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Intensification of thermal and rheological processes in a scraped-surface apparatus

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Abstract: The operation parameters of a special heat exchange scraped-surface apparatus ware studied and mathematically described in the article. The feature of the apparatus was the use of perforated cleaning devices in order to increase the turbulence of a product. The developed device can be used in the dairy, meat, and fat and oil industry to cool cream, animal fats, margarine emulsions, cooking fats, and other viscous food products. The increase in the productivity of the apparatus was achieved as a result of the more intensive mixing of the cleaned wall layers with the bulk of the cooled product due to the presence of cylindrical holes in the slats with a diameter of at least 0.05–0.1 of the diameter of the working cylinder. As a result of processing experimental data on heat exchange taking into account energy dissipation, a calculated criterial heat exchange equation for the nonisothermal motion of products and their different flows – laminar and transient – was obtained explicitly. In addition, the article considers the effect of starting modes on the operation of apparatus with mixing devices. These data can make it possible to take into account the possible deviations of parameters caused by nonsteady operating modes. On the basis of the data obtained, we have proposed assumptions about the degree of impact of viscosity and inertia in the considered range of parameters on a starting mode. The results of the study are relevant since they allow us to intensify the thermal processes in this type of common apparatus by 10–12%.

Keywords: Heat exchange, viscosity, rheology, mixing, dairy products

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INTRODUCTION

A significant proportion of food products have viscous and quasi-viscous properties.

Viscous media require new engineering knowledge on the development of their production technology and techniques, taking into account the rheological properties of processed raw materials and finished products.

The data on the patterns of changes in rheological characteristics make it possible to affect the quality and structure of products both by adding supplements and by regulating the treating modes of a product.

The method of intensifying heat exchange when treating viscous products by mixing the treated medium in apparatus with special blade-type mechanisms is used widely. It is necessary to study this method deeper, especially when heat-treating viscous media with non-Newtonian properties. Mixing viscous materials requires a lot of energy. Therefore, to reduce the power used for mixing, it is necessary to minimize the speed of rotation, taking into account the rheological characteristics of the medium treated and ensuring the required treating mode.

In many cases, it may be reasonable to use mixing devices for such apparatus that come into contact with the heat exchange surface in order to clean a product layer. This method was studied by L.K. Nikolaev, B.L. Nikolaev, and a number of other authors [1, 2, 3, 4, 5]. Nevertheless, there are a lot of aspects of operation of apparatus with cleaning devices that require a deeper study, in particular, when heat-treating viscous media with non-Newtonian properties such as cream, animal and cooking fats, margarine emulsions, meat and fish mincemeat, and other viscous food products. There are also some ideas for changing the design of mixing mechanisms to activate the process that requires development.

The statement of the problem of nonsteady heating or cooling of an infinite cylinder is based on the cases when:

– axial heat fluxes are negligible as compared to radial ones;

– the coefficient of convective transfer of heat from the outer surface α and the ambient temperature t_c are constant;

– there is a symmetry of the initial temperature distribution θ_g (r) round the radius of the cylinder;

– the internal heat sources are assumed to be absent (q = 0).

The assumptions made correspond to the following mathematical model of the process of nonsteady thermal conductivity of cylindrical bodies:

$$\left.\begin{array}{c}\dfrac{\partial\theta}{\partial\tau}=\alpha\left(\dfrac{\partial^2\theta}{\partial r^2}+\dfrac{1}{r}\dfrac{\partial\theta}{\partial r}\right)\\ \hline \left.\dfrac{\partial\theta}{\partial r}\right|_{r=0}=0;\ -\lambda\cdot\left.\dfrac{\partial\theta}{\partial r}\right|_{r=R}=\alpha\cdot\theta\big|_{r=R};\ \theta\big|_{\tau=0}=\theta_0(r)\end{array}\right\}. \quad (1)$$

However, this theoretical model does not take into account a number of significant practical circumstances that affect the process, such as the curvature of the surface, the frequency of scraper passages, the non-Newtonian nature of ryazhenka [fermented baked milk], viscosity, and a lot of other food products. The solution of the arising engineering problems can be implemented by experimental methods ensuring the extension of the obtained results using the similarity theory and dimensional analysis.

