Evaluation of phase separator number in hydrodesulfurization (HDS) unit

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Abstract. The removal process of acid gases such as \( \text{H}_2\text{S} \) in natural gas processing industry is required in order to meet sales gas specification. Hydrodesulfurization (HDS) is one of the processes in the refinery that is dedicated to reduce sulphur. In HDS unit, phase separator plays important role to remove \( \text{H}_2\text{S} \) from hydrocarbons, operated at a certain pressure and temperature. Optimization of the number of separator performed on the system is then evaluated to understand the performance and economics. From the evaluation, it shows that all systems were able to meet the specifications of \( \text{H}_2\text{S} \) in the desired product. However, one separator system resulted the highest capital and operational costs. The process of \( \text{H}_2\text{S} \) removal with two separator systems showed the best performance in terms of both energy efficiency with the lowest capital and operating cost. The two separator system is then recommended as a reference in the HDS unit to process the removal of \( \text{H}_2\text{S} \) from natural gas.

1. Introduction

Hydrotreating process (HDT) is one of the most important processes in the refinery to reduce sulfur, nitrogen, oxygen, metals and other contaminants from the oil fraction at high operating conditions [1]. When the process is dedicated to remove sulfur only, the process known as hydrodesulfurization (HDS). One of the common schematic diagram of HDS in the petroleum refinery unit is shown in Figure 1. Currently, there were ca. 30 licensed HDS processes and most of them have the same basic process principles.

Various studies have been conducted to improve the HDS unit to produce the desired product while increasing profit, eg. [2] or other promising technologies, eg. [3-8]. However, none of studies was found in the literature that focuses on the separation configuration (see the configuration inside the box of Figure 1). In the HDS, phase separator serves to separate fluid in different phases, ie. oil, water, and gas, at a certain pressure and temperature. Some of the refining industries, the HDS units were equipped with one separator while others have two separators [9,10]. These two different configurations should produce different result in term of utility consumption and economic consideration. To understand the influence of the number of separator on the HDS unit, in terms of both performance and cost HDS unit, optimization of the number of separator in HDS unit were required to be done. In this study, we evaluated the separation process modelling (process configuration inside the box of Figure 1) by varying the number of phase separators in the HDS unit.
2. Methodology
The quantitative analysis was initiated by the construction of the process system model. The established process models that have been made were then validated by data literature or actual data from the field. This step is necessary to allow the model to be correct and could be used for the next step of the simulation.

2.1. Simulation Process Specification
In this study, two scenarios have been made to consider the H$_2$S concentration in the feed. Scenario 1 simulated the H$_2$S concentration of 0.59%-mol while Scenario 2 was conducted by using H$_2$S concentration of 10%-mol. Detail feed and product specification used in this model as well as the feed process condition are shown in Table 1 and 2.

| Process Properties | Scenario 1 | Scenario 2 |
|--------------------|------------|------------|
| Pressure           | 689 psig (47.5 barg) | 689 psig (47.5 barg) |
| Temperature        | 550°F (287.8°C) | 550°F (287.8°C) |
| Flow rate          | 2355 kmol/h | 2355 kmol/h |
| Component          |             |            |
| H$_2$              | 82.58%-mol  | 73.31%-mol |
| H$_2$S             | 0.59%-mol   | 10%-mol    |
| Ammonia            | 0.09%-mol   | 0.09%-mol  |
| C1                 | 4.09%-mol   | 4.06%-mol  |
| C2                 | 0.43%-mol   | 0.43%-mol  |
| C3                 | 0.16%-mol   | 0.16%-mol  |
| iC4                | 0.04%-mol   | 0.04%-mol  |
| nC4                | 0.04%-mol   | 0.04%-mol  |
| iC5                | 0.05%-mol   | 0.05%-mol  |
| nC5                | 0.1%-mol    | 0.1%-mol   |
| Diesel             | 2.31%-mol   | 2.30%-mol  |
| Gas Oil            | 8.53%-mol   | 8.48%-mol  |
| Naphtha            | 0.98%-mol   | 0.98%-mol  |
Table 2. Product composition and properties

| Process Properties | Naptha | Diesel | Gas Oil |
|--------------------|--------|--------|---------|
| Molecular weight   | 152.3  | 210.6  | 282.7   |
| Boiling point (°C) | 197.5  | 277    | 335.8   |
| Density (kg/m³)    | 803.6  | 843.3  | 886.8   |
| Critical temperature (°C) | 388.2 | 465.6  | 526.5   |
| Critical pressure (bar.g) | 21.97 | 17.24  | 15.65   |
| Component          |        |        |         |
| H₂S (ppm)          | < 650  | < 10   | < 10    |
| H₂O (ppm)          | < 300  | < 50   | < 50    |

2.2. Model Development

Three different simulation models were built to evaluate to suitable number of separators, ie. one (HDS-1), two (HDS-2), and three (HDS-3) phase separator, used in HDS unit. Figure 2 shows the three simulation models of separator in HDS unit.

Feed is cooled to a temperature of 122°F prior to entry into the separator. The temperature of 122°F is the optimal temperature for the desired separation. Wash water is added to the flow to reduce the concentration of unwanted gas in the recycle gas (increasing purity) and to dissolve NH₄Cl that may form and cause deadlock. Vapor result from separator flow into the amine treating gas scrubber, while the liquid heated to 413°F before entering stripper that uses steam as a medium discharger. At the bottom of the cold separator is the output of sour water. Stripper aims to control the sour water until the content of H₂S and NH₃ in the water effluent are quite low and safe for the environment to be disposed. This unit also serves to sharpen separation of components; so that it can improve the quality of a product by separating unwanted light fraction in the product. Stripper top output is sour gas and naphtha while in the bottom is the desired product. In the bottom of the stripper is injected steam at a pressure of 50 psig and temperature of 446°F. Steam injection aims to lower the partial pressure above the liquid surface, so that the light fraction is entrained to the bottom of stripper column will be more volatile and returned to the fractionation column. Stripper top output is sour gas and naphtha while in the bottom is the product.

