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ФІЗИКА АЕРОЗОЛІВ

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Modeling the kinetics of cavitation boiling up of liquid.

With respect to study of the kinetics of cavitation boiling up of liquid a thermodynamic analysis has been carried out for considering the isothermal formation and growth of micro-bubbles in water, produced by an abrupt decrease in liquid pressure. The critical activation pressure, which determines the onset of irreversible growth of nuclei as well as the cavitation incipience, was calculated. Using the previously created mathematical model of bubble ensemble dynamics, the features of the bubble cluster development are considered with due account of the force and thermal interaction of the bubbles. Isothermal and isobaric boiling should be considered as identical phenomena that obey the same thermodynamic and physical laws and are described by the same equations

Key words:

Introduction. Cavitation methods have many applications for a variety of modern technologies concerning the treatment of liquid dispersed media, in particular, for controlling at the molecular level various physical, chemical and biophysical processes in liquid media, as well as for local energy effects on supramolecular structures and microorganisms. To solve these problems, it is necessary to understand the physical nature of cavitation mechanisms and the possibility of their adequate description in spatial and temporal micro- and nanoscales.

In many scientific publications, cavitation is defined as the formation and growth of vapor-gas cavities in liquid due to lowering liquid pressure to the saturated vapor pressure value [1-4]. As will be shown below, this definition is not entirely correct from a physical point of view and, in addition, it is applicable only to determining the stage of cavitation boiling of a liquid. The subsequent final stage of compression and collapse of the bubble ensemble is absent in this definition. At the same time, when solving practical problems, the most important stage of cavitation is the collapse of the cavitation cavities, which, in fact, determines the abnormally strong dynamic and thermal cavitation effects [1, 5-8].

Despite the different and often contradictory definitions of cavitation, we will adhere to the following general wording. “Cavitation refers to a combination of phenomena that occur in a liquid, when external pressure p_l drops below the saturation pressure level at a given temperature $p_{sat}(T_l)$, and then rises rapidly above that level.” If $p_l < p_{sat}(T_l)$, the processes of formation and intensive growth of vapor-gas bubbles are carried out in liquid, what is determined as cavitation boiling. When

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$p_l > p_{sat}(T_l)$, rapid compression and subsequent collapse of these bubbles occurs with the emission of powerful dynamic pulses.

The objective of present article is to study the physical nature of cavitation mechanisms and phenomena that occur in the initial stage of cavitation boiling. It is at this stage that those important processes take place, which, in essence, determines the subsequent efficacy of dynamic and thermal effects at the final stage of cavitation development. It is particularly discussed the difference between the *cavitation boiling pressure* of a liquid, which is always equal to the saturated vapor pressure $p_{sat}(T_l)$, and *cavitation boiling up pressure*, which determines the onset of cavitation. In this analytical study, for simplicity of presentation and without losing the generality, water was used as a model liquid. However, the basic concepts discussed here and the main findings regarding the kinetics of cavitation boiling apply to any liquid.

1. Thermodynamic analysis of boiling processes. Thermodynamically, cavitation boiling and usual (thermal) boiling should be considered as identical phenomena, caused by the relaxation of a non-equilibrium liquid-vapor system to the state of thermodynamic equilibrium.. These phenomena differ only by the transition path of the system to a stable state. The criterion for the equilibrium of such two-phase system is the simultaneous equality of pressure ($p_v = p_l$), temperature ($T_v = T_l$) and chemical potentials ($\mu_v = \mu_l$) in both phases. [1,3,5,6]. If one of these conditions is violated, the system becomes non-equilibrium, and tends to go over in steady state.

The features of the liquid-vapor phase transition in the process of cavitation boiling of a liquid and in the process of thermal boiling are depicted schematically in Fig. 1, which shows $p-T$ (Fig. 1-a) and $p-V$ (Fig. 1-b) phase diagrams for water. The binodal line (Bi), shown in both figures, separates the region of single-phase states and the region of equilibrium existence of vapor and liquid. This curve is formed by a combination of temperature ($T_v \equiv T_l = T_{boil}(p_l)$) and system pressure values ($T_v \equiv T_l = T_{boil}(p_l)$), that satisfy the above criteria. Thermodynamically, this means the equality of chemical potentials of the coexisting phases on the binodal line.

