NUMERICAL SIMULATION OF THE PROCESSES OF HYDRODTNAMICS AND HEAT TRANSFER PROCESSES IN ROTOR-PULSATION APPARATUS

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Abstract. The development of energy-saving technologies that meet the modern requirements of product production is based on the development of new concepts, conducting comprehensive scientific research, and a detailed study of the essence of physical phenomena, which determines the possibility of purposeful management of the technological process and ensuring optimal conditions for its implementation. In the existing devices for the preparation of mixtures, grinding methods are used in hammer crushers and mills, which requires significant expenditure of mechanical (electrical) energy. Therefore, it is necessary to develop devices with a high degree of influence on the processed environment, which increases productivity and reduces energy consumption in technological processes. Such devices include rotary-pulsation devices, the principle of operation of which is based on the method of discrete-pulse energy input. The basis of this method is the multifactorial influence on the processed liquid homogeneous or heterogeneous environment, consisting of pressure pulsations, changes in the liquid flow rate, intense cavitation, developed turbulence, rigid cumulative impact, as well as high shear forces. The current task in this work is the study of the impact of discrete-pulse energy input mechanisms that take place in rotary-pulsation devices during the processing of heterogeneous media, as well as the development of new designs of devices of the specified type to obtain high-quality products. Therefore, the work is devoted to the development of a new design of the rotor-pulsation apparatus for the preparation of liquid mixtures, the principle of which is the use of

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a working chamber with a rotor and a stator, which have holes of different configurations. The purpose of the study is to conduct a comprehensive analysis of kinematic and dynamic characteristics and establish the features of discrete-pulse energy input during the dispersion of mixtures in a rotary-pulsation apparatus and to develop, on this basis, energy-saving technology and equipment for their preparation. Numerical modeling and experimental research of the processes of hydrodynamics and heat transfer in the mixture during its preparation were carried out. The working chamber of the device consists of a cylindrical rotor and stator containing round and rectangular perforated holes. The mathematical model includes the two- or three-dimensional Navier-Stokes equations, the κ-ε transport equation of the turbulence model, and the energy equation. Factors that affect the processes of deformation and destruction of dispersed particles in heterogeneous media processed in rotary-pulsation devices are pressure pulsations, as well as normal and tangential stress pulsations that occur in the flow when it passes through the working zone of the device. As a result of numerical studies, the fields of velocities, pressures and temperatures of the studied media were found, and the most optimal geometric characteristics of the working chamber of the rotary-pulsation apparatus were determined. Based on the obtained results of numerical simulation, the designs of the rotor-pulsation apparatus will be selected, which will be used for the production of industrial research samples of this device.

1. Introduction

The experience of operating cylindrical rotary-pulsation devices in various technological processes shows their high efficiency when used as mixers and homogenizers [1–2]. These devices are widely used in the food, chemical, pharmaceutical and other industries.

The working elements of the cylindrical-type RPA are two concentric cylinders with holes that can be arranged in a staggered or corridor pattern. The inner cylinder (rotor) rotates at a given speed relative to the outer fixed cylinder (stator). rotor and stator are located in series. When the rotor rotates, its channels periodically coincide with the stator channels. The treated medium is fed under pressure into the rotor cavity, passes through the channels of the rotor and stator holes, enters the working chamber and leaves the device through the outlet pipe. As a result of the rotation of the rotor, the heterogeneous environment is affected by such factors as the speed of the liquid flow, pressure pulsations, intense cavitation, high shear and shear stresses. Such influencing factors are able to cause deformation and destruction of dispersed inclusions in the carrier fluid flow [3–6]. The higher the values of the values that characterize the dynamic influence of the working bodies of the apparatus on the heterogeneous flow, the smaller the dispersed particles can be crushed. In addition to the specified factors of particle grinding in the working zone of the RPA, as a result of periodic pressure drops, cavitation processes also occur and turbulent pulsations occur [6–7].

During the operation of the RPA, the productivity of the finished product, energy consumption, dimensions, processing time of the initial mixture to the required size of dispersed inclusions, as well as the dispersed composition itself are important indicators. The indicator that characterizes the required quality of the obtained product is considered the main one.

At present, the question of the operating parameters of the apparatus, at which it is possible to obtain a product that meets the requirements for its quality, remains problematic. Because in order to create optimal designs of the apparatus, the task of the necessary mode parameters of their operation, it is necessary to find their connection with the dispersed composition of the finished product [8–11]. It is possible to solve this issue by analyzing the kinematic and dynamic characteristics of the flow of the carrier dispersed medium (gradients of pressure, voltage, speed, intensity of their pulsations over time).

The effect of shear, cavitation, and vortex mechanisms on the environment in the rotary-pulsation apparatus is accompanied by thermal energy dissipation. As a result of the transition of mechanical energy into thermal energy, the processed product is heated, which can lead to changes in the necessary properties of the product itself, as well as to the failure of the device elements. Dissipative heat emissions occur in limited areas adjacent to working bodies. For example, upon local heating of a mixture including protein, its thermocoagulation may occur. This process is unacceptable according to the technological instructions for the preparation of food products. In such cases, it is necessary to organize a heat removal system from the device or to reduce the speed of rotation of the rotor. Therefore, for each processed system there is an optimal temperature at which the preparation of final products of one or another type will take place most efficiently. In this regard, determining the thermal characteristics of the equipment when obtaining homogeneous media is an urgent task. Therefore, in order to solve the tasks of grinding dispersed particles in the working area of the RPA, possible energy costs for the implementation of this process, it is necessary to study the dynamic and temperature characteristics of the flow of liquid in the RPA and numerical modeling of the processes of hydrodynamics and heat transfer in these devices.

