NUMERICAL INVESTIGATION OF THE EFFECT OF PROPERTIES OF THE LIQUID ON CAVITATION AT SOLID SURFACES

G. I. Kuvshinov, G. Ernetti,
A. Francescutto, P. Cuti, and
P. P. Prokhorenko

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Numerical calculations were carried out on a computer with Mercon's method to investigate the effect of properties of the liquid, namely, density, pressure of the saturated vapor (gas content in a bubble), surface tension, viscosity, and wave resistance, on the instantaneous radius, velocity, and shape of the surface of a compressed cavitation bubble for various distances between two parallel solid walls confining the liquid, times, and angular coordinates. The theoretical relations found agree with earlier experimental data. Recommendations are given for using the present results in practical development of technological sonication processes and in operation of ultrasonic equipment and hydrosystems.

The interest of researchers in problems of cavitation at solid surfaces can be explained not only by their wish to expand knowledge about the physical nature of cavitation but also by the necessity of controlling the cavitation effect [1, 2]. On the one hand, researchers strive to enhance the intensifying effect of cavitation on the course of chemical reactions in order to produce new compounds and suspensions and try to accelerate flotation, leaching, surface degreasing, and crystallization purification of metal melts and semiconductor and other materials; they try to obtain strong junctions in ultrasonic metallization by sonication of metal melts. On the other hand, they want to reduce as much as possible the destructive effect of acoustic cavitation on the surface of an ultrasound emitter itself, to prevent the erosive effect of hydrodynamic cavitation on the surface of propellers for vessels, parts of high-power pumps and nuclear power plants, and other power systems and technological processes operating at high speeds and pressures.

Results of theoretical studies of the effect of properties of the liquid on the cavitation action on solid boundary surfaces are also of great interest since experimental investigation of the effect of properties of the liquid on the dynamics of cavitation bubbles is very difficult, because changes in one of the properties bring about changes in the others. These changes can be accompanied by worse transparency, which is very important in direct experimental studies of cavitation bubbles by high-speed filming. Therefore, theoretical methods employing numerical calculations on a computer are very useful for the investigating the dynamics of a cavitation bubble with account for changes in one or a few properties of the liquid, the others being unchanged.

Calculation Method. The effect of properties of the liquid can be determined in terms of the Cauchy-Lagrange integral, which is a consequence of the differential equation of liquid motion and serves as one of the boundary conditions for the potential of the liquid flow velocity on the surface of a collapsing bubble [3–5].

This study was carried out to investigate the following properties of the liquid with account for the effect of two parallel solid walls confining the liquid: density ρ, the parameter of the gas content in a bubble $\nu = p_v/p_0$ (where p_v is the pressure of a vapor-gas mixture inside the cavitation bubble at the start of collapse; p_0 is the hydrostatic pressure), surface tension σ, viscosity μ, and wave resistance W.

With the above properties of the liquid, the Cauchy-Lagrange integral will be written in the following form [6–9]:

Institute of Applied Physics, Academy of Sciences of Belarus, Minsk, Belarus. University of Trieste, Physics Department, Cavitation Laboratory, Italy. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 66, No. 4, pp. 412-420, April, 1994. Original article submitted March 22, 1993.

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$$\frac{\partial \varphi}{\partial t} + \frac{1}{2}\left(\frac{\partial \varphi}{\partial r}\right)^2 + \frac{1}{2r^2}\left(\frac{\partial \varphi}{\partial \theta}\right)^2 = \frac{1}{\rho}(p_0 + M_1 W + M_2 \mu + M_3 \sigma - p_0 \nu M_4) \quad \text{at} \quad r = R. \tag{1}$$

It should be stressed that Eq. (1) is valid only for small μ.

The numerical calculations followed the procedure developed earlier in [3–5]. Use was made of the spherical coordinate system $\{r, \theta\}$ with origin at the center of the bubble. In calculating the motion, the potential of the flow velocity and the instantaneous radius of the collapsing bubble were represented as series in Legendre polynomials.

