperature difference between the process requirement (300 °C) and the inside of the fired heater (>800 °C), fuel combustion causes a large exergy loss. The reactor effluent stream is cooled down by the heat exchanger and the cooling water cooler.

2.3 Applying Self-Heat Recuperation Technology

Figure 2.2 shows the application of SHRT (proposed case) to naphtha HDS process. A reactor charge compressor is installed and the heat exchanger is revamped to increase its surface area. The liquid naphtha is pumped and mixed with hydrogen gas without the necessity of a hydrogen compressor, and then the mixed stream of naphtha and hydrogen gas is heated and vaporized totally in the heat exchanger by the effluent heat. Finally, the feed stream is compressed by the reactor charge compressor to satisfy the operating conditions of both pressure and temperature for the reactor. The heat of the reactor effluent stream completely preheats and vaporizes the feed stream. As a result, the self-heat of the process streams can be recirculated in the process without requiring any additional heat source, leading to the reduction in the aforementioned exergy loss.

Fig. 2.1 Conventional case of naphtha HDS process

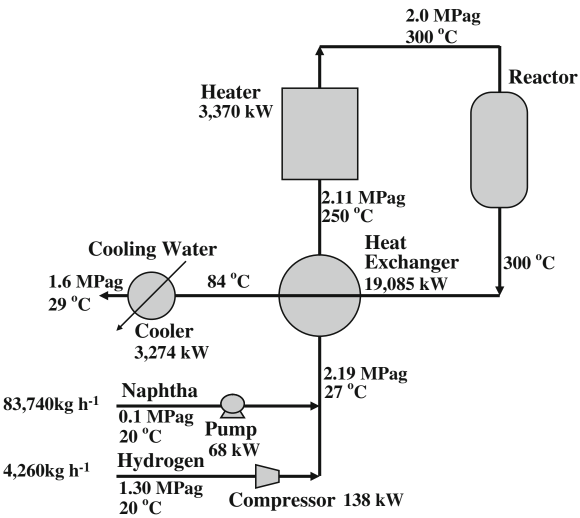
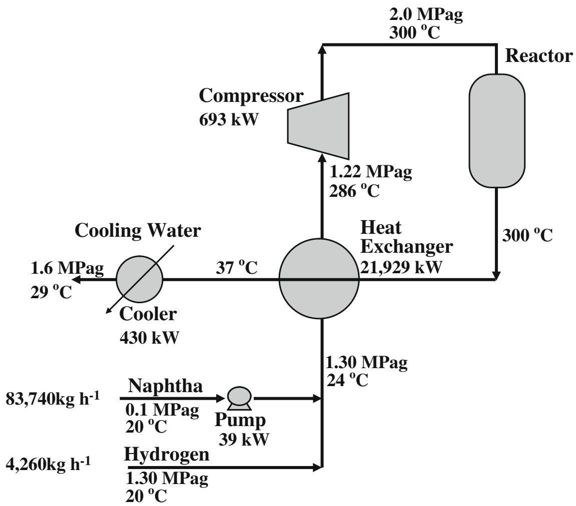


Fig. 2.2 Proposed case



2.4 Prospect of Applying Self-Heat Recuperation Technology

Tsuru et al. 2008 and Kansha et al. 2009 reported that SHRT was used for heating and cooling in thermal processes by pressure change and it could achieve perfect internal heat circulation in a feed-effluent heat exchanger as shown in the temperature-heat diagram of the proposed case from Sect. 1.2. The reactor charge compressor is used in the naphtha HDS process as shown in Fig. 2.2. By compressing the stream, the stream pressure and its temperature are both increased simultaneously. The feed stream to the heat exchanger needs to be set at a lower

Table 2.1 Study basis

Case	Conventional	Case-1	Case-2 [ultimate]	Proposed
Minimum temperature difference in heat exchanger, K	16.2	11.5	0.01	11.5
Heat exchanged, kW	19,085 (−)	19,806 (+4 %)	21,658 (+13 %)	21,929 (+15 %)

pressure than that in the conventional naphtha HDS process (conventional case), which then allows the reactor inlet pressure in the proposed case to remain the same as in the conventional case. As explained in Sect. 1.2, the boiling temperature is shifted from T_b to $T_{b'}$ by the pressure change of the feed stream, which allows the latent heat to be exchanged between the feed and effluent streams. All the heat of the process stream is recirculated in the process without the necessity of a fired heater, which means that the heat of the reactor effluent stream can be used completely to preheat and vaporize the feed stream, resulting in a drastic reduction in the energy consumption of the process.