2. Statement of the problem of fluid dynamics in the working space of cylindrical RPA

Currently, to solve hydrodynamic problems using a three-dimensional problem statement. However, the calculation of such three-dimensional problems requires a large amount of memory, and for a numerical solution requires a powerful computer technology that requires large resources for speed, etc. As a result, an approach to solving the problem of fluid dynamics and heat transfer in RPA is proposed, based on approximate two-dimensional hydrodynamic models. To inform the considered three-dimensional problem to two-dimensional, cylindrical holes in the rotor and stator are conditionally replaced by rectangular slots, the hydraulic diameter of which corresponds to the diameters of these holes.

The solution of the problem is constructed for the case of a fixed stator and rotor (Figure 1). Since the main working elements of the apparatus are coaxial cylindrical bodies, the system of equations of fluid dynamics and

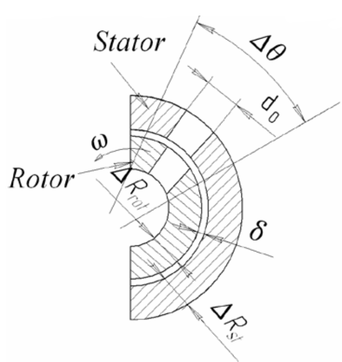

Figure 1. Calculation scheme of the working space of a cylindrical rotor-pulsation apparatus with round holes

heat transfer should be represented in the polar coordinate system (r, θ), the beginning of which lies on the common axis of the working elements.

The system of equations of dynamics and energy for a viscous fluid in polar coordinates has the form:

$$\frac{\partial(r\nu_r)}{\partial r}+\frac{\partial\nu_u}{\partial u}=0; \tag{1}$$

$$\begin{aligned}&c\frac{\partial\nu_r}{\partial r}+\frac{1}{r}\frac{\partial(r\nu_r^{\ 2})}{\partial r}+\frac{1}{r}\frac{\partial(\nu_r\,\nu_u)}{\partial u}-\frac{\nu_u^{\ 2}}{r}=-\frac{\partial p}{\partial r}+\frac{2}{r}\frac{\partial}{\partial r}\mu_{eff}r\frac{\partial\nu_r}{\partial r}-\\&-\frac{2\mu_{eff}}{r^2}\frac{\partial\nu_u}{\partial u}+\frac{1}{r}\frac{\partial}{\partial u}\mu_{eff}\frac{1}{r}\frac{\partial\nu_r}{\partial u}+r\frac{\partial}{\partial r}\frac{\nu_u}{r};\end{aligned} \tag{2}$$

$$\begin{aligned}&c\frac{\partial\nu_u}{\partial r}+\frac{1}{r}\frac{\partial(r\nu_u\nu_r)}{\partial r}+\frac{1}{r}\frac{\partial\nu_u^{\ 2}}{\partial u}+\frac{\nu_u\nu_r}{r}=-\frac{1}{r}\frac{\partial p}{\partial u}+\frac{2}{r^2}\frac{\partial}{\partial u}\mu_{eff}\frac{\partial\nu_u}{\partial u}+\\&+\frac{1}{r^2}\frac{\partial}{\partial r}\mu_{eff}r\frac{\partial\nu_r}{\partial u}+r^3\frac{\partial}{\partial r}\frac{\nu_u}{r};\end{aligned} \tag{3}$$

$$\begin{aligned}&C_p c\frac{\partial T}{\partial r}+\frac{1}{r}\frac{\partial(r\nu_r T)}{\partial r}+\frac{1}{r}\frac{\partial(\nu_u T)}{\partial u}=\frac{1}{r^2}\frac{\partial}{\partial u}л_{eff}\frac{\partial T}{\partial u}+\\&+\frac{1}{r}\frac{\partial}{\partial r}л_{eff}r\frac{\partial T}{\partial r}+\mu_{eff}S^2,\end{aligned} \tag{4}$$

where

$$S=\left(2\frac{\partial\nu_r^{\ 2}}{\partial r}+\frac{1}{r}\frac{\partial\nu_u}{\partial u}+\nu_r^{\ 2}+\frac{1}{r}\frac{\partial\nu_r}{\partial u}+r\frac{\partial}{\partial r}\frac{\nu_u^{\ 2}}{r}\right)^{0,5}.$$

Equation (4) describes the heat transfer by flow taking into account the dissipation of mechanical energy due to friction.

In equations (1)-(4): v_r – the radial component of velocity; v_u – tangential velocity; p – pressure; T – temperature.

