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TECHNOLOGICAL WEAR INFLUENCE ANALYSIS ON THE DECREASE IN THE EFFICIENCY OF A CLOSED LOOP CONTROL OF HEAT EXCHANGE EQUIPMENT

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Abstract

A physical model of heat and mass transfer processes in industrial equipment is presented in the work. The transfer functions of the model main signals taking into account the equipment's technological wear are obtained. The effect of deposits on the operation of a closed loop for temperature control has been studied. As a result of numerical experiments, a quantitative dependence has been established between the thickness of deposits on the inner working surface of heat exchange equipment and the quality indicators of the control system. Conclusions are drawn about the inefficiency of linear control systems in the conditions of technological wear during in real operation of heat exchange equipment.

Keywords: heat and mass transfer; heat exchange surface fouling; linear control systems, modelling control object; simulink matlab.

1. Introduction

Deposits on the surfaces of heat exchange and process equipment are a serious problem in the heat power industry, as well as in the chemical, food and other industries. These deposits impair the efficiency of heat transfer, which leads to an increase in specific energy consumption, reducing the effective flow area of equipment elements and pipelines, and increasing hydraulic resistance leads to an increase in energy consumption for transporting the coolant [1], [2], [3], [4], [5], [6], [7]. As a result, the chance of an accident at work due to the failure of the heat exchanger increases. The above factors in the framework of control theory can be classified as perturbations of a parametric nature [8]. The lack of compensation for parametric perturbation in combination with the most common linear PID controllers in the industry can lead to a decrease in the accuracy of maintaining the required process parameters and reduce the overall efficiency of the process. To solve this problem, in most cases, traditional PID regulation is used with the use of special corrective links that ensure the adjustment of the linear control system to the changing parameters of the control loop [9], [10], [11], [12], [13]. However, such approaches require significant effort for the study of mathematical models of specific technological objects and the qualifications of service personnel. The construction of a universal analytical model of heat exchange equipment, taking into account polluting deposits on internal surfaces, can make it possible to assess the degree of influence of deposition on the operation of the control loop and design corrective actions to compensate for the operation of the regulator.

The purpose of this study is to identify the influence of the deposits thickness of the closed-loop control systems performance for heat exchange equipment while maintaining the required temperature regime using linear control systems.

2. Mathematical model of the heat exchanger taking into account technological wear

The schematic diagram of the simulated heat exchanger displaying energy and mass flows is shown in Figure 1. The object of the simulation is the heating circuit of raw water (two heat exchangers T-3 and T-1, connected in series) for technological needs, where it is required to maintain the temperature within 20-30 °C, the permissible fluctuation is ± 1 °C per hour.

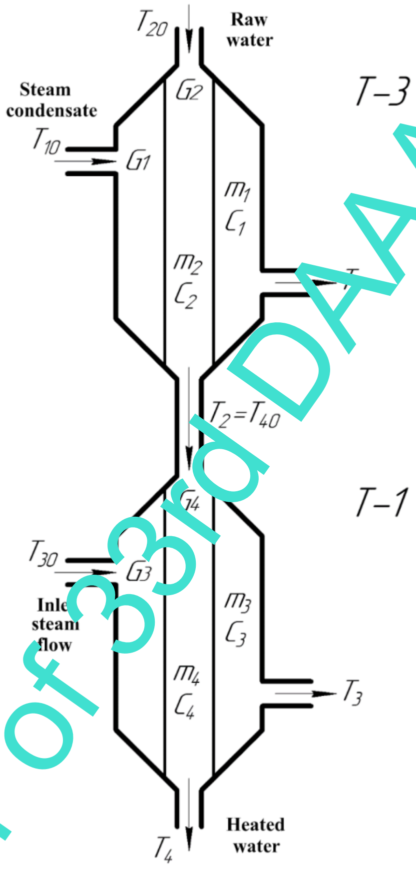

Fig. 1. Scheme of the simulation object

The value of this parameter is influenced by raw water temperature T_{20}, steam temperature T_{30}, condensate temperature T_{10} and other system parameters. The maximum water flow through the heat exchanger is assumed to be no more than 250 m3/h. The temperature of the heat carrier entering the unit can vary within different limits depending on technological factors, and in order to comply with the optimal conditions of the technological process, the temperature at the outlet of the heat exchanger must be maintained within the specified limits.