The solution of the Laplace equation for the liquid velocity potential with boundary conditions on the solid surface, at the cavitation bubble, and far from it and initial conditions gave the dependence of the instantaneous radius, the collapse velocity, and the shape of the surface of the collapsing cavitation bubble on the properties of the liquid for different values of the gap δ between two parallel solid walls confining the liquid, the time, and the angular coordinate. All the calculations were carried out on a BESM-6 computer by Mercon's method with automatic choice of the integration step and a relative accuracy of 10^{-7}.

Density. The present results on the effect of the density of the liquid on the collapse of a cavitation bubble in the gap have shown that the higher the density, the larger the bubble size for the same times, gaps, and angles, i.e., the slower the collapse process. This can be explained by an increase in the additional liquid mass. It is also found that the effect of ρ increases with the gap and the time and is maximum at $\theta = \pm 90^\circ$. These results can be ascribed to an increase in the collapse velocity of the bubble with increase in the gap (at equal t and θ) and in the time (at equal δ and θ) and the maximum collapse velocities at $\theta = \pm 90^\circ$, which leads to an increase in the velocity of the additional mass of the liquid, which moves at a high velocity.

The higher the density of the liquid, the greater the sphericity of the collapsing cavitation bubble, which can be attributed to the maximum effect of the liquid density at $\theta = \pm 90^\circ$.

Gas Content in Cavitation Bubbles. The parameter of the gas content of cavitation bubbles is a main characteristic that determines collapse of cavitation bubbles and, consequently, the activity of the various cavitation processes such as erosion, initiation of chemical reactions, etc.

It is shown that the effect of the gas content is substantial at $\nu > 10^{-2}$ and the higher the gas content, the larger the size of the bubble for the same times, gaps, and angles, i.e., the slower the collapse of the bubble. This can be explained by an increase in the pressure of the vapor-gas mixture inside the bubble, preventing its collapse.

It is also found that the effect of ν increases with the gap and the time and is maximum at $\theta = \pm 90^\circ$. These results can be explained by a decrease in the radius and an increase in the collapse velocity with increase in the gap (with the same t and θ) and in the time (with the same δ and θ) and the maximum collapse velocities and minimum radii of the bubbles at $\theta = \pm 90^\circ$. These changes result in an increase in the backpressure exerted by the vapor-gas mixture inside the bubble, preventing its collapse, and in the maximum value of this backpressure at $\theta = \pm 90^\circ$, respectively. It should be noted that the higher the gas content, the greater the sphericity of the collapsing cavitation bubble and, consequently, the more stable the shape of its surface. In these cases, the increase in the stability of the spherical shape of the collapsing cavitation bubble can be explained by the maximum effect of the gas content of the bubble at $\theta = \pm 90^\circ$ (see above). Therefore at $\theta = \pm 90^\circ$ collapse is retarded more than at other angles. Consequently, since deviations from the spherical shape associated with smaller radii of the bubbles in this region are the highest, this results in a decrease in the off-sphericity of the surface of the cavitation bubble collapsing in the gap. .

Nonspherical Collapse of Cavitation Bubbles in Three-Dimensional Space. The above results were obtained with one of the characteristics of the liquid or bubble varied, the others remaining constant. Investigation of the collapse process with simultaneous variation of several parameters is of great interest.

In Fig. 1 one can see the general form of the dependence of the instantaneous radius $\overline{R}$ of a collapsing cavitation bubble on the gas content ν of the bubble and the dimensionless density $\overline{\rho}$.

As can be seen from the figure, at a fixed moment the relation $\overline{R} = f(\nu, \overline{\rho})$ in the space of the variables $\{\overline{R}, \nu, \overline{\rho}\}$ is a surface whose shape allows the following conclusions.