The numerical solution of the system of equations (1)-(4) is performed under the following boundary conditions. At the entrance to the calculation area ($r = r_{rot.ins} - \Delta r$) pressure and temperature are zero, in addition $\frac{\Delta\nu_\theta}{\partial r}=0$. At the output of the calculation area ($r = r_{stat.outs} + \Delta r$) the value of pressure

$\Delta P > 0$ is set, and also $\nu_u = 0, \frac{\partial t}{\partial r} = 0$. On the surface of the stator $\upsilon_r = 0; \nu_u = 0$; on the surface of the rotor $\upsilon_r = 0; \nu_u = \omega \cdot r$. When $\theta = 0$ and $\theta = \Delta\theta$ the periodicity condition of periodicity of all functions (υ_r, ν_u, t) on angular coordinate θ is set.

The solution of the system of equations (1)-(4) is performed for $0 < \theta < \Delta\theta$ and Rвн, $p_{om} - \Delta r < r < r_{нар}, c_m + \Delta r,$ where $\Delta\theta$ is the geometric period of the working bodies of the apparatus; Δr = 3 mm – the width of the included area (Figure 1).

The calculation area (Figure 1) includes sections of the working space consisting of a stator and a rotor, as well as gaps between them. The working elements are cylindrical bodies with periodically repeating holes. In solving the problem, a segment with an opening angle is considered, which includes one hole and half of the adjacent wall that separates this hole from the neighboring ones.

In this formulation of the problem, a dispersion medium having physical properties corresponding to the effective properties of the starch-containing medium is considered. In the laminar flow of a Newtonian fluid, the effective transfer coefficients μ_{eff} and λ_{eff} will correspond to its coefficients of molecular viscosity and molecular thermal conductivity.

3. The results of numerical modeling of fluid dynamics and heat transfer in the rotar-pulsation apparatus

The results of numerical modeling of hydrodynamics and heat transfer in the rotor apparatus were obtained by the calculation method proposed in the monograph [12]. It is based on the method of finite differences for solving the system of equations (1)-(4).

Let's consider the results of solving problems about fluid flow and heat transfer in a rotor-pulsation apparatus, the working bodies of which are the stator and the rotor. The device has the following geometric characteristics:

– stator: $r_{вн}$ = 85,85 mm; $r_{зовн}$ = 97,85 mm;

– rotor: $r_{вн}$ = 67,5 mm; $r_{зовн}$ = 85,25 mm,

where $r_{вн}$ and $r_{зовн}$ – respectively, the inner and outer radii of the corresponding cylindrical element. Stator width – 44,5 mm; rotor width – 44 mm. The width of the gaps between the rotor and the stator is δ = 0,6 mm.

Each cylindrical working element has 24 round holes. The speed of rotation of the rotor is – 2880 revolutions per minute.

Since the feature of the starch-containing mixture during its dispersion in the apparatus is the increase of its temperature-dependent viscosity, the temperature changes of this mixture in the working space of the rotor-pulsation apparatus, that is, in the channels of the rotor and stator was calculated.

Heat release in the gap.

The intensity of heat release in the RPA gap is determined by the equation

$$Q_{\delta 0} = \mu \frac{{\nu_\delta}^2}{\delta} = \mu \frac{{\omega R_{r2}}^2}{\delta}, \tag{5}$$

where ν_δ – the tangential speed in the gap; δ – gap thickness; ω – angular speed of rotation of the rotor; R_{r2} – the outer radius of the rotor.

The parameter $Q_{\delta 0}$ is the amount of heat released per unit time in a unit gap due to viscous dissipation. The amount of heat released in the volume of the gap per unit time is defined as $Q_{\delta 0} \cdot V_\delta$, where V_δ – the volume of liquid inside the gap is equal to $V_\delta = 2\pi R_{r2}\delta h$ (the product of the length, width and height of the gap).

Then the amount of heat released per unit time inside the gap is described by the equation

$$Q_\delta = Q_{\delta 0} \cdot V_\delta = \mu \frac{2\pi R_{r2}^3 \omega^2 h}{\delta} \tag{6}$$

This heat is spent on heating the fluid passing through the channels of the rotor and stator, as well as on heating the metal mass of the rotor, stator and RPA housing. Part of the heat released in the gap is transferred through the outer surface of the housing to the environment.

Mass flow of liquid through the RPA.

The mass flow rate of fluid through the RPA is described by the equation

$$G_m = S_0 \sqrt{\frac{\omega^2 \left(R_{r2}^2 - R_{r1}^2\right)}{\zeta_z}} \tag{7}$$

where R_{r1} and R_{r2} – the inner and outer radius of the rotor; ζ_z – the sum of the coefficients of hydraulic resistance in the line. These supports include the track supports of the rotor and stator channels – ζ_{rot} and ζ_{stat}. Accordingly, the track supports of the pipelines connecting the RPA with the hopper, as well as the supports that determine the pressure loss before entering the rotor channel and leaving the stator channels. However, the greatest contribution to the hydraulic fluid loss in the apparatus is the resistance of the inter-cylindrical gap $\zeta_\delta = f(\tau)$, the value of which periodically changes with high frequency in a wide range during the rotation of the rotor and the overlap of the rotor and stator channels. The difficulty of estimating the magnitude of hydraulic losses is that the coefficients of hydraulic resistance included in the equation, in turn, depend on the magnitude of the costs of the treated medium G_m. This is explained by the fact that the values of the coefficients of local and integral resistances are a function of the Reynolds number, and Reynolds number is determined by the value G_m. These difficulties are largely related to the operation of this RPA, because in the process of processing the viscosity of the mixture, and hence the value of the Reynolds number varies by 5-6 orders of magnitude.