Let's develop a mathematical model of the heat exchanger T-3. The heat carrier in it is water vapor condensate. The basis for creating a mathematical model of heat exchange processes is the equation of the law of conservation of energy in differential form.

Equation 1 of the energy conservation law has the form [14], [15]:

$$mC\frac{dT}{dt} = \sum Q, \tag{1}$$

where m is the mass [kg], C is the specific heat capacity [kJ/(kg °C)],
T – temperature [°C], Q – heat flow [kJ]

On the basis of equation 1, we will compose differential equations for the temperature of the coolant T_1(t)and the heated product T_2(t), characterizing the water heating model - equations 2 and 3, respectively:

$$m_1C_1\frac{dT_1(t)}{dt}=G_1C_1T_{10}-G_1C_1T_1(t)-k_{T-3}S_{T-3}\big(T_1(t)-T_2(t)\big), \tag{2}$$

where m1 is the mass of the heat carrier (condensate) [kg], C_1 is the specific heat capacity of the heat carrier [J/(kg °C)], T_1(t) is the temperature of the heat carrier [°C], T_2(t) is the temperature of the heated product [°C], G_1 is the mass coolant flow rate [kg/s], $k_{T\text{-}3}$ – heat transfer coefficient through the wall T-3 [W/(m^2 °C)], $S_{T\text{-}3}$ – heat exchange surface area T-3 [m2].

$$m_2C_2\frac{dT_2(t)}{dt}=G_2C_2T_{20}-G_2C_2T_2(t)+k_{T-3}S_{T-3}\big(T_1(t)-T_2(t)\big), \tag{3}$$

where m_2 is the mass of the product to be heated [kg], C_2 is the specific heat capacity of the product to be heated [J/(kg °C)], T_2(t) is the temperature of the product to be heated [°C], G_2 is the mass flow rate of the product to be heated [kg/s], $k_{T\text{-}3}$ – heat transfer coefficient through the wall T-3 [W/(m^2 °C)], $S_{T\text{-}3}$ – heat exchange surface area T-3 [m^2].
Similarly, we obtain a mathematical model of the heat exchanger T-1 - equations 4 and 5. The heat carrier in it is steam.

$$m_3C_3\frac{dT_3(t)}{dt}=G_3C_{30}T_{30}-G_3C_3T_3(t)-k_{T-3}S_{T-3}\big(T_3(t)-T_4(t)\big), \tag{4}$$

where m_3 is the mass of the heat carrier (condensate) [kg], C_3 is the specific heat capacity of the heat carrier [J/(kg °C)], T_3(t) is the temperature of the heat carrier [°C], T_4(t) is the temperature of the heated product [°C], G_3 is the mass coolant flow rate [kg/s], $k_{T\text{-}1}$ – heat transfer coefficient through the wall T-1 [W/(m^2 °C)], $S_{T\text{-}1}$ – heat exchange surface area T-1 [m^2].

$$m_4C_4\frac{dT_4(t)}{dt}=G_4C_4T_{40}-G_4C_4T_4(T)+k_{T-1}S_{T-1}\big(T_3(t)-T_4(t)\big)+r\cdot G_3, \tag{5}$$

where m_4 is the mass of the heated product [kg], C_4 is the specific heat capacity of the heated product [J/(kg °C)], T_4(t) is the temperature of the heated product [°C], G_3 is the mass flow rate of the heat carrier [kg/s], G_4 is mass flow rate of the heated product [kg/s], $k_{T\text{-}1}$ – heat transfer coefficient through the wall T-1 [W/(m^2 °C)], $S_{T\text{-}1}$ – heat exchange surface area T-1 [m^2], r – specific heat vaporization of water [J/kg].
The heat transfer coefficient k through a single-layer wall is defined as [16]:

$$k=\frac{1}{\frac{1}{\alpha_1}+\frac{\delta}{\lambda}+\frac{1}{\alpha_2}}, \tag{6}$$

where δ is the wall thickness [m], λ is the thermal conductivity of the wall material [W/m °C], α_1 is the heat transfer coefficient from the hot coolant to the wall [W/(m^2 °C)], α_2 is the heat transfer coefficient from the wall to the cold substance [W/(m^2 °C)].
The physical and technical parameters used for the simulation are given in tables 1 and 2.