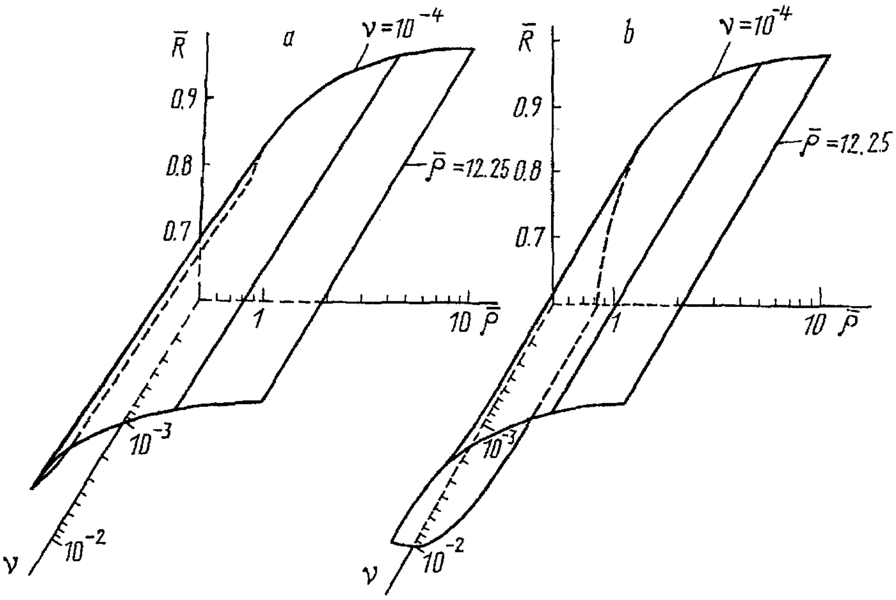

Fig. 1. Relation of the dimensionless instantaneous radius of a collapsing cavitation bubble $R = f(\nu, \rho)$ at $\lambda = 1/3$, $\theta = \pm 90^{\circ}$: a) $\tau = 0.6$; b) $\tau = 0.7$.

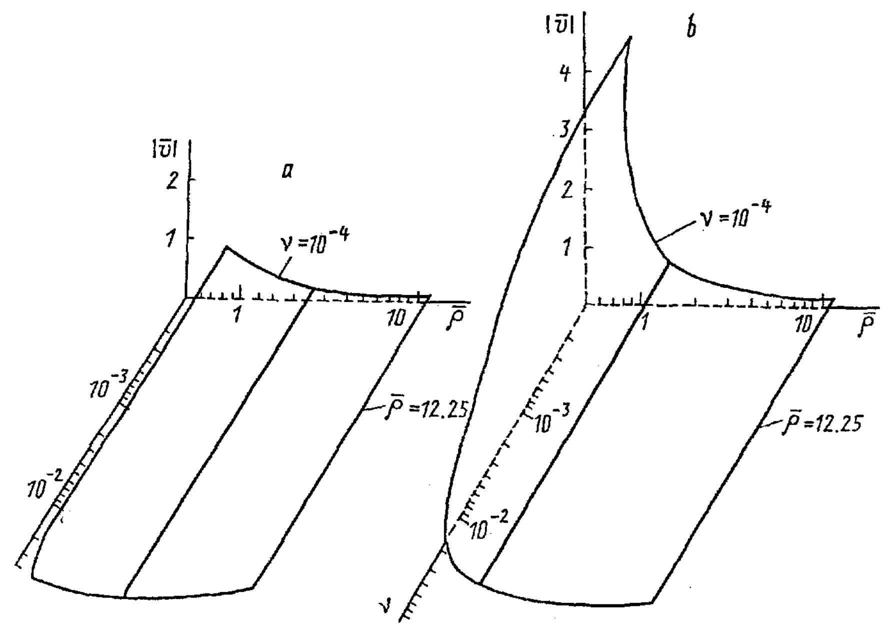

Fig. 2. Relation of the dimensionless collapse velocity of a cavitation bubble $|\bar{v}| = f_1(\nu, \bar{p})$ at $\lambda = 1/3$, $\theta = \pm 90^{\circ}$: a) $\tau = 0.6$; b) $\tau = 0.7$.

At $\bar{p} > 1$ the gas content of the bubble has a slight, if any, effect on its radius. However, when $\bar{p} \lesssim 1$, the larger the gas content of the bubble, the higher its radius, i.e., at $\nu > 10^{-2}$ an increase in the gas content retards the collapse. The effect of the liquid density increases as the gas content decreases.