Therefore, the average values of hydraulic losses in the studied RPA are usually determined experimentally.

Calculation of temperature change in RPA.

Denote the temperature at the entrance to the rotor channels T_{ent}; the temperature at the outlet from the stator channels – T_{out}; the temperature of the liquid in the hopper – T_b; the temperature of the liquid at the entrance to the hopper – T_1; the initial temperature of the liquid T_0 and the device itself is denoted by and equal to the ambient temperature T_a; the volume of liquid in the hopper is – V_0.

The weight of the metal hopper – m_1; the mass of the pipeline located between the outlet of the hopper and the entrance to the rotor channels – m_2; mass of the rotor – m_{rot}; stator mass – m_{stat}; body weight of the RPA – m_{corp}; the mass of pipelines from the exit from the RPA housing to the entrance to the hopper – m_3.

The density of the liquid – ρ; heat capacity of liquid – c_0; heat capacity of metal (steel) – c_m. Mass flow of liquid through the RPA – G_m; volume flow – G_V.

The liquid in the hopper with a volume of V_0 at the moment of time τ has a temperature T_b. For a unit of time, an amount of liquid G_V with temperature T_1 and an amount of liquid G_V with a temperature T_b is discharged. The amount of heat entering the hopper per unit of time $Q_1 = \rho c_0 G_V (T_1 - T_0)$, the amount of heat removed – $Q = \rho c_0 G_V (T_b - T_{0b})$. Since the temperature of the liquid entering the hopper $T_1 > T_b$, the heat that enters the hopper per unit time goes to heat the liquid in the hopper and the material from which the hopper itself is made.

From the equation of heat balance

$$\left(\rho c_0 V_0 + m_1 c_m\right)\frac{dT_b}{d\tau} = \rho c_0 G_V\left(T_1 - T_b\right) \tag{8}$$

it follows that the increase in temperature of the liquid in the hopper and the walls of the hopper per unit time is determined from the condition of heat balance and is described by the equation

$$\frac{dT_b}{d\tau} = \frac{\rho c_0 G_V\left(T_1 - T_b\right)}{\rho c_0 V_0 + m_1 c_m}. \tag{9}$$

The liquid leaving the hopper with the temperature T_b enters the gaps at the outlet of the rotor channels, heating along the way the supply pipeline and adjacent metal structures with a total mass m_2, including the mass of the rotor m_{rot}. The temperature of the liquid in this area decreases. Due to the supply of heat from the heated liquid, the temperature at the outlet of the rotor channels R_{ent} increases per unit time by the amount dT_{ent}.

From the equation of heat balance

$$m_2 c_m \frac{dT_{ent}}{d\tau} = \rho c_0 G_V\left(T_b - T_{ent}\right) \tag{10}$$

it follows that the increase in temperature of the liquid in the hopper and the walls of the hopper per unit time is determined from the condition of heat balance and is described by the equation

$$\frac{dT_{ent}}{d\tau} = \frac{\rho c_0 G_V\left(T_b - T_{ent}\right)}{m_2 c_m}. \tag{11}$$

When passing through the channels of the rotor and stator, as well as through the gap between them, the liquid is heated due to intense viscous dissipation and rises to the temperature Tout at the outlet of the gap at the entrance to the stator channels. From the heat balance equation it follows that

$$\rho c_0\left(T_{out} - T_{ent}\right) = Q_\delta, \tag{12}$$

where the amount of heat released per unit time inside the gap is described by the equation

$$Q_\delta = \mu\frac{2\pi\omega R_{r2}^3\omega^2 h}{\delta}. \tag{13}$$

It is obvious that due to the dissipation of mechanical energy when entering the inlet of the rotor channels, the temperature of the liquid at the outlet of the stator channels T_{out} must also increase by a certain amount per unit time dT_{out}.

We assume that the liquid leaves the stator channels with the temperature T_{out} of the heating mass of the stator, the mass of RPA housing and the mass of the pipeline between RPA housing and the entrance to the hopper. The total mass of the metal structures heated in this area is equal to m_3, including the mass of the stator m_{stat} and the mass of the housing m_{corp}. At the entrance to the hopper, the liquid comes with a temperature $T_1 < T_{out}$. In this case, due to the receipt of more heated liquid, the temperature of the liquid at the entrance to the hopper per unit time increases by dT_1.

From the equation of heat balance for this section

$$m_3 c_m \frac{dT_1}{d\tau} = \rho c_0 G_V \left(T_{out} - T_1\right) \tag{14}$$

it follows that the increase in temperature of the liquid at the inlet to the hopper per unit time is described by the equation

$$\frac{dT_1}{d\tau} = \frac{\rho c_0 G_V \left(T_{out} - T_1\right)}{m_3 c_m}. \tag{15}$$

Summarizing the left and right parts of equations (5), (7), (11), we obtain

$$\left(\rho c_0 V_0 + m_1 c_m\right)\frac{dT_b}{d\tau} + m_2 c_m \frac{dT_{ent}}{d\tau} + m_3 c_m \frac{dT_1}{d\tau} = \rho c_0 G_V \left(T_{out} - T_{ent}\right) \tag{16}$$

