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MODELING THE DYNAMICS OF HEAT AND MASS TRANSFER PROCESSES IN A TUBULAR HEAT EXCHANGER UNDER PULSED INFLUENCES

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The paper discusses the results of experimental studies of the influence of the degree of inhomogeneity of a liquid flow on the dynamics of heat and mass transfer processes under pulsed impacts. High-voltage electric discharges in a liquid medium were used as impulse actions, through which an electro-hydraulic effect is realized, accompanied by the appearance of shock waves. The dynamics of the occurring nonlinear, rapidly changing heat and mass transfer processes at high hydraulic pressures cannot be described using differential equations. The simulation was carried out on the basis of the method of group consideration of arguments, the advantage of which is the construction of polynomial dependencies using a small amount of experimental data. The results of constructing polynomial dependences made it possible to reveal the synergistic effect of the influence of flow parameters on the dynamics of the impulse pressure amplitude and the intensity of heat transfer.

Keywords: heat and mass transfer, tubular heat exchanger, diffuser, method of group consideration of arguments, impulse action, electrohydraulic effect, heat transfer rate.

Introduction

The widespread use of electricity and thermal energy leads to the development of methods for increasing the efficiency of heat exchange processes, which helps to reduce overall energy consumption and protect the environment. At industrial and energy enterprises and branches of technology, the task of intensifying the heat transfer process and creating highly efficient heat exchangers is very relevant. The efficiency of each stage of electricity production is discussed and ways to improve the efficiency of heat production are proposed [1-7]. It's known that at the transport enterprises of thermal power engineering and in many industrial production processes, processes are responsible for heat consumption due to the movement of the coolant in the form of hot water through pipelines that are limited by parameters and configuration. To implement specialized technologies, a heterogeneous flow is used, consisting of water-soluble solutions with gaseous solutions and chemical impurities in the form of components.

At thermal power plants, industrial water is used as a heat carrier, which, before entering the heating boilers and steam generators, undergoes a 2- or 3-stage purification from impurities. But during operation, a layer of solid scale deposits is formed on the internal surfaces of tubular heat exchangers, which impair the efficiency of the heat exchanger by reducing the diameter of the pipeline [3-5]. Thus, after a certain period of operation, the purified water becomes a non-uniform flow. The degree of heterogeneity associated with the presence of gaseous and solid impurities can sometimes cause undesirable effects, such as an increase or, conversely, a decrease in pressure, which leads to a significant change in the intensity of heat transfer. These factors necessitate the study of the mechanisms of formation of hard scale deposits on the internal surfaces of tubular heat exchangers, and, accordingly, the development of technologies for removing such deposits.

Among the many methods of treating heat exchange objects from deposits, the most effective method is the electrohydraulic effect (EHE), in which the conversion of thermal energy into mechanical energy without intermediate energy conversion takes place [8]. EHE is based on the phenomenon of a strong effect of a hydraulic wave, accompanied by a high-voltage pulsed development of a discharge in an aqueous medium [9]. Non-linear, non-stationary, rapidly changing heat transfer processes, in which physical parameters increase with large gradients, cannot be described using differential features. In practice, semi-empirical formulas with large numerical constants are used to describe them, but they are valid in a narrow range of parameters. In this regard, modeling of heat transfer processes in pipes with a two-phase coolant under pulsed impacts is still an urgent engineering problem. The development of computer technology and the creation of new application software packages make it possible to quickly process data and simulate complex physical processes with great care. In this paper, we consider the results of modeling the parameters of a pulsed heat transfer process in an inhomogeneous aqueous medium using the method data regression analysis

1. Method of group consideration of arguments

Method of group consideration of arguments (MGCA) consists in building statistical models using regression analysis of experimental data and allows you to get the most adequate solutions that are consistent with the real physical picture [10]. The correct choice of support functions is carried out automatically by the combinatorial MGCA algorithm. Interpolation is reduced to direct restoration of a polynomial function from a small number of points (interpolation nodes) determined from the experiment. Based on the universal laws of the theory of self-organization, MGCA allows you to get the most adequate solutions that are consistent with the real physical picture. A preliminary model is compiled, which is further refined using single and multiple forecasts synthesized using the MGCA. The advantage of MGCA is that even when using 6 - 10 points taken from observations, this method allows you to build a model of arbitrarily high complexity.