As time passes (Fig. 1), the slope of the curve of the radius of the bubble versus the density of the liquid (at a fixed gas content of the bubble) increases and with time the surface "curls" due to an increase in the effect of the liquid density on the instantaneous radius with time (see above). The slope of the curve $\bar{R} = \bar{R}(\nu)$ (at fixed $\bar{p}$) increases only slightly. Moreover, with time the surface of the bubble is displaced downward along the $\bar{R}$ axis, which is caused by a decrease in the radius of the bubble during collapse.

Figure 2 shows the general form of the dependence of the dimensionless collapse velocity of a cavitation bubble. Just as in the case of the instantaneous radius of the bubble (see Fig. 1), an increase in the slope of the relations $|\bar{v}| = |\bar{v}|(\bar{p})$ (at fixed ν) plays the main role in the time changes in the shape of the surface determined by the function $|\bar{v}| = f_1(\nu, \bar{p})$. In this case the surface is displaced upward along the $|\bar{v}|$ axis due to an increase in the collapse velocity of the bubble with time.

Surface Tension. It is found that surface tension accelerates the collapse process. It should be noted that an increase in the coefficient of surface tension $\bar{\sigma}$ by two orders of magnitude (from 10^{-3} to 10^{-1}) results in a decrease in the instantaneous radius $\bar{R}$ of the bubble by only 10%. Thus, the surface tension has a substantial effect on the bubble size when $\bar{\sigma} \geq 10^{-1}$ or $\sigma \geq 0.05 R_{max} p_0$. With $p_0 = 10^5$ N/m^2 (atmospheric pressure) we obtain

$$\sigma \geq 5 \cdot 10^3 \ (\mathrm{N/m^2}) \ R_{max} \ (\mathrm{m}) .$$

Thus, the smaller the bubble size R_{max}, the lower the value at which the effect of the surface tension becomes appreciable. This relationship can be explained by the fact that the pressure of the surface tension forces p_σ is inversely proportional to the bubble size: $p_\sigma = 2\sigma/R$. At $R_{max} \simeq 10^{-4}$ m (this value is typical of many ultrasonic technological processes based on the cavitation effect) we have

$$\sigma \geq 0.5 \ \mathrm{N/m} .$$

For example, for water the coefficient of surface tension is 7.6×10^{-2} N/m, i.e., in a calculation of cavitation processes in water the surface tension can be neglected.

It is also found that the effect of the surface tension increases with the gap (for equal t) and the time (for equal δ). This finding can be explained by an increase in the instantaneous radius, leading to an increase in p_0, and, hence, in the effect of the surface tension on the bubble size and the velocity of collapse.

It should be noted that for very small slotted gaps between solid confining surfaces ($\lambda = R_{max}/\delta > 1/10$), the effect of the solid walls is so large that the bubble can collapse nonspherically [3]. In this case

$$p_\sigma = 2\sigma/R_{cur} ,$$

where R_{cur} is the radius of curvature of the bubble surface at the point considered. In a plane passing through the center of the bubble parallel to the solid walls, the bubble is flattened to the greatest extent, the radius of curvature of its surface is maximum, and the pressure of the surface tension forces is, consequently, minimum. Thus, in this region the surface tension will accelerate collapse of the bubble to a lesser extent, decreasing the off-sphericity of its surface. When hollows appear on the bubble surface in the case of formation of a liquid microjet, there the surface tension force changes its sign and direction toward the liquid, decelerating the collapse process, while in the other region on the bubble surface, the surface tension will accelerate the collapse. This effect also decreases the off-sphericity of the bubble. Therefore, in liquids with a high surface tension it can be expected that the character of the cavitation in the slotted gap will change qualitatively, and a spherically symmetric collapse will be substituted for the "jetlike" one. Because of this, the results obtained in this section can be used in the present case.

