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Heat Transfer Efficiency Analysis and the Impact of Fouling Factor on Shell and Tube Heat Exchangers in Petroleum Processing

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Abstract
Heat exchangers are essential equipment in petroleum processing, functioning to transfer heat between fluids to enhance process energy efficiency. Over extended periods of operation, the performance of these heat exchangers can decline significantly due to the formation of fouling on the heat transfer surfaces. This study aims to analyze the heat transfer efficiency and evaluate the impact of the fouling factor on a shell and tube heat exchanger (HE-05) operating in the crude oil refinery unit at PPSDM MIGAS Cepu. The research method employs a quantitative approach based on actual operational data obtained through direct field observations, including temperature data, flow rates, fluid densities, and equipment technical specifications. Performance evaluation was conducted by calculating the overall heat transfer coefficient, fouling factor, pressure drop, and thermal efficiency. The analysis results indicate that the overall heat transfer coefficient under clean conditions (U_c) was 4.65 Btu/ft².hr.°F, while under actual operating conditions (U_d), it decreased to 4.31 Btu/ft².hr.°F. The obtained fouling factor reached 0.0169 ft².hr.°F/Btu, exceeding the recommended minimum standard value, which indicates an accumulation of foulants. Nevertheless, the heat transfer efficiency of the equipment was recorded at 82.8%, which is classified as good and remains within the ideal efficiency range for shell and tube types. The pressure drop values on both the shell and tube sides were also confirmed to be far below the maximum allowable limits, suggesting that the equipment is still hydraulically suitable for operation. Based on these findings, scheduling periodic maintenance and cleaning is highly necessary to sustain the operational efficiency and performance of the heat exchanger.

Keywords: Heat transfer efficiency, fouling factor, shell and tube heat exchanger, petroleum processing, pressure drop.

1. Introduction

The oil and gas processing industry is one of the strategic sectors that plays an important role in fulfilling national energy needs. The processing of crude oil into high economic value products such as diesel, gasoline, and residue involves a complex and interconnected series of unit operations. In this industry, aspects of energy efficiency, suitability of process equipment, and operational safety are primary factors that must be considered as they directly affect operational costs, production sustainability, and occupational safety [5].

PPSDM MIGAS Cepu is a government agency

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under the Ministry of Energy and Mineral Resources (KESDM) that has a strategic role in developing human resource competencies in the oil and gas sector. In addition to functioning as an education and training center, PPSDM MIGAS Cepu also has a refinery unit facility that operates as a field laboratory. The existence of this refinery unit provides an opportunity for students and training participants to directly study the petroleum processing process, starting from crude oil processing to the production of its derivatives [6].

The implementation of standard-compliant petroleum processing is inseparable from the role of institutions that focus not only on the management of industrial facilities but also on human resource development. One of the strategic institutions in Indonesia carrying out this role is the Oil and Gas Human Resources Development Center (PPSDM MIGAS). Apart from being an education and training center in the oil and gas sector, PPSDM MIGAS also operates an oil refinery unit that produces various products, including Pertasol CA, Pertasol CB, Pertasol CC, diesel, and residue [8]. The entire processing procedure is carried out through an integrated series of unit operations, as illustrated in the petroleum processing flowchart at PPSDM MIGAS.

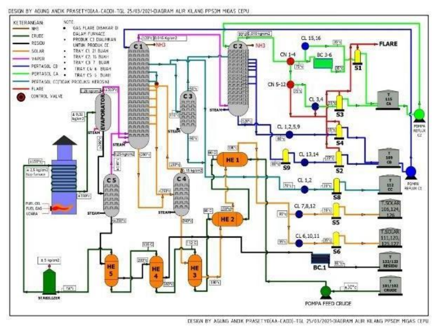

Figure 1. Process Flow Diagram at PPSDM MIGAS

To support the smooth operation of this processing, PPSDM MIGAS utilizes various process equipment such as heat exchangers, furnaces, evaporators, distillation units, and other auxiliary equipment. A heat exchanger is a device that functions to transfer heat energy between two or more fluids with a temperature difference [4]. In the PPSDM MIGAS refinery unit, there are five operating heat exchangers, namely HE-01 to HE-05, all of which are the shell and tube type. HE-01 to HE-03 use diesel as the heating fluid, while HE-04 and HE-05 use residue [8].