From the obtained equation it follows the obvious conclusion that the heat supplied to each section of RPA line per unit time is equal to the amount of heat released by the heat source in the gap due to viscous dissipation. Using equations (9) and (10), the equation of heat balance (8) can be represented as

$$\left(\rho c_0 V_0 + m_1 c_m\right)\frac{dT_b}{d\tau} + m_2 c_m \frac{dT_{ent}}{d\tau} + m_3 c_m \frac{dT_1}{d\tau} = \mu \frac{2\pi\omega R_{r2}^3 \omega^2 h}{\delta} \tag{17}$$

Next, we can make an important assumption that during the operation of RPA, the temperature in each section of the line increases by the same amount

$$\frac{dT_b}{d\tau} = \frac{dT_{ent}}{d\tau} = \frac{dT_1}{d\tau} \tag{18}$$

Substituting this condition into equation (9) we arrive at equation

$$\left(\rho c_0 V_0 + m_1 c_m + m_2 c_m + m_3 c_m\right)\frac{dT_b}{d\tau} = \mu\frac{2\pi\omega R_{r2}^3\omega^2 h}{\delta} \tag{19}$$

from which it follows that the temperature change in the hopper is described by a differential equation of the form

$$\frac{dT_b}{d\tau} = \mu\frac{2\pi R_{r2}^3\omega^2 h}{\delta\left(\rho c_0 V_0 + m_1 c_m + m_2 c_m + m_3 c_m\right)} \tag{20}$$

In the right part of this equation, all parameters except viscosity are constant.

Therefore, the equation can be written in a simpler form

$$\frac{dT_b}{d\tau} = K\mu\left(\tau\right), \tag{21}$$

where the constant K is described by the expression

$$K = \frac{2\pi R_{r2}^3\omega^2 h}{\delta\left[\rho c_0 V_0 + c_m\left(m_1 + m_2 + m_3\right)\right]} = \frac{2\pi R_{r2}^3\omega^2 h}{\delta\left(\rho c_0 V_0 + m_{sum} c_m\right)}, \tag{22}$$

where m_{sum} – the total mass of metal in the RPA line.

The denominator in parentheses contains the entire mass of the components of RPA, including the treated liquid, which are heated during processing.

It is easy to calculate that at the total mass of metal (steel) in the line RPA at quantity of liquid of 100 liters on heating of metal no more than 10 % of total expenses of heat are spent.

The solution of equation (18), which determines the dependence of temperature in the hopper on time, is reduced to the form

$$T_b - T_0 = K\int_0^\tau \mu\left(\tau\right)d\tau. \tag{23}$$

The calculation by formula (19) gives the value $K = 4{,}25\times10^{-3}$.

The solution of equation (20) is complicated by the fact that the dependence of the viscosity of the mixture treated in RPA cannot be determined theoretically. To find this dependence should use the results of experimental determination of the viscosity of the samples of the treated mixture, taken at different stages of processing.

When processing the data of this table, the dependence of viscosity on time for the studied water-grain mixture can be approximated by the equation

$$\mu(\tau) = \mu_0 + k_\mu \tau^{2,2}. \tag{24}$$

where μ_0 – the viscosity at time τ = 0, which is taken equal to the viscosity of water (0,001 Pa·s), where the coefficient k_μ = 1,23×10^6.

Substituting these values into equation (23) and carrying out the integration, we obtain

$$T_b - T_0 = T_0 + K\int_0^\tau \left(\mu_0 + k_\mu \tau^{2,2}\right) d\tau = K\int_0^\tau \mu(\tau)\, d\tau = K\tau\left(\mu_0 + k_\mu \tau^{2,2}\right) \tag{25}$$

At τ = 5 min = 300 s – temperature T_b = 28,75 ºC;

at τ = 9 min = 540 s – temperature T_b = 45,15 ºC;

at τ = 14 min = 840 s – temperature T_b = 90,15 ºC.

The increase in liquid temperature when passing through the gap can also be estimated based on the analysis of experimental data. The heat Q_δ released per unit time in the gap due to the effect of viscous dissipation can be estimated using equation (10).

The amount of heat received by the liquid as a result of the dissipation process at a given volume flow rate G_V is determined according to equation (9)

$$\rho c_0 G_V \left(T_{out} - T_{ent}\right) = \rho c_0 \Delta T_\delta = Q_\delta. \tag{26}$$

The temperature difference at a certain point in RPA is determined by the formula

$$\Delta T_\delta = \frac{Q_\delta}{\rho c_0 G_V}. \tag{27}$$

Therefore, if the flow rate G_V and viscosity μ are known for a given time, then it is easy to estimate the increase in liquid temperature for a given time. For calculation we will use the data of table 1.

For the same time values for 5, 9 and 14 minutes we take the experimental values of flow rate G_V and viscosity μ, which are given in the table 1. Knowing the viscosity, we calculate by formula (10) for these moments of time the heat Q_δ, and by formula (19) we find the increase in liquid temperature in the gap ΔT_δ. The same table also shows the above data on the value of the liquid temperature in the hopper T_b for the specified points in time.

As can be seen from the table 2, the temperature in the hooper according to the estimated data reaches 90 ºC. This high value is due to the fact that only experimental viscosity data are used for the calculation.