2.5 Mass and Heat Balance Calculation

The energy required for the conventional and the proposed cases of the naphtha HDS process in a refinery was calculated by using a commercially available simulator, PRO/II^{TM} version 8.1 (Invensys). The Soave–Redlich–Kwong equation of state was applied. Figures 2.1 and 2.2 show the results of the case studies. The throughput of the naphtha HDS process was 18,000 barrel per stream day (BPSD) with the inlet condition of the reactor set to 2.0 MPag and 300 °C. Table 2.1 shows the conditions of the minimum temperature difference (ΔT_{min}) in the case studies. In the conventional case (current operating condition in a commercial plant), ΔT_{min} was 16.2 K. Another simulation was then run, for comparison purposes, under ΔT_{min} (11.5 K) to establish the heat and pressure balance around the compressor for proposed case and conventional process (Case-1). In order to confirm the thermodynamic limit in the conventional process, Case-2 (0.01 K) was prepared as the ultimate condition requiring an infinitely large surface area.

2.5.1 Conventional Case

As shown in Fig. 2.1, the naphtha pump and hydrogen compressor in the conventional case raised the pressure of the streams to 2.19 MPag, so as to meet the required pressure at the inlet of the reactor. After heat recovery through the heat exchanger, the stream was 2.11 MPag and 250 °C at the inlet of fired heater, which was then heated to 300 °C in the fired heater. The heat duty (3,274 kW) of

Table 2.2 Study results

Case	Conventional	Proposed	
Minimum temperature difference in heat exchanger, K	16.2	11.5	
1. Exergy input, kW			
1) Fired heater	3,370	–	
2) Naphtha pump	68	39	
3) Hydorgen compressor	138	–	
4) Reactor charge compressor	–	693	
Total	3,576 (100 %)	732 (20 %)	
2. Energy input, kW			Efficiency
1) Fired heater	3,965	–	1) 85 %
2) Naphtha pump	310 a	172 b	2) a: 60 %, b: 62 %
3) Hydorgen compressor	454	–	3) 83 %
4) Reactor charge compressor	–	2,014	4) 94 %
Total	4,729 (100 %)	2,186 (46 %)	(2)–(4) Power generation efficiency: 36.6 %

the cooling water cooler was almost the same as the heat duty (3,370 kW) of a fired heater, which meant that this process consumed a large amount of high-grade heat in the fired heater and exhausted a large amount of low-grade heat in the cooling water cooler.

Table 2.1 indicates that the heat duty in the heat exchanger increased, as Case-1 and Case-2 were 4 and 13 % larger respectively than that in the conventional case. In Cases 1 and 2, $\Delta T_{\min}$ decreased, meaning that surface area of the heat exchanger increased compared with conventional case.

Table 2.2 shows the exergy and energy input to the naphtha HDS process (conventional case). The sum of exergy input in conventional case (a fired heater, a naphtha pump and a hydrogen compressor) was 3,576 kW and the sum of energy input was 4,729 kW.

2.5.2 Proposed Case

In the proposed case (Fig. 2.2), the installation of a compressor resulted in a decrease in the pressure of the feed stream at the inlet of the heat exchanger (1.30 MPag) compared with the conventional case (2.19 MPag), which reduced the naphtha pump power from 68 to 39 kW. Because hydrogen gas at 1.3 MPag was supplied from an outside process, it could be fed directly in the proposed case without the requirement for a hydrogen compressor, resulting in further energy saving. The power of the compressor was 693 kW, which was only 20 % of the heat duty of the fired heater in conventional case (3,370 kW). The heat duty (430 kW) of the cooling water cooler was almost the same as the power of the compressor.