The time-varying parameters of a number of technological processes are also important parameters of theoretical description of the processes carried out in a great number of food industry equipment. The starting modes of machines and apparatus can be considered a common example of such nonsteady processes. In many cases, it is necessary to take into account the effect of starting mode characteristics since the absence thereof results in inaccurate measurements, as well as in errors in the choice of operating modes of equipment. Thus, the estimation of the features of the starting mode is necessary [12, 13]. The studies of thermal and hydrodynamic processes in apparatus with cleaning mixing devices are presented in the works by Begachev V.I., Braginskiy L.N., Glukhov V.P., Pavlushenko I.S., and Pavlov M.G. [7]; Konviser I.A. [8]; Konsetov V.V., Kudryavitskiy F.M., and Novichkov A.N. [9], Pavlushenko I.S. and Gluz M.D. [12], Abichandani H. [19]; de Goede R. and de Jong E. J. [20]; Dumont E., Fayolle F., and Legrand J. [21], et al.

The studies of the mentioned above authors were carried out using the equipment that consisted of an apparatus with mixing devices that differed from the experimental plant used in our paper. Part of the considered results of the studies can be regarded only as a first approximation.

STUDY OBJECTS AND METHODS

To successfully design and calculate the considered type of mixer, it is necessary to have the formulae for calculating the energy consumed in the flow apparatus with mixing devices obtained from the experimental data. Some data were obtained using directly an industrial mixer equipped with a set of sensors. To study the process of interaction of a rubber scraper with the cooling surface and the working body deeper, a special experimental laboratory plant based on a modified rotational rheometer was designed and tested [7, 8, 9]. A series of experimental studies were carried out using this modified rheometer. The manufactured scrapers were installed on the rotor cylinder of the rheometer. Alternative stator cylinders were used fo study for various volumes of operating area. When carrying out the studies, a set of methods was used that made it possible to determine the rotation speed of the rotor with a high accuracy, as well as to determine the dynamic pattern of the speed to estimate the starting modes.

Experimental plant no. 1, a scraped-surface heat exchanger, is shown in Fig. 1, 2 and 3 where:
1 – cooling jacket, 2 – working cylinder, 3 – inflator, 4 – motor-reducer, 5 – product supply branch, 6 – coolant outlet, 7 – elastic tape, 8 – metal perforated slat, 9 – hole in the blade, 10 – gap between the blade sections, 11 – crosspiece holder, 12 – shaft, 13 – product outlet, 14 – coolant supply branch, 15 – cleaning blade, 16 – inflator blade, 17 – elastic tape bolt, 18 – crosspiece hub bolt, 19 – crosspiece hub.

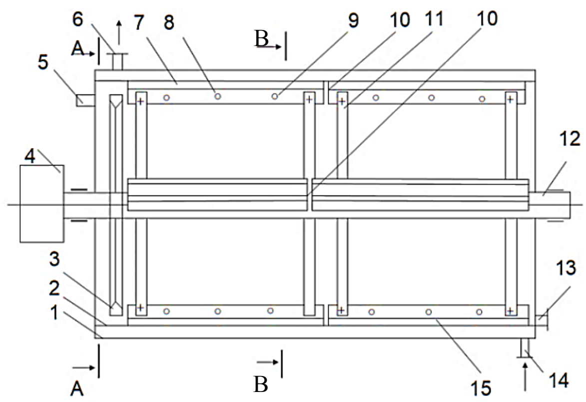

Fig. 1. Experimental plant no. 1 for studying thermal and hydrodynamic processes.