There are two possibilities for the phase change from liquid to vapor [1,2,9,10].

Let water initially be in the equilibrium state of liquid at atmospheric pressure $p_{l0} = 100\,\text{kPa}$ and temperature of 20°C (point A in Fig. 1a,b). To transfer liquid water into vapor state, it is necessary to violate the equilibrium conditions. The phase transition can be carried out by isobaric heating of water at the given pressure p_{l0} up to the boiling point $T_l = T_{boil}(p_{l0})$, and passing through the binodal line (point B in Fig. 1a,b), which ensures the formation and growth of vapor nuclei. In this case, the relaxation of the thermally non-equilibrium vapor-liquid system to a stable vapor state is controlled both by the difference in temperature ($T_l - T_v$) and chemical potentials ($\mu_l - \mu_v$).

It is also possible to transfer liquid water to vapor with isothermal decrease in liquid pressure p_l to the saturated vapor pressure value $p_{sat}(T_{l0})$ and subsequent transition through the binodal line (point C in Fig.1a,b), which ensures the formation

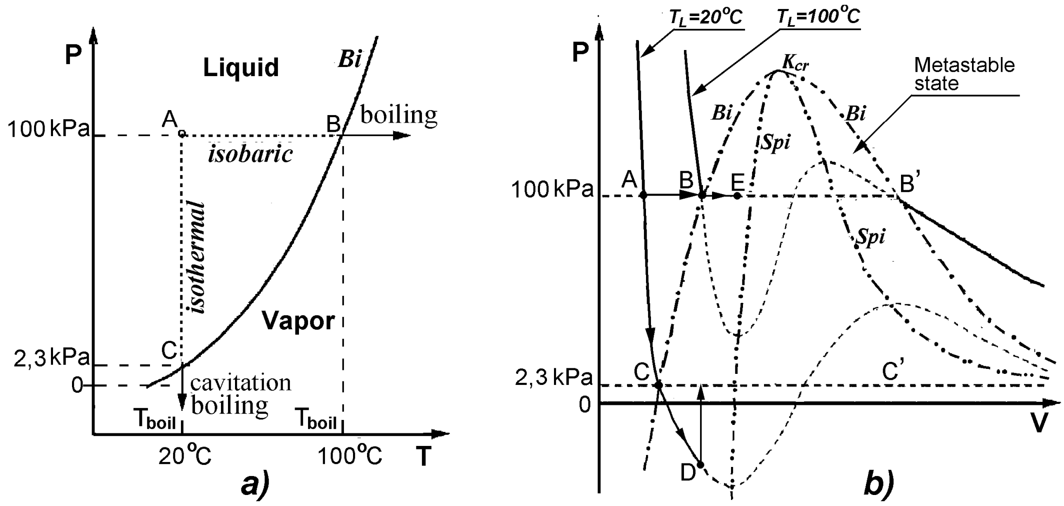

Fig.1. Representation of boiling up kinetics for water in $P-T$ *(**a**)* and in $P-V$ (***b***) state diagrams.

and intensive development of the bubble structure in liquid. In latter case, the relaxation of the mechanically non-equilibrium vapor-liquid system to vapor state is controlled by the pressure difference ($p_v - p_l$). This kind of phase transition is hold to be inertially controlled [1,5]. In most publications, boiling is defined as the process of nucleation in liquid when its isobaric heating, while cavitation is the process of nucleation that occurs when the liquid pressure is isothermally reduced [1-5,10]. In both cases, when crossing the binodal line the intensive nucleation is observed. From a physical point of view, there are certain differences between the two processes.

In fact, it is quite easy to change rapidly the pressure immediately in a body of the liquid, but it is practically impossible to change quickly and uniformly liquid temperature. The relaxation time of mechanical nonequilibrium is much shorter than the relaxation time of two other types of nonequilibrium processes associated with the difference in temperature and chemical potentials in liquid and vapor phases.