The selection criterion is the most important parameter that must be set in the design module for the MGUA. The criterion used is the GCV - Generalized Cross Validation criterion, which is defined as

$$GCV = Norm.\ MSE / (1 - KK \times k/N)^2,$$

where Norm. MSE is the normalized *mean squared error*;

KK - criterion coefficient;

N is the number of points in the data file;

k is the number of coefficients to minimize the mean squared error.

Based on the enumeration of various models, a combinatorial MGCA algorithm is determined. On each MGCA layer, a polynomial of the following form is constructed:

$$C_0 + C_1 \cdot X_1 + C_2 \cdot X_2 + C_3 \cdot X_3 + C_4 \cdot X_1 \cdot X_2 + C_5 \cdot X_1 \cdot X_3 + C_6 \cdot X_2 \cdot X_3 + C_7 \cdot X_1^2 + C_8 \cdot X_2^2 + C_9 \cdot X_3^2,$$

where C_0 is a constant, C_1, C_2, ... are coefficients, and X_1, X_2, X_3 are input variables.

Based on the results of the calculations, a technique for constructing binomial dependencies was developed that most accurately describes the experimental data on the dependence of the intensity of heat and mass transfer processes on the frequency of electro-hydro-impulse action in a liquid coolant [11]. Let us consider the possibility of constructing functional dependences of the impulse pressure and heat transfer intensity on the parameters of the coolant motion using the method of group consideration of arguments (MGCA).

2. Experimental data

The relevance of the study of rapidly changing, high-gradient processes associated with the propagation of shock waves in inhomogeneous media is of great practical interest. This is due to the importance of its application in a wide variety of technological processes, where the energy of impulse pressure is widely used for pressing, crushing, destruction of solid deposits on the inner surfaces of pipes of heat exchangers, pipelines, oil pipelines, etc. [6]. The pulse pressure amplitude reaching $\sim(10^8 \div 10^9)$ N/m^2 within $\sim(10^{-4} \div 10^{-5})$ s depends on the state of the working medium and on the geometry of the working area where the shock wave propagates [12-17]. The propagation of the shock wave is fast, the pressure pulses have a duration of $\sim 10^{-4}$ s. The study of the patterns of propagation of wave processes is important for the development of methods for regulating the intensity of the dynamic impact of shock waves.

The analyzed experiments were carried out in technical water with the presence of solid, conical reflectors, rigidly fixed in the working area in order to enhance the action of the shock wave accompanying the discharge in a given direction [6]. In [16] presents the results of an experimental study of methods for controlling the power of the electrohydraulic effect by varying the degree of heterogeneity of the working medium and the geometry of the working channel with the same electrical parameters of the discharge. The possibility of cumulation of impulse pressure by using conical reflectors with a certain degree of heterogeneity of the working medium has been established.

The control and measuring system of the electro-hydraulic installation makes it possible to observe the change in pressure pulses by time sweeps of voltage and current. Description of the electro-hydraulic installation, the device and the principle of measuring pulsed pressure with an amplitude of up to (50-60) bar and a signal duration of ~ (0.001÷0.005)s using a piezometric sensor are given in [6, 8-10]. Calibration of the sensor was carried out in the installed state on the working section of the experimental stand using the dynamic method. During calibration, the cover of the working area was replaced by a device consisting of a cylinder and a piston. Using a storage oscilloscope, the electrical signals from the piezometric sensor were recorded at a given hydraulic force of the piston impact. In the experiments, reflectors with a taper angle θ: 0°, 10°, 30°, 45°, were used, made of a sufficiently strong synthetic material, kapralan. Testing was carried out repeatedly, the measurement error was 5-7%. The volumetric gas content coefficient φ and the angle θ of cone-shaped reflectors placed in the working area in order to increase the pressure force in a given direction were used as variables [6]. The degree of volumetric gas content is equal to:

$$\varphi = \frac{V_g}{V_g + V_l},$$

were V_g, V_l - volume of gas and liquid.

As a result of repeated measurements, a nonlinear dependence of the pressure amplitude on the value of the taper angle was found.

