Представлені результати досліджень процесів пароутворення в рідинах, що знаходяться в стані метастабільної рівноваги. Розглянуто закономірності тепломасообміну у термодинамічно нестійких рідинах у стані квазістаціонарної термодинамічної рівноваги (перегріті рідини). Моделюються процеси термодинамічного подрібнення вторинної фази рідкої суміші. Запропоновано методику визначення основних термодинамічних параметрів перегрітої рідини і пару. Отримані результати можна застосувати для оцінки енергетичних параметрів технології термодинамічної гомогенізації

Ключові слова: перегріта рідина, пароутворення, тепломасообмін у метастабільних рідинах, математичне моделювання

Представлены результаты исследований процессов парообразования в жидкостях, находящихся в метастабильном состоянии. Рассмотрены закономерности тепломассообена в термодинамически неустойчивых жидкостях в состоянии квазистационарного термодинамического равновесия (перегретые жидкости). Моделируются процессы термодинамического дробления вторичной фазы жидкостной смеси. Предложена методика определения основных термодинамических параметров перегретой жидкости и пара. Полученные результаты можно применить для оценки энергетических параметров технологии термодинамической гомогенизации

Ключевые слова: перегретая жидкость, парообразование, тепломассообмен в метастабильных жидкостях, математическое моделирование

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FORMATION OF THE STEAM PHASE IN SUPERHEATED LIQUIDS IN THE STATE OF METASTABLE EQUILIBRIUM

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1. Introduction

The study of dynamics of vapor cavity growth in liquids in a metastable thermodynamic state involves certain theoretical and experimental difficulties. In these processes, they deal with the objects characteristic size of which lies in the micron range of measurement and the time scale of the measured parameters varies within 1 ns to 10 ms. However, complexity of the observed phenomena as well as understanding of their physical nature are of greatest interest to researchers since heat and mass transfer processes in liquids in a thermodynamic quasi-stationary state have not yet been fully studied. Another reason is that the data already available to date on the processes occurring when thermodynamic equilibrium is disturbed can be the basis for development of new high-intensity technologies in various industries, in particular preparation of fine emulsions, homogeneous compounds, new fuels, etc. However, in order to realize this task, further studies of metastable liquids aimed at establishing the patterns of energy conversion in these systems are necessary.

To date, there are many studies [1–30] with an objective to determine optimal modes of emulsification, dispersion and homogenization of mixtures of two and/or more mutually insoluble liquids. Steam bubbles and steam cavities play an important role in these processes. The authors of papers [1–30] suggest mathematical models of the of vapor bubble growth in a volume of boiling liquid or in an ensemble of the same bubbles. The collapse processes in drops during their stretching and under dynamic effect of streams on the drops, their behavior in these conditions are described. Other works are aimed at studying the behavior of vapor bubbles and liquid drops when various factors influence them.

In the study of the velocity and pressure fields [1], data were obtained which show that in the inter-bubble space of the ensemble, even with monotonically expanding bubbles, there are sharp jumps in pressures and velocities characteristic of turbulent flows. This type of flow contributes to intensification and stimulation of heat and mass transfer and hydrodynamic processes in the liquid phase of the bubble system.

Condensation of superheated steam in an underheated liquid is used in many industrial installations, such as feed water heaters, jet pumps, etc. Collapse of steam caverns and individual bubbles in a supercooled liquid is characterized by abnormally high-pressure pulse values. Initiation of such powerful dynamic effects with subsequent control of their level of influence can be used to intensify emulsification, dispersion and homogenization processes in liquid multicomponent media.

2. Literature review and problem statement

The process of explosive effervescence can be achieved, for example, when a drop of volatile liquid is placed in a volume of a hard to boil liquid that is immiscible with it (for example, a water-oil type emulsion) [1, 2]. When temperature of the mixture rises to a temperature higher than the boiling point of the low-boiling liquid, the latter will be in a state of overheating at an appropriate pressure. Temperature of liquids is determined by spinode [3], i. e. the maximum possible overheating. In these works, the effect of dropping surface tension at the interface of the mixture fluids was not taken into account. It is in these boundary zones that activation energy of the light-boiling component is much lower than in the volume and evaporation occurs more intensively at lower temperatures.

In experimental study [4], butane droplets were used that float to the surface in the volume of a difficult-boiling liquid, ethylene glycol. Photographing revealed how a bubble grew inside the drop during boiling and this growth continued until the entire mass of liquid has evaporated into the bubble.