Parameter name	Parameter designation	Meaning
Condensate temperature for heating (T-3)	T_{10}	80°C
Raw water temperature per unit	T_{20}	3°C
Steam temperature for heating (T-1)	T_{30}	280°C
Water temperature after T-3 for reheating in T-1	T_{40}	T_2
Mass flow of condensate for heating	G_1	$44\,\frac{kg}{s}$
Mass flow of raw water per plant	$G_2=G_4$	$70\,\frac{kg}{s}$
Mass flow of steam for heating	G_3	$0\ldots2{,}7\,\frac{kg}{s}$
Mass of coolant (condensate) in T-3	m_1	680 kg
The mass of the heated product in T-3	m_2	550 kg

Mass of coolant (steam) in T-1	m_3	1,253 kg
The mass of the heated product in T-1	m_4	250 kg
Heat exchange surface area T-3	S_{T-3}	80 m^2
Heat exchange surface area T-1	S_{T-1}	48$м^2$
Wall thickness of the heat exchanger T-3 and T-1	δ	0,002м

Table 1 - Initial data

Calm water - metal wall	$450\ \frac{W}{m^2{\cdot}°C}$
Flowing water - metal wall	$450 + 2100\sqrt{v}\ \frac{W}{m^2{\cdot}°C}$
Condensing water vapor	$10500\ \frac{W}{m^2{\cdot}°C}$
Specific heat of the heat carrier (water) in T-3, specific heat of the heated product (water) in T-3 and T-1	$4183\ \frac{J}{kg \cdot °C}$
Specific heat capacity of the coolant in T-1 (steam)	$2200\ \frac{J}{kg \cdot °C}$
Specific heat of vaporization of water	$2256\ \frac{kJ}{kg}$
Thermal conductivity coefficient of heat exchanger material (steel «12X18H10T»)	$15\ \frac{W}{m \cdot °C}$

Table 2 - Physical constants and dependencies [15]

The proposed model makes it possible to accurately consider the process of water heating in shell-and-tube heat exchangers T-3 and T-1. The model takes into account the thermal process of the phase transition when steam is used as a heat carrier, as well as the heat transfer coefficient through the walls of the heat exchanger. The use of such a model provides a mathematical tool for analyzing the behavior of control systems with changing parameters in a known range.

The system of equations (2)-(5) will be used as a basis for obtaining a linear model of the control object in the form of transfer functions, taking into account the pollution of the working surfaces of heat exchange equipment.

3. Modelling of the functional elements of the temperature control loop by transfer functions

The block diagram of the temperature control loop is shown in Figure 2.

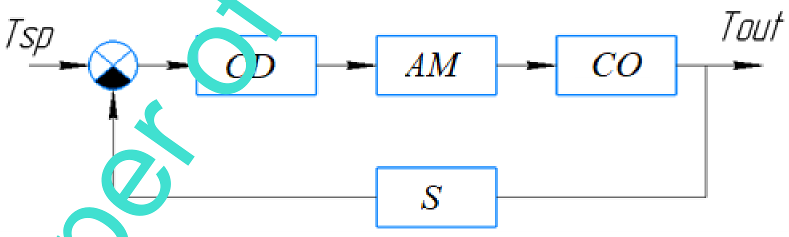

Fig. 2. Scheme of the simulation system

This scheme consists of the following elements:
- control device (CD) – PID controller;
- actuating mechanism (AM) – steam flow control valve at T-1;
- control object (CO) – T-3 and T-1 heat exchangers connected in series;
- sensor (S) – thermal converter.

For the synthesis of the control system, we obtain the transfer functions of the sensor (thermal converter) and the actuating mechanism (control valve) and the control object.

Thermal resistance is a first-order aperiodic link, since the sensor converts signals of various physical nature: the input signal (temperature) into the output signal (resistance). The transfer function of the thermal resistance will be written as:

$$W_S(p) = \frac{k_S}{T_S p + 1}. \qquad (7)$$

The dependence of the analog output signal of the sensor on temperature is linear, therefore, in order to simplify the model, we will accept the gain factor k_S=1. The time constant in the liquid, according to the reference data for the thermal converter, is T_S= 15 s.

