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CAVITATION IN TECHNOLOGICAL PROCESSES

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ABSTRACT

The paper considers the phenomenon of cavitation observed in various types of technological equipment. The nature of the appearance of ultrasonic and hydrodynamic cavitation and the factors accompanying it is analyzed. It is shown that these two types of cavitation have been successfully used to improve the quality of technological processes. The results of an experimental study of the effect of cavitation on the physicochemical and rheological properties of a liquid are presented. At the same time, both positive effects accompanying cavitation and undesirable phenomena are considered, for example, in a number of machines and devices in chemical technology, for example, the emergence of hydrodynamic cavitation in a closed volume of a gear pump is revealed. Designs of devices for cavitation treatment of liquids are considered.

INTRODUCTION

One of the most important directions in applied hydromechanics is the direction associated with physicochemical processes occurring in viscous and anomalously viscous liquids under the influence of cavitation.

As is known, one of the most energetically effective methods of influencing liquid media is cavitation.

EXPOSITION

Numerous experimental and theoretical studies [1-11] have established that the formation of cavitation bubbles-cavities in a liquid occurs when the pressure drops locally below a certain critical value, which corresponds to the cavitation threshold. Typically, the critical value corresponds to a pressure that is slightly less than the vapor pressure at a given temperature. Cavitation bubbles filled with steam, gas or their mixture, falling into the area of increased pressure, collapse abruptly, which is accompanied by the appearance of shock pressure pulses that reach 10^3 MPa, an increase in temperature to 1000°C and electric discharges [12, 13].

Depending on the method of lowering the pressure in the liquid, inertial or hydrodynamic cavitation is distinguished, which occurs due to high local velocities in the flow of liquid, and acoustic or ultrasonic cavitation, which occurs due to the passage of a sound wave of high intensity [10, 13, 14 - 16].

In hydrodynamic cavitation, several forms of its flow are distinguished. Near bodies with smooth contours, under the condition of insignificant pressure gradients in the flowing stream, a bubble form of cavitation usually takes place. Based on the theory of separated flows, the process of cavity formation during hydrodynamic cavitation can be represented as shown in Fig. 1.

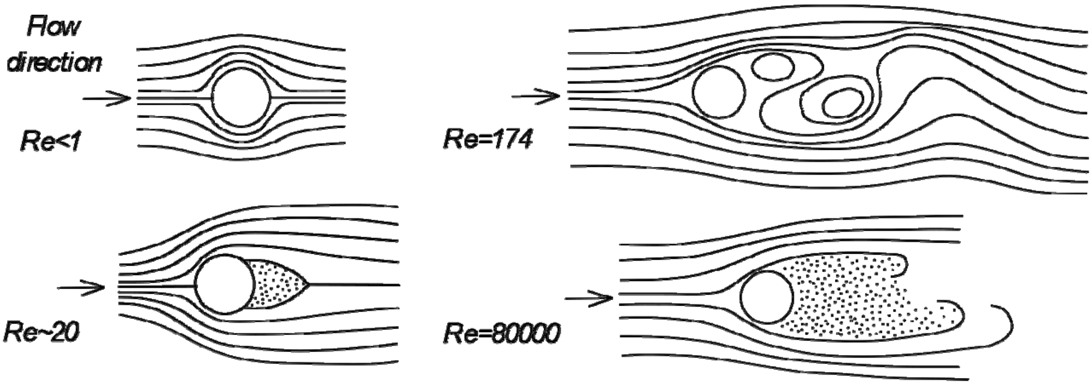

Fig. 1.The cavity formation process downstream the bluff body at various values of Reynolds number

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If there are sections of a sharp decrease in pressure in the flow, a so-called cavity associated with the body arises, which is filled with cavitation bubbles and can transform into a detachable or, as it is called otherwise, a film form. The location of the cavity relative to the streamlined airfoil, the nature of its behavior and shape are determined by the level of static pressure, the speed of the oncoming fluid flow, the quality of the airfoil streamlining, as well as the presence of conditions for the appearance of free vortices [10].

In an intense sound wave, the formation of cavitation bubbles occurs in half-periods of dilution, and their collapse in half-periods of compression. In this case, the cavitation bubble, which appears in the half-period of the dilution, due to the inertia of the liquid, may not have time to collapse in the half-period of compression. Therefore, it only slightly reduces its radius and, thus making a pulsating motion, it can miss one or several half-periods of compression. There is a kind of accumulation of energy in the bubble followed by its rapid release when it collapses. Thus, the instantaneous power that is released is significantly higher than the average power that the ultrasonic transducer injects into the liquid. It was shown in [17] that the average energy density and specific power, which correspond to the moment of collapse of a cavitation bubble in water under the action of sound vibrations, are 10^5 and 10^3 times higher, respectively, than the parameters of the excitation wave.

