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ANALYSIS OF THE HEAT EXCHANGER ENERGY EFFICIENCY OF VARIABLE CROSS SECTION WITH AN INHOMOGENEOUS COOLANT

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One of the main priorities in the modern thermal power engineering development is the problem of energy saving due to the economical use of fuel and energy reserves. Increasing energy consumption with a simultaneous increase in energy prices and widespread environmental degradation necessitates the development and implementation of energy efficient technologies to save fuel, materials and labour costs. The object of study is tubular heat exchangers of variable cross section, which are widely used in steam generators of nuclear power plants, gas turbines and transport plants. Scale deposit properties and the composition of the heat coolant were studied, and their influence on the energy efficiency of heat exchangers was analysed. To study the scale deposits and coolant influence on the energy efficiency of heat exchangers, their properties were examined using an atomic emission analysis with the help of a TESCAN electron microscope. The principles of implementing technologies aimed at intensifying heat transfer, reducing hydraulic and heat losses in heat exchangers were formulated.

Keywords: *Condenser tube, heat transfer, inhomogeneous coolant, peak boiler, scale deposits, variable cross-section.*

1. INTRODUCTION

Efficient use of energy is the most pressing problem in energy development at the present stage. Energy conservation includes a wide range of interrelated activities and techniques to ensure efficient use of energy, i.e., solving problems of reducing energy losses and its effective use at all stages [1]–[4]. In many energy and technological processes, inhomogeneous liquid media are widely used as a coolant, for example, water vapour in the flow part of turbines, in steam generators, mixtures in various heat exchangers, etc. The parameters and state of the coolant largely determine the hydrodynamics of the flow, which in turn affects the rate of heat exchange processes.

The intensity of heat exchangers depends on many factors and conditions, including the degree of variability of the cross section of the pipeline, which is often found in various heat exchange devices [5], [6]. The narrowing or expansion of the channel leads to a change not only in the flow rate of the coolant, but also in a transition in the nature of the flow from laminar to turbulent due to the appearance of vortices and additional swirling of the flow. The flow pressure on the pipeline walls changes, and the amount of friction increases. The presence of a variable cross section affects the hydrodynamics of the flow of a non-uniform coolant, its thermophysical properties and the intensity of various reactions. The appearance of reaction heterogeneity can cause a decrease in the heat transfer of the reactor. In the study [7], a "model of thermal coupling between the powder layer and the coolant" was established for a reactor with an annular fin of variable cross section. It has been discovered that it is possible to effectively eliminate the phenomenon of inhomogeneous response by adjusting the angle of inclination between the outer profile and the outer edge of the layer.

The creation of efficient heat exchangers is one of the priority tasks of thermal power engineering that arises when designing heat supply for industrial structures and residential buildings. To increase the efficiency of heat exchange in heat exchangers, as a rule, turbulization of coolant flows is used [4], [8]–[11]. For example, [9] proposes to use porous metal inserts in a shell-and-tube heat exchanger, which increase the heat transfer surface and the apparent conductivity of the porous medium. With such optimization, it is important to balance two opposing contributions: increased heat transfer and losses due to pressure drop. In addition, the manufacture and installation of porous inserts require additional costs.

Article [12] provides a description of the technological process for purifying process water to prevent scale formation in heat exchangers at production facilities in the energy industry. Quantitative costs for reagents and additives used to purify source process water at thermal power plants can be found in article [13]. The authors also analysed the dosing of additional water to soften the antiscale agent.

Obviously, the degree of heat transfer depends on the purity of heat exchange processes, during which scale deposits occur over time [14]. The presence of even a very thin coating of intra-pipe deposits masks the heat transfer process. In [6], a description is given of an effective method for cleaning heat transfer surfaces from standard deposits using electrohydraulic action. Despite the technique used, cleaning using electrohydraulic action occurs no more than 1–2 times a year, and sometimes even after a year or two. In this case, the operation of the heat exchanger itself temporarily stops. During the heating season, it is necessary to take into account the influence of scale deposits on the heat exchanger.