As can be seen in Table 2.1, the heat exchange duty in the proposed case, which was 11 % more than that of Case-1, could be increased by 15 % as compared with the conventional case.

In the proposed case in Table 2.2, the sum of exergy input (a naphtha pump and a reactor charge compressor) was 732 kW, which was only 20 % of the conventional case. Taking equipment efficiency and power generation efficiency into account (36.6 % in the Japanese energy saving law), the sum of energy (enthalpy) input was 4,729 kW in the conventional case and 2,186 kW in the proposed case, and the energy consumption in the proposed case was 46 % of that in the conventional case. The amount of energy saving was calculated to be 1,900 kL y^{-1} (kiloliter per year) by annual crude oil conversion. This is equivalent to 7.4×10^4 GJ y^{-1} (gigajoule per year).

2.6 Discussion

The design strategy of a heat pump was recently introduced, with process integration under optimal matching (Fonyo and Benko 1996; Wu et al. 1998; Smith et al. 2005). Energy and exergy analysis of the heat pump was applied by Ceylan et al. 2007. Pavlas et al. 2010 designed the heat pump system with the aid of Grand Composite Curve. The heat pump was applied to several thermal processes; the liquefaction process of natural gas (Aspelund et al. 2007), the open air–vapor compression refrigeration system (Hou et al. 2007), multi-function heat pump system (Gong et al. 2008), the ground source heat pump system (Tarnawski et al. 2009), and the refrigeration process using moist air and water (Hou and Zhang 2009). The ambient heat or the process waste heat is generally pumped by the heat pump to heat/cool the process stream by the working fluids (steam, CO_2, etc.). Because the temperature difference between the heat source and the feed stream is much larger than that in the heat exchanger in proposed process, the heat pump system requires more power to improve the quality of the heat from the heat source to the heater condition than the power required in the proposed process based on SHR.

As one of the heat recovery technologies, the vapor recompression technology has been applied to evaporation (Ettouney 2006; Nafey and Fath 2008), distillation (Brousse et al. 1985; Annakou and Mizsey 1995; Haelssig et al. 2008), and drying (Fehlau and Specht 2000). This technology compresses the vapor to a higher pressure and then the pressurized vapor provides a heating effect when condensing. However, such technology did not utilize the condensation heat efficiently in the heat exchanger. In contrast, SHRT can utilize the condensation heat thoroughly by changing the shape of the temperature-heat line in the heat exchanger because the installation of a compressor results in a change in the pressure balance. The feed stream is completely preheated and vaporized by the heat of the reactor effluent stream, which means that all the heat of the process streams was recirculated in the process without needing to use a fired heater. Consequently, SHRT could reduce