Ideal fluids are weakly susceptible to discontinuity even at sufficiently high tensile stresses. For example, the theoretical value of the critical pressure for water is $1{,}5 \cdot 10^8\ Pa$ [12]. In real liquids, cavitation processes are observed at pressures that are slightly lower than the saturated vapor pressure.

DYNAMICS OF A CAVITATION BUBBLE

The main hypothesis that explains this fact is the assumption of the presence in the liquid of nonwettable solid particles, undissolved gases, microcracks on nonwettable solid surfaces adjacent to the liquid, as well as vapor-gas bubbles that are initiated by high-energy cosmic particles. The greatest influence on the strength of a liquid is exerted by independently existing vapor-gas bubbles or vapor-gas bubbles, which are located in microcracks of solid insoluble surfaces. The possibility of long-term existence of independent vapor-gas bubbles in a liquid is explained by the ionic theory [18, 19], according to which the stable existence of a bubble is possible due to the uniform distribution of like charges on its surface. Like charges, repelling, do not allow the bubble to close [20, 21]. These impurities, falling into the region of reduced pressure, act as nuclei of cavitation [4, 10].

The effect of cavitationoccurrence is a consequence of the loss of stability by the nuclei under the influence of reduced pressure in the sound wave. The growth of the bubble size occurs due to the internal pressure of the vapor-gas mixture, which in the half-period of the discharge exceeds the external pressure of the liquid, due to the diffusion of gas from the liquid into the bubble, as well as due to the evaporation of the liquid from the inner surface of the bubble and an increase in the vapor mass in the bubble [12]. The prevalence of one or another mechanism for increasing the size of the bubble depends on the frequency of the pressure wave and on the gas saturation of the liquid.

At high oscillation frequencies in a liquid with low gas saturation in the temperature range that are far from the boiling point, the main factor in the increase in the size of the bubble is the periodic excess of the internal pressure of the bubble over the external one.

The diffusion mechanism is the main one in the region of low vibration frequencies, when there is a low rate of pressure change in a liquid with high gas saturation. With a decrease in the concentration of gas in the bubble due to a gradual increase in its size, the gas diffuses from the liquid into the bubble. In the half-period of pressure increase, the bubble size decreases and gas diffusion from the bubble into the liquid occurs. Since the amount of diffusing gas is proportional to the bubble surface area, which is larger in the bubble growth phase, then, in general, during the oscillation period due to the rectified diffusion process, there is an increase in the gas mass in the bubble and a corresponding gradual increase in its size [2].

If a sound wave is emitted into a liquid whose temperature is close to the boiling point, then the main reason for the increase in the size of the bubble is the evaporation of the liquid. In the half-period of the vacuum, due to the pressure difference and the corresponding forced increase in the size of the bubble, the liquid evaporates from the inner surface of the bubble. Evaporation leads to cooling of the bubble surface and the vapor-gas mixture in it. The resulting temperature difference provides an influx of thermal energy to the bubble surface, thereby supporting the evaporation process. The increase in the amount of vapor causes the bubble to grow. In the half-period of compression, the vapor begins to condense and the temperature on the bubble surface increases. The heat flow will now be directed from the bubble to the liquid. Incomplete compensation of heat fluxes in half-periods of compression and depression leads to the effect of rectified heat transfer, which, in general, during the period of oscillation of the sound wave provides an increase in the size of the bubble.

The above mechanism of evaporation is the main reason for the growth of sufficiently small bubbles. If the bubble radius exceeds 10^{-7} m, then the increase in bubble size is mainly due to the non-adiabatic nature of the process of changing the state of the contents in the bubble. The consequence of this is the release of additional energy in the bubble, which causes heating and the corresponding evaporation of the liquid into the bubble.

Only nucleus of a certain size interval can initiate ultrasonic cavitation.

The lower boundary of the specified interval is limited by the bubble size, which is determined by the relationship [10]

$$R_{cr} = \sqrt{3} R_0 \left[\frac{R_0}{2\sigma} \left(p_0 + \frac{2\sigma}{R_0} \right) \right]^{1/2}, \tag{1}$$

where σ - the surface tension coefficient; R_0 - initial bubble radius; p_0 - hydrostatic pressure.

The above expression is valid provided that the saturated vapor pressure is negligible compared to the amplitude sound pressure.

The upper boundary is limited by the size of the nuclei, the natural frequency of which is equal to the frequency of the exciting sound wave. The resonant size of the nucleus and the vibration frequency are related by the dependence [10].

$$(2\pi f)^2 = \frac{3\gamma_a}{\rho_p R_{res}^2}\left(p_a + \frac{2\sigma}{R_{res}}\right), \qquad (2)$$

where f - the frequency of sound vibrations; R_{res} - the resonant size of the nucleus; γ_a - the adiabatic exponent; ρ_p - the density of the undisturbed liquid; p_a - sound pressure generated by the sound field.