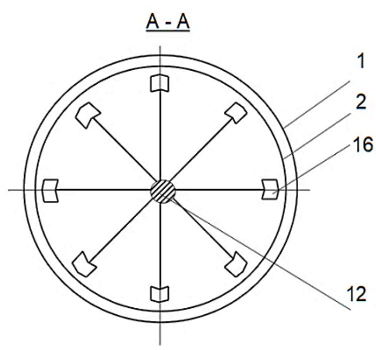

Fig. 2. Inflator.

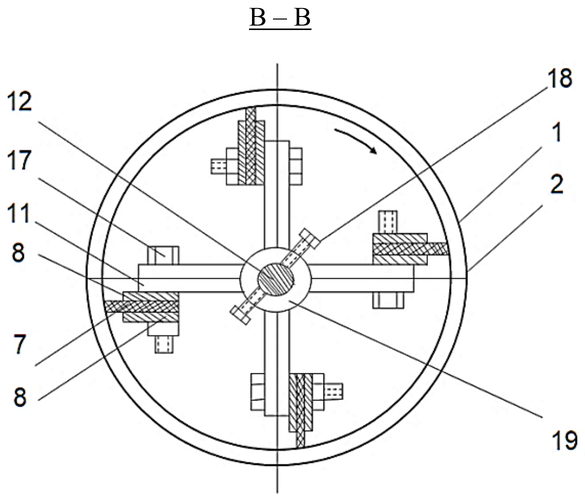

Fig. 3. Cleaning devices of the experimental plant.

The experimental plant is similar to a T1-OM-2T heat exchanger in design, but at the same time it is distinguished by the fact that in order to increase the productivity of the apparatus, the mixing device located in the working cylinder has some perforated cleaning-type blades installed at an angle of 90° to the surface of the working cylinder. Each of the blades is made of two metal plates, between which an elastic tape the upper edge of which rises above the plates by no more than 15–10 mm is clamped. The distance between the peripheral edges of diametrically located blades is greater than the internal diameter of the working cylinder D_c by 0.5–0.1 mm. The blades have holes of at least 0.05–0.1 D_c and are divided into sections with a length of no more than 3 D_c, with each successive blade displaced in relation to the previous blade in the longitudinal axial direction by 0.2 D_c, (the blade width is 0.2–0.4 D_c). There is also an inflator in the apparatus the diameter of which for the peripheral edges of the blades is equal to 0.9 D_c. This combination of features and their distinctive relationship make it possible to increase the productivity of the apparatus.

The new design allowed us to conduct further experimental studies of heat exchange and consumed energy. As a model medium, 2.5% fat ryazhenka was used. The studies were performed within the range of the Reynolds criterion from 90.7 to 6380, while the effective viscosity values were found within the range from 0.03 to 0.14 Pa·s. The studies were carried out in the rheology laboratory of the Mega-department of biotechnologies and low-temperature systems of the ITMO University.

The Table 1 presents the results of the studies of rheological processes.

RESULTS AND DISCUSSION

Studies of the hydrodynamic processes in an apparatus with scraping mixing devices were conducted.

The obtained data, when there is a change in the product temperature and there are different values of a shear rate gradient, show that the effective viscosity of the studied product depends significantly on the value of a product velocity and temperature gradient.

When treating ryazhenka in a heat exchanger with cleaning devices at values of the Reynolds criterion below 2400, there is a laminar motion of the medium in the apparatus. With a further increase in the Reynolds criterion, there is a transitional flow range.