Bubble growth (and compression) in cavitation processes are not limited by heat transfer or kinetics of phase transitions, but only by quick inertial effects in the surrounding liquid. Therefore, cavitation at both stages of its development is an explosive process that is stronger and more destructive than the corresponding bubbles dynamics in slower boiling or condensation processes.

In the $p-V$ state diagram (Fig. 1b), the boiling process is described by a certain trajectory or point inside the region of the metastable state. limited on one side by the binodal (Bi) and on the other side by the spinodal (Spi), which defines the boundary of the thermodynamic stability of the liquid. With an isothermal depressurization in water, which was initially at the point A ($p_{l0} = 100$ kPa , T_{l0} = 20°C), the liquid passes along the isotherm $A - C$ through the binodal line at the point C and enters the metastable region. The depth of penetration into the metastable region, where water is still in liquid state, is determined by point D (Fig. 1b). Further, the following system development options are possible.

If the concentration of relatively coarse nuclei is sufficiently high (the criteria of “coarseness” and “sufficiency” will be considered below), the process of nucleation occurs. The liquid pressure p_l increases rapidly to the $p_{sat}\left(T_{l0}\right)$ value, and the boiling liquid from the state D immediately passes to the line of the real isotherm $C-C'$. A monotonic boiling process proceeds along this trajectory at constant temperature T_{l0}=20°C and constant pressure $p_{sat}\left(T_{l0}\right)$ until the final transition of the liquid water to the stable vapor state.

At low concentrations and small nucleus sizes the point D shifts deeper into the metastable region, closer to the spinodal line. The liquid at the point D is believed to be in a state of tension, and the pressure difference between C and D determines the degree of the tension. Moreover, as can be seen from Fig.1b, the liquid pressure can decrease to negative values ($p_l < 0$). Next, a short-time explosive boiling of stretced liquid occurs. and the system leaps to the trajectory of monotonous boiling $C-C'$. In both cases, boiling is carried out exclusively due to heterogeneous nucleation due to the presence of gas micro-bubbles in the liquid.

The maximum tensile stresses of an ideal liquid, which corresponds to the minimum on the van der Waals isotherm, are possible only for a specially purified liquid, which does not contain dissolved gases at all [2-5, 8]. According to modern concepts, liquid rupture under tensile stresses action occurs on gas nuclei. The tensile strength values, obtained in the experiments for usual settled water, does not exceed 0.1 MPa, although for specially purified water values of 25 MPa were reached [1,5].

It is also worth noting that all the modes of the boiling processes considered above are also observed when isobaric increase in temperature of liquid [10]. When isobaric heating water from the initial point *A* passes along the isobar $A-B'$ through the binodal line (point *B*) and enters the metastable region ($T_l < T_{boil}\left(p_{l0}\right)$). The degree of penetration into the metastable region is determined by a point *E* (Fig. 1b), which in isobaric process is analogous to point *D*. The temperature difference between points *E* and *B* determines the degree of liquid superheating before the onset of nucleation and subsequent intensive vaporization.

Hence, the onset and development of the processes of both thermal and cavitation boiling equally depend on the concentration and on the size of the gas nuclei. Water contains a wide variety of stable gaseous nuclei in the range of radii from 0.1 μm to 10 μm, which are potential centers of cavitation and thermal boiling [1-5,9]. In settled water a maximum bubble density was observed at 2.5 μm [1]. In recorded size range $R_0 = 1.2 \div 12\,\mu\text{m}$ more than 90% of the gas volume in distilled water were occupied by bubbles with radii of $R_0 = 1.4 \div 2.2\,\mu\text{m}$, and in settled tap water - by bubbles with radii of $R_0 = 4 \div 8.5\,\mu\text{m}$ [8]. It is also proved that 1 m^3 of water at 20°C contains about $2{\cdot}10^{15}$ bubbles with an average radius of 20 nm [9,11].

