Economic evaluation of use of heat exchange equipment diagnostic software at diesel hydrotreating unit

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Abstract. This study focuses on problems related to fouling of heat exchange equipment of diesel hydrotreatment (DHT) processes and diagnostics of heat exchanger condition. Fouling is a critical aspect directly affecting the performance of a heat exchanger. The objective of this study is to determine, using a mathematical model, an optimal timing for cleaning of DHT heat exchange equipment for the removal of fouling. In accordance with results of calculations performed with a mathematical model of a typical DHT unit (L-24/9), condition assessment index for a heat exchanger of the reactor section increases from 1 to 1.37 when shell side fouling factor increases from 0.00003 to 0.00150 (°C·h·m²)/kJ. This results in a decrease of the feed temperature at the vessel outlet, and an increase of costs related to additional fuel consumed by heaters by over RUB 1 million/month. Therefore, activities related to the cleaning of tube bundles of reactor section heat exchangers pay back in full in 1 month, as fuel savings brought about by the cleaning exceeded 12.6%. In order to carry out diagnostics of heat exchange surface fouling and to determine an optimal timing for tube bundle cleaning in order to remove deposits, vessels have to be equipped with transmitters measuring temperatures of all inlet/outlet streams. The use of on-line heat exchanger diagnostics makes it possible to choose an optimal timing of tube bundle cleaning based on comparability of costs related to additional fuel consumption and cleaning costs.

1. Introduction
The commissioning of machinery for the monitoring of equipment condition at refineries [1, 2] has ensured safe and resource-efficient operation of this equipment. The next step in ensuring the safe operation of the equipment is the development of systems for monitoring the state of heat exchanger equipment, columns, reactors and pipelines.

Long-term monitoring of the condition of diesel hydrotreatment (DHT) heat exchange equipment have made it evident that it is necessary to identify causes leading to deposits forming on heat exchange surfaces and resulting in an increased utility consumption [3]. It has been revealed that utility consumption of a DHT unit was mainly affected by reactor section heat exchangers in particular. In this work, methods used to determine composition of deposits were reviewed [4], equations, used to calculate the thickness of such deposits, were applied [5], and applicability of existing methods for the diagnostics of DHT heat exchange equipment was studied.

In the works [6] and [7], a key role in methods used for the diagnostics of deposits on heat exchange surfaces is played by hardness salts only specific to refrigeration equipment using water as a coolant. Hardness salts have certain thermodynamic characteristics, and this method is therefore only applicable to vessels in water service.

In the studies [8], equations are provided for the calculation of deposit thickness in recuperative heat exchangers of CDU/VDU processes. Applicability of this method is also limited by the fact that deposits are formed by paraffins that are mainly characterized by thermodynamic parameters of the stream itself.
Studies of the hydrotreating process [9] should be considered a step forward in works on the
diagnostics of the condition of heat exchange equipment. It should be noted that constant flow rates of
streams are typical for the reactor section of a hydrotreating process in steady operation of the unit. It
was this fact that served as a basis for the development of a method based on comparison of
temperature differences at the hot side and the cold side of a heat exchanger.

The objective of the study consists in development of a procedure for the evaluation of the
condition of heat exchange equipment used in refining processes, and, in particular, in diesel
hydrotreating processes, on the basis of process data and the influence the efficiency of the heat
exchange process has on economics.

2. Theory
Temperature measurement is the most commonly used and the least expensive process indicator. The
applicability of temperature measurements for the diagnostics of heat exchanger surface condition was
therefore the first to be considered.

At present, refiners do not have any reliable method allowing them to determine whether heat
exchange equipment requires cleaning. This results in an unjustified increase of operating costs due to
ill-timed cleaning. Such costs may be caused by excessive fuel consumption by heaters as well as by
additional expenses related to heat exchanger maintenance.

Critical fouling parameters of heat exchange equipment of the hydrotreater reactor section were
determined in 3 areas. Firstly, on the basis of the developed mathematical model, heat transfer
coefficients were determined and their influence on thermal processes occurring in the process
equipment [10]. Secondly, a comparison of utility (fuel gas) consumption for “dirty” and “clean” heat
exchange surfaces was performed. Thirdly, permissible deviation of the thermal duty of a heat
exchanger from the initial condition was determined for heat exchangers with the use of regulatory
documents related to equipment operation.

