Identification of the Equipment Failure Fundamental Causes by the Condition Monitoring Using Twin Digital Models

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Abstract. The work is devoted to the problems of identifying the fundamental reasons that led to an increase in energy consumption for heating raw materials and cooling reaction products to the required temperatures, as well as to a decrease in the productivity of a diesel hydrotreating unit when the limiting parameters of the technological regime are reached. The purpose of the work is to determine the parameters of heat exchangers, in particular, pollution factors, and parameters of the technological process, in particular, the consumption of raw materials, the consumption of fuel gas. Monitoring was carried out during the introduction of reagents in order to solve the problems associated with the formation of resinous deposits. It was revealed that the reagents have an insignificant effect both on improving the heat transfer coefficient and on reducing the specific consumption of fuel gas. It is proposed to clarify the dosage of reagents and to develop a project on the use of reagents to maintain the cleanliness of the heat exchange surface of the raw material heat exchangers of the diesel fuel hydrotreating unit.

1. Introduction

The modern advances in condition monitoring of dynamic equipment [1, 2, 3], to which should be attributed primarily centrifugal rotary mechanisms, provide a perfectly acceptable level of assessment and protection of equipment from unexpected failures [3, 4, 5]. It should be noted that progress in monitoring the condition of reciprocating machines, in particular, reciprocating compressors, which are used in the oil and gas industry [3, 6-9]. At the same time, it is still difficult to solve the problem of monitoring the state in real time of static mechanical and technological equipment, which includes process pipelines, column-and-vessel equipment operating under pressure, heat exchange and furnace equipment of oil refineries [10-13].

The well-known principles of constructing systems for complex monitoring of the state of technological objects of hazardous industries [10-14] provide resource-saving safe operation of equipment of oil refining enterprises based on real-time monitoring of parameters of physical processes that operate on the basis of non-destructive testing methods. The monitoring task is to observe the technical state of technological objects in order to assess their current state and predict the moment of their transition to the limiting state. The monitoring result is a set of diagnoses of technological objects that make up the production complex, obtained at inseparably adjacent time intervals, during which the state of the objects does not change significantly [9, 11, 14-19].

The requirements for monitoring systems of hazardous production facilities equipment are set out in the current state standards of the Russian Federation and regulatory documents of professional public organizations [14].
The long-term observation of the heat exchange equipment of the diesel fuel hydrotreating process the state's led to the realization of the need to determine the causes of the appearance of deposits on the heat exchange surfaces, leading to an increased consumption of energy resources [20]. It was found that it was the heat exchangers of the reactor block that had the main influence on the energy consumption of the diesel hydrotreating unit. In [21], methods for determining the composition of deposits, formulas for calculating their thickness [22] are considered, as well as the possibilities of existing methods for assessing the state of heat exchange equipment for the process of hydrotreating diesel fuel [23] are studied.

In [24] and [25], the main role in methods for diagnosing deposits on heat exchange surfaces is assigned to hardness salts, which are characteristic only for refrigeration equipment that uses water as a heat carrier. The hardness salts have known thermodynamic characteristics, which is why this method is of limited use only for devices that work with water as a refrigerant. In studies [25], calculation formulas are given for determining the thickness of deposits of recuperative heat exchangers of processes of atmospheric-vacuum tubular. This technique is also of limited use due to the fact that the deposits are in the form of paraffins, which are largely characterized by the thermodynamic properties of the stream itself.

The hydrotreating process studies [27] should be considered as the development of work in the direction of diagnostics of the state and evaluation of the residual service life of heat exchange equipment [26]. Note that the reactor block of the hydrotreating process is characterized by the constancy of flow rates at a stationary operating mode of the unit. This fact was the basis for the development of a method based on comparing the temperature differences of different flows at the inlet and outlet of the heat exchanger [20, 27-33].