Viscosity. The effect of viscosity was studied at $\sigma = 0$, $\nu = 0.02$, $\bar{p} = 1$. It is found that the viscosity retards the collapse process and has a substantial effect on the bubble size at the dimensionless viscosity $\bar{\mu} > 10^{-2}$ ($\mu > 10^{-3}$ Pa·sec). In this case the viscosity forces lead to a decrease in the off-sphericity of the surface of a collapsing cavitation bubble caused by the effect of the solid walls. It is also found that the effect of viscosity increases with increase in the gap and the time, which can be explained as follows. As the gap increases (for the same times), in the course of collapse of the bubble, its instantaneous radius decreases and the collapse velocity rises, leading to a decrease in the pressure of viscous forces, proportional to $\dot{R}/R$, and, consequently, to an increase in the effect of viscosity.

Estimation of the Cavitation Activity of Working Liquids. The cavitation activity of working liquids is their main characteristic when the cavitation effect is used for intensifying processes in liquid media and on a liquid-solid interface and in predicting the longevity of ultrasound emitters, blades of propellers, and parts of pumps subjected to the erosion effect of cavitation.

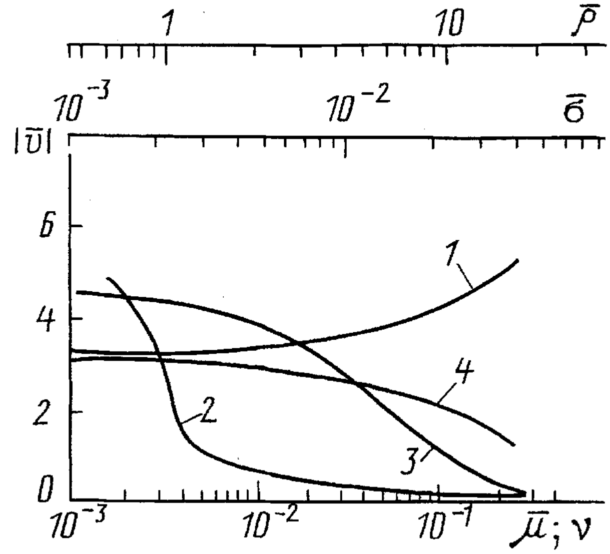

Fig. 3. Plot of the collapse velocity of a cavitation bubble versus physical properties of the liquid, namely, the surface tension $\bar{\sigma}$ (1), density $\bar{\rho}$ (2), viscosity $\bar{\mu}$ (3), and the gas content parameter ν (4) at $\lambda = 1/3$, $\tau = 0.75$.

At present the cavitation activity of liquids is most often estimated by the following methods: erosion tests, where a specimen is placed in the cavitation region and then the loss of its mass is measured; an acoustic method based on measurement of cavitation noise; and a method employing the chemical effect of cavitation, where the amount of the product of a cavitation-induced reaction is determined. A disadvantage of the first two methods is the necessity of bringing solid walls (specimens and sensors) into the cavitation region. As is confirmed theoretically and experimentally by the present and other authors [3, 6, 9], solid walls basically change the development and character of collapse of a cavitation bubble. Moreover, on the surface of the specimens and sensors introduced, there are microcracks and micropores with entrapped vapor-gas phase, which is an additional nucleus of cavitation bubbles. As a result, the cavitation region changes substantially from that in a free liquid or at the interface of a liquid-treated part. The chemical method has low accuracy because of the lack of correlation between cavitation erosion and the chemical effect of cavitation.

In any scheme of collapse of cavitation bubbles (spherically symmetric, cumulative, or radial [3]), their effect depends on the collapse velocity. The present results make it possible to determine the net collapse velocity of a cavitation bubble as a function of physical properties of the liquid, namely, the viscosity, surface tension, and density, and the parameter of the gas content in the bubble. A generalized plot of the collapse velocity is given in Fig. 3. From this plot it is possible to estimate theoretically the cavitation activity of a liquid as a function of the mentioned factors with account for the effect of two solid boundary surfaces or neglecting this effect (for $\delta >> R_{max}$).