Over extended periods of operation, the performance of the heat exchanger has the potential to decline due to the formation of fouling or scale on the heat transfer surfaces. This condition can reduce heat transfer efficiency and result in increased energy consumption and operational costs [2]. This decrease in efficiency can also affect the performance of other process equipment within the integrated processing system.

Based on these problems, this research was conducted to evaluate the performance of heat exchangers, specifically HE-05, at the PPSDM MIGAS Cepu Refinery Unit using a quantitative approach based on actual operational data. This evaluation aims to determine the current performance condition of the heat exchanger and identify potential improvements that can be made, such as periodic cleaning and maintenance, fluid quality monitoring, and optimization of operating conditions [9]. The results of this study are expected to provide benefits to PPSDM MIGAS Cepu and serve as a reference for other oil and gas industries in their efforts to improve the efficiency and reliability of process equipment.

2. Materials and Methods

This research was conducted using a quantitative approach utilizing actual operational data obtained through direct observation at the PPSDM MIGAS Cepu Refinery Unit. The initial phase of the study began with a literature review to understand the working principles and performance parameters of heat exchangers. The collected data encompassed the technical specifications of Heat Exchanger-05 (HE-05), the inlet and outlet fluid temperatures on the shell and tube sides, flow capacities, and the densities of the crude oil and residue obtained from the field, control room, and analytical laboratory. Data collection was carried out on December 8, 2025. Subsequently, these data were used to calculate the fouling factor, pressure drop, and heat transfer efficiency in order to evaluate the actual performance of HE-05 and determine its operational feasibility.

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3. Heat Exchanger Efficiency Calculation

To determine the operational feasibility of Heat Exchanger-05 (HE-05), a series of thermodynamic and fluid mechanics analyses were conducted using the following mathematical approaches:

3.1. Heat Duty

The quantity of thermal energy transferred during the thermal exchange process was evaluated through the basic energy balance equation:

$$Q_S = W_s \times Cp \times (T_1 - T_2)$$

Calculations indicate that the heating fluid (residue) in the shell compartment released an energy (Q_s) of 810,941.5 Btu/hr. Meanwhile, the actual energy successfully absorbed by the crude oil in the tube pass (Q_t) was recorded at 671,829.34 Btu/hr.

3.2. Log Mean Temperature Difference (ΔLMTD)

The temperature gradient driving the fluid's heat transfer rate is represented by the ΔLMTD equation:

$$LMTD = \frac{\Delta T_2 - \Delta T_1}{ln\left(\frac{\Delta T_2}{\Delta T_1}\right)} = \frac{(T_1 - t_2) - (T_2 - t_1)}{ln\left(\frac{(T_1 - t_2)}{(T_2 - t_1)}\right)}$$

By incorporating the operational parameters, the corrected LMTD value (ΔLMTD), which represents the actual temperature profile within HE-05, was obtained at 129.52 °F.

3.3. Overall Heat Transfer Coefficient

The equipment's thermal conductivity performance was calculated under two operational scenarios, namely the clean design state (U_c) and the actual operating condition (U_d):

$$Uc = \frac{h_{io} \times h_o}{h_{io} + h_o} \qquad U_d = \frac{Q_t}{A \times \Delta LMTD}$$

Analytically, the thermal transfer capacity of HE-05 under ideal conditions without fouling (U_c) is 4.639 Btu/ft².hr.°F. However, based on field observations, this actual capacity value (U_d) was reduced to 4.31 Btu/ft²·hr.°F.

3.4. Fouling Factor

The reduction in heat transfer capacity was quantified as the thermal resistance caused by the accumulation of scale or fouling (R_d):

$$R_d = \frac{U_c - U_d}{U_c \times U_d}$$

The evaluation of this parameter yielded a fouling factor value of 0.0163 ft²·hr·°F/Btu.

3.5. Thermodynamic Efficiency

The effectiveness rate of thermal energy absorption by the cold fluid was compared against the total thermal energy supplied, utilizing the following equation:

$$\eta = \frac{Q_t}{Q_s} \times 100\%$$

Based on the heat duty calculations, the actual heat transfer effectiveness of HE-05 was able to reach 82.84%.