With an increase in the vibration frequency under unchanged other conditions, the value R_{res} decreases, which indicates a decrease in the probability of cavitation at high frequencies due to a narrowing of the interval of the required sizes of nuclei. Therefore, at vibration frequencies that reach dozens of MHz, ultrasonic cavitation and associated physicochemical effects are not observed.

In a standing sound wave, cavitation nucleus with sizes smaller R_{res} pulsate in phase with pressure fluctuations and move to the pressure antinodes, and if they are larger than R_{res} they move to the pressure nodes. The speed of such movements is determined by the relationship [12]

$$\upsilon_{mov} = \frac{R_0^2}{10\mu\left(p_0 + \frac{4\sigma}{3R_0}\right)} p_a \frac{\partial p_a}{\partial x}, \qquad (3)$$

where μ - the coefficient of fluid viscosity; x - spatial coordinate.The translational movement of bubbles to the nodes of a standing sound wave leads to coagulation of bubbles in them, an increase in their size and the formation of cavitation cavities, the sizes of which are much smaller than in hydrodynamic cavitation. When a standing wave of deformation is created, the maximum sound intensity and, accordingly, the zone of the most developed cavitation are on the surface of the ultrasonic emitter. In this case, all nuclei, which are located both on the surface of the emitter and in the liquid itself, take part in the process of cavitation.

In the case of a traveling sound wave, cavitation bubbles move in the direction of wave propagation. That is, the so-called sonic wind takes place, under the action of which the bubbles are removed from the zone of intense sound, which is located on the surface of the emitter. If the traveling sound waves from several emitters are focused, then at the focal point there is a concentration of sound energy and the emergence of a zone of developed cavitation, which is fed by the nucleus flying up to it. In this case, cavitation nuclei located on the surfaces of the emitters and the cavitation chamber do not take part in the cavitation process. From the zone of developed cavitation, which has arisen in the area of the focal spot or on the surface of a flat emitter in a chamber with a standing wave of deformation, ropes or strands of cavitation bubbles are constantly pulled out.

The adiabatic compression of a vapor-gas mixture in a cavitation bubble leads to a significant local increase in temperature, which results in gas ionization and the appearance of bubble luminescence, which is called sound luminescence.

For the case of the formation of a cavitation bubble in a viscous compressible fluid when an ultrasonic wave is introduced into it, the velocity of the bubble wall can be described by the Herring-Flynn equation [4, 7]:

$$R\left(1 - \frac{2U}{c_p}\right)\frac{d^2R}{dt^2} + \frac{3}{2}\left(1 - \frac{4U}{3c_p}\right)\left(\frac{dR}{dT}\right)^2 + \frac{1}{\rho}\left[p_0 - p_n - p_a \sin\omega t + \frac{2\sigma}{R} + \frac{4\mu U}{R} + \left(p_0 + \frac{2\sigma}{R_0}\right)\left(\frac{R_0}{R}\right)^{3\gamma}\right] + \\ + \frac{RU}{\rho c_p}\left(1 - \frac{U}{c_p}\right)\frac{dp(R)}{dR} = 0 \qquad (4)$$

where p_n - the steam pressure; $U = \frac{dR}{dt}$ - the bubble collapse rate; c_p - the speed of sound in an undisturbed fluid; $\omega = 2\pi f$ - circular frequency; γ - the polytropic index. The solution of equation (4) for the case of the formation of a cavitation bubble was carried out at the values given in Table 1. The calculation results are presented in the form of graphical dependencies in Fig. 2 [23].

Both hydrodynamic and ultrasonic cavitation are widely used in technological processes. Hydrodynamic cavitation is successfully used in the processes of mixing poorly miscible rheological media, in processes associated with cleaning various kinds of surfaces, solving problems of destruction of media.

THE EFFECT OF CAVITATION ON A LIQUID

Ultrasonic cavitation is used in mechanical engineering, food industry, medicine, agriculture, etc. Ultrasonic cavitation makes it possible to increase the efficiency of technological processes for cleaning solid and elastic surfaces, dispersing solid materials, activating and purifying liquids, reagent-free disinfection of liquids from microorganisms harmful to human health, extracting, spraying with obtaining a fine aerosol, obtaining metal nanopowders, homogenizing liquid components due to turbulent stirring at the molecular level, etc. In this case, secondary phenomena accompanying cavitation are usually used - shock waves arising from the collapse of cavitation bubbles and caverns, energy-intensive cumulative jets formed during the collapse of cavitation bubbles near neighboring bubbles or solid surfaces, a local increase in pressure and temperature during the collapse of cavitation bubbles, leading to formation of active radicals, mechanical destruction of microorganisms by spherical shock waves and cumulative jets, intensification of oxidative processes in the cavitation region, luminescence and sonoluminescence, etc.