2. Problem Statement

The diesel fuel hydrotreating unit is designed to remove organic sulfurous, nitrogenous, oxygen-containing, organometallic compounds from straight-run diesel fuel fractions, as well as gas oil fractions of catalytic cracking and delayed coking units, delayed coking naphtha, by their destructive hydrogenation and hydrogenation of unsaturated hydrocarbons in order to obtain the summer diesel component fuel that meets the requirements of the fifth ecological class (Euro V).

The plant operation during, problems with heat exchange at the reactor unit were identified, which lead to increased energy consumption for heating raw materials and cooling reaction products to the required temperatures, as well as to a decrease in the plant's performance when the maximum parameters of the process mode are reached.

In accordance with the pilot run program, the company's specialists decided to use reagents and dosing equipment for their supply in order to solve problems associated with the formation of resinous deposits, i.e., more efficient and long-term operation of heat exchange equipment. The pilot industrial run was initiated after the work related to the technical re-equipment of the diesel hydrotreater and is designed for 6 months. In accordance with the manufacturer's recommendations, a polymerization inhibitor is introduced into the gasoline coking line from a delayed coking unit, because in this stream, a sufficiently high bromine number is recorded (about 60 grams of bromine per 100 cm³), and the dispersant is introduced directly at the diesel fuel hydrotreater to receive feed pumps. An experimental industrial run was carried out until April of this year.

A decision was made to monitor the process of pilot industrial operation and determine the effectiveness of the measures taken during operation. To assess the state of heat exchange equipment, we used methods and tools that were proposed by the authors and are successfully used for monitoring heat exchangers in diesel fuel hydrotreating plants [28-33].

3. Theory

To assess the effectiveness of the reagents use, a simulation model was formed, including the flows of raw materials and hydrogen-containing gas (HSG) with division along the branches "A" and "B" of the heat exchange network, as well as bypass lines of heat exchangers, heat exchangers of the reactor block in accordance with their passport characteristics, equipment for heating the gas-feed mixture (GFM) in front of the reactor and cooling the gas-product mixture (GPM) after the heat exchangers.
to the required temperatures, as shown in Figure 1. In one part of the model, the heat exchangers are constructed as a "Calibration calculation in a steady state" so that the flow temperatures are determined at the outlet from the apparatus when setting the average daily values of the temperatures at the inlet, and the outlet temperatures are calculated taking into account the pollution coefficients for the annular space, after which the calculated values are compared with the specified ones. The change in the contamination coefficients occurs until the calculated temperature values are equivalent to the set temperatures that were recorded during the monitoring of the technological mode parameters.

Figure 1. Calculation diagram of the heat exchange of the reactor block of flow "A" of the diesel fuel hydrotreating unit (DFHTU)

To determine the consumption of raw materials through bypass lines bypassing the heat exchangers, the model is supplemented with duplicate heat exchangers, which, in contrast to the main scheme, are formed "By end points", i.e. the loads of these devices are determined by the thermal balance in accordance with the specified information on the consumption of raw materials and hydrogen-containing gas, as well as taking into account the temperatures of the heated and cooled streams. The particular attention is paid to the mixing temperature of the streams before entering the furnace.

In addition, to assess the additionally burned fuel as a result of the growth of deposits on the heat transfer surface, an additional block was created in the model, consisting of heat exchangers, a furnace and a refrigerator, the difference from which from the main one is that the pollution coefficients of the heat exchangers correspond to the state of clean surfaces.

For monitoring, a spreadsheet is generated that provides data on the flow rates of raw materials and hydrogen-containing gas, as well as flow temperatures, according to the current values, for example, according to the values shown in Figure 1. In the simulation model, the coefficients are automatically selected contamination in such a way that the calculated temperature values correspond to the temperatures entered as initial data. Also, in the automatic mode, the consumption of raw materials for bypass lines and the load of the furnace with clean and dirty heat exchangers are calculated. Further, in the same table, calculations are made of the percentage deviation of the furnace load from the current time and the cost of the additionally consumed fuel per month.
In the simulation model, calculations are performed to determine the amount of heat transferred through recovery in accordance with the basic heat transfer equation

\[ Q = K \times F \times \Delta T, \]

where \( K \) is the heat transfer coefficient, kcal/(m²·h·°C), which is determined from the conditions of flow through the pipe and inter-tube spaces, pipe material in accordance with the passport data of heat exchangers, as well as pollution coefficients for pipe and inter-tube spaces (determined by the selection method); \( F \) – heat transfer surface area, m², determined from the structural dimensions of heat exchangers; \( \Delta T \) – the average temperature, °C, determined by the initial and final temperatures of flows involved in the heat exchange based on monitoring results.

