The analysis of the deposits formation on the working surfaces of heat exchange industrial equipment

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Abstract. The article considers the processes of deposits formation on the walls of heat exchangers. Experimental studies of the composition and structure of deposits in heat exchange equipment elements are carried out. The regularities of deposition are studied. The possibility of virtualization of deposits monitoring sensors is analyzed. The conclusion is made about the possibility of analytical prediction of the behavior of heat exchange equipment during the deposition and their influence on the heat transfer process. A partial replacement of experimental physical and chemical studies by simulation is proposed.

1. Introduction

The use of hardware and software control complexes is widely used in automation systems of thermal industry. The main task of these complexes is to monitor the state of power equipment and devices according to a number of indicators that reflect the compliance of the actual characteristics with the required ones [1]. Based on the data obtained, if the indicators deviate from the specified ones, adjustments are made to the operating mode of the equipment. As for extreme cases, decisions are made about the need in repairing or replacing the equipment. Software and hardware complexes can be applied to various units and equipment that are widely used not only in the energy sector, but also in other industries without the need to complicate the system itself.

The solved task of evaluating the efficiency and reliability of heat exchange equipment in the current mode is very important for the economical operation of the entire complex of equipment. Therefore, the issues of calculation, design and operation of heat exchange control systems are very promising. The issue of improving the system without installing many monitoring sensors requires special attention [1]. The importance of research in this direction is caused by two factors. On the one hand, a decrease in the number of physical sensors due to their high cost significantly reduces the cost of technological solutions; on the other hand, there are system parameters that cannot be directly measured during operation. For heat exchangers, one of these parameters is the state of deposits on the unit wall. Deposits on the heat exchange device walls affect the entire set of its operational characteristics: operating pressure, temperatures, coolant flows, heat transfer coefficients, and run-to-failure time. Correct information about the state of deposits provides reducing the consumption of expensive materials or maintaining the equipment operation in the set modes [2].
Information about the state of deposits on the walls of heat exchangers can be obtained indirectly on the basis of data taken by real physical sensors. The information received, if correctly interpreted, allows us to draw a conclusion about the state of the deposits. In this sense, the algorithm for processing data from physical sensors works as a virtual sediment monitoring sensor. However, for the correct operation of the virtual sensor, at least two conditions must be met:

- understanding physical nature and mechanisms of deposition;
- availability of an appropriate built-in mathematical tools that correctly describe the corresponding mechanisms.

In this regard, the development of virtual sensors requires both experimental studies of the composition and structure of deposits and the analysis of existing dependencies describing the mechanisms and processes of deposits formation.

2. Experimental results

The formation of deposits on the walls of heat exchange devices is a complex process based on the concurrent series of interrelated physical and chemical phenomena. The description of the processes in general form is not possible either from the point of view of the analytical formulation of the question, or from that of the numerical solution. The most rational approach deals with conducting preliminary experimental studies that allow us to identify the main factors and mechanisms of deposition. Steel pipes with a diameter of 42.3 mm, with a wall thickness of 4 mm (GOST 3262-75 - Steel water and gas pipes) were selected as objects of the research. The choice of the research object is resulted from the fact that these pipes are widely used in the water supply industry of the Omsk region by both industrial enterprises and housing and utilities infrastructural objects. As research methods, optical and electron microscopy were used to assess the structure of deposits on the walls, while X-ray fluorescence analysis – to assess the chemical composition of the deposits.

The results of electron microscopy are shown in figures 1 and 2.

![Figure 1. General view of deposits](image)

Figure 1 shows that the deposits are complex layered structures. Deposits delamination is resulted from the fact that strong differences in the physical properties of the deposits themselves and the pipe material lead to the formation of large mechanical stresses leading to delamination. Mechanisms of this kind are well known and are observed, for example, during the formation of coatings [2]. The tendency of deposits to delamination creates a problem itself – with a sufficiently large deposits thickness, the probability of peeling off massive fragments that can cause clogging of the internal
conditional passage increases, which will require premature replacement of the pipe and an increase in 
the cost of operating facilities.

![Figure 2. Deposits structure](image)

The deposits structure shown in Figure 2 is a spliced agglomerations of needle crystals, which let 
us identify the main mechanism of deposition. The formation begins at the primary crystallization 
centers, which can be solid particles of iron oxides, microparticles of impurities introduced by the 
water flow, as well as particles precipitating from an aqueous solution when the solubility limit is 
exceeded. Then a needle crystal is formed from the primary centers, which direction of growth is 
determined by the local gradient of the medium properties. The gradient of properties in this case can 
have both a physical nature (inhomogeneity of the temperature field, inhomogeneity of the medium 
flow) and a chemical one, for example, associated with local inhomogeneity of concentration. The 
results of X-ray fluorescence analysis are shown in Table 1.

**Table 1. Results of X-ray fluorescence analysis**

| Element | Mass fraction, % | Atomic fraction, % | Relative detection error, % |
|---------|------------------|--------------------|-----------------------------|
| O       | 27.80            | 55.84              | 1.18                        |
| Al      | 1.47             | 1.75               | 0.98                        |
| Si      | 2.85             | 3.26               | 0.91                        |
| S       | 0.19             | 0.19               | 0.63                        |
| Fe      | 67.69            | 38.96              | 1.89                        |

Thus, it is found out that the overlays in water pipes are mainly formed by iron oxides in a complex 
stoichiometric composition. The presence of aluminum and silicon is probably resulted from 
aluminosilicates that are found in the water stream due to insufficient purification. The presence of 
sulfur compounds is connected with its presence in the pipe material (allowed by the current GOST).