4. Pressure fields in the working zone of RPA

The most important dynamic characteristic of the flow is the pressure field, which changes over time. Factors influencing the processes of deformation and destruction of dispersed particles in heterogeneous media treated in RPA are pressure pulsations, as well as pulsations of normal and tangential stresses that occur in the flow when during its passage through the working zone of the apparatus. The distribution of pressure over the volume of the working zone has a significant degree of non-uniformity and the nature of its distribution changes rapidly over time. The pressure gradients that occur in the flow contribute to the deformation of the particles, and its pulsations over time can cause high-frequency oscillations of their shells, which leads to a rupture of the interfacial interface. The reason for the adiabatic boiling of the treated medium and subsequent cavitations effects in the working area of the apparatus may be the pulsating nature of the pressure change. This fact also contributes to the destruction of particles of the substance being dispersed.

In Figure 2 presents the fields of excess pressure in the working zone of the apparatus, obtained by the method of numerical simulation of fluid flow with a viscosity of $\mu = 1{,}1$ Pa·s at different times. Since this process is periodic in time, we can assume that the moment of coincidence of the slots of the rotor and stator corresponds to the time $\tau = 0$. As shown in Figure 2, a, excessive positive pressure (up to +190 kPa) is observed in the gaps between the rotor and the stator. As the stator slots gradually overlap with the rotor wall (Figure 2, b), the pressure at the left inner end of the stator slots begins to increase, and the pressure near the right rotor wall decreases. With a further increase in the degree of mutual overlap of the slots, the pressure in the flow near the inner wall of the stator increases (between the rotor and the stator).

Until the complete mutual overlap of the stator slots with the rotor wall (Figure 2, c), the area of positive pressure near the left inner end of the stator slot moves downstream and is between the rotor and the stator. The highest positive pressure (up to +260 kPa) in this zone is achieved in the gap between the rotor and the stator (Figure 2, d).

As mentioned above, an important dynamic characteristic of the flow is the pressure field, which, like the velocity field, changes over time. Analysis of the above figures shows that the highest pressure is observed at the

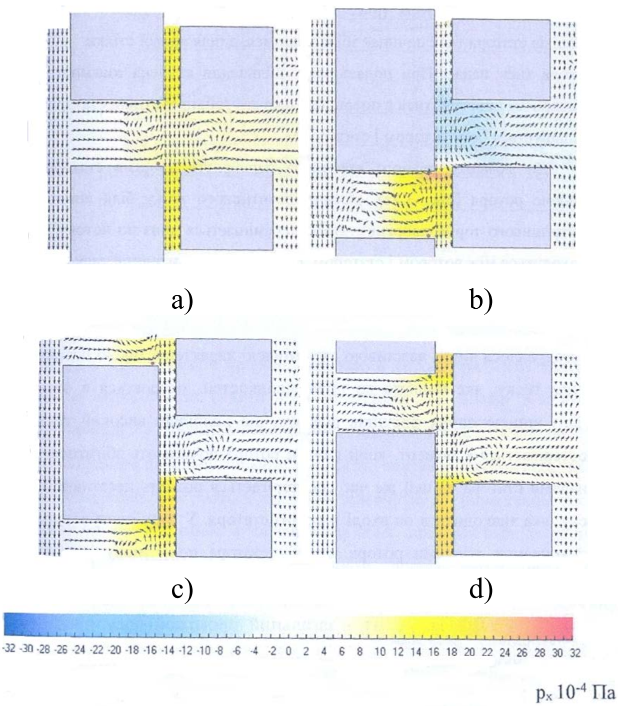

Figure 2. Fields of excess pressure in the working area of the apparatus at different moments of time at the viscosity of the treated medium μ = 1,1 Pa·s

moment when the rotor channels begin to coincide with the stator channels. At the same time, this is zone of negative pressure, which is located at the entrance to the stator slot. As the walls of the rotor gradually overlap the stator channels, the pressure field changes significantly. As can be seen from Figure 3 in the period of time $\tau = 0,3\Delta\tau$, when the edges of the channels of the rotor and stator converge, the pressure increases to +260 kPa, where $\Delta\tau$ is the total time of the material processing. This reduces the pressure near the outer wall of the rotor channel, which blocks the entrance to the stator channel. At the moment $\tau = 0,3\Delta\tau$, the pressure in this region drops to – 80 kPa.

As a result of the fact that the areas of minimum and maximum pressure are located in close proximity to each other, near the edges of the edges of the slots, there are high pressure gradients, as well as normal and tangential stresses than can cause deformation of dispersed particles. As the pressure drop increases, the absolute values of the pressure maxima near the edges increase. It should also be noted that the increase in pressure near the edges of the edges, as well as its decrease, occur in relatively short of time. Thus, the process of pressure change has the character of short-term pulsations.

From the presented results it follows that when processing the water-grain mixture in the rotor-pulsation apparatus, the pressure changes most intensively in the gaps between the rotor and the stator. Significant pressure differences in the gaps can be explained by the fact that the main physical and chemical property of the liquid that affects the process is its high viscosity.