Since the surface area of the heat transfer does not change during the operation of heat exchangers, the flow temperatures are fixed based on monitoring data, the necessary values of the heat transferred in the heat exchanger can be obtained by varying the heat transfer coefficient by changing the pollution coefficients along the pipe and annular spaces. The results of calculating the heat transfer coefficients for the start-up periods of 2017 and 2019, performed on the simulation model, are summarized in a table and, based on these data, graphs of the dependence of the heat transfer coefficients for each of the heat exchangers are built, which are presented in the figures below.

4. Experimental the results

The analysis of the regime parameters shows that heat transfer coefficients of heat exchangers of branch "A" of flow "A" in 2019 are 20÷25% higher than in 2017 (Figure 2). This is explained by the fact that in 2019 the raw material load increased by 10%, which resulted in higher flow rates and higher heat transfer coefficient. At the same time, the heat transfer coefficient at the heat exchanger 100A-E1/1,2 dropped 15% in 2019, and at the heat exchanger 100A-E1/1,2 – 53% lower than in 2017. This is due to the supply of reagents that prevent the growth of deposits on the heat transfer surface. The "A" stream "A" branch’s heat exchangers of the diesel fuel hydrotreating plant results comparison is most adequate, since it was these devices that were fully cleaned of contaminants both during the idle period in 2017 and during the idle period in 2019.

![Figure 2](image_url)

**Figure 2.** Change in the heat transfer coefficient of branch "A" of flow "A" after start-up

In contrast to the branch "A" flow "A" on the branch "B" flow "A", only one of the two heat exchangers was cleaned during the downtime in 2019, which is clearly seen from the values of heat transfer coefficients (Figure 3). So, on the apparatus pos. 100A-E1/B/1,2, the heat transfer coefficient after start-up in 2019 is 25% lower than in 2017, and on the apparatus position 100A-E1/B/3,4 is 20% higher due to the fact that the first heat exchanger in 2019 was not cleaned of deposits, and the second was cleaned.
Figure 3. Change in the heat transfer coefficient after the start of the "B" branch of the "A"

A jump in heat transfer coefficient on the heat exchangers of one branch with a simultaneous fall on the other after start-up in 2019 (Figure 4) is due to the fact that in the pipe space of the first in the course of the gas-air mixture of the exchanger desublimation of ammonium chloride salts, which clog a certain number of tubes, which leads to a redistribution of the gas-product mixture flow between the branches of the heat exchangers A and B. Such a situation was already in 2017, when there was a sharp temperature change at the outlet of the gas-air mixture (GFM) and gas-product mixture (GPM) from the heat exchangers of branches "A" and "B" of the flow "A" and to equalize the input temperature of the flow into the furnace had to redistribute the amount of raw materials entering each of the branches (Figure 5).

Figure 4. Raw material consumption at branches "A" and "B" of flow "A" after start-up in 2019.

During the repair of heat exchangers in 2019, the reason for this situation was revealed – a blockage of some of the tubes with ammonium chloride salts was discovered. Since ammonium chloride salts are water-soluble, the process licensor provided lines for supplying flushing water between heat exchangers to the gas-product mixture (GPM) streams to deal with such situations. The operations carried out on the salvo supply of the entire volume of flushing water to one of the branches of the heat exchangers led to the fact that the heat transfer coefficients on the heat exchangers were restored to their previous values. Due to the performance of these operations, it was possible to avoid both the redistribution of the flows of the gas-feed mixture (GFM) between the branches of the heat exchangers, and a decrease in the load on the raw material Figure 4).