In accordance with method proposed by Alfa Laval for plate heat exchangers, it is advisable to
carry out the condition monitoring as follows:

1. Heat transfer coefficient (\( K, \text{W} \cdot ^\circ \text{C}/\text{m}^2 \)) of a vessel at normal duty is calculated by the equation (1):
\[
K = \frac{Q}{F} \cdot \Delta t_{av},
\]
where: \( F \) — heat exchange surface area determined based on vessel specifications, m\(^2\); \( \Delta t_{av} \) —
average logarithmic temperature difference, \(^\circ\)C; \( Q \) — vessel thermal duty calculated based on heat
balance, \( W \).

The average logarithmic temperature difference (\( \Delta t_{av}, \text{^\circC} \)) is calculated by the equation (2):
\[
\Delta t_{av} = \frac{\Delta t_h - \Delta t_i}{\ln \left( \frac{\Delta t_h}{\Delta t_i} \right)},
\]
where: \( \Delta t_h = t'_1 - t''_2 \) and \( \Delta t_i = t''_1 - t'_2 \) — higher and lower values of temperature difference.

Inlet and outlet temperatures of the primary circuit (\( t'_1 \) and \( t''_1 \)) as well as inlet and outlet
temperatures of the secondary circuit (\( t'_2 \) and \( t''_2 \)) are measured with standard conventional
thermocouples installed on heat exchangers.

Thermal duty (\( Q, W \)) is calculated by the equation (3):
\[
Q = G_1 \cdot C_p \cdot (t'_1 - t''_1) = G_2 \cdot C_p \cdot (t''_2 - t'_2)
\]
where: \( G_1, G_2 \) — stream flow rates in tube side and shell side of heat exchanger, kg/s; \( C_p \) —
product heat capacity, kJ/kg·^\circC determined based on average product temperature in heat exchanger.

2. The heat transfer coefficient determined based on operating conditions (\( K_{\text{actual}} \)) is compared with
the design heat transfer coefficient (\( K_{\text{design}} \)) taken from the heat exchanger specifications.
3. If the deviation between operating and design values of the heat transfer coefficient exceeds 33–35%, the heat exchanger must be cleaned.

The difficulty of applying this method resides in the fact that it requires complex mathematical calculations in order to determine the heat transfer coefficient, and all required input data are not always available.

In accordance with the regulatory documentation [11], a tube bundle of a heat exchanger is discarded if more than 30% of the tubes are defective, and therefore, thermal duty also decreases by 30% as in the calculation example above. This served as a basis for the determination of critical diagnostic features to be used as a preliminary estimate.

Process variables of DHT units have been monitored for a long period of time in order to determine diagnostic features of heat exchange equipment. During the turnaround of the units, the surface condition was determined when heat exchangers were disassembled, and the information obtained was analyzed. Heat transfer coefficients were determined by means of a computer model on the basis of increase in fouling of heat exchange surfaces of the vessels.

It is impossible to evaluate the degree of fouling of heat transfer surface based only on results of monitoring of inlet and outlet stream temperatures of DHT heat exchangers. In order to evaluate growth of deposits on the heat transfer surface, it is necessary to perform additional calculations, and the search for diagnostic features was therefore continued.

The main heat transfer equation is the equation (4):

\[ Q = K \cdot F \cdot \Delta t_{av}, \]  

where: \( K \) – heat transfer coefficient, W/m²·ºC, as determined by the equation (5);

\[ K = 1 \cdot \left( \frac{1}{\alpha_1} + \frac{\delta_w}{\lambda_w} + \frac{1}{\alpha_2} \right)^{-1}, \]  

where \( \delta_w \) — wall thickness, m; \( \lambda_w \) — thermal conductivity coefficient of wall material, W/(m·ºC); \( \alpha_1 \) and \( \alpha_2 \) — thermal transmission coefficients for thermal transmission from hot heat carrier to separating wall, and from the wall to cold heat carrier, respectively, W/(m²·ºC).

As deposit thickness increases, a decrease of heat transfer coefficient is detected, and, as a result, there is an increase in average logarithmic temperature difference and temperature difference at the cold side and the hot side of a heat exchanger. A similar situation is observed when plugging of some of tubes results in decreased heat exchange area, i.e. temperature difference at heat exchanger sides also increases as compared with the initial value.