The hydrodynamic effect of cavitation can lead to significant changes in the rheological characteristics of working fluids. Experimental studies have shown that cavitation treatment of rheologically complex non-Newtonian fluids can lead to a significant change in viscosity. Thus, experiments carried out using rheologically complex media such as fuel oil and its derivatives, as well as aqueous solutions of carboxymethyl cellulose, confirm a decrease in viscosity during cavitation treatment. In fig. 3 shows the dependence of the change in viscosity on the time of cavitation action for the indicated media.

Table 1 *Initial values used to simulate the dynamics of a cavitation bubble*

	f, kHz	$t, ^\circ C$	$\mu, \frac{N.s}{m^2}$	$\rho, \frac{kg}{m^3}$	$\sigma, 10^{-3} \cdot \frac{N}{m^2}$	$p_0, \frac{N}{m^2}$	$p_n, \frac{N}{m^2}$	$p_a, \frac{N}{m^2}$	R_0, m
Water	22	20	0,001	1000	74	$4 \cdot 10^6$	2300	$4 \cdot 10^6$	$3{,}2 \cdot 10^{-6}$
Petrol	22	20	0,0005	750	21	$4 \cdot 10^6$	66000	$4 \cdot 10^6$	$3{,}2 \cdot 10^{-6}$
AMG-10	22	20	0,51	850	28,9	$4 \cdot 10^6$	-	$4 \cdot 10^6$	$3{,}2 \cdot 10^{-6}$

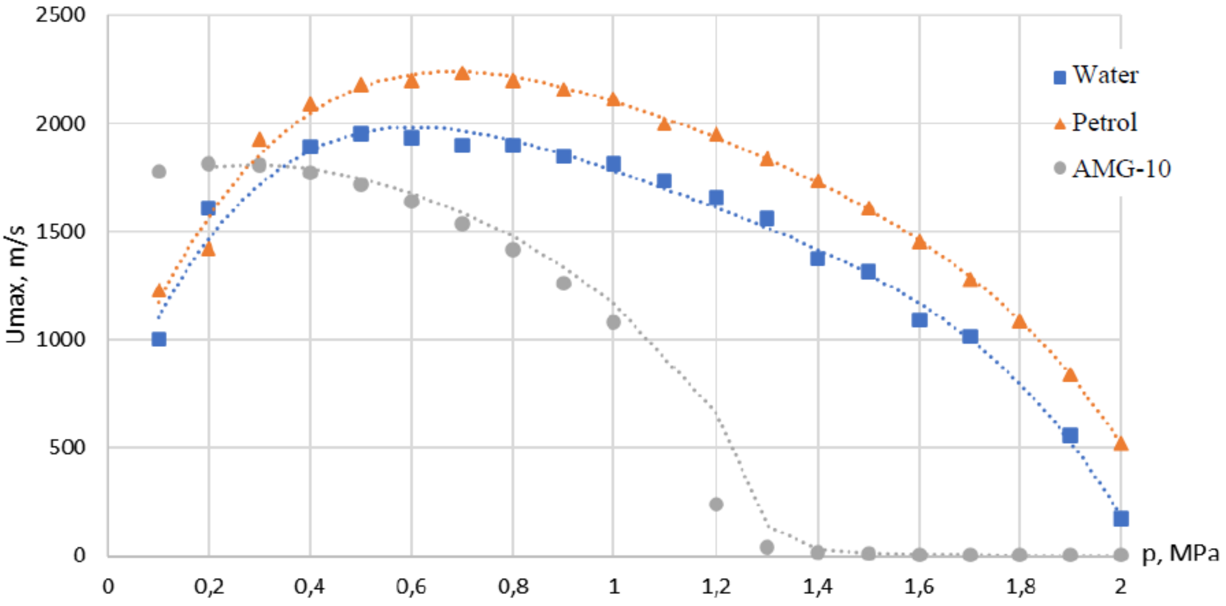


Fig. 2. Dependence of the velocity of the wall of the cavitation bubble in the compression phase on the static pressure in the liquid