The present study mainly focuses on the patterns of formation of scale deposits in heat exchange pipes taking into account the treatment of process water (coolant) in accordance with established standards at existing heat and power facilities. To carry out the experiments, separate fragments of turbogenerator condenser pipes and peak boiler pipes were taken, cut from various sections from heat exchangers after seasonal operation in 2021–2022 at CHPP-3 in Karaganda.

2. EXPERIMENTAL PART. MATERIALS AND RESEARCH METHODS

Let us consider the features of some technologies for processing coolant in combined heat and power plants using the example of a water treatment plant (WTP). The standard technology of the water treatment process includes several stages, such as filtration, ultrafiltration, softening with Na-cation resin, etc. [15]. This step-by-step water treatment technology makes it possible to reduce to a minimum the amount of hazardous chemicals used (sulfuric acid, sodium alkali) compared to traditional technologies. At the water treatment facility, process water, preheated to a temperature of 25□35 °C, is supplied through a pipeline. Since the amount of water being treated is quite large (>1200 m^3/h), to ensure the stability of the WTP, the flow is divided into four parallel flows between pressure filtration units, with four filter columns in each. The filters are loaded with anthracite. Part of the filtrate is accumulated in filtered water storage tanks TW-40/1 and TW-40/2 to provide the required amount of water for backwashing the filters, part is used to prepare a coagulant solution, and the rest of the filtrate is supplied to the ultrafiltration unit. If the water preparation technology allows for a higher content of hardness ions, clarified water pre-treated with antiscalant after ultrafiltration units can be immediately sent to storage tanks.

Effluents from pressure filters and ultrafiltration units are transported through water pipelines, into which, to accelerate the deposition of suspended matter into sediment, a 0.1% flocculant solution is dosed by flocculant preparation and dosing unit. In wastewater from chemical backwashes using sodium hypochlorite, the concentration of free chlorine in the wash water will be up to 20–25 mg/l. To neutralize free chlorine in wastewater, sodium bisulfite is dosed during recirculation. Wastewater with a neutral pH value is discharged into the wastewater system. The listed water treatment processes should ensure uninterrupted operation of the heat and power process. However, as practice shows, after long-term operation, solid scale deposits form in heat exchange pipes [16], [17].

As noted above, during the heating season, due to the formation of scale deposits, the cross section of the pipeline becomes variable. Visual analysis of longitudinal and transverse sections of heat exchange pipes with diameter *d* showed that the nature and thickness of scale deposits were changing along the length of the pipe (see Fig. 1). Another photograph of the same boiler pipe fragment is shown in [6] (Fig. 2a). The uneven formation of scale deposits is clearly visible here.

a *b*

Fig. 1. Photos of a cross section of heat exchange pipes with scale deposits:
(a) – condenser pipe, *d* = 28mm; (b) – peak boiler pipe, *d*=19 mm.

The greatest thickness of deposits is formed, as a rule, at the inlet section of the coolant or immediately after the turn (bend) of the pipe. Even in a straight section, scale deposits form in the form of rings of varying thickness and width, alternating at certain distances. Between these so-called annular scale formations, the coolant actually moves as if through a pipe of variable cross section.

3. RESULTS AND DISCUSSION

As part of the study, a spectral analysis of the coolant used in the peak boiler tube and the condenser pipe was carried out for the content of chemical elements. According to standard technology, atomic emission analysis of the dry residue of the coolant liquid was carried out. Table 1 shows the content of chemical elements in coolant samples before and after treatment at the WTP. It can be seen that if the content of some elements, such as P, Zr, practically does not change after treatment on WTP, then the concentration of other elements decreases (Pb, Ag) or increases (Sc, Mn, Ga, Be, Zn) several times. The spectral analysis protocol dated 16 October 2022 noted that the elements Au, Hf, Hg, In, Pt, Ta, Te, Th, Tl, U were not detected.