Taking into account the previous large-scale studies carried out by a number of authors [1, 2, 5, 14, 15], to apply the obtained data to a wider range of equipment and treated media, a criterial heat exchange equation for Newtonian and non-Newtonian fluids was proposed taking into account the similarity theory:

Table 1. Change in the rheological characteristics of 2.5% fat ryazhenka during heat treatment

Product temperature t_{pr}, °C	Temperature of the heat exchange surface t_{at}, °C	Product density ρ, kg/m^3	Scraper agitator rotation speed n, r/s	Consumed energy N, W	Effective viscosity μ_{ef}, Pa·s	Reynolds criterion Re
Heating ryazhenka						
18.4	24.8	1031.1	0.783	1.5	0.140	90.7
22.4	27.2	1028.1	1.250	2.9	0.105	192.5
23.2	27.2	1027.9	1.800	4.7	0.086	338.3
24.5	27.8	1027.4	2.617	8.0	0.070	604.0
29.9	33.4	1024.8	3.367	8.8	0.048	1130.0
31.2	34.2	1024.3	4.300	14.0	0.042	1649.0
32.7	35.3	1023.7	5.200	17.1	0.036	2325.0
Cooling ryazhenka						
31.9	26.6	1023.9	1.367	2.3	0.071	310.0
30.3	26.1	1024.7	1.933	4.1	0.064	486.7
29.6	25.5	1024.8	2.217	5.1	0.062	576.2
28.0	24.8	1025.8	2.567	6.3	0.060	690.1
26.7	23.9	1026.2	3.367	10.8	0.057	953.2
24.5	22.1	1027.3	4.367	14.9	0.049	1440.0
22.0	20.4	1028.4	8.500	41.7	0.039	3158.0
20.5	19.5	1028.9	11.83	160.8	0.030	6380.0

$$Nu = B \cdot \mathrm{Re}^a \cdot \mathrm{Pr}^b \cdot \left(\frac{\mu}{\mu_{ñò}}\right)^{0.14}, \quad (2)$$

where: $Nu = \frac{\alpha \cdot l}{\lambda}$ is the Nusselt criterion;

$\mathrm{Re} = \frac{\omega \cdot l \cdot \rho}{\mu}$ is the Reynolds criterion;

$\omega = \pi \cdot D \cdot n$ is the speed of the cutting edge of the scraper, m/s;

$\mathrm{Pr} = \frac{c \cdot \mu}{\lambda}$ is the Prandtl criterion;

$l = \pi \cdot \frac{D}{z}$ is a characteristic dimension which is a distance between the outer edges of the cleaning devices, m;

D is the internal diameter of the apparatus, m;

z is the number of blades of the mixing device, pcs;

μ and μ_{at} are the effective viscosity of the product at the average product temperature and at the wall temperature, respectively, Pa·s;

B is the empirical coefficient;

a and b are the dimensionless coefficients determined in the course of the experiments.

The use of l in the calculations, which is a distance between the edges of the blades of the mixing device, allows us to take into account the effect of the number of scrapers and the inner diameter of the working cylinder.

When performing the theoretical description of the operation of a great number of apparatus and measuring equipment, an important problem is the technological processes the parameters of which can vary with time. Equipment starting modes are one of the common examples of such nonsteady processes. Variable parameters lead to deviations in the hydrodynamics of a medium, can affect the heat exchange in heat exchange equipment, they also lead to significant changes in a number of other processes carried out in food processing equipment. In many cases, ignoring the effect of starting mode parameters results in measurement errors and the selection of incorrect operating modes for machines and apparatus.

To describe theoretically the operation process of this type of apparatus, it is possible to present the hydrodynamic pattern of a flow, which is a nonsteady flow in a flat gap, in a simplified form:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho v_x) + \frac{\partial}{\partial y}(\rho v_y) + \frac{\partial}{\partial z}(\rho v_z) = 0 \quad (3)$$

$$\rho\left(\frac{\partial v_x}{\partial t} + v_x \frac{\partial v_x}{\partial x} + v_y \frac{\partial v_x}{\partial y} + v_z \frac{\partial v_x}{\partial z}\right) = -\frac{\partial p}{\partial x} + \left(\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z}\right) + \rho g_x \quad (4)$$

where v_x, v_y, v_z are the projections of flow velocities; x, y, z are the coordinates; ρ is density; p is the pressure; g_x is the projection of the acceleration of gravity; τ are the components of the stress tensor.