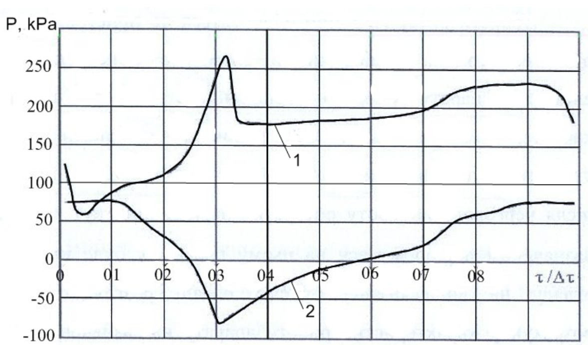

Figure 3 Change in time of excess pressure:
1 – at the entrance to the gap between the rotor and the stator;
2 – at the entrance to the stator slot

5. Consumption and speed of heterogeneous liquid flowing through the working zone of the apparatus

Devices of rotor type belong to devices of periodic action. The geometric periodicity of the structural elements of the working elements of the apparatus determines the periodicity of the changes in time of the dynamic characteristics of the fluid flow through the working zone. In other words, at a constant mode of operation of the apparatus, the pattern of fluid flow is repeated after the next rotation of the rotor by a periodic angle of rotation $\Delta\theta$. The specified time period on this interval will be the interval $\Delta\tau$. In view of the above, we will further consider the results of calculating the performance of the apparatus at the specified time interval $0<\tau<\Delta\tau$.

As studies conducted in [12] have shown, one of the important indicators of the rotary-pulsation apparatus is the flow of fluid flowing through the working zone in the radial direction. This value can be found from the data on the distribution of the radial velocity at the entrance to the stator holes at different points in time. The fluid flow in the radial direction is proportional to the value of the average velocity of the radial flow.

In Figure 4 shows the change in time of the average velocity of the treated medium in the inlet section of the working zone for one period at different viscosity values. The values of $\tau/\Delta\tau = 0$ and $\tau/\Delta\tau = 1$ correspond to the moments of coincidence of the axes of the slots of the rotor and the stator. As can be seen from the graph, the curves $V(\tau)$ during the period $\Delta\tau$ have both minima and maxima. The maximum velocity corresponds to the time value $\tau/\Delta\tau = 0{,}2$. At this point, there is a shift of the axis of the rotor hole relative to the axis of the stator hole by some angle $\Delta\theta>0$, that is, after the alignment of the axes of the rotor and the stator. The minimum velocity is observed somewhat later than the complete mutual overlap of the rotor and stator holes ($\tau/\Delta\tau = 0{,}6$). The nature of the increase in velocity from its minimum value to the maximum is smoother than the nature of the decrease in velocity from the maximum value to the minimum. The time interval corresponding to the decrease in velocity is about 0,4 of the duration of the entire period $\Delta\tau$. From the presented graph in Figure 4 it is also seen that for one period the values of the velocity $V(\tau)$ decrease with increasing viscosity of the medium μ.

In Figure 5 presents the results of calculation the cost of the treated medium from the viscosity. As can be seen from the graph, the comparison of the calculation results (curve 2) with the results of experimental studies (curve 1) show their satisfactory agreement. In this case, for $\mu > 0{,}8$ Pa·s, the flow rate of the medium obtained by the calculation is lower than that found in the experiment, and for $\mu < 0{,}7$ Pa·s it is higher.

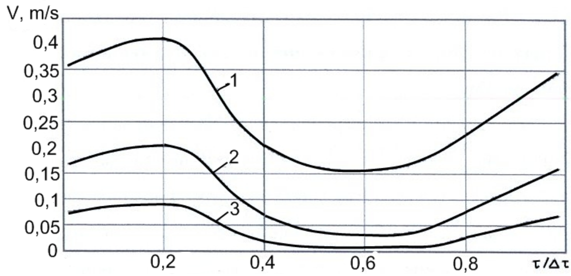

Figure 4. Change in time of the average mass radial velocity of the treated medium in the inlet section of the working zone for one period: 1 – μ = 0,2 Pa·s; 2 – μ = 1,1 Pa·s; 3 – μ = 2,0 Pa·s

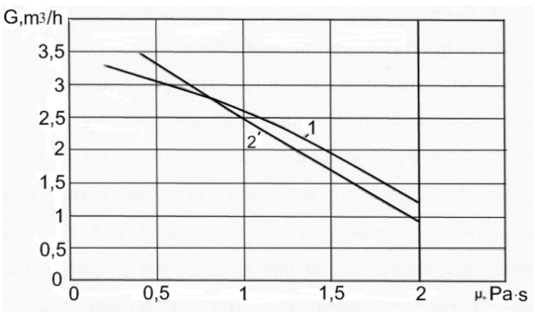

Figure 5. Dependence of the consumption of the treated medium on the viscosity: 1 – experiment; 2 – calculation

6. The influence of viscosity of the processed environment on the degree of its heating and on the level of dissipative heat release in the working volume

The flow of liquid through the working zone of RPA is accompanied by its heating. The heating of the liquid in the apparatus is a consequence of the dissipation of mechanical energy into heat. A number of scientific publications [13; 14] are devoted to the study of this question, where the assumption of the linearity of the circumferential velocity distribution function in the gap was used to calculate the degree of liquid heating in the inter-cylinder gaps. In this case, the space of the apparatus, in which the dissipative phenomena were considered, was actually limited to the zones of gaps. The theoretical results obtained in these works were close to the results of experimental studies, although it is obvious that more reliable results would be obtained when considering the dissipation of mechanical energy in the entire working space RPA, including the radial slots of the rotor and stator.