Diagnostic software has been developed in order to determine the condition of heat exchange equipment [12]. The operating efficiency of a heat exchanger can be evaluated as the difference between the inlet and outlet stream temperatures at the cold side and the hot side. The time variation of heat exchanger operating efficiency is defined as a ratio of temperature differences at the present moment and at a moment when the heat exchanger was clean.

3. Experimental results

A typical DHT unit is designed to remove organic sulfur, nitrogen, and oxygen compounds by their destructive hydrogenation (figure 1). The experience of operating DHT units has shown that main deposit-related problems occur in heat exchangers of the reactor section. In contrast to laboratory experiments involving active impact on the object, this study involved an industrial DHT unit, and therefore, the experiment was carried out in the form of passive observations.
Due to the fact that E-3/1 and E-3/2 heat exchangers are located upstream of the point where the feed is mixed with the HRG (hydrogen-rich gas), they are equipped with valves making it possible to isolate them at any time, which is consistent with explosion and fire safety regulations. The above heat exchangers have not been cleaned since 2015 when they were put into operation, which resulted in a significant decrease of their efficiency. Utility consumption has so increased that the unit started to exceed allowable reference fuel consumption rates. Various diagnostic software tools are commonly used to determine an optimal timing of heat exchanger cleaning.

PI ProcessBook (PI PB) system includes a program for on-line diagnostics of feed exchangers of the reactor section of a typical DHT unit (L-24/9), which functions by comparing the difference between the hot side temperatures of a vessel at the present moment and at a moment when the heat transfer surface was clean. However, no temperature transmitters are available at the inlet of E-3/1 and E-3/2 heat exchangers for the hot stream of hydrotreated diesel, and it is therefore not possible to evaluate the fouling degree of the above vessels using diagnostic software. Due to the impossibility to evaluate the fouling of heat transfer surface of E-3/1 and E-3/2 vessels by means of PI PB, a simulation model of a typical DHT unit (L-24/9) in Aspen HYSYS software product was used. This mathematical model includes all heat exchange equipment that is involved in heat recovery process and influences utility consumption. Besides, all columns have been modeled in the mathematical model in accordance with their specifications. In accordance with the equation (6) used in the on-line diagnostic software, a spreadsheet has been created, and all required parameters have been calculated in the mathematical model with the aim of determining a condition assessment index of E-3/1 and E-3/2 heat exchangers. The difference between a mathematical model and on-line diagnostics in PI PB consists in the fact that momentary temperature values corresponding to clean and dirty heat transfer surfaces are considered instead of average temperature values for an extended period.

$$D = \frac{\Delta T^*_{H}}{\Delta T_{H}}$$

where $\Delta T^*_{H}$ is the temperature difference at hot side of heat exchanger with dirty heat exchange surface (at the present moment), °C; $\Delta T_{H}$ is the temperature difference at hot side of heat exchanger with clean heat exchange surface, °C.
The next step consisted in designing calculation studies with an aim to detect dependence of various parameters on the variation of fouling factors of E-3/1 and E-3/2 heat exchangers while all other model parameters remained constant.

4. Results and discussion
In accordance with results of studies performed with a mathematical model of a typical DHT unit (L-24/9), the condition assessment index of E-3/1 heat exchanger increases from 1 to 1.37 as shell side fouling factor increases from 0.00003 to 0.00150 (°C·h·m²)/kJ. At the same time tube side fouling factor remained constant at 0.00003 (°C·h·m²)/kJ, which corresponds to the condition of a clean heat exchange surface. A change in the condition assessment index of E-3/1 heat exchanger results in decrease of feed temperature at the outlet of the vessel and increased fuel consumption of the F-1 heater. In accordance with calculations made with the mathematical model, the value of the condition assessment index of E-3/1 and E-3/2 heat exchangers exceeded 1.3 in November 2018, while at the same time costs related to additional fuel consumed by F-1 and F-2 heaters exceeded RUB 1 million/month.

Cleaning of the heat exchangers has been performed based on diagnostic features. The temperature upstream of E-1/1 heat exchanger was no higher than 70°C before cleaning of E-3/1 and E-3/2 heat exchangers, it was no higher than 60°C during cleaning of the vessels, and increased up to 90°C after the cleaning (figure 2). At the same time, HRG temperature at the compressor discharge remained at about the same level.