Despite the fact that flow "A" load for raw materials in 2019 is 10% higher than in 2017 (see Figure 6 a), fuel gas consumption in both cases is approximately at the same level Figure 7 a). At the same time, fuel
gas consumption increased by 30.6% in 4 months of operation after start-up in 2017, and in the same period after start-up in 2019 fuel gas consumption growth of 100A-H1 furnace was only 2.7%.

This suggests that in 2017 the growth rate of deposits on the heat transfer surface is much higher than in 2019, which is certainly a "merit" of the reagent supply. The positive effect of reagent supply can also be seen in the stable specific consumption of fuel gas after start-up in 2019 (see Figure 8 a), which is at the same level, unlike the same period in 2017, where there was a noticeable increase.

![Figure 5. Raw material consumption at branches "A" and "B" of flow "A" after start-up in 2017](image)

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![Figure 6. Consumption of raw materials](image)

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![Figure 7. The consumption of fuel gas](image)
a) Furnace 100A-H1 after start-up in 2017 and 2019  
b) 100B-H1 furnace after starting in 2017 and 2019 and before stopping for repairs in 2019

Figure 8. Specific consumption of fuel gas

5. Discussion of results

The same simulation model as for flow "A" was used to evaluate the efficiency of reagents use at flow "B" (Figure 1). The heat transfer surface contamination and raw materials consumption coefficients calculations, along bypass lines were performed in the same sequence as for flow "A".

In contrast to flow A, where the heat exchangers were cleaned, with the exception of position 100A-E1B/1,2 (Figure 3 a), the heat exchangers of flow B were not cleaned during the idle period in 2019, and the period before shutdown was considered to assess the effectiveness of the reagent supply in order to prevent the growth of contamination, except for the start-up periods.

If we consider the start-up period in 2017 and 2019 of 100B-E1A/1,2 heat exchangers (Figure 9a), we can see that the rate of reduction of the heat transfer coefficient in 2019 is an order of magnitude less than this parameter in 2017. At the same time, before stopping for repairs in 2019, there was a slight increase in the heat transfer coefficient at the 100A-E1B/1,2 heat exchanger due to an increase in the consumption of raw materials and hydrogen-containing gas (HG). However, after the start-up in 2019, the average heat transfer coefficient of this heat exchanger is higher than before the shutdown. This is due to higher flow rates (Figure 9 a) due to increased productivity. In addition, it can also be noted that in connection with the supply of a dispersing reagent, an episodic increase in the heat transfer coefficient is observed.

The heat transfer coefficient of 100B-E1A/3,4 heat exchangers (Figure 9 b) in 2019 is 20% higher than in 2017, despite the fact that the heat transfer coefficient was cleaned in 2017 and no maintenance was performed in 2019. This is due to a 10% increase in raw material load in 2019, which resulted in higher flow rates and higher heat transfer coefficient.
At the same time, the heat transfer coefficient at the 100B-E1A/3,4 heat exchanger was 30% lower in 2017 than in 2019. In addition, it should be noted that there is a significant spread in the values of the heat transfer coefficient after launch in 2019 (from 230 to 330 kcal/(m²·h·°C)), in contrast to the same period after start-up in 2017 or before a shutdown for repairs in 2019. This is due to the supply of reagents that contribute to the detachment of contaminants from the heat transfer surface, their transfer from the first apparatus along the gas-feed mixture (GFM) to the second, settling on the surface of the second apparatus and subsequent separation from the surface of the second apparatus. In this regard, the heat transfer coefficient on the first heat exchanger changes more smoothly, in contrast to the second.

Of the interest are diagrams of change in heat transfer coefficients of heat exchangers of branch "B" of flow "B" (Figure 10 a, b). Here, on the first gas-feed mixture heat exchanger 100B-E1B/1,2 (Figure 10 a) we can see a gradual decrease of heat transfer coefficient, although before the shutdown for repair it was 13% higher than after the launch in 2019. This indicates unsatisfactory condition of the heat exchanger in terms of deposits on the heat exchange surface and its gradual improvement.

