Methods for modeling cavitation in pulp fiber grinding processes

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Abstract. This article presents the main results of theoretical studies of the process of hydrodynamic grinding of cellulose suspension, based on mathematical modeling methods. Cavitation currents are a factor in effective milling of cellulose fiber. In this regard, it is necessary to develop a comprehensive model of the occurrence of the cavitation effect with parameterization of the indicators of the energy that arises.

1. Introduction
One of the main factors of effective grinding of cellulose fiber in an electromechanical converter with a discrete secondary discrete part is directly the parameters of the resulting cavitation flow. Due to the importance of cavitation action, it is necessary to develop a model of the occurrence of cavitation flow with parameterization of the parameters of the released energy.

The cavitation effect is conditionally divided into several stages: the occurrence, growth and collapse of bubbles. Since in this case the grinding of cellulose fiber occurs in a liquid medium (suspension), each collapse of the cavitation cavity is accompanied by the release of energy and the formation of hydrodynamic currents.

By cavitation in a liquid is meant the process of forming in the liquid flow cavities (bubbles, cavities) filled with gas, as a result of local pressure reduction. It should be noted that there is a distinction between acoustic cavitation occurring when acoustic oscillations pass through the liquid and hydrodynamic cavitation occurring due to a local decrease in pressure in the liquid flow when the solid is streamlined.

The subject of research in the present work is a device with a discrete secondary part, which has received in the cycle of work on the study of physical processes, as an electromechanical converter with a discrete secondary part [1-3]. In this device, under the influence of an external electromagnetic field, an intensively moving large set of ferromagnetic elements creates a large energy density per unit volume of a substance, while processing various kinds of liquid materials [4,5], including a cellulosic suspension [6,7].

The most important energy effect is hydrodynamic cavitation caused by the flow of ferromagnetic elements with a viscous liquid medium. The intense movement of ferromagnetic elements under the influence of a rotating electromagnetic field is accompanied by a constant change of directions. Between the liquid flows moving along the ferromagnetic elements in opposite directions, zones of reduced pressure appear, in which cavities (cavitation bubbles) are formed, filled with steam of the treated raw materials, which are then collapsed when they enter the high pressure zone.
The general picture of the formation of the cavitation bubble is presented in the following form. In the vacuum phase, a gap is formed in the liquid in the form of a cavity, which is filled with saturated liquid vapor. In the compression phase, under the influence of increased pressure and surface tension forces, the cavity collapses. A significant effect of cavitation processes is associated with a high concentration of energy released during the collapse process in the treated medium. At the moment of collapse, the gas pressure and temperature reach significant values, and according to some data reach 100 MPa and 10000 °C, respectively [8]. This phenomenon is explained by the small volume of the substance when the bubble reaches its minimum radius preceding the collapse. Based on the results of scientific research [9-11], it can be argued that the radius of the cavitation bubble at the time of collapse can reach, as a rule, $10^{-7}$-$10^{-8}$ m, against the radius in the equilibrium state of $10^{-10}$ m. Changing the volume of the cavitation bubble, reaching 1000 values, leads to high values of stored energy. It is known that the cavitation "germ" receives its maximum radius $R_{\text{max}}$ in the rarefaction phase (acoustic wave, the movement of the ferromagnetic element along the liquid flow). The $R_{\text{max}}$ value is significantly greater than the minimum radius $R_{\text{min}}$ preceding the collapse process. As a result, the equation of energy stored in the cavitation bubble can be written as follows:

$$ W = \frac{4}{3} \pi R_{\text{max}}^3 P_0 $$

(1)

where, $P_0$ - is the pressure of the surrounding liquid, Pa; $W$ - energy, J.

If the following values $R_{\text{max}} = 100 \mu$m, $P_0 = 0.1$ MPa are taken as the initial data, then the amount of energy stored by the cavitation bubble will be $4 \cdot 10^{-7}$ J, which, when such a bubble is compressed by 1000 times, will allow the energy density to be $10^{15}$ J/m³ [11].

The accumulation of a large amount of energy is explained by the fact that the initially stored energy is first converted into kinetic energy.

2. Approaches to describing the occurrence of cavitation

The majority of the cavitation currents applied at the moment use the eylero-eyerlovsky description of the two-phase environment. As a basis considerations of emergence of cavitation in the electromechanical converter with a discrete secondary part it can be partially assumed the models used at the description of processes of flow of elements in the liquid environment of aerodynamic profiles of ship pumps of bladed type, in tasks of ship propellers and other similar installations. The analysis of works in the field showed that at the heart of modeling of cavitation currents the barotropic equations of a condition of the environment [12], thermodynamic ratios [13] and also the communication equations between the istochnikovy members responsible for an interphase mass transfer, and dynamics of growth and compression of bubbles can be used [13,14].

Despite the fact that the experimental creation of cavitation processes in a liquid medium does not present great difficulties, until now, the processes of creating physical models of processes during hydrodynamic cavitation have a number of difficulties. Basically, the difficulties of creating physical models are associated with a large range of radii of cavitation bubbles and small intervals of compression, growth and collapse times that make up a fraction of nanoseconds.

All stages of evolution of the cavitation bubble are divided into several main intervals each of which corresponds to its time:

- Growth and expansion of cavitation cavern. In general, cavitation growth is divided into two stages. The first stage is associated with growth, but is accompanied by a decrease in pressure and continues on average 15 μs. At the second stage of cavitation bubble growth, pressure in it begins to increase due to diffusion of steam into the bubble.

- Following the expansion of the cavitation bubble, it is compressed, called Rayleigh compression. The compression of the bubble is accompanied by an increase in pressure and continues until the bubble reaches its original radius.
The cessation of condensation of water vapor, accompanied by the cavitation bubble reaching its minimum size and averaging about 50 ns.