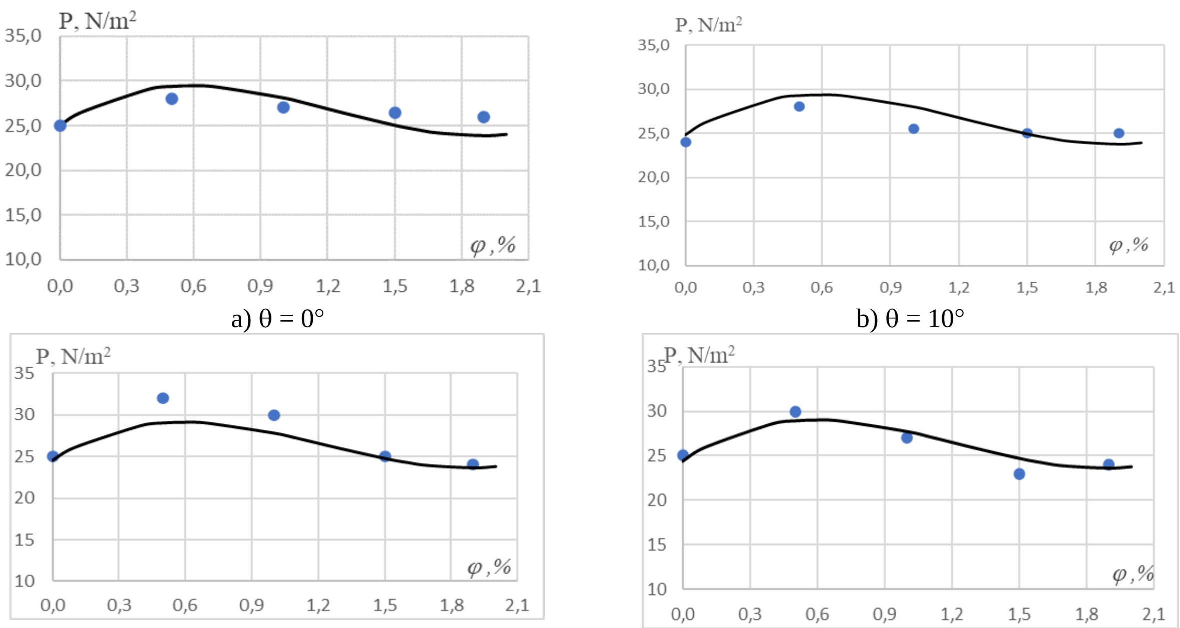
3. Results and discussion

3.1 Modeling impulse pressure dynamics

Let us consider the results of the analysis of experimental data on the study of the dependence of the pressure amplitude accompanying a high-voltage electric discharge in an inhomogeneous medium. Experiments have shown that the magnitude of the amplitude of the pulsed pressure during EHP exposure in an inhomogeneous aquatic environment depends on the degree of gas content. As a result of the regression analysis of the experimental data using various selection criteria, polynomial models were constructed that describe the dependences of the impulse pressure amplitude at various concentrations of the gas phase and various boundary conditions. To calculate the magnitude of the pulse pressure amplitude based on the MGCA method, an expression was obtained in the form of binomials:

$$P = 25 + 17.2\cdot\varphi - 0.85\cdot\theta + 0.063\cdot\theta^2 - 0.00096\cdot\theta^3 - 19.25\cdot\varphi^2 + 5.2\cdot\varphi^3 + 0.26\cdot\varphi\cdot\theta - 0.02\cdot\varphi\cdot\theta^2 + 0.00031\cdot\varphi\cdot\theta^3 \quad (1)$$

The results of modeling the magnitude of the impulse pressure according to this formula with a change in the degree of gas content of the liquid working medium at different taper angles are shown in Fig.1.



c) θ = 30° d) θ = 45°

Fig.1. Dynamics of the impulse pressure amplitude on the degree of gas content: lines are calculated by MGCA dependences, points are experimental data

Calculations show that at a volume concentration of carbon dioxide bubbles φ=0.5%, as a result of the simultaneous influence of two effects of cumulation and cavitation, the pressure amplitude can increase up to 1.5 times (Fig.1c). Model (1) describes well the behavior of the experimental data for all values of the angles of the reflectors (the calculation error does not exceed 2÷3%) and confirms the possibility of increasing the pulse pressure at a certain degree of gas content of the working medium.