All simulation was conducted by process simulator Aspen Hysys v.8.8 as well as Aspen Economic Evaluation for plant cost estimation. In some cases, process simulator could calculate and predict to evaluate the plant process performance, eg. [11]. From the simulation results of each scenario, it will be observed product specifications, system performance, sizing equipment (separator, stripper, reboiler, and condenser), as well as capital and operating costs of the system. Once all steps have been done, the final step is to evaluate the final result and determine which model is most suitable to be applied to the process of H₂S degassing.
Figure 2. Process Flow Diagram of three HDS simulation models: (1) One separator system or HDS-1; (2) Two separator system or HDS-2; and (3) Three separator system or HDS-3.

3. Result and Discussion
The simulation result of three models are tabulated in Table 3. All separator systems were capable to remove $\text{H}_2\text{S}$ and $\text{H}_2\text{O}$ below the limit value in the product. The product has a high purity $>99.5\%$ and naphtha produced from all separator system contains $\text{H}_2\text{S}$ below the limit value. The content of $\text{H}_2\text{O}$ in all separator system exceeds a predetermined limit, each 610.87 ppm, 497.78 ppm, and 496.84 ppm. As the $\text{H}_2\text{O}$ content is still very high (above 400 ppm), dehydration is required before naphtha is supplied to the consumers.
Table 3. Comparison simulation result of three HDS with different separator systems

| Process Properties | HDS with 1 Separator | HDS with 2 separators | HDS with 3 separators |
|--------------------|---------------------|-----------------------|-----------------------|
| Diesel Product     |                     |                       |                       |
| Flow rate (kg/h)   | 68,323.25           | 68,322.23             | 68,323.25             |
| Content of H₂S (ppm)| 0                  | 0                     | 0                     |
| Content of H₂O (ppm)| 27.85              | 27.93                 | 27.85                 |
| Purity (%-wt)      | 99.88              | 99.88                 | 99.88                 |
| Naptha Product     |                     |                       |                       |
| Flow rate (kg/h)   | 3,449.75            | 3,437.84              | 3,449.75              |
| Content of H₂S (ppm)| 333.74             | 332.82                | 333.74                |
| Content of H₂O (ppm)| 496.84             | 497.78                | 496.84                |
| Purity (%-wt)      | 98.79              | 98.80                 | 98.79                 |

As shown in Figure 3, HDS unit with one separator system (HDS-1) has the highest workload of heating and cooling among other separator systems. One separator system used a heater that requires high energy consumption, as well as its cooler that has very large workload than any other separator systems. At one separator system, all feed cooled from 550°F into 122°F. The large of feed flow rate which is still in two phases increases the workload on the heat sink. This could be the reason why workload on the cooling unit is very high. In two (HDS-2) and three (HDS-3) separator system, the feed was separated first at hot separator. Vapor outlet from separator then cooled from 550°F to 122°F. Although the temperature difference among HDS-1, HDS-2, and HDS-3 are same, but the flow rate of one separator system (HDS-1) is the highest than others. The fluid flow rate of one separator system which shall be cooled was ca. 2,355 kmol/h while two and three separator system was only 2,095 kmol/h.

![Figure 3](image_url)  
**Figure 3.** Utility workload comparison of the three HDS units.

At one separator system (HDS-1), the fluid has to be heated from the cold separator is very large. While the two other separator systems, the fluid to be heated is divided into two streams. The first stream coming from the hot separator and the second comes from the cold separator. This results the load heating of HDS-2 and HDS-3 were not as big as one separator system (HDS-1).

Although it seems one separator system is a simple process, it shows that the capital cost (CAPEX) to build the system is the highest among others. Figure 4 shows that the HDS unit with one separator (HDS-1) requires capital and operational costs the highest among the other separator systems. Total cost for the HDS one separator system reached 26.98 million USD while HDS two separators system (HDS-2) have the lowest investment costs 15.64 million USD.
The biggest capital cost of one separator system (HDS-1) is on the use of heater. These heaters have the largest portion of the capital costs. The high of workload on the heater, making the heater size becomes larger than the other separator systems. In three separator system (HDS-3), refrigeration system and one additional separator raise the capital cost for this system.

One separator system has very large steam utility thus affecting the total cost of utilities. At one separator systems, fluid to be heated all come from the cold separator enters the heater so the steam needs to be very large. While the two other separator systems, the fluid to be heated is divided into two streams. The first stream coming from the hot separator and the second comes from the cold separator. So the need of steam for both separator is not as big as one separator system.

HDS one separator system has large cooling utilities. The amount of fluid to be cooled in the separator affects the utility costs on cooling. The more fluid to be cooled, the more water cooling needed to cool the fluid. As a result, the cost is greater. The more amount of fluid to be cooled in one separator system due to the fluid from reactor flow into cooler directly while the others separator systems need to be flow into the hot separator and then the vapor which produced flow into cooler.

4. Conclusion
The simulation of three different separator systems in Hydrodesulfurization (HDS) unit has been conducted. It shows that HDS unit with two separator system (HDS-2) has the lowest workload (heating and cooling) while the highest work load at one separator system. From the results of the simulation and calculation of investment costs, HDS unit with one separator system (HDS-1) requires the greatest capital and operational costs while two separator system requires the lowest capital and operating costs. Taking into account the total investment costs both for CAPEX and OPEX as well as the utility workload the two separator system (HDS-2) selected as the best system in the hydrodesulfurization (HDS) unit.

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