However, if the required level of the cavitation effect on the working surface, determined with the aid of some standard liquid, in particular, water, is known for a concrete technological process, then, having found the collapse velocity of cavitation bubbles from Fig. 3, it is possible to select physical properties of liquids and the gas content in a bubble that would provide the required collapse velocity and to choose optimum properties of working liquids, used or to be created, from Fig. 3.

E x a m p l e. Let us compare the cavitation activities of water and gasoline, using the present method. The density and viscosity of water are higher than those of gasoline (see Table 1). Judging from these parameters, the collapse velocity in water should be lower than that in gasoline. On the other hand, proceeding from the values of surface tension (higher in water) and the gas content parameter (lower in water), the collapse velocity in water should be twice as high as that in gasoline. Thus, in this case even a qualitative estimate of the comparative cavitation activity of water and gasoline cannot be made from the values of the physical properties. However, a qualitative comparison of the collapse velocities in water and gasoline from the curves given in Fig. 3 shows definitely

TABLE 1. Estimation of the Cavitation Activity of Water and Gasoline

Parameters of liquid and collapse velocity	Water	Gasoline
$\rho \cdot 10^{-3}$, kg/m^3; $\bar{\rho}$; $\lvert\bar{v}\rvert$	1.0; 1.0; 3.2	0.7; 0.7; 4.5
$\sigma \cdot 10^3$, N/m; $\bar{\sigma} \cdot 10^2$; $\lvert\bar{v}\rvert$	72.6; 1.5; 3.7	22.6; 0.45; 3.3
$\mu \cdot 10^3$, kg/(m·sec); $\bar{\mu} \cdot 10^3$; $\lvert\bar{v}\rvert$	1.0; 4; 3.0	0.53; 2.1; 3.0
$p_v \cdot 10^{-3}$, N/m^2; $\nu \cdot 10^2$; $\lvert\bar{v}\rvert$	2; 2; 3.2	11; 11; 0.9
$\lvert\bar{v}_{nt}\rvert$	3.3	2.9

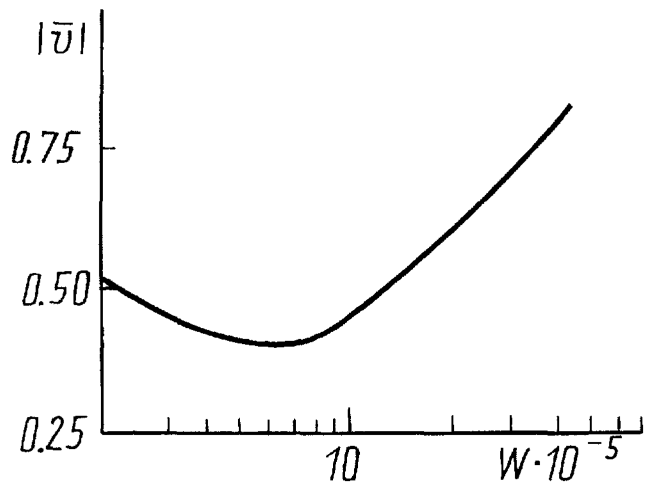

Fig. 4. Plot of the collapse velocity $\lvert\bar{v}\rvert$ of a cavitation bubble versus the wave resistance W of the cavitation region at $\lambda = 1/20$, $\tau = 0.12$, $f = 20$ kHz, $A = 10$ μm. W, kg/(m^2·sec).

that the collapse velocity in water is higher than that in gasoline: the net velocity $\lvert\bar{v}_{nt}\rvert$ in water is 15% larger than $\lvert\bar{v}_{nt}\rvert$ in gasoline. This allows us to conclude that the cavitation activity of water is higher than that of gasoline. This conclusion agrees with experimental data [10]. This result is very important for practical use because in ultrasound treatment the cavitation activity of working liquids is more important than their dissolving power. Since the cavitation activity of water is higher than those of acetone, gasoline, and other organic liquids, many flammable and toxic working liquids can be replaced by water and aqueous solutions without any loss of performance [3].