3.6. **Pressure Drop**

A hydraulic review was conducted to validate the smooth circulation of the fluid by calculating the pressure drop parameter, which is influenced by friction factors and flow geometry:

$$\Delta P_s = \frac{f \times (G_s)^2 \times ID \times (N+1)}{5{,}225 \times 10^{10} \times D_e \times SG \times \emptyset_s}$$

$$\Delta P_t = \frac{f \times (G_t)^2 \times L \times N}{5{,}225 \times 10^{10} \times ID_t \times SG \times \emptyset_t}$$

The calculation results demonstrated that the pressure loss due to friction remained highly minimal, specifically 0.0076 psi on the shell side (ΔPs) and 0.0010 psi on the tube flow pass (ΔPt).

4. Results and Discussion

Table 1. Spesifikasi HE-05 PPSDM MIGAS Cepu

No.	Description	Notation	Unit	Dimension
	Shell Side			
1	Outer Diameter	ODs	Inch	37.402
2	Inner Diameter	IDs	Inch	36.457
3	Number of Baffles	N	Pcs	4
4	Baffle Spacing	B	Inch	25.866
5	Number of Passes	N	Pcs	1
6	Fluid Type	Residue		
	Tube Side			
1	Outer Diameter	ODt	Inch	1
2	Tube Length	L	Feet	11.482
3	Number of Tubes	Nt	Pcs	400
4	BWG	-	-	12
5	Pitch	Pt	Inch	1.25
6	Tube Spacing	C'	Inch	0.25
7	Number of Passes	N	Pcs	1
8	Fluid Type	Crude Oil		

The operational data for HE-05 in the refinery unit was obtained through observation and data collection on December 8, 2025, at 08:00 WIB. Temperature observations were conducted directly by monitoring the temperature sensors installed on the heat exchanger. Meanwhile, production capacity data was determined using the production records from the control room, and the analytical data was acquired from the refinery's analytical laboratory

Table 2. Data HE-05

Date	Capacity (L/Day)	Inlet Temp (°C)	Outlet Temp (°C)	Density (kg/m³)	Specific Gravity
Shell (Residue)					
8/12/2025	66736	280	150	897.1	0.8979
Tube (Crude Oil)					
8/12/2025	301814	112	140	843.3	0.8441

Thermal Performance and Operational Feasibility of HE-05

4.1. *Equipment Role and Function*

Heat Exchanger-05 (HE-05), operating at the PPSDM MIGAS Cepu Refinery Unit, is a vertically oriented shell-and-tube heat exchanger. This equipment functions as a pre-heater for the crude oil flowing through the tube side, utilizing the heat from the residual fluid stream of the preceding process routed through the shell side. The role of HE-05 is essential in alleviating the workload of the furnace during the primary heating stage. Consequently, the thermal efficiency of the refinery can be enhanced, and equipment failure due to overheating can be prevented.

4.2. *Evaluation of Heat Transfer Coefficient and Fouling Factor*

Operational data recorded that the mass flow rate of the crude oil reached 23,385.87 lb/hr, while the residual flow was 5,500.89 lb/hr. Thermodynamic evaluation indicates a performance degradation from the clean overall heat transfer coefficient (U_c) of 4.65 Btu/ft².hr.°F to an actual design coefficient (U_d) of 4.31 Btu/ft².hr.°F. This reduction serves as a strong indicator of the formation of thermal resistance over the course of operation. This is further substantiated by a high fouling factor (R_d) reaching 0.0169 ft².hr.°F/Btu. This value exceeds the design tolerance limit specified by Kern [7] (1983) for hydrocarbons, which is 0.005 ft²·hr·°F/Btu. The magnitude of this resistance confirms the accumulation of scale in the heat transfer area. Without routine cleaning, this accumulation of impurities poses a risk of generating localized hot spots, which may lead to physical leakage or corrosion in the equipment.