Since there is a shear flow of a viscous fluid in the experimental apparatus, it is necessary to take into account an equation that relates the rate of shear deformation and stress.

$$\tau_{yx} = \eta \frac{\partial v_x}{\partial y}. \quad (5)$$

To simulate the motion of an incompressible viscous fluid between the plates of the apparatus, let us take the lower plate as a stable one and the upper plate is the one that constant voltage is applied to. The Eqs. 3–5 take the following form in the partial derivatives:

$$\frac{\partial v_x}{\partial t} = \frac{\eta}{\rho} \frac{\partial^2 v_x}{\partial y^2}. \quad (6)$$

The boundary and initial conditions are assumed to be equal to:

$$v_x(0,t) = 0; \quad v_x(y,0) = 0;$$
$$\frac{\partial v_x}{\partial y}(H,t) = \frac{\tau_н}{\eta}; \quad \frac{\eta}{\rho} = \mu. \quad (7)$$

Let us transform the Eq. 6 in the partial derivatives to the equations represented in the ordinary derivatives:

$$v_x(y,t) = f(y)\psi(t). \quad (8)$$

Then:

$$f(y)\frac{\partial \psi(t)}{\partial t} = v\psi(t)\frac{\partial^2 f(y)}{\partial y^2}. \quad (9)$$

Therefore:

$$\frac{1}{v\psi(t)} \cdot \frac{\partial \psi(t)}{\partial t} = \frac{1}{\varphi(y)} \cdot \frac{\partial^2 \varphi(y)}{\partial y^2}, \quad (10)$$

$$\frac{1}{v\psi(t)} \cdot \frac{\partial \psi(t)}{\partial t} = \frac{1}{f(y)} \cdot \frac{\partial^2 f(y)}{\partial y^2}. \quad (11)$$

Hence:

$$\frac{1}{f(y)} \cdot \frac{\partial^2 f(y)}{\partial y^2} = -k^2, \quad (12)$$

$$\frac{1}{v\psi(t)} \cdot \frac{\partial \psi(t)}{\partial t} = -k^2. \quad (13)$$

In the ordinary derivatives, the equations take the form:

$$\frac{\partial^2 f(y)}{\partial y^2} + k^2 \varphi(y) = 0, \quad (14)$$

$$\frac{\partial \psi(t)}{\psi(t)} = -k^2 v \partial t. \quad (15)$$

Let us integrate the Eqs. 14 and 15 with allowance for the boundary and initial conditions (7) that determine the constants C_1, C_2 and C_3:

$$f(y) = C_1 \cos ky + C_2 \sin ky, \quad (16)$$

$$\psi(t) = C_3 e^{-k^2 \nu t}, \qquad (17)$$

$$v_x(y,t) = (C_1 \cos ky + C_2 \sin ky) C_3 e^{-k^2 \nu t}. \qquad (18)$$

The solution to the Eqs. 16–18 allows us to carry out the mathematical study of the development of the velocity profile of a flow in the space between the cylinders and to calculate the starting mode time of the apparatus:

$$v_x(y,t) = \frac{\tau_H}{\eta}\left[\left(\frac{y}{H}\right) - \frac{8}{\pi^2}\sum_{n=1,3...}^{\infty} \frac{\sin\left(\frac{n\pi}{2}\right)}{n^2} e^{-\frac{\nu n^2 \pi^2 t}{4H^2}} \sin\left(\frac{n\pi y}{2H}\right)\right]. \qquad (19)$$

where τ_H is tangential stresses constant voltage, η is the dynamic viscosity coefficient.

The analysis of the data shows that when studying the initial phase of the apparatus with mixing devices, it is necessary to take into account the starting period.