The reasons for the long-term (almost unlimited in time) stability in water of micro-bubbles with radii of $R_0 < 2.5$ μm are still not completely clear, and this topic has been the subject of wide discussion to date [1-4, 8-9].

2. Activation of micro-bubbles. Consider the necessary conditions for activation of micro-nuclei to initiating boiling up of liquid. Let in water with temperature T_{l0} and pressure p_{l0} there be a bubble with radius R_0 which contains a non-condensable gas with partial pressure p_{g0} and vapor with partial pressure $p_v = p_{sat}(T_{l0}) = \text{const}$. The mass of gas in the bubble is considered to be constant. The inner surface of the bubble is under the effect of pressure $p_{g0} + p_{sat}(T_{l0})$, and its outer surface is affected by both the liquid pressure p_{l0} and capillary pressure $p_{\sigma 0} = 2\sigma/R_0$, where $\sigma = f(T_l)$ is the surface tension of the liquid.

The equilibrium of pressure on both sides of the interface requires that the following condition be satisfied:

$$p_{g0} + p_{sat}(T_{l0}) = p_{l0} + 2\sigma/R_0 , \tag{1}$$

The evolution of the bubble is assumed to be isothermal [1-4, 8-9], so that, using the perfect gas law, the gas pressure is inversely proportional to the bubble volume:

$$p_g = p_{g0}(R_0/R)^3 = K/R^3 , \tag{2}$$

where $K = p_{g0}R_0^3 = \text{const}$. The initial gas pressure p_{g0} is determined from Eq.(1)

$$p_{g0} = p_{l0} - p_{sat}(T_{l0}) + 2\sigma/R_0 . \tag{3}$$

From equation (1) it follows that with any increasing liquid pressure p_l the bubble always goes into a new equilibrium state, but with a smaller size.

With decreasing the pressure p_l two variants of bubble evolution are possible.

When liquid pressure p_l decreases to a certain value $p_{l1} < p_{l0}$, the equilibrium conditions in (1) are violated. The bubble expands and stabilizes in a new equilibrium state with $R_1 > R_0$. The new equilibrium condition in this state is written as

$$K/R_1^3 + p_{sat}(T_{l0}) = p_{l1} + 2\sigma/R_1 . \tag{4}$$

As the bubble expands in liquid the gas pressure $p_g \propto R_b^{-3}$ decreases much faster than the counteracting capillary pressure $p_\sigma = R_b^{-1}$. When subsequent bubble expansion the influence of gas pressure p_g becomes negligible and can be neglected. Then the condition for the onset of irreversible growth (activation) of the bubble can be presented as follows

$$p_{l\,cr} \le p_{sat}(T_{l0}) - 2\sigma/R_{cr} . \tag{5}$$

The $p_{l\,cr}$ value determines the limit level to which it is necessary and sufficient to reduce the liquid pressure p_l to activate a bubble with a given radius R_0.

To find the dependence $p_{l\,cr} = f(R_0)$ let us carry out a numerical calculation. In view of equation (4), the equilibrium condition of the bubble can be re-written as

$$p_{l\,i} = K/R_i^3 - 2\sigma/R_i + p_{sat}(T_{l0}). \tag{6}$$

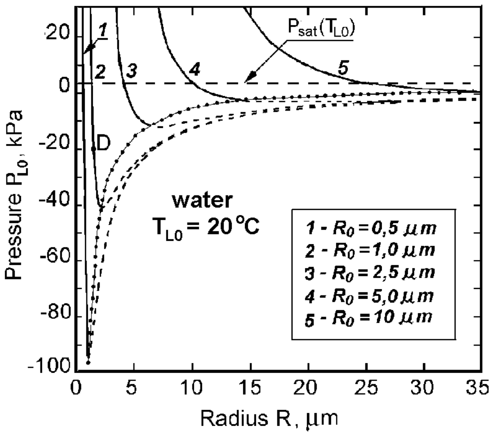

Fig.2. Stable (solid lines) and clearly unstable (dashed lines) states of micro-bubbles on the equilibrium curves $R_{eq} = f(p_l)$ for five R_0 values.