Therefore, the transfer function of the temperature sensor has the form:

$$W_S(p) = \frac{1}{15p+1}. \tag{8}$$

As the transfer function of the control valve, we use an first-order inertial link:

Time constant T_{am} is defined as the valve opening time with a small input action T_{am} = 0.03 s. We find the proportionality coefficient based on the maximum flow rate G_3=2.7 kg/s as the ratio $k_{\text{am}} = \frac{2{,}7\frac{kg}{s}}{100\%} = 0{,}027\,\frac{kg}{s{\cdot}\%}$.

The transfer function of the steam control valve has the form:

$$W_{\text{am}}(p) = \frac{0{,}027}{0{,}03p+1}. \tag{9}$$

The heat exchanger described by equations (2)-(5), taking into account changing parameters, is a non-linear element of the model. To carry out the synthesis of the control system, the linearization of the control object was carried out and the transfer function was obtained for the control channel and the perturbation channel using the Linear Analysis Tool Simulink.

The calculated transfer function for the disturbance channel has the form:

$$W_{\text{dist}}(p) = \frac{0{,}427082p^2 + 10{,}0575p + 0{,}86435}{11{,}9832p^4 + 288{,}197p^3 + 147{,}394p^2 + 22{,}5285p + 1} \tag{10}$$

The calculated transfer function for the control channel has the form:

$$W_{ctrl}(p) = \frac{0{,}00886758p + 0{,}264018}{0{,}00456621p^3 + 0{,}260913p^2 + 3{,}65342p + 1}. \tag{11}$$

The resulting transfer functions describe the control object behaviour dynamics, and are used for values close to some steady value.

4. Investigation of the influence heat exchange equipment pollution processes on decrease in the control quality of linear control systems

To perform a study of the influence of contamination processes of heat exchange equipment on reducing the quality of regulation, it is necessary to assess the quality of closed loop single-circuit regulation of the heat exchanger, taking into account the technological wear of the equipment and to simulate the change in its characteristics over time. The main study objective is to find out linear regulators are able to provide the required control quality of a non-stationary control object.

In the software environment Matlab/Simulink a complete model of the temperature control loop was developed (fig. 3).

As the initial conditions, the parameters of the plant operation in winter were used: the temperature of heat exchanger T-3 inlet water in the range of 2-5 °C. Subsequent heating of water and temperature control at the outlet heat exchangers cascade is carried out by changing the mass flow rate of steam at T-1 with a set range of 0-2.7 kg/s. Control action on the system is G3 - the mass flow rate of steam at T1, and the disturbing action T20 is the temperature of raw water at the plant. The simulation results are shown in fig. 4.

From the simulation results, it can be concluded that the system reaches the required temperature value of 27 °C. According to the technological regulations, deviations in the outlet temperature should not exceed ±1 °C per hour. This condition is met even if the inlet water temperature deviation widely (1°C…11°C).

At the second stage, modeling was carried out taking into account technological wear (2 mm fouling), which leads to a decrease thermal conductivity coefficient by 4 times. The simulation results are shown in fig 5. The graph shows deviation in the outlet temperature in the range of 26.6°C ... 27.3°C. These deviations meet the requirements (not exceed ±1 °C per hour).