Considering a number of assumptions in deriving the formula (19) for the experimental studies of starting modes, Plant no. 2 shown in Fig. 4 and 5 was used.

It is a modified Volarovich viscometer [10, 11] equipped with devices for measuring the rotor speed. In addition, the modification included the use of alternative external cylinders and the installation of scraping action simulating devices on the rotor cylinder. The experiments consisted in measuring the dependence of rotor speed on the time from the starting moment, while a constant torque was having an impact on the rotor. A series of experiments were carried out with external cylinders with a radius of 19 mm, 34 mm, and 72 mm with a radius of the inner cylinder of 16 mm. As a model medium, 2.5% fat ryazhenka as a sample of a food product with non-Newtonian properties and 99.5% glycerin which is a medium with Newtonian properties were used. The use of glycerin is caused in particular by its well-known physical characteristics.

As a result of processing the experimental data obtained using Experimental plant no. 1, the dimensionless coefficients a, b, c for the criterion equation (2) were obtained.

The exponential factor of the Reynolds criterion was determined as a result of processing the experimental data obtained in the logarithmic coordinates:

$$\lg\left(\frac{Nu}{\left(\frac{\mu}{\mu_{\tilde{N}\grave{O}}}\right)^{0.14}}\right) = f(\lg(\mathrm{Re})), \qquad (20)$$

The study was carried out for the groups of experiments the Prandtl criterion in which was: $Pr_1 = 388$, $Pr_2 = 2462$.

The graphical-analytical processing of the obtained dependences presented in Fig. 6 showed that the both groups of experiments had the same slope to the abscissa axis. The exponent a of the formula (2) was determined as the slope of the graph to the axis of abscissae and was equal to a = 0.59. The value of the exponent indicated the significant effect of the Reynolds criterion on heat exchange.

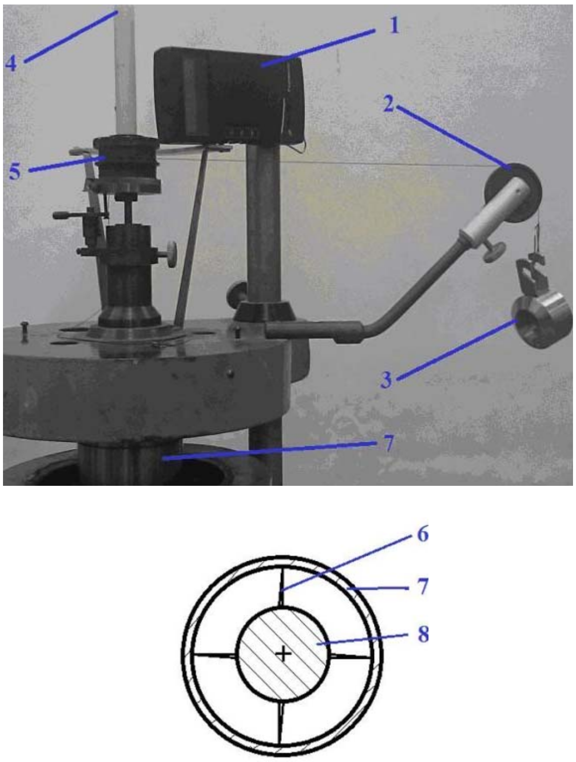

Fig. 4. Experimental plant No. 2 for the study of starting modes in apparatus with cleaning devices: 1 – digital non-contact tachometer; 2 – block; 3 – weight; 4 – tachometer mark; 5 – pulley; 6 – scraper; 7 – stator capacity; 8 – rotor cylinder.