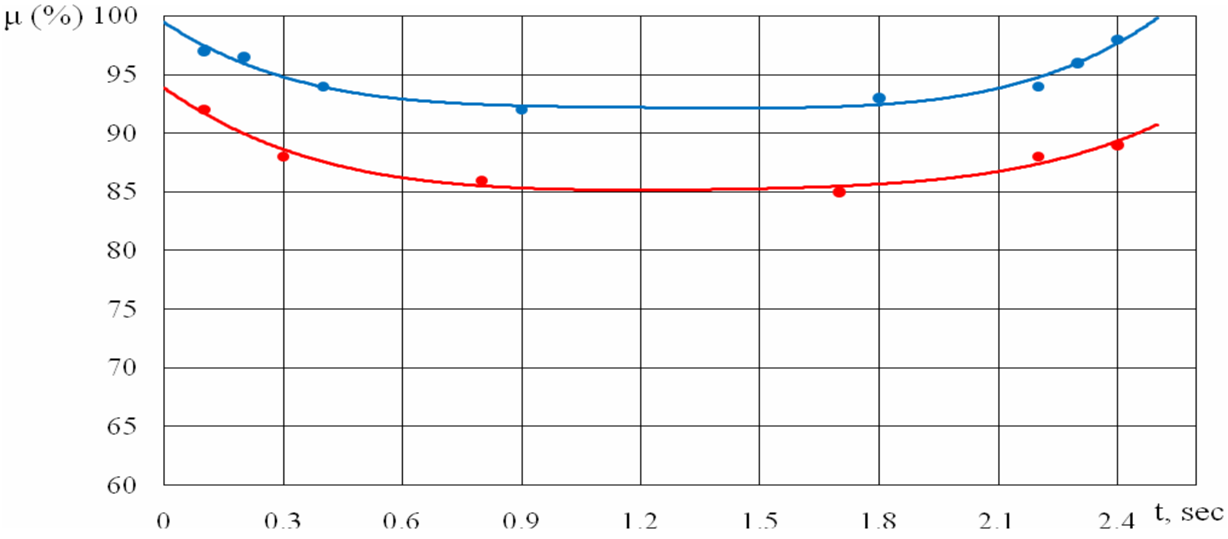


Fig. 3. Change in the viscosity of non-Newtonian liquids under the influence of cavitation treatment (solution of carboxymethyl cellulose - CMC and polyvinyl alcohol - PVA)

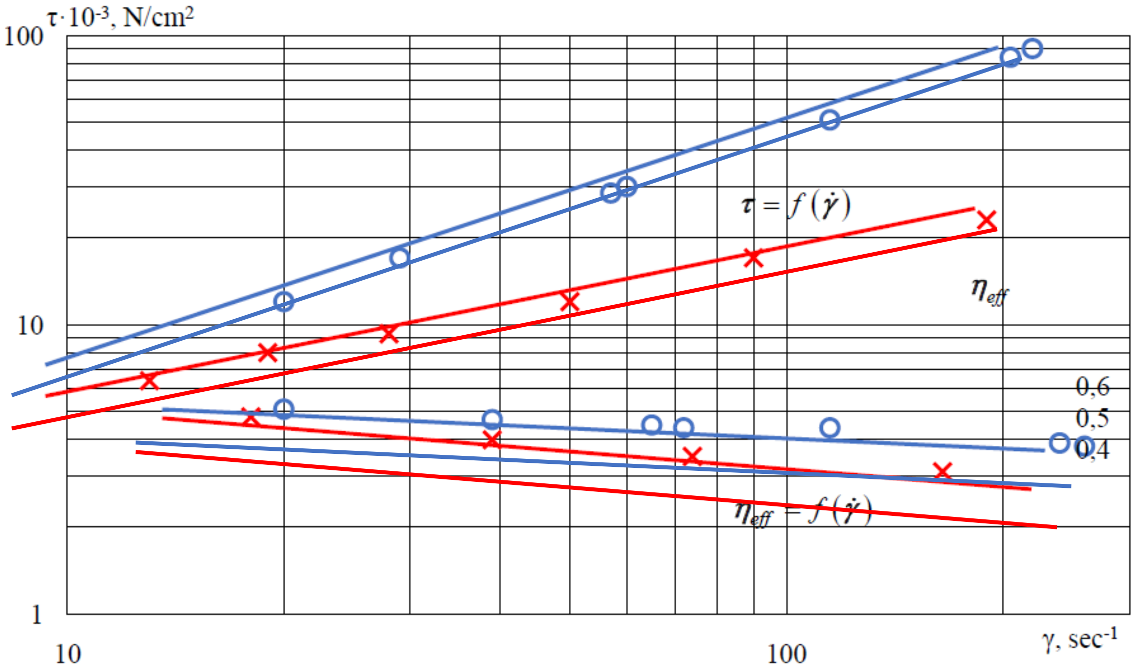
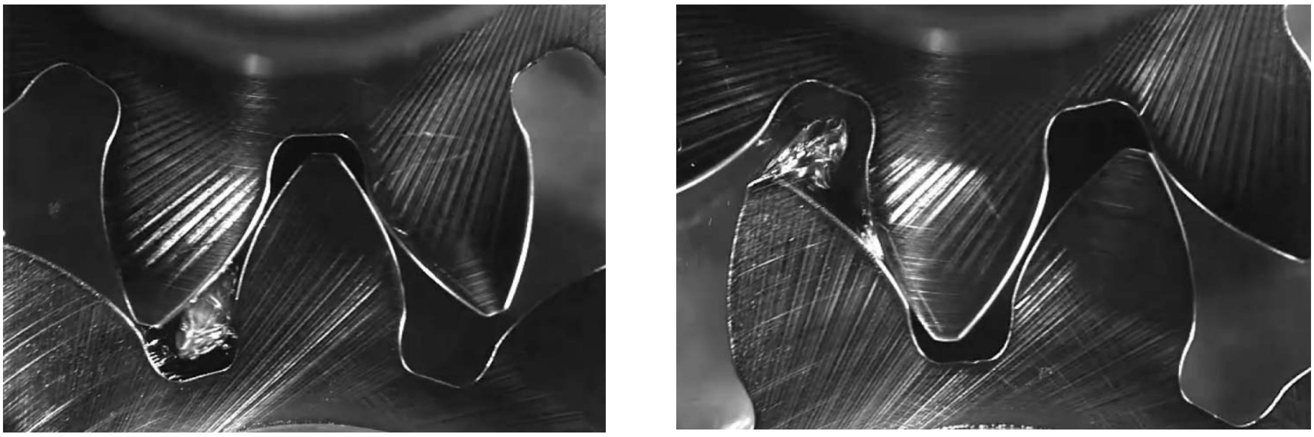