Wave Resistance. The dependence of collapse on the wave resistance W of a liquid is very important since it gives information not only about the collapse of individual cavitation bubbles but also the entirety of bubbles that occur in the cavitation region, in other words, it allows us to include the effect of the concentration of cavitation bubbles and the interaction of cavitation bubbles corresponding to their effect on the wave resistance of the medium.

In the process of development of the cavitation region, the concentration of cavitation bubbles changes from zero to a constant, decreasing the wave resistance.

These factors also change the collapse velocity as the sonication time increases. We have found the dependence of the collapse velocity $\bar{v}$ on the wave resistance W of the cavitation region (Fig. 4). As can be seen from the figure, as the wave resistance of the cavitation region decreases (the concentration of cavitation bubbles increases), the collapse velocity of cavitation bubbles decreases at first, and then upon a substantial decrease (by more than an order of magnitude) in the wave resistance of the medium it starts increasing.

Thus, there exists a minimum in the relation $\lvert\bar{v}\rvert = F(W)$, because of which an optimum collapse velocity can be chosen by selecting appropriate values of the wave resistance which is determined by the time of ultrasound exposure; for example, in pulsed sonication, they are such that $\lvert\bar{v}\rvert \neq \lvert\bar{v}\rvert_{min}$.

CONCLUSIONS

1. A increase in the viscosity, density, and gas content parameter of a bubble retards the collapse process, whereas an increase in the surface tension accelerates it.

2. The effects of viscosity, surface tension, and the gas content parameter are substantial at $\bar{\mu} > 10^{-2}$ (or $\mu > 10^{-3}$ Pa·sec), $\bar{\sigma} \geq 10^{-1}$ (or $\sigma \geq 0.5$ N/m), and $\nu > 10^{-2}$, respectively.

3. In liquids with a high surface tension, density, and gas content parameter (exceeding substantially the corresponding values for water), it should be expected that cavitation near solid surfaces will change qualitatively, i.e., "jetlike" collapse (formation of radial and cumulative microjets) will be replaced by spherically symmetric collapse.

5. The effects of the viscosity, surface tension, density of the liquid and the gas content parameter of a bubble increase as the gap between two parallel solid walls and the time increase. It should be noted that the effects of the density and the gas content parameter are strongest at $\theta = \pm 90^{\circ}$, i.e., in a plane passing through the center of the bubble, parallel to the solid walls.

6. A method is suggested for estimating the cavitation activity of working liquids and choosing their optimum properties. The method is based on computation of the net collapse velocity as a function of physical properties of the liquid, namely, the viscosity, surface tension, and density, and the gas content parameter of a bubble, with account for the effect of two solid boundary surfaces or neglecting their effect, for gaps exceeding substantially the maximum diameter of a cavitation bubble.

NOTATION

φ, velocity potential of the liquid flow; t, time; r, θ, spherical coordinates; $M_1 = 2\pi fA \cdot \sin 2\pi f/t$; f, frequency of ultrasonic oscillations; A, amplitude of displacement of the emitting surface; $W = \rho c$, wave resistance of the liquid; c, speed of sound in the liquid; $M_2 = 4\dot{R}/R$; R, instantaneous radius of a cavitation bubble; $M_3 = 2/R$; p_v, pressure of saturated vapor of the liquid; $M_4(R_{max}/R)^4$; R_{max}, radius of the bubble at the time $t = 0$; δ, magnitude of the gap; $\bar{R} = R/R_{max}$, $\bar{\rho} = \rho/\rho_*$; ρ_*, density of water; v, collapse velocity; $\bar{v} = v\sqrt{\rho/p_0}$, dimensionless collapse velocity; $\bar{\sigma} = 2\sigma/R_{max}p_0$, dimensionless surface tension; $p_\sigma = 2\sigma/R$, pressure of surface tension forces; $\lambda = R_{max}/\delta$; R_{cur}, radius of curvature of the bubble surface at the point considered; $\bar{\mu} = 4\mu/(R_{max}\sqrt{p_0\rho})$; $\bar{v}_{nt}$, dimensionless net collapse velocity; $\tau = (t/R_{max})\sqrt{p_0/\rho}$, dimensionless time.

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