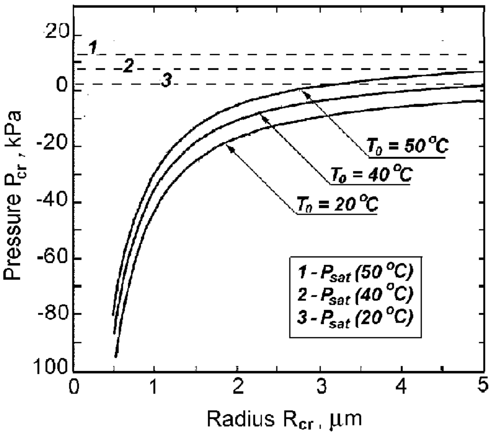

Fig.3. Critical pressure values versus radius of stable bubbles R_0 for three water temperature T_{l0} values: 20, 40 and 50°C.

Equation (6) determines the radius R_i, at which the bubble stabilizes with a successive decrease in pressure p_l from p_0 to certain values p_{li}, and also allows calculation of $R_i = R_{cr}$ and $p_{li} = p_{lcr}$ values, which determine the beginning of irreversible bubble growth. Figure 2 shows the dependences $p_{li} = f(R_i)$ for five different values of radius R_0 of equilibrium bubbles, which are in water with temperature T_{l0}= 20°C and pressure p_{l0}= 0.1 MPa. In accordance with equation (2), these bubbles should contain different amounts of gas ($m_g \propto R_0^3$).

A remarkable feature of the equilibrium curves $p_{li} = f(R_i)$ is the presence of a minimum, which corresponds to the values p_{lcr} and R_{cr} for a bubble with a specified radius R_0. The dotted line drawn through these peak values is the curve of thermodynamic stability loss. To the left of the dotted line is a stable equilibrium region, while to the right of it the equilibrium conditions are violated. Consequently, the dotted line can be considered as an analogue of the spinodal in the van der Waals diagram (Fig.1b), which defines the boundary of thermodynamic stability. Then the isobar $p_l = p_{sat}$, shown in Fig. 2 by the horizontal dashed line, is the binodal line. Between these two curves lies the metastable region. By this analogy, the equilibrium curves 1–5 in Fig. 2 can be considered as isotherms, crossing the lines of the binodal and spinodal. The left part of the equilibrium curves (solid line) corresponds to a stable state, while the right part of the curves (dashed line) is completely unstable.

As an example, let us consider the equilibrium curve 2, corresponding to a bubble with R_0=1 μm. As liquid pressure decreases from p_0=100 kPa to p_{l1}= –20 kPa the bubble expands ($R_i > R_0$) and passes into a new stable equilibrium state, which is indicated by point D. The point D in Fig.2 is an analogue of the point D in Fig.1b, which determines the condition of the quasi-equilibrium state of liquid in metastable region. When the liquid pressure p_l drops to p_{li} = –40 kPa, which is the critical pressure for the bubble on curve 2, this bubble with radius R_{cr} goes over to the unstable part of curve 2 (dashed line) and begin to grow unlimitedly. All bubbles with radii $R_i < R_{cr}$ are in stable equilibrium, while with $R_i > R_{cr}$ they are unstable.

It was noted above, that the depth of liquid penetration into the metastable region before the onset of intensive bubble growth depends on the size of the nuclei.

Fig.2 shows, that at pressure p_l =–40 kPa, which is critical one for bubbles with R_0= 1 μm (curve 2), the bubbles with initial size R_0= 0.5 μm (curve 1) are still in an equilibrium state, far from the spinodal line. The larger bubbles (curves 4 and 5) begin to grow unlimitedly even with relatively slight decrease in pressure. However, as it is seen from Fig.2, for all bubbles with $R_0 < 5$ μm the pressure values $p_{l\,cr} < 0$.