Fig. 4. Dependence of the shear stress τ on the velocity gradient for an aqueous solution of carboxymethylcellulose: ○ - before cavitation treatment, × - after cavitation treatment



a b

Fig. 5. Visualization of the flow in the chambers of the external gear pump: a - the appearance of a cavity in a closed volume; b - the appearance of a vortex and a cavity after the opening of a closed volume [25]

According to molecular theory of Bondi liquid [24], the equation for determining the viscosity has the form:

$$\mu = \frac{v_f^{1/3}}{v} 4\pi \sqrt{mkT}\, g^n \exp\left[\left(y\beta\varepsilon_a - 1 \right) ln\left(\frac{y+1}{y} \right) \right], \qquad (5)$$

In this formula, one of the basic quantities is the activation energy E, which can be determined based on the Arrhenius equation:

$$E_a = -RT\, ln\left(\frac{k}{A} \right) \qquad (6)$$

where: k - the reaction rate constant; A - pre-exponential factor (frequency factor) for the reaction; R - the universal gas constant; T - the universal gas constant

In accordance with Bondi's ideas, the viscosity can be determined from the expression:

$$\mu = constA \frac{e^E}{RT} \qquad (7)$$

As can be seen from the above ratios, the activation energy has a significant effect on the viscosity. The experimental determination of this value has shown that the activation energy can change significantly under the action of hydrodynamic cavitation.

An experimental study of the cavitation effect on carboxylmethylcellulose solutions showed changes in the dependence of the shear stress on the velocity gradient (Fig. 4).

The study of the influence of hydrodynamic cavitation on technical working fluids used in aviation (fluid of the AMG-10 type) showed that hydrodynamic cavitation can significantly affect the acid number.

Secondary effects accompanying the phenomenon of cavitation have both a negative effect on hydromechanical objects and can significantly increase the efficiency of many technological processes.

CAVITATION IN HYDRAULIC MACHINES

It should be noted that hydrodynamic cavitation can occur under certain conditions in various types of hydraulic machines, both positive and non-positive displacement pumps. Studies carried out at Wrocław University of

Science and Technology aimed at visualizing the flow in the working section of a gear pump showed that the appearance of hydrodynamic cavitation (vortex formation and cavities) is possible in a trapped volume (Fig. 5) [27].

The presence of such cavitation can have a negative effect on the operation of the gear pump, in particular on the surface quality of the gear teeth. The figure shows the appearance of cavitation in the closed volume of the pump, and such cavitation can be observed with different properties of the pumped liquid. There are several methods for extinguishing cavitation energy in these machines (grooving, preparation of the working fluid before the pump by degassing).

EQUIPMENT FOR CAVITATION TREATMENT OF LIQUIDS

Ultrasonic cavitation makes it possible to implement the technology of reagent-free inactivation of microorganisms hazardous to human health in liquid media, for example, in drinking water or wastewater. High efficiency of this technology can be achieved at an ultrasound intensity of about 100 W/cm^2 and higher. Introducing ultrasonic vibrations of such intensity into a liquid is very problematic.

This is due to the fact that on the emitting surface of the ultrasonic transducer immersed in water, a cavitation layer is formed in the form of a two-phase medium, which absorbs and scatters ultrasound. As a result, the intensity of the ultrasonic wave decreases sharply. In addition, the emitting surface is rapidly destroyed due to cavitation erosion. The problem can be solved using the focusing properties of the radiation surface. In this case, low-intensity ultrasound with high efficiency is introduced into the liquid, and the required high intensity is achieved in the focal region. For this purpose, special ultrasonic tubular flow cavitators have been developed (Fig. 6a, b, c) [26-28].