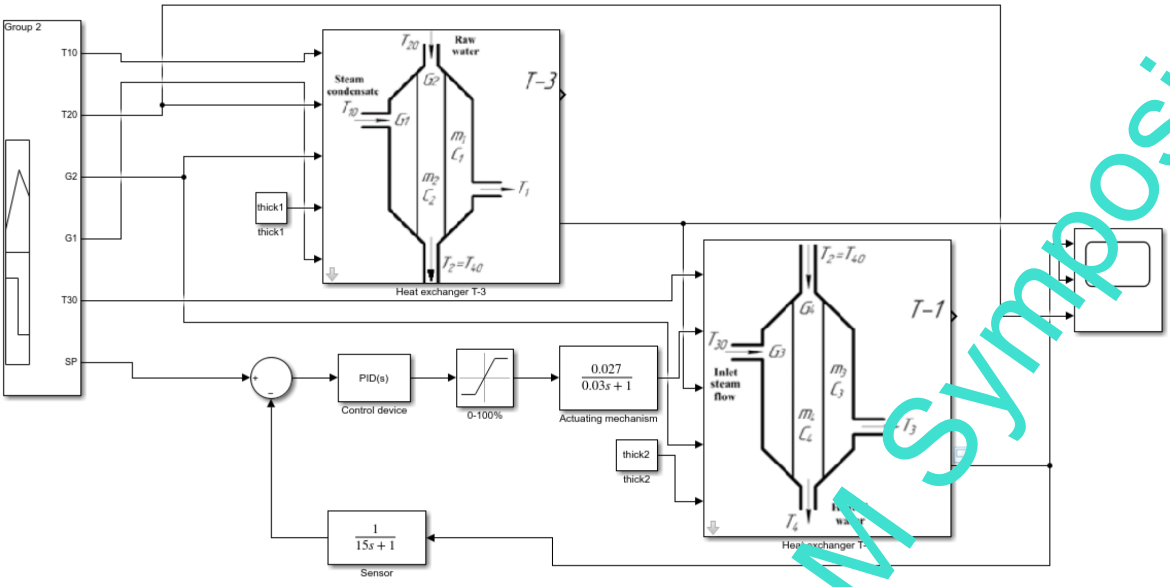

Fig. 3. System simulation diagram in Matlab/Simulink

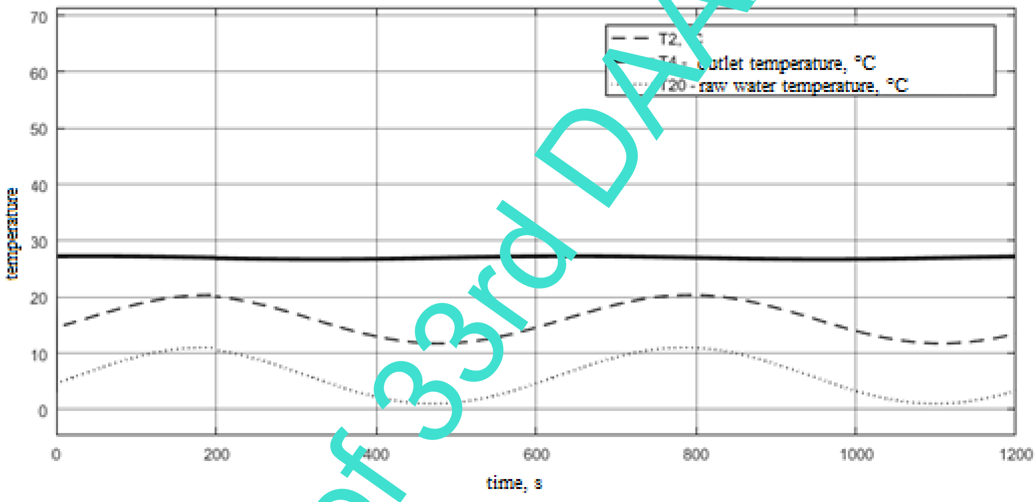

Fig. 4. System simulation results

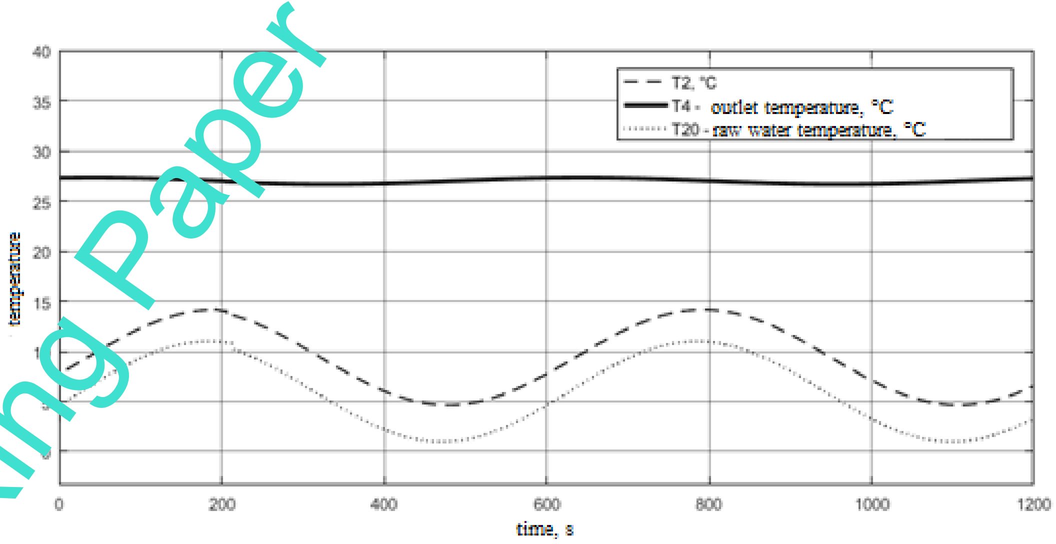

Fig. 5. System simulation results with technological wear

At the final stage, the operation of the automatic control system was simulated, taking into account scale deposits of 3 mm (the results are shown in fig. 6). In this case, temperature deviation is observed in the range of 25.9-29.8 °C, which does not meet the requirements of the water treatment process.

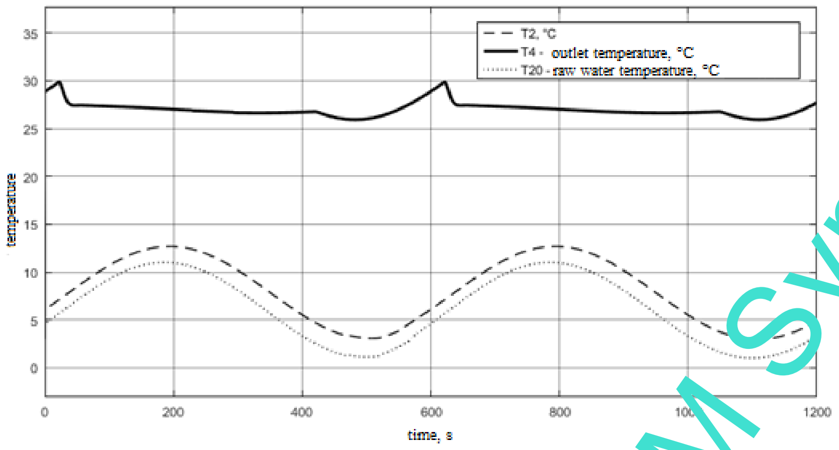

Fig. 6. System simulation results with strong technological wear

5. Conclusion

The main purpose of the work was to investigate the negative impact of the deposits thickness on the walls of heat exchange equipment on the linear control systems performance.

A system consisting of two heat exchangers connected in series was chosen as the control object under study. The physical and mathematical model of this system took into account the deterioration of the thermal conductivity of the system with an increase in the thickness of deposits through the thermal conductivity coefficient. The resulting differential equations were used to build the model in the form of transfer functions of the entire outlet water temperature control system in the Matlab/Simulink environment. System studies were carried out taking into account winter operating conditions (2-5 °C of raw water) and various degrees of pollution.

The optimally tuned PID controller provided the required outlet temperature range, up to 3 mm of deposition on the inner walls of the heat exchanger. Further operation of this facility without human intervention is not advisable due to a decrease in economic and technological efficiency.

The performed simulation of the temperature control loop operation with a PID controller, taking into account technological wear, shows that linear control systems are not able to provide the required quality of control of an object with characteristics that change due to strong wear. An analysis of the causes of this phenomenon requires additional research; as a hypothesis, it can be assumed that a decrease in the heat transfer coefficient due to scale layers formed during operation seriously affects both the time constants of the controlled system and other static coefficients. To compensate for these changes in real practice, the control system has to adjust the parameters or introduce special corrective links, which requires an individual approach to each installation and type of coolant. In special cases, ignoring such processes can lead to a loss of stability of the control system, followed by a violation of the technological process and a loss in the quality of temperature-dependent processes.

There are also positive aspects in the discovered phenomenon - since the difference in signals in heat exchange equipment is associated with deposits on its walls, then in the presence of an adequate physical and mathematical model, a comparison of these signals can make it possible to calculate the thickness of the degree of contamination. Thus, the linear control method can be indirectly used as a virtual analyzer of fouling in heat exchangers.