Equation (6) allows calculation of the value R_{cr} and the corresponding critical pressure $p_{l\,cr}$ for a bubble with a specified radius R_0. To do this, let us differentiate equation (6) with respect to R and determine the value $R = R_{cr}$, at which the derivative $dp_l/dR = 0$. for a bubble with a given value R_0

The critical radius value for a bubble with radius R_0 is defined by the formula

$$R_{cr}(p_l) = \sqrt{3K/2\sigma =} R_0 \sqrt{3p_{g0}/p_{\sigma 0}}\,, \tag{7}$$

and the critical pressure value cam be calculated from m the equation

$$p_{l\,cr} - p_{sat} = -4\sigma/3R_{cr} = -p_{\sigma 0}\sqrt{(32p_{\sigma 0})/(\ )}\,. \tag{8}$$

If liquid with given parameters p_{l0}, T_{l0}, and $\sigma(T_{;0})$ contains stable bubbles of different sizes, equation (8) allows calculation of the critical value $p_{li\,cr}$ necessary for activation of any bubble with a given radius R_{0i}. Figure 3 presents the dependences $p_{l\,cr} = f(R_0)$ calculated according to equation (8) for three different values of water temperature T_{l0} (20°C, 40°C and 50°C). With increasing T_{l0} critical pressure $p_{l\,cr}$ raises due to increasing the saturation vapor pressure $p_{sat}(T_{l0})$ inside the bubble.

To activate bubbles with $R_0 < 9$ μm at T_{l0}=20 ° C, the liquid pressure must be reduced to negative values ($p_{l\,cr} < 0$). Microbubbles with $p_{l\,cr} < 0.01$ μm are activated at –550 kPa, and to activate nano-nuclei with a radius of R_0 = 20 nm, the pressure must be reduced to –3 MPa. From the foregoing, the following conclusion could be made. If liquid contains a set of stable nuclei with a wide spectrum of size distribution ($R_{0\min} \le R_0 \le R_{0\max}$), then to activate their and start the irreversible growth of all these nuclei, it is sufficient to reduce the liquid pressure to the value $p_{l\min} \le p_{l\,cr}(R_{0\min})$. In this case the pressure $p_{l\min}$ should determine the beginning of cavitation boiling of the liquid, or the cavitation incipience.

However, this does not correspond to the real development of events.

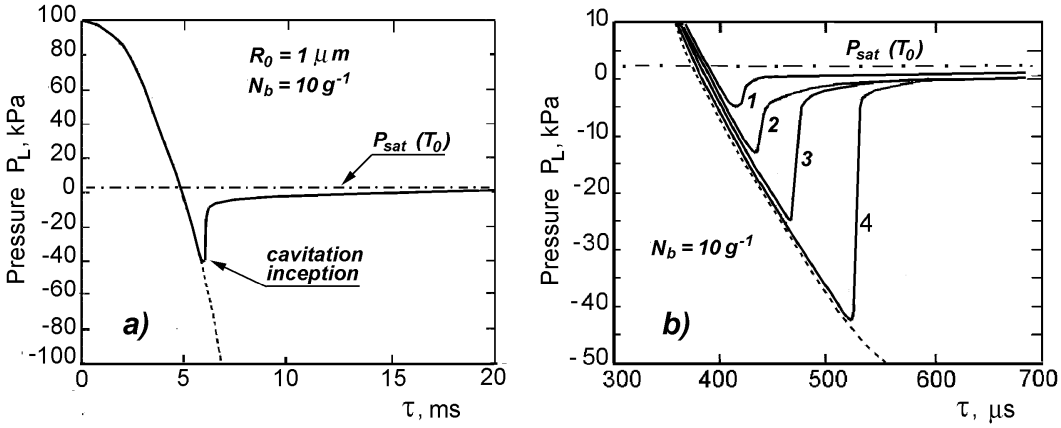

Fig.4. The change in time of pressure p_{cl} inside the bubble cluster (solid line) when decreasing water pressure p_l (dashed line) from p_{l0} = 0,1 MPa up to $p_{l\min}$ = –1 MPa. ***a)*** illustration of the difference between boiling pressure $p_{sat}(T_{l0})$ and boiling up pressure $p_{l\,cr}(R_0)$; ***b)*** change in cluster pressure in initial stage of nucleation depending on R_0 value: **1** – 5 μm; **2** – 2.5 μm; **3** – 1.5 μm; **4** – 1 μm.