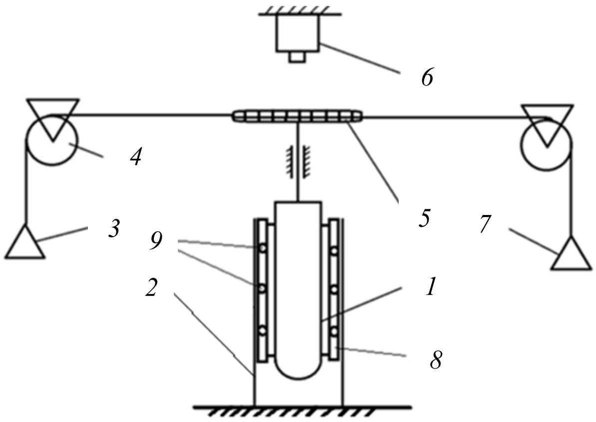

Fig. 5. Diagram of the experimental plant based on a modified rheometer: *1* – rotor cylinder; *2* – stator capacity; *3, 7* – weight; *4* – block; *5* – pulley; *6* – electronic IT 5-ChMTermit contactless tachometer, *8* – scraper, *9* – holes in the blades of the working bodies.

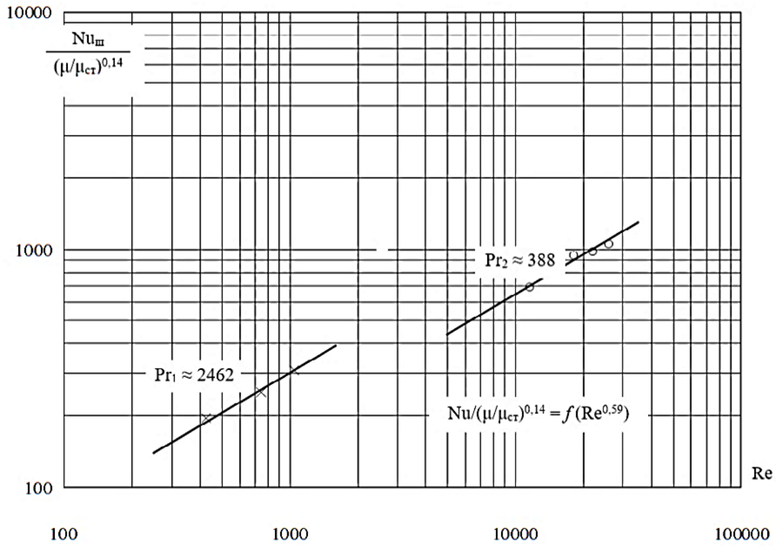

Fig. 6. Dependence of the Nusselt criteria and the Reynolds criterion in an apparatus with mixingdevices – the determination of the exponent of degree of the Reynolds criterion.