Most of the procedures and approaches [5–10] have been aimed at studying dynamics of growth of vapor bubbles that arise either in the bulk of a liquid or on an overheated surface. The authors did not take into account the fact that formation of the vapor phase will occur at the interface of the liquids. In this case, one liquid (e. g., oil) is a surfactant.

To describe the processes that occur with a vapor bubble during its growth or collapse, a model was created for studying dynamics of a single vapor bubble which appears in the volume of a continuous liquid [5, 6]. Dynamics of a vapor bubble in a fluid volume is described by a system of equations of hydrodynamics and heat and mass exchange. The results of calculations using this model for a bubble with an initial radius R_0=10 μm at a temperature of 120 °C and placed in a liquid with t=30 °C at normal pressure have shown oscillations of the vapor-water interface radius and high values of parameters at the moment of compression: t≈1,500 °C, p≈12,000 atm. It also follows from these calculations that the amplitude decreases by 20 % to several percent in each of the subsequent oscillation periods of the vapor bubble collapse.

In fact, emulsions consist of a plurality of drops of one component distributed in the other component and when one of the components boils up, not a single bubble is formed but a plurality of bubbles distributed in the volume. To describe behavior of a vapor bubble under the influence of other bubbles in the liquid volume, a model of behavior of an ensemble of vapor bubbles is proposed in [7, 8]. Behavior of a single bubble within an ensemble at a varying external pressure is more complicated than it was presented in the mathematical model of a single bubble [9, 10] in an infinite volume of liquid because it is determined by the correlating influence on the evolution of the bubble exerted by its nearest neighbors which in their development create their own field of pressures in the vicinity of this bubble.

As a result of the surfactant action, the interphase tension at the interface between the dispersion medium (water) and the dispersed phase (oil) decreases [11, 12]. For example, in a water-oil type emulsion, interfacial tension is σ_{wo}≈16 mN/m, and tension at the water-vapor interface σ_{wv}≈73 mN/m [13]. At the same time, tension at the water-vapor interface with microscopic oil additives decreases to a value of σ_{wv}≈39...41 mN/m. Due to the decrease in interphase tension at the interface, the critical work of formation of a vapor bubble [14, 15]

$$A_{cr}=\frac{16\pi\sigma^3}{3\left(p_s-p_l\right)^2} \quad (1)$$

is a function of surface tension and will be the smallest at the interface of two liquids.

Taking into account these facts, it was concluded that appearance of the vapor phase in the case of superheated liquids will occur at the interface of the mixture, i. e., in the zone of low interfacial tension which is also proved by the experimental data obtained in [16, 17]. Experimental data [18–20] indicate that the process of formation of a new phase (vapor) is initiated by an internal thermal action at the interface of the mixture. For example, at a sudden pressure drop, the pre-heated water-oil mixture will be in the supersaturated state of the thermolabile aqueous phase (water is superheated with respect to the temperature of saturation at the given pressure), i. e., it will contain an excessive amount of heat. This excess of heat is expended on the work of forming a vapor interlayer and further vaporization.

The effect of oil films on the boiling dynamics was considered in [19, 20]. It is indicated that when heated, they play the role of thermal resistance, thereby slowing down the heating process. But on the other hand, they are carriers of heat which can be used in formation and growth of the vapor phase. In addition, they are surfactants and promote attainment of lower temperatures of water supersaturation, i. e., early boiling. Accounting for the thermal effect from the high-boiling liquid of the mixture is very important in consideration of the heat and mass exchange processes during boiling of mutually insoluble liquid mixtures (emulsion media).

The processes of deformation and fragmentation of the dispersed phase have been considered in [21–30] but these processes are still not fully understood and require large energy consumptions for their practical realization.

The classical theory of deformation and fragmentation of drops depending on the degree of flow turbulence belongs to Kolmogorov [21, 22]. In these works, the process of boiling was considered as the result of the manifestation of a large number of random phenomena. But when considering these processes, the drop stability to the action of the forces seeking to destroy it is important. The main factors responsible for the drop fragmentation in a liquid medium are as follows: relative velocity of the droplet flow, acceleration of the flow, density of the dispersed and continuous phases, surface tension, viscosities of both liquids, and characteristic time of their interaction. The types of hydrodynamic instability that occurs when these factors are affected are as follows [23, 24].

1) Tolmin-Schlichting instability arising as a result of transition from laminar flow to turbulent flow.