3. Cavitation cluster development. Cavitation effects are caused not by single bubbles, but by the combined action of a polydisperse ensemble of bubbles (so-called cavitation cluster). When external pressure is released, a growing bubble inside the cluster is under the influence of neighboring growing bubbles. After rapid liquid depressurization from the initial value p_{l0} to $p_{l\min} << p_{l0}$ the liquid pressure in the inter-bubble space of the cluster p_{cl} increases rapidly, asymptotically approaching the saturated vapor pressure $p_{sat}(T_{l0})$. As a result, the onset of unlimited growth of the still inactivated nuclei will no longer depend on external pressure $p_{l\min}$, but on the pressure p_{cl} inside the cluster.

When describing the evolution of a cavitation cluster, the dynamics of a single bubble are usually used without taking into account the interaction of bubbles inside the cluster [1,2,5], what introduces an unacceptably high error.

One of the most detailed mathematical models that enables the adequately description of the cavitation cluster behavior is the model of the dynamics of a bubble ensemble.[6,7]. Unlike other known models, it takes into account the force and thermal interaction of bubbles in the ensemble, which enables accurate calculation of the pressure change in liquid inside the cluster ($p_{cl} = f(\tau)$) and precise definition of the cavitation incipience. The model uses the generally accepted assumption that the bubble ensemble is monodisperse one at all stages of its development.

Using the same general system of equations, this model adequately describes the dynamics of a bubble cluster in boiling processes, as well as the hydrodynamic and acoustic cavitation processes over the entire temperature range of the existence of liquid phase up to the thermodynamic critical point. [6,7]

Within the scope of the model, the initial stage of development of the bubble cluster after rapid pressure drop from p_{l0} to a specified $p_{l\min} << p_{l\,cr}(R_0)$ has been analyzed. Monodisperse ensembles with various values of the initial bubble radius R_0 and mass concentration N_b were considered. Concentration $N_b = \mathrm{const}$ determines the number of bubbles in a unit mass of a liquid and remains constant throughout the development of a bubble cluster. The results of the study are presented in Fig. 4a b.

Figure 4a,b illustrates the alteration of the pressure inside the cluster p_{cl} in water when lowering the external pressure p_l from 0.1 MPa to –1 MPa. As the external pressure decreases from initial p_{l0} to $p_{l\min} < p_{l\,cr}(R_0)$, the pressure p_{cl} in the interbubble space of the cluster for a short period of time ($\Delta\tau \propto 200$ мкс) increases from $p_{cl} = p_{l\,cr}$ to, $p_{lc} \cong p_{sat}(T_{l0})$ although water continue to stretch under the influence of external pressure. This leads to the simultaneous growth of all bubbles in the ensemble. The subsequent process of stationary boiling of water proceeds for a long time at a constant value, which is usually accurately recorded in experiments with using a pressure gauge. It is the pressure that most researchers defines as the pressure of the onset of cavitation [1-5].

The rate of approaching the cluster pressure p_{cl} to the $p_{sat}(T_{l0})$ value, raises both with increasing bubble size and with increasing concentration N_b. In real liquids this prevents the activation of smaller bubbles [5,6,9,10]. The competition between the rate of decreasing the external pressure ($dp_l/d\tau = f(\tau)$) and the rate of increasing the pressure rate inside the bubble ensemble ($dp_{cl}/d\tau = f(\tau)$) would determine a quantity of activated bubbles. Let water during its processing be continuously recycled through the zone of reduced pressure of a cavitation device (for example, a Venturi nozzle). Obviously, at first, the largest activated bubbles will intensively grow and leave the liquid and only then smaller bubbles can be activated. Recall that the content of small nuclei in water is substantially large.