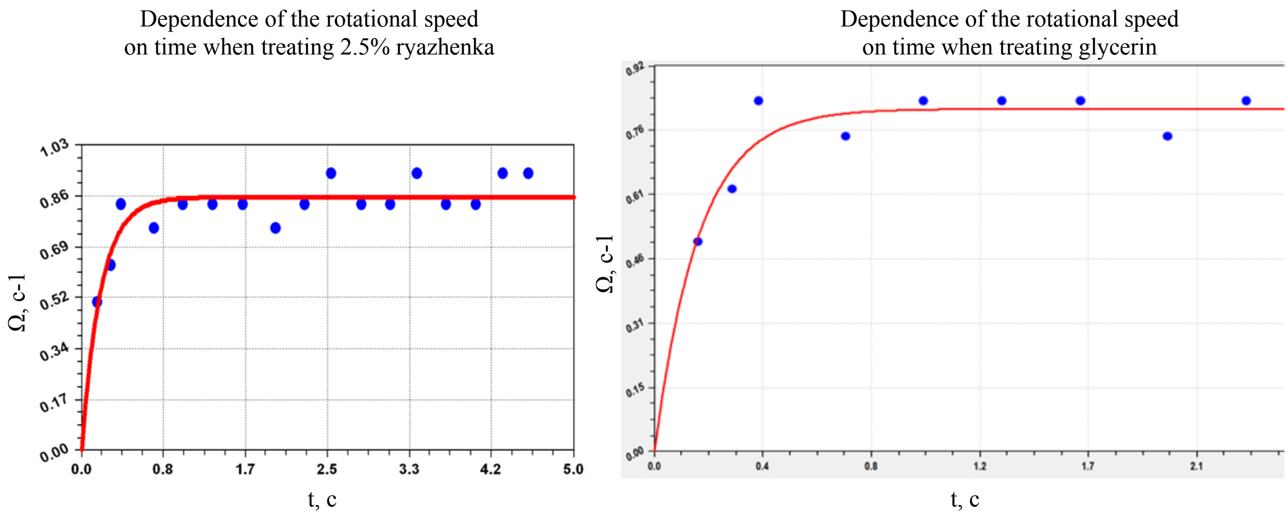

Fig. 7. Dependence of the rotor speed on time from the starting moment for 2.5% fat ryazhenka and for 99.5% glycerin.

Similarly, the effect of the Prandtl criterion on heat exchange was determined. The obtained graphical dependence uses the Reynolds criterion coefficient obtained at the previous stage.

$$\lg\left(\frac{Nu}{\mathrm{Re}^{0.59}\left(\frac{\mu}{\mu_{CT}}\right)^{0.14}}\right) = f(\lg(\mathrm{Pr})). \quad (21)$$

As a result of graphical-analytical processing of the experimental data, the value *b* of the exponential factor for the Prandtl criterion for the formula (2) was found to be equal to 0.37.

To obtain the coefficient *B* of the formula (5), the data are processed mathematically on the basis of the dependence (2):

$$\lg\left(\frac{Nu}{\mathrm{Pr}^{0.37}\left(\frac{\mu}{\mu_{CT}}\right)^{0.14}}\right) = f(\lg(\mathrm{Re})). \quad (22)$$

As a result of the made experiments and mathematical processing of the experimental data, the criterial equation (2) takes the form:

$$Nu = 0.923 \cdot \mathrm{Re}^{0.59} \cdot \mathrm{Pr}^{0.37}\left(\frac{\mu}{\mu_{CT}}\right)^{0.14}. \quad (23)$$

As a result of processing the experimental data obtained using Experimental plant no. 2, the starting mode parameters of the apparatus the character of which is close to an exponential dependence were obtained, they can be described in the form of a formula (24), the coefficients a and b in this formula have been determined by processing the data using CurveExpert (Fig. 7).

$$\Omega = a(1 - e^{b\tau}) \quad (24)$$

where Ω is the rotor speed, s-[1];
a and b are the empirical coefficients:
$a = 0.626 \cdot 10^{-1}$; $b = 5.32$ – the correlation coefficient for 2.5% fat ryazhenka is: $R = 0.964$; the rms deviation $\delta = 0.0607$.

For 99.5% glycerin, $a = 0.814$; $b = 5.89$; the correlation coefficient $R = 0.957$; the rms deviation $\delta = 0.0425$.

CONCLUSION

The effect of the Reynolds and Prandtl criteria on the heat exchange in an apparatus with modified cleaning devices has been determined. For the scraper devices with holes, there was an increase in the Reynolds criterion by 3–5% compared to the measurements made for the devices without holes.

In order to apply the obtained data to a wider range of equipment and treated media, a criterial heat exchange equation for Newtonian and non-Newtonian fluids taking into account similarity simplexes was proposed that takes into consideration the similarity theory. The effect of the Reynolds and Prandtl criteria on the heat exchange in the apparatus were determined.

The lawfulness of describing the characteristics of the starting mode were established using an exponential dependence of the form of $\Omega = a\ (1 - e^{-bt})$. The experimentally expected theoretical predominance of the effect of medium density on the starting mode compared to the effect of viscosity properties were established. The value of the coefficient of the exponent b differed by 8–15% for the measurements with ryazhenka and glycerin under other equal conditions.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest related to this article.

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