Cessation of heat exchange between gas and liquid.

Maximum compression. The density of the gas inside the bubble at this stage becomes comparable to the density of the liquid outside. At the same time, a shock wave is observed in the liquid.

Due to the consumption of a large amount of energy per shock wave, further expansion of the cavitation bubble occurs much slower than its previous compression.

The formation of cavitation in the cellulosic suspension will differ from the same process in aqueous media. First of all, high viscosity and surface tension help stabilize the spherical symmetry of the cavitation bubble during its compression. This effect will accordingly lead to a higher energy release when it collapses. According to the results of the studies given in works [15], the viscosity of the processed raw materials also has a significant effect on the intensity of bubble collapse.

3. Mathematical model of fluid flow in working chamber of electromechanical converter with discrete secondary part

In connection with the proliferation of installations with a discrete part implementing liquid treatment processes by hydrodynamic cavitation, the issues of modeling cavitation streamlining have not only not lost their relevance, but have also gained even greater interest from scientists. The difficulty of calculating the cavitation flow under the conditions of the working chamber of the electromechanical converter from the discrete secondary part is due to the large set of ferromagnetic elements moving under the influence of the external electromagnetic field. Each element, moving in the liquid medium at a rate close to critical, at which cavitation cavities are formed, creates its own cavitation cloud, at the same time each ferromagnetic element acts on similar cavitation field of nearby elements with its cavitation field. The solution of this problem can be the first step towards solving the more complex problem of modeling the cavitation current arising during the operation of an electromechanical converter with a discrete secondary part.

The analysis of scientific literature showed two main approaches used to model the currents of multiphase media, including the Lagrangian-Eulerian and Eulerian-Eulerian descriptions.

The Navier-Stokes equation in the cylindrical coordinate system \( x, y, z \) is used as the basis for this study of processes in the working chamber of an electromechanical converter with a discrete secondary part:

\[
\begin{align*}
\frac{du}{dt} + u \frac{du}{dx} + v \frac{du}{dy} + w \frac{du}{dz} &= -\frac{1}{\rho} \frac{dp}{dx} + \mu \frac{d^2u}{dx^2} + \mu \frac{d^2u}{dy^2} + \mu \frac{d^2u}{dz^2} \\
\frac{dv}{dt} + u \frac{dv}{dx} + v \frac{dv}{dy} + w \frac{dv}{dz} &= -\frac{1}{\rho} \frac{dp}{dy} + \mu \frac{d^2v}{dx^2} + \mu \frac{d^2v}{dy^2} + \mu \frac{d^2v}{dz^2} \\
\frac{dw}{dt} + u \frac{dw}{dx} + v \frac{dw}{dy} + w \frac{dw}{dz} &= -\frac{1}{\rho} \frac{dp}{dz} + \mu \frac{d^2w}{dx^2} + \mu \frac{d^2w}{dy^2} + \mu \frac{d^2w}{dz^2} + g \\
\frac{dp}{dt} + u \frac{dp}{dx} + v \frac{dp}{dy} + w \frac{dp}{dz} &= 0
\end{align*}
\]  

where \( u, v, w \) - are flow velocity vectors of the liquid feed to be treated; \( \rho \) - density of the water environment; \( P \) - hydrodynamic pressure; \( g \) - acceleration of gravity, \( \mu,v \) - coefficients of turbulent exchange in the horizontal and vertical directions.

In addition, to simulate cavitation, it is necessary to solve the equation for transferring the mass or volume fraction of steam of the two-phase seven liquid-pairs.
4. Numerical models of cavitation mass transfer

The purpose of mass transfer during calculation and simulation of cavitation currents is to calculate the masses of released and condensed steam.

In work, the Relay-Plesset equation is used to calculate the mass of the released and condensed steam, taking into account the dynamics of the cavitation bubble:

\[ R \frac{d^2 R}{dt^2} + \frac{3}{2} \frac{dR}{dt} \rho \frac{2\sigma}{\rho R} = \frac{p_u - p}{\rho} \]  \hspace{1cm} (6)

In view of the difficulties encountered in solving this equation in general, it is most often simplified, neglecting the second order. As a result, bubble dynamics are described as follows:

\[ \frac{dR}{dt} = \sqrt{\frac{2}{3} \left( \frac{p_u - p}{\rho} \right)} \]  \hspace{1cm} (7)

Mass transfer of steam is considered depending on the volume concentration of steam, which is found by methods of mathematical statistics from the number of cavitational bubbles \( n \):

\[ \alpha = \frac{n}{1 + n} \frac{4}{3} \pi R_0^3 \]  \hspace{1cm} (8)

Mass transfer equations:

\[ p < p_u m_b = \frac{\rho_v \rho_l}{\rho} \alpha (1 - a) \frac{3}{R_0} \sqrt{\frac{2}{3} \frac{p_u - p}{p_l}} \]  \hspace{1cm} (9)

\[ p > p_u m_c = \frac{\rho_v \rho_l}{\rho} \alpha (1 - a) \frac{3}{R_0} \sqrt{\frac{2}{3} \frac{p - p_u}{p_l}} \]  \hspace{1cm} (10)

The advantage of this method of describing mass transfer lies in proportional mass transfer in the formation of steam and condensation, which automatically provides good convergence.

5. Conclusion

Thus, as a result of the work carried out, mathematical models were studied describing both the movement of the turbulent flow of liquid in the working chamber and the process of collapsing cavitation cavities to determine the energy released in this process, allowing grinding of cellulosic fibers. The obtained results will allow to develop a set of recommendations on formation of operating conditions of process of pulp fibres grinding.

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