2) Kelvin-Helmholtz instability observed when two liquids move with different tangential velocities relative to the interface. Rupture of the surface can be observed even at low speeds when the flow is laminar. This kind of instability is characterized by the Weber number

$$We=\frac{2R\rho w^2}{\sigma}. \quad (2)$$

The critical Weber number is assumed to be ten [25–27].

3) Rayleigh-Taylor instability arises if the surface between two liquids undergoes acceleration from a lighter liquid to a heavier one. This type of instability is characterized by the Bond number

$$Bo = \frac{4\rho g R^2}{\sigma}. \quad (3)$$

The critical Bond number is assumed to be equal to 40 [28, 29].

4) Benard's instability occurs due to density fluctuations which consist in the fact that under the influence of certain factors (gradient of temperature, concentration) the heavier layers find themselves above the lighter ones.

Tolmin-Schlichting and Benard instabilities are observed in both homogeneous and heterogeneous systems while the Rayleigh-Taylor and Kelvin-Helmholtz instabilities are only observed in heterogeneous systems.

The calculations presented in the literature are mostly based on the Bond and Weber criteria [18, 19, 30], that is, they only consider the Rayleigh-Taylor and Kelvin-Helmholtz instabilities which are most typical for emulsion media. In [1, 2, 5], the influence of each of the above factors on deformation and potential subsequent fragmentation of the drops of disperse liquid phase was studied. The processes of deformation and fragmentation of drops during their motion in a liquid are described in [7, 12]. At the same time, none of the existing models consider the process of fragmentation of the disperse phase taking into account formation of a vapor interlayer at the interface of two phases and the force interaction with respect to several simultaneously boiling particles of the dispersed phase. Mostly described are the possible processes of deformation and fragmentation under the influence of either explosive effervescence, growth of steam bubbles or under the influence of steam caverns, cavities at the time of their collapse when the greatest dynamic effect is possible. Formation of the vapor cavity (bubble) is assumed to be homogeneous and only maximum dynamic effects are considered. But fragmentation of the dispersed phase can occur when a maximum force is reached exceeding the critical one calculated according to the Weber or Bond criteria. If we consider the process of fragmentation of the disperse phase which itself gets boiling, then the process becomes even more complicated and requires detailed study.

The main factors determining fragmentation of the dispersed phase were shown above. In accordance with the Weber and Bond criteria, the main factors determining fragmentation of the disperse phase are, respectively, velocity (relative velocity) w and acceleration g, acting on a given particle. Velocity at any point of space in the vicinity of a growing or collapsing vapor volume can be determined from the relation

$$w(r) = \frac{w_4 R_4^2}{r^2}. \quad (4)$$

It can be seen from this relationship that the given velocity is inversely proportional to square of the radius (starting from the value of the radius of the vapor volume itself).

Acceleration distribution in vicinity of the bubble is given by

$$g(r,\tau) = \frac{dw(r,\tau)}{d\tau} = \frac{\partial w(r,\tau)}{\partial \tau} + w(r,\tau)\frac{\partial w(r,\tau)}{\partial r}. \quad (5)$$

Taking into account equation (3)

$$\frac{\partial w}{\partial \tau} = \frac{dw_4}{d\tau}\frac{R_4^2}{r^2} + 2\frac{w_4^2 R_4}{r^2}; \quad \frac{\partial w}{\partial r} = -\frac{2w_4 R_4^2}{r^3}. \quad (6)$$

Substituting (5) into (4), we obtain

$$g(r,\tau) = \frac{1}{r^2}\left[\frac{dw_4}{d\tau}R_4^2 + 2w_4^2 R_4 - \frac{2w_4^2 R_4^4}{r^3}\right]. \quad (7)$$

Then, taking into account the Rayleigh-Plesset equation (4), we can write

$$g(r,\tau) = \left(p_4 - p_\infty + 0.5w_4^2\rho_\infty - \frac{2\rho_\infty w_4^2 R_4^2}{r^3}\right)\frac{R_4}{\rho_\infty r^2}, \quad (8)$$

where $w_4 = dR_4/d\tau$.

The results of calculations using equation (8) are shown in Fig. 1. Acceleration at specific times may have a negative value at the oil-vapor interface, increase with increasing r and, having reached a maximum, decrease. Even at a distance four times the radius of the drop, acceleration is many times greater than the gravity acceleration. So, it can be concluded that the drop of a disperse phase located at a distance several times greater than the radius of the boiling particle, undergoes accelerations. As a result, a destabilizing effect arises, and the drop can be destroyed at certain bubble radii, surface tension values and the bubble boundary acceleration.