Table 1. Chemical Composition of the Heat Coolant

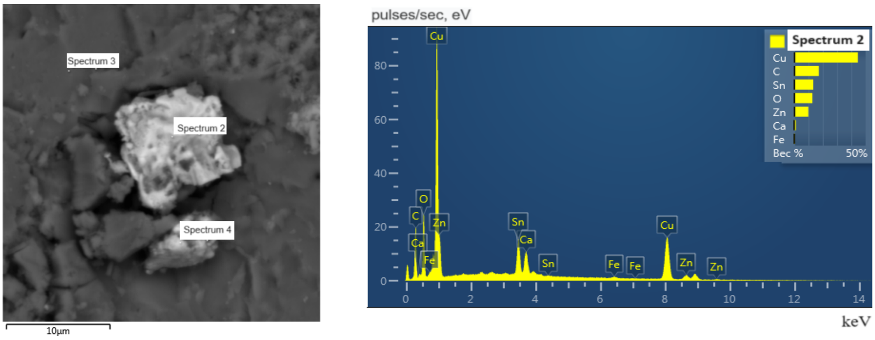
Heat coolant samples:	Sc, mg/kg	P, mg/kg	Mn, mg/kg	Pb, mg/kg	Zr, mg/kg	Ga, mg/kg	Ni, mg/kg	Be, mg/kg	Mo, mg/kg	Yb, mg/kg	Zn, mg/kg	Ag, mg/kg
before processing	<1	<300	50	15	≤5	<1	≤2	<0.3	1	<0.5	<20	0.15
after processing	8	<300	150	<2	5	20	10	1.2	5	1.5	40	0.12

Despite the fact that the same coolant was used in the experiments on the studied sections of the heat exchanger, differences in the concentrations of the same chemical elements were found in samples of scale deposits taken in different sections of the heat exchanger (see Table 2). For example, zinc present in the coolant was not detected in scale sample No. 2.

Table 2. Chemical Composition of Scale Deposits

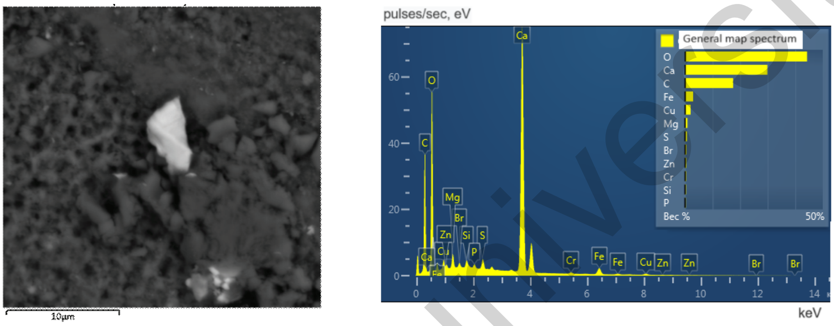
Scale deposits samples	Sc, mg/kg	Pb, mg/kg	Ti, mg/kg	Zr, mg/kg	Ga, mg/kg	Cr, mg/kg	Ni, mg/kg	Mo, mg/kg	Sn, mg/kg	Li, mg/kg	Yb, mg/kg	Zn, mg/kg	Ag, mg/kg
No. 2	4	120	300	15	3	80	50	3	500	<10	0.5	8000	1.2
No. 3	≤1	10	30	5	<1	5	250	≤1	12	<10	<0.5	800	<0.05

The structure and composition of scale deposits was studied using a TESCAN electron microscope. Atomic emission (spectral) analysis was used as a determination method; the results are shown in Figs. 2–6. General map spectrum was obtained as a result of superposition and processing of several spectra taken at different points of the sample (see Fig. 2a). For example, for deposits in the boiler pipe at different points 12 spectra were obtained.