3.2 Modeling of heat transfer dynamics under electro-hydro-pulse impact

Practice has shown that with a constant pulse action, the nature of the coolant flow changes from laminar to turbulent, which in turn contributes to mixing and, accordingly, more intense heat transfer. Analysis of the data showed that the main parameter that determines the degree of heat transfer intensification is the electric discharge frequency f. The intensity of heat transfer, which is determined by the thermophysical properties of the heat exchange surface and depends on the regime of the coolant flow, characterized by the Reynolds criterion. To assess the influence of the main factor - the frequency of the applied electrical pulses in a wide range of boundary conditions, the nature of the dependence of the average value of the Nusselt numbers were analyzed.

$$Nu = \alpha \times a / \Delta\lambda_f , \qquad (2)$$

where α is a heat transfer coefficient, a is a characteristic linear scale, λ_f is the thermal conductivity of the pipe walls.

A pulsed electric discharge causes turbulence in the coolant flow with energy-containing large-scale vortices, the repetition frequency of which determines the nature of the flow and the intensity of heat transfer from the surface. The mechanism of heat transfer intensification by electrohydraulic action is the turbulization of the boundary layer. To describe the results of the experiment using the MGCA, the following dependences for the dimensionless Nusselt number were obtained:

$$\frac{Nu}{Nu_*} = 0.56 + 1.19{\cdot}10^{-5} fq - 1.41{\cdot}10^{-4} q + 0.43{\cdot}10^{-8} q\, Re - 1.09{\cdot}10^{-6} f^2 q + 3.01{\cdot}10^{-8} f^3 q, \qquad (3)$$

$$\frac{Nu}{Nu_*} = 0.56 + 1.19{\cdot}10^{-5} fq - 1.41{\cdot}10^{-4} q + 0.51{\cdot}10^{-8} q\, Re - 1.05{\cdot}10^{-6} f^2 q + 3.01{\cdot}10^{-8} f^3 q, \qquad (4)$$

where: f is a discharge frequency, Hz; q is the heat flux, W/m2; Re is the Reynolds number.

In the experiments, the magnitude of the discharges was maintained constant, equal to the discharges q = 3393 W/m^2, only the discharge frequency f was varied. It can be seen from the graphs (Fig. 2) that model (3) describes the experimental dependence well at low Reynolds numbers, while model (4) is more suitable for regimes with Re > 20000. As can be seen from the graphs, the heat transfer dynamics is determined by the degree of flow turbulence. The difference between the polynomials lies solely in the numerical values of the coefficients, reflecting the joint synergistic effect of the influence of turbulence intensity on heat transfer.

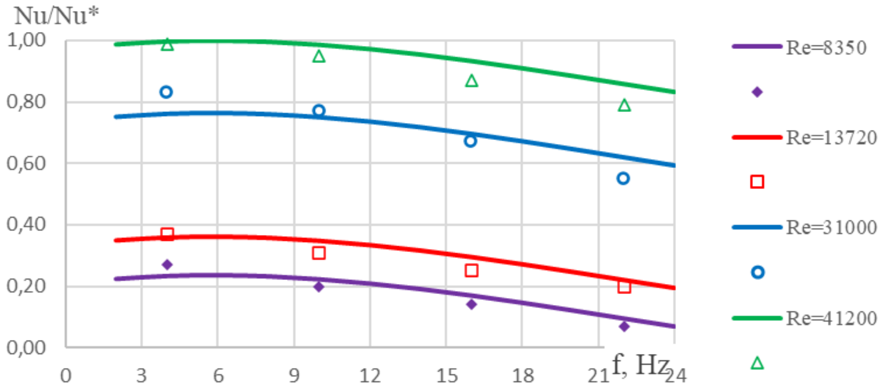


Fig.2. Dynamics of the heat transfer from the change in the frequency of discharges *f*;
line - calculation according to MGCA; points - experimental data.

In general, the nature of the regularity does not change, which confirms the fact that the physics of the process is the same for all modes. The use of the MGCA method made it possible to quickly and accurately process the experimental data of complex nonlinear processes of heat-mass-transfer in inhomogeneous flows and, at the same time, to detect implicit synergistic effects of the mutual influence of various arguments.