At the second heat exchanger 100B-E1B/3,4 of the gas-feed mixture (GFM), a gradual decrease in the average heat transfer coefficient is observed, although the rate of reduction is 46% lower than in 2017 (Figure 10 b). At the same time, due to increased productivity in 2019, the average heat transfer coefficient for this device is 7% higher than in 2017.

The abrupt nature of the change in the heat transfer coefficient on the heat exchanger pos. 100B-E1B/3,4 after start-up in 2019 is caused, as in the branch "A" of stream "B", by the fact that due to the supply of reagents, contaminants are separated from the heat exchange surface, they are transferred from the first gas-feed mixture GSS to second, settling on the surface of the second vehicle and subsequent separation from the surface of the second vehicle. In this regard, the nature of changes in the heat transfer coefficient on the first heat exchanger is smoother, in contrast to the second.

Due to the fact that in 2019 the pipe bundles of flow "B" heat exchangers were not cleaned from contaminants, the fuel gas consumption of 100B-H1 furnace significantly exceeds that of 2017 (Figure 7 b), including the 10% increase in raw material load. At the same time, specific fuel gas consumption increased by 8.7% in 4 months of operation after start-up in 2017, and in the same period after start-up in 2019, specific fuel gas consumption of 100B-H1 furnace increased by 7.4%. This indicates that in 2017 the growth rate of deposits on the heat transfer surface exceeds this figure in 2019, which is the result of reagent supply.

The trend of fuel gas consumption growth (Figure 7 b) and specific fuel gas consumption growth (Figure 8 b) in 2019 is the same as in 2017, which indicates the ineffectiveness of reagents’ action when fed to uncleaned heat exchange surfaces.
6. Summary and Conclusion

1. Despite the supply of reagents to the raw heat exchangers, a decrease in the heat transfer coefficient is observed both at the stream "A", where cleaning was performed, and at the stream "B", where the tube bundles were not cleaned, with the exception of the heat exchanger position 100B-E1B/1,2, which recorded a slight increase in the heat transfer coefficient, which indicates an insufficient dosage of the supplied reagents.

2. When feeding reagents on most heat exchangers, a decrease in the rate of degradation associated with deposits on the heat exchanging surface is observed, which suggests a positive effect of this measure.

3. Fuel gas consumption at the stream "A" in 2019 is comparable to this indicator in 2017, while in 2019 the productivity is 10% higher than in 2017.

4. Specific fuel gas consumption at the stream "A" has changed insignificantly over the period of reagent supply, unlike the same period in 2017, which indicates a positive effect of reagent supply provided that the preliminary cleaning of the tube bundles from contaminants is carried out.

5. On heat exchangers of stream "B" that were not cleaned during the shutdown period in 2019, the heat transfer coefficient tends to improve periodically, most likely due to the action of a dispersing agent and the "self-cleaning" effect when deposits are detached from the heat exchange surface.

6. The fuel gas consumption and its specific consumption at the stream "B", where the heat exchangers were not cleaned after the start-up in 2019, is higher than in 2017, mainly due to an increase in feedstock productivity.

7. The upward trend in the specific consumption of fuel gas at the stream "B" in 2019 and in 2017 remained practically unchanged, which indicates an insufficient efficiency of reagent supply without preliminary cleaning of the heat exchange surface.

7. Recommendations

1. Extend the supply of polymerization inhibitor and dispersant reagents at diesel fuel hydrotreating unit and at delayed coking unit;

2. Specify the dosage of reagents, taking into account that oxygen in the raw material comes not only with the flow of gasoline and light gasoil coking, but also with other flows;

3. To develop a project for constant dosage of reagents to maintain the cleanliness of the heat exchange surface of the raw material heat exchangers of the diesel fuel hydrotreating process unit;

4. To reduce the amount of dissolved oxygen to provide for the installation of pontoons on the tanks from which the raw materials are supplied to the diesel hydrotreating unit.

8. References

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