By the developed flow-through cavitator (Fig. 6a), it was possible to increase the efficiency of technological processes of inactivation of microorganisms in lubricating-cooling liquids and in bioorganic fuel, cold sterilization of milk, obtaining liquid humic fertilizers, homogenization, extraction, degassing, activation of liquids and fuels, etc.

Homogenization of liquid components occurs due to turbulent mixing at the molecular level by intense microflows arising from oscillations and collapse of cavitation bubbles.

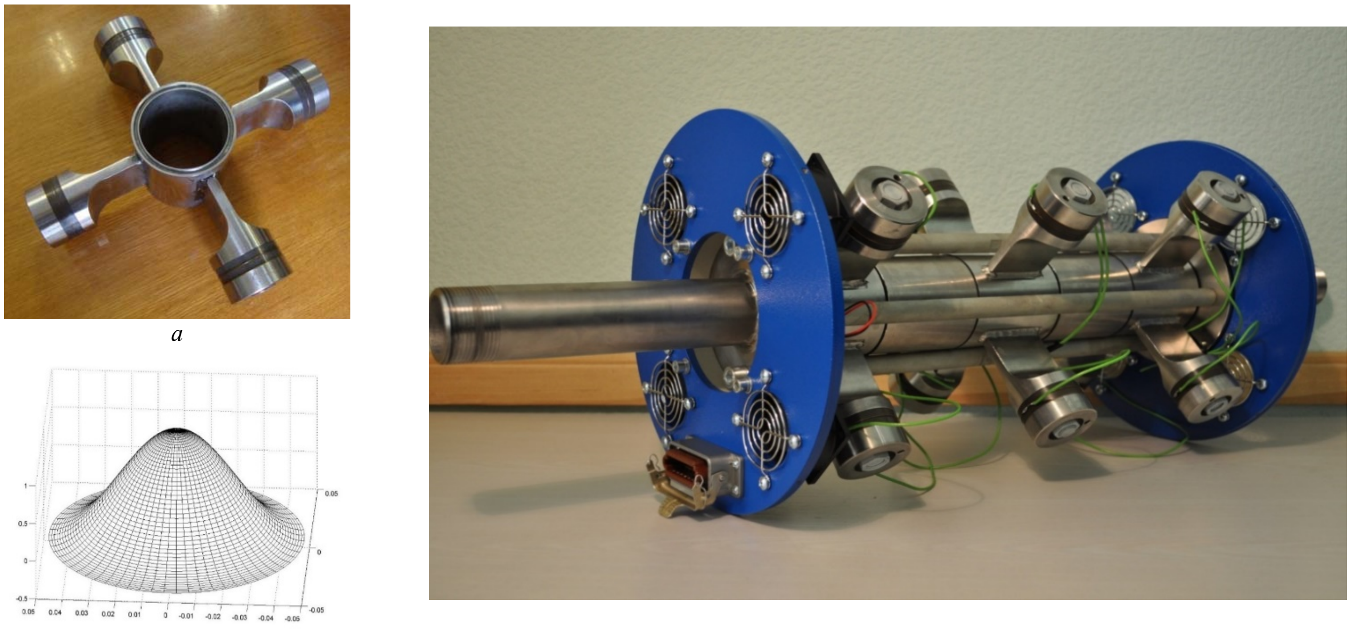
The activation of liquids occurs due to the creation of conditions for the appearance of electric charges rich in energy of dissociated and ionized molecules inside the microvolumes of collapsing cavitation bubbles, as well as atoms and free radicals, which contribute to the intensification of chemical processes.

An increase in the nutritional properties of milk is achieved by cavitation dispersion of the fat globules that make up the milk to a very small size.

Cavitation disinfection of liquid occurs regardless of the degree of its transparency and mechanical contamination.

Ultrasonic cavitators are widely used in the implementation of the technological process for obtaining fine aerosols. In this case, the so-called effect of ultrasonic spraying in a thin layer or in a fountain is used. When ultrasonic spraying in a thin layer, the liquid wets the vibrating surface of the ultrasonic transmitter. As a result of the formation of capillary waves on the vibrating surface of the liquid and their periodic loss of stability, monodisperse aerosol droplets break off from their crests [26, 31, 33].