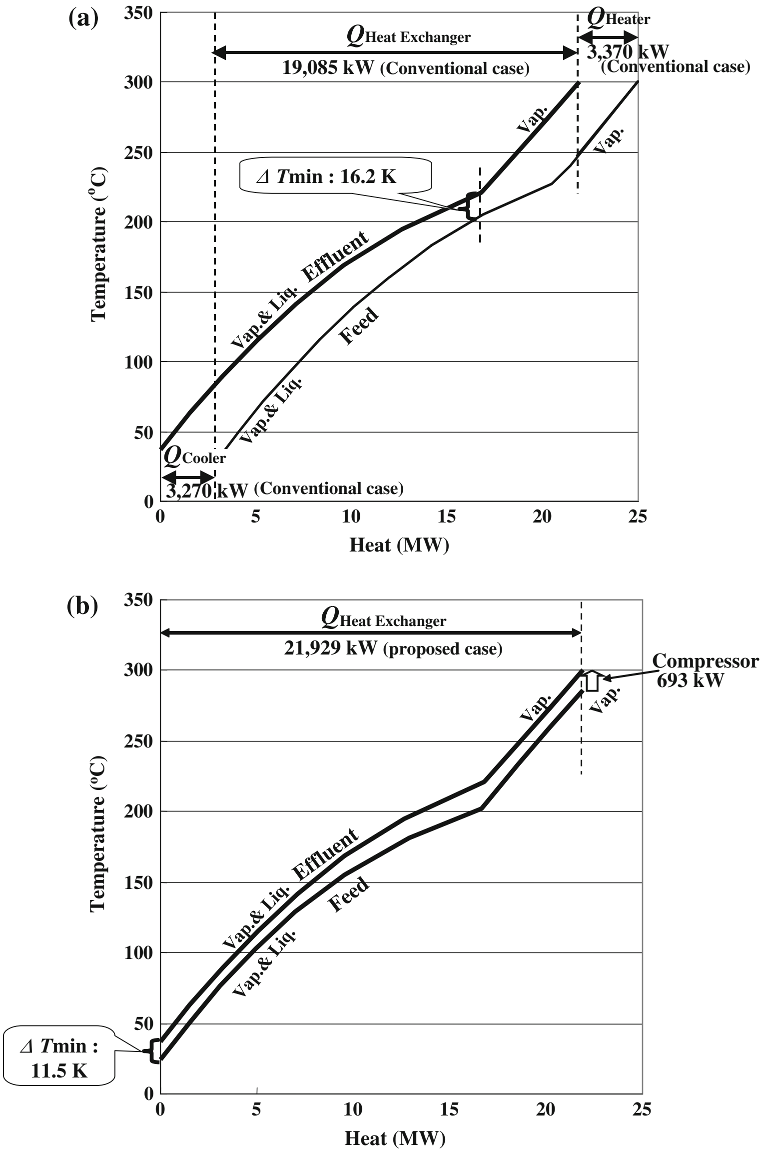


Fig. 2.3 Temperature-heat diagram of **a** conventional case and **b** proposed case

the exergy loss in a fired heater and in a cooling water cooler. It should be noted that the required heat input in the proposed case was obtained not by firing fuel but by working power.

Figure 2.3 shows the temperature-heat diagram for feed and effluent streams in the conventional and proposed cases, respectively. The feed stream and the effluent stream are both represented in Fig. 2.3a. The feed stream, which is a mixed stream of naphtha and hydrogen gas, has a pinch point (ΔT_{min} = 16.2 K) against the effluent stream in the conventional case. By following pinch technology, the cold composite curve is moved horizontally within the temperature limits to pinch point in order to increase the heat recovery. By increasing the surface area in the conventional case, the feed stream could be moved closer, horizontally. This would be Case-1 whereby ΔT_{min} became 11.5 K, resulting in an increase of 4 % in the heat recovery as shown in Table 2.1.

In Fig. 2.3b, the installation of the reactor charge compressor in the proposed case can reduce the pressure of the feed stream at the heat exchanger compared with the conventional case. By decreasing its pressure, the feed stream was moved and finally approached the effluent stream much more closely. As a result, the heat recovery was vastly increased to 21,929 kW, 15 % more than the conventional case, where ΔT_{min} was 11.5 K. It should be noted that the amount of heat recovery (21,929 kW) in the proposed case was still more than 21,658 kW of the ultimate condition in Case 2 as shown in Table 2.1, which indicates that the SHRT is effective to increase energy efficiency.

2.7 Conclusion

In the naphtha HDS process (conventional case) with a fired heater, the heat energy was heretofore cascaded from high-grade heat to low-grade heat and then low-grade waste heat was discarded from the process. The advanced process using SHRT (proposed case) was developed to utilize the heat of the stream itself by effectively introducing a reactor charge compressor. The process heat energy itself was recuperated and utilized based on exergy recuperation, which ensured that the necessary heat input was obtained not by firing at the fired heater but by working power from the reactor charge compressor. As the heat exchange duty could be increased by 15 %, the energy and the exergy inputs in proposed case were significantly reduced (46 and 20 %) as compared with the conventional case. The cooling water cooler duty could also be decreased considerably from 3,274 to 430 kW.

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