a b

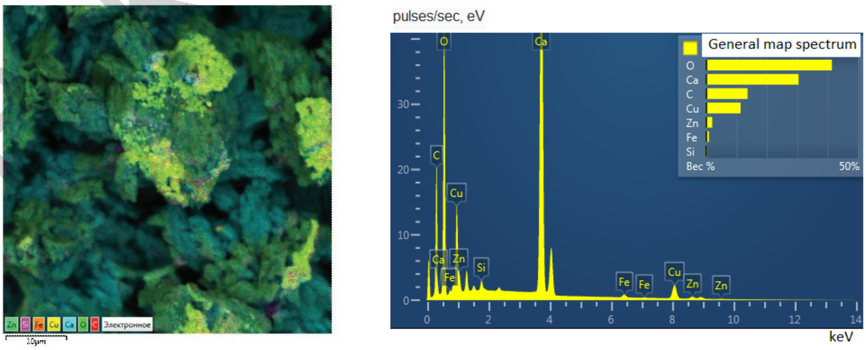
Fig. 2. Electronic image of (a) and (b) elemental composition of scale deposits in the condenser tube; $d = 24$ mm.



a b

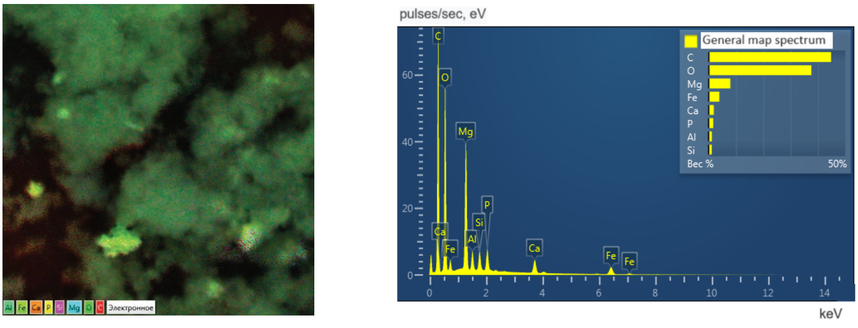
Fig. 3. Electronic image of (a) and (b) elemental composition of scale deposits in the condenser tube; $d = 28$ mm.

Figures 4–6 show multilayer EDS maps obtained as a result of energy dispersive analysis (EDS) of chemical elements across layers of scale deposits. On the EDS-map, chemical elements are shown by different colours.



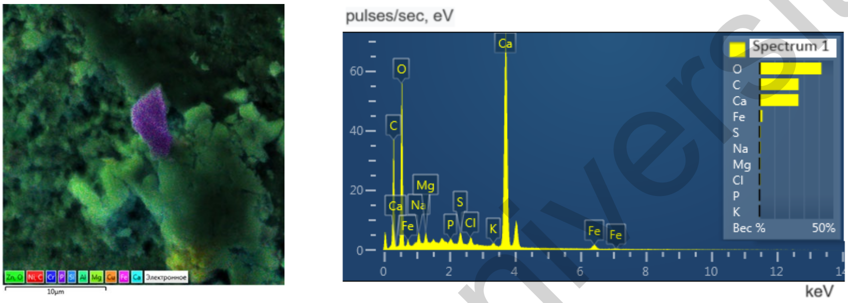
a *b*

Fig. 4. Multilayer EDS-map (a) and (b) elemental composition of scale deposits in condenser tube; $d = 24$ mm.



a *b*

Fig. 5. Multilayer ECD map (a) and (b) elemental composition of deposits in boiler pipe; d = 19 mm.



a b

Fig. 6. Multilayer ECD map (a) and (b) elemental composition of scale deposits in the condenser tube; d = 28 mm.

Thus, in fact, the coolant is a multicomponent mixture of technical water with various chemical elements, in which phase transformations also occur. When flowing at different speeds in an inhomogeneous coolant, due to temperature changes, gas bubbles appear, which also affect the intensity of heat exchange processes. To construct a computational model, a regression analysis of experimental data was carried out using the method of group consideration of arguments (GMCA). The principle of constructing the calculation algorithm and the methodology for choosing a criterion to ensure the quality and accuracy of the model are described in [18]. It is shown in [19] that, if all conditions are maintained, the presence of a narrowing or expansion of the tubular channel leads to a significant restructuring of the nature of the flow in the initial section of the pipe, which in turn determines the intensity of heat transfer along the entire length. As a result of the regression analysis of the data, the following calculation formula for the heat transfer coefficient was obtained:

$$Nu = 101{,}5 - 14{,}5\frac{l}{d} + 445\beta^2 + 0{,}75\left(\frac{l}{d}\right)^2 + 39{,}5\beta\cdot\frac{l}{d} + 0{,}01\alpha^3\cdot\beta\cdot\frac{l}{d} - 13\alpha\cdot\beta^2\cdot\frac{l}{d},$$

where α is the angle of narrowing or expansion of the channel; *l/d* is the calibre, determined by the ratio of the distance from the edge of the pipe to the measured section to the diameter of the pipe; *β* is a gas content coefficient.

As a result of the calculations, graphs of the dependence of the heat transfer coefficient on the concentration of the gas phase at various distances from the edge of the pipe at different constriction angles (α = 10°, 20°, 30° и 60°) were obtained. It was shown that along the entire length of the pipe, an increase in the concentration of the gas phase led to an increase in the intensity of heat transfer at the same flow rate.

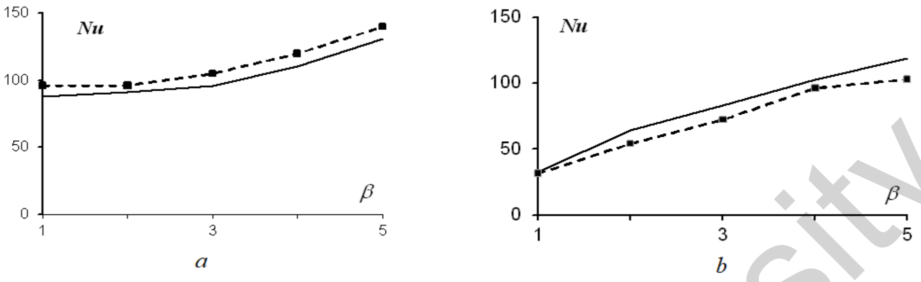


Fig. 7. Dependence of the heat transfer coefficient on the concentration of the gas phase in a non-uniform coolant along the length of the pipe: (a) l/d=1 and (b) l/d=10; channel narrowing angle α=10°; Re = 2450; ■ – an experiment, line – a calculation.

In the immediate vicinity beyond the sharp expansion (expansion angle α=180˚) at a speed of Re≈5103, the presence of gas bubbles has virtually no effect on the level of turbulence of the flow. In the separated flow zone, the intensity of heat exchange is the same as during the movement of a homogeneous fluid. With an increase in the Reynolds number, gas bubbles in a zone of high turbulence play the role of dampers of turbulent pulsations, as a result of which the intensity of heat transfer decreases. At small diffuser expansion angles (α ≤ 20˚), the size of the separation zone and the level of flow turbulence increases; the presence of gas bubbles can also lead to an increase in the level of flow turbulence. Thus, the addition of a gas phase can help increase heat transfer intensification by 10–12 %.

4. CONCLUSIONS

The performance of the heating system will reduce over time without proper care and annual maintenance. Hard water can result in scale deposits lowering the heat transfer rate. Large deposits in the heat exchanger will also reduce the heat transfer rate and negatively affect the boiler efficiency.

It is known that the intensity of a heat exchanger depends on the characteristics of its hydrodynamics of motion and the properties of the inhomogeneous coolant. As part of the project, the structure and chemical composition of scale deposits and the coolant were studied using a spectral analysis. The effect of the scale deposits nature and sizes on the energy efficiency of heat exchangers was considered.

A regression analysis of experimental data was carried out, which made it possible to identify some patterns of heat transfer during the flow of a non-uniform flow through channels of variable cross section. The research results can be used to develop a reagent in the process of treating a coolant liquid, which helps prevent the formation of scale deposits. In addition, by creating a variable cross section it is possible to further turbulize the flow and, accordingly, intensify heat exchange processes.

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