![Figure 2. Variation of HRG and feed temperature upstream of E-1/1 and E-1/2 heat exchangers.](image)

- gas-feedstock mixture temperature downstream of E-3/1 and E-3/2 heat exchangers, °C;
- HRG temperature downstream of compressor, °C.

![Figure 3. Specific reference fuel consumption rate at unit L-24/9.](image)

- actual specific consumption rate, kg of reference fuel/t;
- planned specific consumption rate, kg of reference fuel/t.

The feed temperature at the outlet of E-3/1 and E-3/2 vessels operating in a parallel arrangement tended to decrease steadily and correlated with the HRG temperature, thus confirming that such values were adequate. During maintenance activities related to tube bundle cleaning of E-3/1 and E-3/2 heat exchangers, the inlet temperature of E-1/1 vessel was at the minimum and corresponded to the feedstock temperature at the inlet of the unit. After cleaning of E-3/1 and E-3/2 heat exchangers, the temperature increased to the maximum values of 118°C.

Increase of the gas-feedstock mixture temperature at the inlet of E-1/1 heat exchanger resulted in an increased gas-product mixture stream temperature upstream of the hot separator, which had an effect on the temperature profile of the stabilization section and also on fuel consumption of F-2 heater. The variation pattern of the temperatures at the inlet of C-1 column fully corresponds to the heat balance, i.e. when hydrogenate temperature increases, the thermal input to the column increases thus leading to a decreased heater duty. Modified temperature parameters of streams at the inlet of the
reactor section heaters and the stabilization column resulted in decreased specific consumption rate of the reference fuel (figure 3).

Based on studies performed with the mathematical model, an optimal timing for cleaning of heat exchange equipment of a typical DHT unit (L-24/9) has been determined based on comparison of costs related to additional fuel consumption and costs related to the cleaning of tube bundles of the vessels.

Total costs related to the cleaning of heat exchange equipment \( (C_{\text{total}}, \text{RUB}) \) are calculated by the equation (7):

\[
C_{\text{total}} = C_M + C_T + C_C,
\]

where \( C_M \) is the costs related to disassembly/assembly of heat exchanger, RUB; \( C_T \) is the costs related to transport of tube bundle to cleaning area and back, RUB; \( C_C \) is the costs directly related to tube bundle cleaning, RUB.

Costs related to disassembly/assembly of a heat exchanger \( (C_M, \text{RUB}) \) are calculated by the equation (8):

\[
C_M = F \cdot K_p \cdot K_0,
\]

where \( F \) is the tube bundle surface area, \( \text{m}^2 \); \( K_p \) is the complexity factor of vessel (allowing for pressure); \( K_0 \) — proportionality coefficient, RUB/m².

Costs related to tube bundle transport \( (C_T, \text{RUB}) \) are calculated by the equation (9):

\[
C_T = A \cdot L \cdot K_L,
\]

where \( A \) is the tube bundle mass, kg; \( L \) is the transport distance, km; \( K_L \) is the proportionality coefficient, RUB/(kg·km).

Costs related to the cleaning of a heat exchanger \( (C_C, \text{RUB}) \) are calculated by the equation (10):

\[
C_C = F \cdot K_C,
\]

where \( F \) is the tube bundle surface area, \( \text{m}^2 \); \( K_C \) is the proportionality coefficient, RUB/m².

Costs related to additional fuel consumption \( (C_{\text{ad.fuel}}, \text{RUB}) \) are determined by the equation (11):

\[
C_{\text{ad.fuel}} = C_{\text{dirty}} - C_{\text{clean}},
\]

where \( C_{\text{dirty}} \) is the cost of fuel consumed by heaters at current condition of (dirty) E-3/1 and E-3/2 heat exchangers, RUB; \( C_{\text{clean}} \) is the cost of fuel consumed by heaters at beginning of operation of (clean) E-3/1 and E-3/2 heat exchangers, RUB.