The results of the calculation of the fields of excess temperature (T – T0) in the laminar regime of the flow of Newtonian fluids at different points in time at the viscosity of the treated medium μ = 1,1 Pa·s are presented in Figure 6. As can be seen from the figures, the liquid is most heated in the gaps between the rotor and the stator (Figure 6, a, b). The most intense heat dissipation due to dissipation occurs when the stator and rotor slots overlap (Figure 6, c, d). The excess temperature at the stator edge at this time interval increases to 2,0...2,5 ºC.

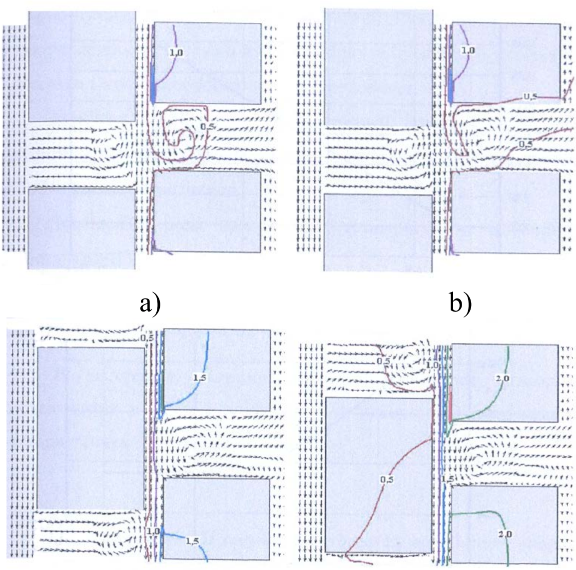

Figure 6. Excess temperature fields in the working zone of the apparatus at different points in time at the viscosity of the treated medium μ = 1,1 Pa·s

As the viscosity increases, the total heat dissipation increases (Figure 7, a), which is due to the fact that the term for the heat source in the energy equation (4) is represented as the product of viscosity μ on the dissipative option depending on the of fluid flow structure. It is clear that with increasing viscosity of the liquid μ, the power of heat should increase. It is also worth paying attention to the dependence on the viscosity of the dissipative function.

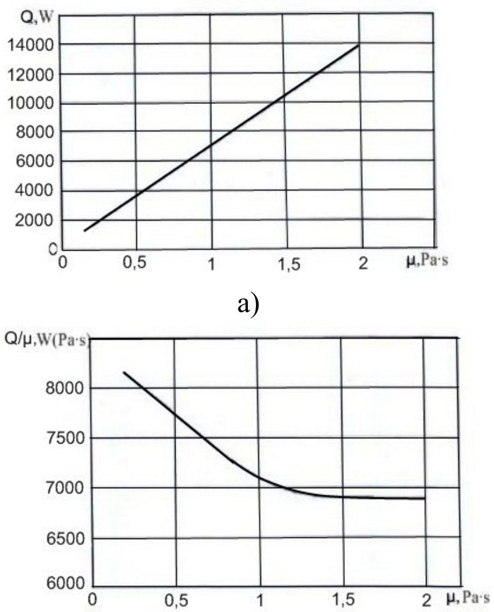

Figure 7. Dependence of total dissipative heat emissions in the working zone on viscosity

Characteristic in this sense is the dependence on the viscosity of the relative value of Q/μ (Figure 7, b). As can be seen from this figure, with increasing viscosity of the liquid, the relative value of Q/μ decreases. This is due to the decrease in the rate of deformation of the flow with increasing viscosity μ.

Thus, as a result of the study of fluid dynamics in the rotary-pulsation apparatus, a significant increase in pressure in the gaps relative to the pressure at the entrance to the working zone of the apparatus, which is associated with high viscosity of the treated medium.

The dependence of the average mass flow rate on the viscosity, as well as the power of sources of dissipative heat in the treated medium is found.

The field of excess temperature in the working zone of the apparatus at different points of time was investigated.

7. Conclusions

1. As a result of numerical calculations in Ansys Fluent application package, all dynamic and thermal characteristics of the liquid mixture during its passage through the rotor-stator system were obtained.

2. The maximum pressure increase in the flow of the mixture is observed in the zones between the rotor and the stator. In these zones, the pressure increase may be 55 kPa compared to the pressure at the inlet to the channel.

3. The maximum values of flow rate of the mixture are observed in the channels between the rotor and the stator, where these values can exceed 7 m/s. When the liquid leaves the rotor-stator channel the flow vortices zones are formed, which turbulizes the flow in the channels and leads to intensive mixing of the mixture. The result is a homogeneous mixture.

4. The highest values of temperatures in the liquid mixture take place in the zones adjacent to the surface of the end plane of the rotor and can exceed 21 ºC. This indicates a dissipation of the kinetic energy of rotation of the rotor and an increase in the temperature of the mixture during its processing.

5. As a result of numerical simulation, the fields of pressures, velocities and temperatures in the liquid mixture were obtained, which made it possible to choose the design of the rotor-pulsation apparatus, which will be used to develop an experimental sample of such device.

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