4.3. *Hydraulic Review and Overall Efficiency*

From a hydraulic perspective, the equipment's feasibility is assessed using pressure drop. The results demonstrate minimal pressure resistance, specifically 0.0076 psi on the shell side and 0.00103 psi on the tube side. Considering that the maximum allowable pressure drop for liquid heat exchangers is 10 psi [7], the fluid circulation within HE-05 is deemed to be highly unobstructed and safe for operation. In general, the overall performance of HE-05 remains highly adequate, with a heat transfer efficiency of 82.84%. Referring to Cengel's [3] (2003) standards, this achievement falls within the ideal range (80%–90%) for shell-and-tube types. These results are also consistent with findings from other literature studies within the same refinery unit, which reported an efficiency of 83.77%. Although the equipment is proven to still operate optimally despite fouling issues, preventive maintenance such as equipment cleaning, inspection of insulation materials, and instrument calibrati on must be routinely scheduled to prevent more critical heat loss.

4.4. *Specification Analysis and Temperature Distribution*

The structural design of HE-05 incorporates 400 tubes (11.482 ft in length, 1 inch OD) and 4 baffles on the shell side with a baffle spacing of 25.866 inches. This design aims to induce turbulent flow and extend the fluid residence time to maximize thermal transfer. The heating fluid (residue) enters at a temperature of 280°C and exits at 150°C, transferring its energy to heat the crude oil from 112°C to 140°C. This temperature distribution yields a Log Mean Temperature Difference (ΔLMTD) of 140.79°F. When calculated with a correction factor (F_t) of 0.92, the corrected LMTD (ΔLMTD) is obtained at 129.52°F. This correction value, approaching 1, proves that the flow routing design of the heat exchanger remains highly effective.

4.5. *Evaluation of Heat Loss*

Field conditions indicate that heat transfer is not entirely absorbed perfectly. The energy balance demonstrates that out of the total

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thermal energy released by the residue (Q_s) amounting to 810,941.5 Btu/hr, the energy successfully absorbed by the crude oil (Q_t) is only 671,829.34 Btu/hr. This indicates a dissipated energy (heat loss) of 139,112.17 Btu/hr, or approximately 17.15%. In open-field operational units, such thermal leakage is a common occurrence due to exposure to external weather convection and radiation. However, this percentage necessitates the operators' attention to promptly evaluate the viability of HE-05's protective insulation material in order to minimize energy waste and improve equipment performance optimization.

4.6. *Flow Characteristics and Convective Performance*

The rate of convective heat transfer is highly dependent on the fluid dynamics profile. Hydraulic analysis reveals that the Reynolds Number for the residual fluid (Re_s) stands at 141.84, while the crude oil flow (Re_t) is valued at 608.34. Given that both values are significantly below the turbulence transition threshold (2100), it is confirmed that the flow on both sides is laminar. This laminar condition is understandable due to the highly viscous nature of the crude oil and residue. Although laminar flow typically reduces the convective heat transfer capacity when compared to turbulent flow, this has been well compensated through the physical design of HE-05, which employs a very large heat transfer area comprising a 400-tube arrangement. Through this design solution, the targeted heating temperature requirements for the crude oil can still be effectively achieved before the fluid is propelled into the furnace.

5. Conclusion

Based on the performance evaluation of Heat Exchanger-05 (HE-05) at the PPSDM MIGAS Cepu Refinery Unit, the following conclusions can be drawn: Refined Products: The refinery unit processes crude oil into valuable products, including Pertasol (CA, CB, CC), Solar, and Residue. Fouling Accumulation: A degradation in heat transfer performance has occurred, primarily induced by scale accumulation (fouling). The fouling factor of HE-05 was recorded at 0.0163 hr·ft²·°F/Btu, which exceeds the acceptable design standard limit for liquid hydrocarbon fluids (0.005 hr·ft²·°F/Btu). Hydraulic Conditions: Fluid circulation within the equipment is highly secure and unobstructed, presenting no significant flow resistance. The recorded pressure drop values are minimal (0.0076 psi on the shell side and 0.0010 psi on the tube side), remaining well below the maximum allowable threshold of 10 psi. Efficiency Level: Despite the fouling issues, the thermal performance of the equipment remains sufficiently effective. HE-05 successfully transfers heat from the residue to the crude oil with a favorable efficiency rate of 82.84%. Operational Feasibility: Overall, the HE-05 unit remains highly feasible for continuous operation. Nevertheless, the elevated fouling factor underscores the critical necessity for periodic maintenance and cleaning procedures to mitigate further performance degradation and sustain optimal efficiency.

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