The results presented in Fig.4, prove the decisive influence of the initial bubble size on the rate of pressure stabilization in the cluster to the value $p_{sat}(T_{l0})$ at the nucleus activation stage. However, in the process of subsequent stationary boiling of water at $p_{cl} = p_{sat}(T_0) = \mathrm{const}$ the initial size of gas nucleus R_0 do not affect the further development of the cavitation cluster. All bubbles, regardless of their initial radius, quickly grow to the same size, which is consistent with video recording data [2,9]. The nucleus concentration has a greater effect on the evolution of a cluster during boiling. As calculations show, with an increase in concentration N_b, the rate of vaporization in water in the process increases sharply.

Conclusion.

The stable gas bubbles contained in the liquid, regardless of their size, are potential centers of cavitation and thermal boiling of liquid, which can be activated with a sufficient degree of expansion of the liquid or its superheating. In industrial technologies related to boiling processes, including cavitation technologies, reliable information about the initial parameters of gas content (concentration and size of the nuclei) and the ability to control these parameters is a necessary condition for successful work.

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Моделювання кінетики кавітаційного скипання рідини

АНОТАЦІЯ

В рамках дослідження кінетики кавітаційного скипання рідини проведено термодинамічний аналіз формування і зростання газових мікробульбашок у воді при ізотермічному зниженні тиску в рідині. Дослідження спрямовано на розуміння фізичних механізмів явищ, що відбуваються на початковій стадії кавітаційного скипання, де беруть початок ті важливі мікро- та наномасштабні процеси, які саме і визначають потім високу інтенсивність динамічних та термічного ефектів на завершальній стадії кавітації. Розглянуто принципову відмінність між тиском кавітаційного кипіння рідини, яке дорівнює тиску її насиченої пари $p_{sat}\left(T_0\right)$ *і тиском кавітаційного скипання* $p_{l cr}$, *який визначає початок кавітації. За будь яких умов* $p_{l cr} < p_{sat}\left(T_0\right)$, *і ця різниця тим бі-*

льша, чим менший середній радіус $\overline{R}_0$ *мікробульбашок, які завжди присутні в рідині, що пов'язано з дією капілярної сили на поверхню цих бульбашок. Ізобаричне кипіння при нагріванні рідини та ізотермічне кавітаційне кипіння слід розглядати як тотожні явища, які підкоряються одним термодинамічних і фізичним законам і описуються тими ж самими рівняннями. Стабільні газові бульбашки, які є потенційними центрами кавітаційного і термічного скипання рідини, можуть бути активовані при достатньому ступені розтягування рідини або її перегріву. Доведено, що кавітаційні ефекти зумовлені спільним впливом усіх бульбашок полідисперсного ансамблю (кавітаційного кластера). За допомогою уніфікованої математичної моделі динаміки ансамблю бульбашок розглянуто специфіку розвитку кавітаційного кластера на стадії скипання рідини з урахуванням силової та термічної взаємодії бульбашок. В сучасних кавітаційних технологіях, пов'язаних з процесами кипіння, достовірна інформація про початкове значення газовмісту. концентрації і розмірах газових зародків, а також можливість контролю цих параметрів є необхідною умовою успішного і ефективного виконання роботи.*

Ключові слова: *кипіння, кавітаційне скипання, газові мікробульбашки, кавітаційний кластер, математичне моделювання, термодинамічний аналіз.*

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Моделирование кинетики кавитационного вскипания жидкости

АННОТАЦИЯ

Применительно к изучению кинетики кавитационного вскипания жидкости проведен термодинамический анализ формирования и роста пузырьков в воде при изотермическом понижении давления в жидкости. Рассчитаны значения критического давления активации, или необратимого роста зародышей, которое определяет начало кавитации. С помощью созданной ранее математической модели динамики ансамбля пузырьков рассмотрена специфика развития пузырькового кластера на стадии вскипания с учетом силового и термического взаимодействия пузырьков. Изотермическое и изобарическое кипение следует рассматривать как тождественные явления, которые подчиняются одним и тем же термодинамическим и физическим законам и описываются одними и теми же уравнениями.

Ключевые слова: *кипение, кавитационное вскипание, газовые микропузырьки, кавитационный кластер, математическое моделирование, термодинамический анализ.*