Cost of fuel consumed by heaters at current condition of (dirty) E-3/1 and E-3/2 heat exchangers \( (C_{\text{dirty}}, \text{RUB}) \) are calculated by the equation (12):

\[
C_{\text{dirty}} = \sum_{i}^{m} \frac{Q_{i\text{dirty}} \cdot C_{\text{fuel}}}{q_{\text{fuel}} \cdot \eta},
\]

where \( Q_{i\text{dirty}} \) is the total daily duty of F-1 and F-2 heaters at current condition of (dirty) E-3/1 and E-3/2 heat exchangers, Kcal; \( 1 \) to \( m \) — number of days in month; \( C_{\text{fuel}} \) is the fuel cost, RUB/t; \( q_{\text{fuel}} \) is the monthly average calorific value of fuel gas, Kcal/t; \( \eta \) — averaged heater efficiency.

Cost of fuel consumed by heaters at the beginning of operation of (clean) E-3/1 and E-3/2 heat exchangers \( (C_{\text{clean}}, \text{RUB}) \) are calculated by the equation (13):

\[
C_{\text{clean}} = \sum_{i}^{m} \frac{Q_{i\text{clean}} \cdot C_{\text{fuel}}}{q_{\text{fuel}} \cdot \eta},
\]

where \( Q_{i\text{clean}} \) is the total daily duty of F-1 and F-2 heaters at beginning of operation of (clean) E-3/1 and E-3/2 heat exchangers, Kcal; \( 1 \) to \( m \) — number of days in month.

Total costs related to the cleaning of E-3/1 and E-3/2 heat exchangers calculated by the equation (7) amounted to RUB 900 000. During the time period in question, total costs related to the cleaning of
E-3/1 and E-3/2 heat exchangers are assumed to be a constant value determined by design features of the vessels and the distance to the maintenance area.

Prior to the cleaning of the heat exchange equipment, consumption of additional fuel by F-1 and F-2 heaters vastly exceeded specified consumption rates (see Figure 3). Costs related to additional fuel consumption were determined by the difference between calculated values at the present moment and at the beginning of the heat exchanger operation. Values of F-1 and F-2 heater duty for clean and dirty heat transfer surfaces of the vessels were calculated with the mathematical model (figure 4).

![Figure 4](image_url)

**Figure 4.** Comparison of maintenance costs (including cleaning) and operating costs of dirty heat exchangers. — total cost of additional fuel, RUB; — costs of maintenance and cleaning of E-3/1 and E-3/2 heat exchangers.

In October 2018, an average reference fuel overconsumption of 5.86% was observed; in November, it increased up to 12.22% as a result of the complete shutdown of E-3/1 and E-3/2 heat exchangers, and in December, an average fuel saving amounted to 0.38% after the cleaning of the vessels.

The calculation of the cost of additional fuel consumed by F-1 and F-2 heaters of a typical DHT unit (L-24/9) was performed; it demonstrated that activities related to the cleaning of tube bundles of E-3/1 and E-3/2 heat exchangers pay back in full in 1 month. After 7.12.2018 (the date E-3/1 and E-3/2 heat exchangers were put into operation after cleaning), the total consumption of additional fuel decreased.

Visual inspection of tube bundles of E-3/1 and E-3/2 heat exchangers showed substantial coke deposits on the entire length of tubes in the shell side (figure 5).

![Figure 5](image_url)

**Figure 5.** Shell side condition of tube bundle of E-3/1 heat exchanger during maintenance on 20.11.2018.

In order to carry out diagnostics of heat exchange surface fouling and to determine an optimal timing for tube bundle cleaning in order to remove deposits, vessels have to be equipped with transmitters measuring temperatures of all inlet/outlet streams. The algorithm for the calculation of the condition assessment index, based on the comparison of stream temperature differences at the hot side of a heat exchanger at the present moment and at a moment when the heat exchange surface was clean, is developed using instrument data. The use of on-line heat exchanger diagnostics makes it possible to
choose an optimal timing of bundle cleaning based on comparability of costs related to additional fuel consumption and cleaning costs.

Thus, the technology and the system of monitoring of the heat-exchanging equipment allows not only to define borders of effective operation of heat exchangers, but also to save energy resources, so to increase the profit of the enterprise and also provides complex monitoring of a condition of the equipment of the process unit, including not only the machine equipment, and heat-exchanging, columned, capacitive, reactor [1, 2, 13, 14, 15]

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