Conclusion

Calculations based on the constructed MGCA model describe well the behavior of the experimental dependences under various boundary conditions. The calculations performed adequately demonstrate the behavior of the experimental data for all angles and confirm the possibility of cumulating the impulse pressure using conical reflectors at a certain degree of heterogeneity of the working medium. The superimposition of the two effects of cumulation and cavitation leads to an increase in the amplitude by almost one and a half times at a given volumetric concentration of the gas phase. An analysis of the results of modeling nonlinear processes shows the advantages of MGCA in building a model of arbitrarily high complexity when using a small number of observations, for example, 6-10 data. This determines its applicability for modeling nonlinear heat transfer processes under variable boundary conditions.

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REFERENCES

1 Zhang T. Methods of Improving the Efficiency of Thermal Power Plants. *ISPECE 2019 IOP Publishing. Journal of Physics: Conference Series*. 2020, 1449, 012001. doi:10.1088/1742-6596/1449/1/012001

2 Popov I.A., Yakovlev A.B., Shchelchkov A.V., et al. Improving the efficiency of boiler units by intensifying heat transfer. *Energy of Tatarstan*. 2010, No.3 (19), pp. 31-36. [in Russian]

3 Karminsky V.D. *Technical thermodynamics and heat transfer*. Moscow, 2005, 222p. [in Russian]

4 Batrakov P.A., et al. The analysis of the deposit formation on the working surfaces of heat exchange industrial equipment. *Journal of Physics: Conference Series,* 2022, 2182. 012040. IOP Publishing. doi:10.1088/1742-6596/2182/1/012040/

5 Karabelas Anastasios J. Scale formation in tubular heat exchangers. *International Journal of Thermal Sciences*. June 2002. doi: 10.1016/S1290-0729(02)01363-7

6 Nussupbekov B.R., Sakipova S.E., Ospanova D.A., et al. Some technological aspects of cleaning pipes of heat exchangers from solid scale deposits. *Bulletin of the Karaganda University. Physics series*. 2022, No.4(108), pp. 106 -114. doi:10.31489/2022PH4/106-114

7 Methods for intensifying heat transfer in heat exchangers. Available at: https://www.teploobmenka.ru/oborud/art-intensification.

8 Yutkin L.A. *Electrohydraulic effect and its application in industry*. Leningrad, 1986, 253 p. [in Russian]

9 Nussupbekov, B.R., Sakipova, S.E., Edris, A., et al. Electrohydraulic method for processing of the phosphorus containing sludges. *Eurasian phys. tech. j.* 2022, 19(1), pp. 99–104. doi: 10.31489/2022No1/99-104

10 Ivakhnenko A.G. Long-term control and forecasting of complex systems. Kyiv: Technique, 1975, 312 p.

11 Kussaiynov K., Sakipova S.E., Shaimerdenova K.M. Modelling of nonlinear processes based on the method of group registration of arguments. *Proceeding of the XI-th Intern. Conf. on the Methods of Aerophysical Research "ICMAR"*, Novosibirsk, 2002, part III, pp.145-147. [in Russian]

12 Fedorov A.V., Fedorova N.N., Fomin P.A., Valger S.A. *Propagation of explosive and shock waves in cluttered spaces.* Novosibirsk, NGASU, 2015, 232 p.

13 Gimaltdinov I.K. Pressure waves in a liquid containing bubble zones. *Bulletin of the Ural State University. Mathematics and mechanics*. Ekaterinburg. 2005,Vol. 8, No. 38, pp. 37 - 52. [in Russian]

14 Gimaltdinov I.K., Bayazitova A.R. Pressure waves in a pipe containing a gas-liquid cluster. *Materials of the XVI session of the Russian Acoustic Society*. Moscow. 2005, pp. 125-129.

15 Dontsov V.E. Propagation of pressure waves in a gas-liquid medium of a cluster structure. *Applied mechanics and theoretical physics.* 2005, Vol.46, No.3, pp. 50 - 60.

16 Sakipova S.E. On the calculation of impulse pressure under electro-discharge action in an inhomogeneous liquid. *Bulletin of Tomsk State University. Mathematics and mechanics*. 2009, No.1(5), pp. 74-81.

17 Lazareva G.G. *Numerical modeling of amplification of shock waves in bubble media*. Diss. cand. phys.-math. Nauk., Novosibirsk, 2003, 155 p. [in Russian]

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