It should be noted that in hydrodynamic cavitation one of the effective methods of its use is the method associated with mixing poorly miscible liquid media. The design of such cavitators can be of two types: on the one hand, cavitators using a discrete mixing method (such devices include paddle mixers operating in cavitation mode), on the other hand, continuous mixers, the design of which is carried out in such a way as to ensure the formation of a cavity as large as possible. sizes. The figure shows possible designs of this type of cavitator.



a

b

c

Fig. 6. Ultrasonic flow-through cavitator (a - tubular section with a cylindrical emitting surface; b - shape of the sound pressure diagram in a tubular cavitator with excitation of a radial vibration mode; c - three-section flow-through ultrasonic cavitator with a power of 1200 W)

Depending on the technological problems that are solved using cavitation generators, their designs can be different. Fig. 7 shows a general view of ultrasonic cavitators, where the technological process is provided due to the action of ultrasound on the working medium. Such devices can be used to solve practical problems associated with fine atomization of the medium.

Fig. 8a presents a general view of a continuous cavitation mixer for mixing media with different rheological properties. Hydrodynamic cavitation in such a mixer is ensured by installing poorly streamlined bodies capable of providing a cavity of specified dimensions outside of them.

Figures 8b, 8c show the types of hydrodynamic cavitators providing different sizes of cavities.

In fig. 8b shows one of the types of cavitator with "controlled" cavity sizes.

These types of cavitators can be used in various fields of industry. So presented in Fig. 8 hydrodynamic cavitators are used more often in mixing processes that are poorly miscible under normal conditions, using mechanical stirrers, media.

The advantages of these mixers are that the mixed media after hydrodynamic cavitation treatment have a sufficiently long separation period. This is due to a number of factors, in particular with the effect of cavitation on the rheological properties of the mixed media

Fig. 7. Examples of ultrasonic cavitation devices for spraying in a thin layer

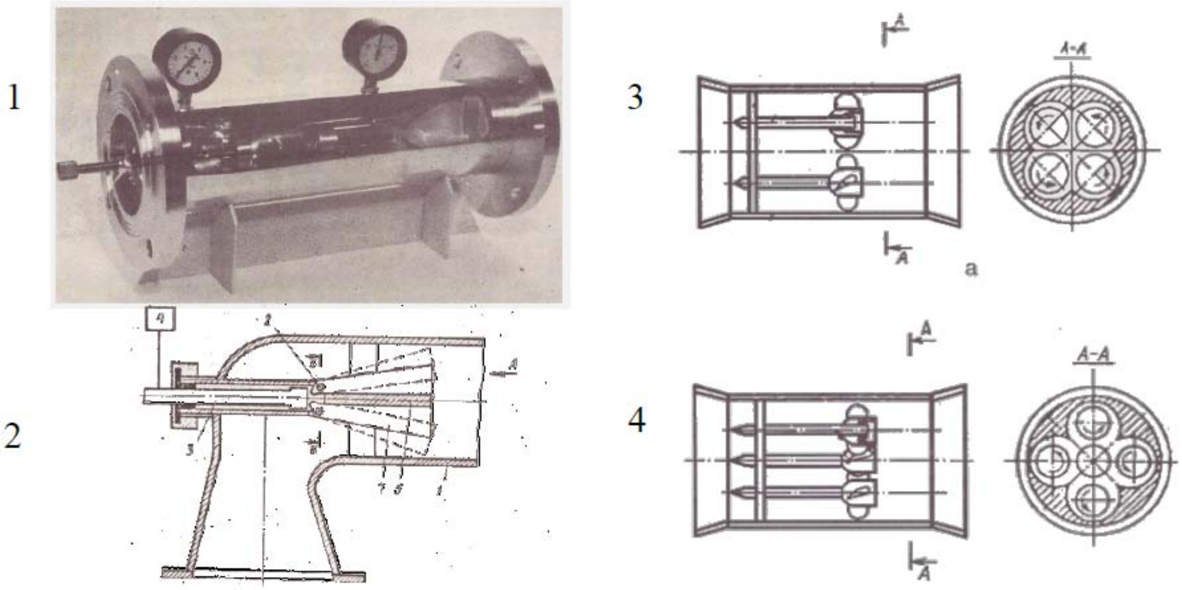


Fig.8. Schemes of cavitation type mixers: 1 - industrial type mixer for mixing fuel oil with water; 2 - cavitation mixer with regulation of the cavity size; 3,4 - in-line type mixers with vane guide vanes

CONCLUSION

The results of the research show that the effect of cavitation on the liquid changes its physicochemical and rheological properties, which can be used in several chemical technologies for mixing, spraying and purification of the substance. There are shown constructive and circuit solutions of cavitators based on the principle of hydrodynamic and ultrasonic cavitation.

In conclusion, it should be noted that this work considers the principles of cavitation effects on working media that are used in technological processes. It is shown that this effect can be different depending on the type of cavitation, ultrasonic or hydrodynamic.

These devices are used in a number of industries - oil, chemical, as well as medicine and technology of physicochemical direction.

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