6. References

[1] Dytnersky Yu. I. (1995). *Processes and apparatuses of chemical technology*, Chemistry, Moscow, Russian Federation

[2] Cernecky Jozef, Jan Koniar, and Zuzana Brodnianska. (2011). *Impact of lower heat exchange plate's geometry on heat transfer in horizontal channel*, Annals of DAAAM for 2011 & Proceedings of the 22nd International DAAAM Symposium, pp. 0245–0246, Published by DAAAM International Vienna, TU Vienna, Austria

[3] Galkovsky V.A., Chupova M.V. (2017). *Analysis of the decrease in the heat transfer coefficient of heat exchangers due to surface contamination*, Internet journal "NAUKOVEDENIE", Vol. 9, Issue 2.

[4] Bolotova Yu. V., Ruchkinova O. I. (2015). *Corrosion of heat exchange equipment of petrochemical industries*, Bulletin of the Perm National Research Polytechnic University. Mechanical engineering, materials science. Vol. 17, Issue 4. pp. 102–119.

[5] Matukhnov T.A., Matukhnova O.D., Yurkina M.Y. and Khomchenko N.V. (2020). *Assessment of scale formation in heat exchangers*, The Third Conference. Problems of Thermal Physics and Power Engineering. Journal of Physics: Conference Series, Ser. 1683 052031, DOI: 10.1088/1742-6596/1683/5/052031.

[6] Ren L., Cheng Y., Yang J., Wang Q. (2020). *Study on Heat Transfer Performance and Anti-Fouling Mechanism of Ternary Ni-W-P Coating*, Applied Sciences, Vol. 10(11), No. 3905. DOI: https://doi.org/10.3390/app10113905

[7] Harche, R., Absi, R., Mouheb, A. (2014). *Study of the fouling deposit in the heat exchangers of Algiers refinery*, International Journal of Industrial Chemistry, Vol. 5. No. 16. DOI: 10.1007/s40090-014-0016-6.

[8] Sivakumar P., Prabhakaran D., Kannadasan T. (2012). *Temperature Control of Shell and Tube Heat Exchanger by Using Intelligent Controllers-Case Study*, International Journal of Computational Engineering Research (IJCER). Vol. 2, Issue 8. p. 285–291.

[9] Bespalov A. V., Kharitonov N. I. (2007). *Chemical Process Control Systems*, ICC "Akademkniga", Moscow, Russian Federation

[10] Shteinberg Sh.E., Zalutsky I.E., Serezhin L.P., Varlamov I.G. (2003). *Adjustment and adaptation of automatic regulators. Tool set of programs*, Industrial ACS and controllers, No. 10, p. 43–47.

[11] Skorospeshkin M.V., Tsapko G.P. *Adaptive corrector of dynamic characteristics of automatic control systems*, Scientific and technical conf. students and graduate students, MPEI, Vol. 1. p. 498–499.

[12] Khare Y.B., Singh Y. (2010). *PID Control of Heat Exchanger System*, International Journal of Computer Applications, Vol. 8 (6), p. 22-28, DOI: 10.5120/1213-1742.

[13] Shanthi K, Bhanumathi V., Singh Ajith. B., Manju P., Narendiran S. (2020). *Investigation Of Intelligent Pid Controller Intended For Heat Exchanger*, International Journal of Future Generation Communication and Networking, Vol. 13, No. 2. p. 1642–1654.

[14] Bukhmirova V.V., Sozinova T.E., Solnyshkov Yu.S. (2015). *Calculation of heat transfer through impermeable walls*, ed. ISPU, Ivanovo, Russian Federation

[15] Nitsche, M., & Gbadamosi, R. O. (2015). *Heat exchanger design guide: a practical guide for planning, selecting and designing of shell and tube exchangers.* Butterworth-Heinemann.

[16] Bilonoga, Y., & Maksysko, O. (2018). *Specific features of heat exchangers calculation considering the laminar boundary layer, the transitional and turbulent thermal conductivity of heat carriers*. International Journal of Heat and Technology, 36(1), p. 11-20.