3. Theory
The reason for the formation of deposits affecting the heat exchange process presupposes a number of 
factors [3]:

• the process of metal corrosion, which proceeds continuously and, depending on the conditions, at different speed, is the main reason of deposition;
• the process of scale formation resulted from the deposition of hardness salts on the heating surfaces, which were found in the coolant in a dissolved form.

In this connection, we can say that the quality of the coolant is its chemical composition, the presence of salts and other solid impurities in it; therefore, in order to obtain accurate data, it is necessary to have an idea about working fluids.

Let us consider a number of factors that have the greatest impact on the rate of deposites formation:

1. Concentrations of dissolved impurities.

The process of precipitation of solid particles on the walls from the coolant begins under the condition that its concentration near the surface \( C_{ct} \) is greater than the solubility at the wall temperature. In this case, the particles are knocked out of the flow and begin to settle on the walls. Such condition is determined using the following equation [3]:

\[
 \frac{dg}{d\tau} = C_f^n,
\]

Where \( C_f \) is the average concentration of the substance in the flow;

\( \frac{dg}{d\tau} \) is the rate of sediment growth;

\( n \) is the exponent.

2. The density of the heat flow.

An increase in the heat flux density \( q \) leads to an increase in the temperature in the boundary layer and the wall; a decrease in the thickness of the viscous sublayer is observed due to an increase in the diffusion coefficient [4]. This leads to an increase in the value of temperature gradients \( dt/dx \) and an increase in the concentration of impurities \( dC/dx \), which leads to the dislocation of solid particles from the flow when the particles begin to sink out on the heat transfer surface. The dependence of the sediment formation rate on the heat flow can be determined using the following formula:

\[
 \frac{dg}{d\tau} = A + B \cdot q + C \cdot q^2,
\]

3. Influence of the flow rate:

An increase in the flow rate taking into account the Reynolds number leads to the flow turbulence which results in an increase in the rate of deposits formation.

Taking into account the analysis of various deposits, it is possible to distinguish the main groups of ones:

− iron oxide deposits.

   Most pipelines are made of steel, so the component of deposits that does not depend on the coolant is iron oxide. In many units its deposits can reach up to 95 % and more.

   Iron oxides convert to \( \text{Fe}_3\text{O}_4 \) which is the basis of iron oxide deposits. Other forms of iron oxides (\( \text{Fe}_2\text{O}_3 \)) form, in the predominant amount, sludge deposits.

   The dependence of the deposits formation rate \( A_f \), mg / (cm\(^2\) * h· on the concentration of \( C_{Fe} \), mg / kg is linear, and on the heat flux density \( q \), W/m\(^2\) is quadratic:

   \[
   \frac{dg}{d\tau} = A_{Fe} = 5,7 \cdot 10^{-14} \cdot C_{Fe} \cdot q^2
   \]

− alkaline earth deposits.

   Many heat carriers in their chemical composition have alkaline earth elements, which include elements containing calcium and magnesium (\( \text{Ca}_2\text{SiO}_3 \), \( \text{CaSO}_4 \), \( \text{CaCO}_3 \), \( \text{CaCl}_2 \) as well as other formations). The formation of alkali leads to the process of oxidation of aluminum.

   The rate of growth of calcium and magnesium deposits from their concentration is nonlinear:

   \[
   A_{(\text{Ca}+\text{Mg})} = 1,3 \cdot 10^{-13} \cdot C_{(\text{Ca}+\text{Mg})} \cdot q^2
   \]

− deposits of aluminum compounds (aluminosilicate, silicate with free SiO\(_2\)).
The corrosion activity of aluminum compounds begins to be observed regularly when there is alkali in the water, otherwise there is almost no corrosion. The process of their oxidation with water can be represented as the following chemical reaction:

$$4K[AlSi_3O_8] + 4H_2O + 2SO_2 = 2K_2CO_3 + 8SiO_2 + Al_4(OH)_8[Si_4O_{10}] \quad (5)$$

The concentrations of silicic acid and aluminosilicates vary widely from 100 micrograms/kg at the initial stage of operation and up to 10 micrograms/kg during continuous stationary operation of the power plant. These concentrations are below the solubility value; nevertheless, both compounds are always present in the sediments. Silicic acid interacts with iron oxides and forms ferrosilicates.

- deposits of copper compounds.

When copper ions come into contact with pure iron, the ions are reduced to pure copper. These deposits are formed in large quantities in the zone of heat flux densities above the value of 200,000 $W/m^2$.

The rate of formation of copper deposits is described by the formula

$$A_{(Cu)} = K \cdot C_{Cu}^{1/2} \cdot q \cdot (q - q_0). \quad (6)$$

4. Conclusion

Analyzing the data considering the structure of deposits and mathematical dependencies describing the process of their formation, we can conclude that the rate of deposition is a complex function of the concentration of impurities, the properties of the metal from which the unit is made, the heat flux density and other system parameters. At the same time, the complexity of the problem makes it extremely difficult to predict the moment when contamination of the pipeline leads to a breakdown. The most reliable information about the duration of the accident-free period of operation of a heating plant can be obtained empirically. However, this method needs much time, as well as financial support and human resources. The most promising approach to solving the problem is the use of simulation. At the same time, a three-dimensional model of the heat exchanger is created, taking into account the presence of deposits on its walls and studying the processes occurring in it with the necessary degree of detail and accuracy. Currently, there are quite a lot of specialized software products for implementing this approach. Examples include ANSYS, SolidWorks, Matlab, Material Studio, Elmer, Salome-Meca, OpenFOAM, COMSOL Multiphysics, and others. As a rule, to solve the problem, it is necessary to use several software working in a sequential bundle [5].

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