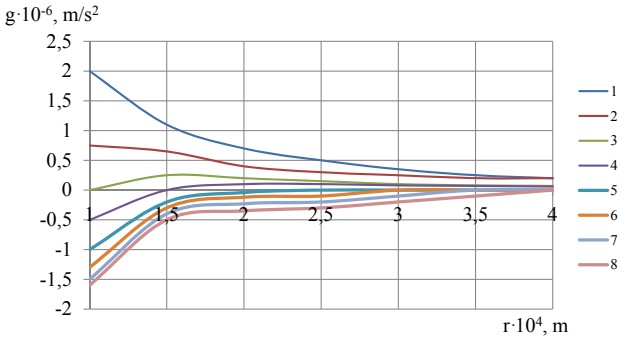

Fig. 1. Distribution of acceleration in the vicinity of the vapor layer at its growth for R_4 (0)=100 μm, t_0=180 °C as a result of pressure drop to 1 at at different time moments: 10^{-6} s (1); $1.5\cdot10^{-6}$ s (2); $2.4\cdot10^{-6}$ s (3); $3.6\cdot10^{-6}$ s (4); $5.2\cdot10^{-6}$ s (5); $7\cdot10^{-6}$ s (6); 10^{-5} s (7); $2\cdot10^{-5}$ s (8)

If we consider the process of fragmentation of the disperse phase which itself gets boiling, then the process becomes even more complicated and requires detailed study.

Thus, in the studies performed, the authors did not take into account the mutual influence of different phases of the mixture when the metastable state of liquids is disturbed. The issue of the conditions of occurrence and the level of dynamic effects occurring during boiling of easily boiling components remains unresolved.

3. The aim and objectives of the study

The study objective was to create a reliable methodology for quantifying the energy parameters of the process of fragmentation (homogenizing) of a mixture of mutually insolu-

ble liquids. This would make it possible to create an effective technology for the homogenization of mutually insoluble liquids. Moreover, it would be possible to predict the size of inclusions of the secondary phase, for example, the size of oil droplets in water, or water droplets in fuel oil (for example, creation of a stable water-fuel oil emulsion).

To achieve this goal, the following tasks were formulated:

– creation of a mathematical model characterizing the dynamic effects that arise when the thermolabile liquid of the mixture is spontaneously about to boil;

– estimation of the level of the dynamic effect from the point of view of possibility of fragmentation of the initial mixture drops taking into account their size and the amount of thermal energy supplied to the mixture;

– estimation of accuracy of the criterion equations for the described homogenization technology.

4. Dynamic effects arising when a metastable equilibrium of a liquid is disturbed

In accordance with the Weber and Bond criteria [18–20], the main factors determining fragmentation of the disperse phase, are as follows: velocity (relative velocity) w, and acceleration g acting on a given particle respectively.

Consider a system consisting of two drops of different sizes located at a distance h from each other when they start boiling as a result of pressure drop (Fig. 2).

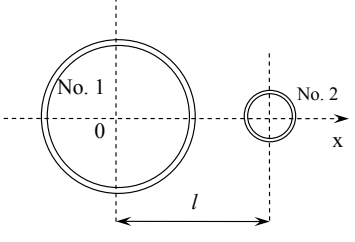

Fig. 2. Model of drop fragmentation

Define the force interaction which can result in emergence of instability. From a joint consideration of the Bond and Weber criterion [18] with the Rayleigh-Plesset equation, it follows that the critical forces leading to appearance of the Rayleigh-Taylor or Kelvin-Helmholtz instability are, respectively, equal to

$$F_{Bo}^{cr}=40\pi\sigma R_i;\quad F_{We}^{cr}=30\pi\sigma R_i. \tag{9}$$

Deformation and fragmentation both of the vapor interlayer and the water drops in the water-oil type emulsions can be caused by different directions of the acceleration vector or the velocity vector. We assume that deformation, fragmentation or displacement will only occur in the case when the acceleration vector has a positive direction and, independently of it, the velocity vector is also positive. Assume that the drop No. 1 (Fig. 2) is at the origin and the drop No. 2 at a distance h from the center of the first drop, that is, $x_1=0$, $x_2=h$. In doing so, we accept the following assumptions:

1) however great the acceleration or velocity of the boundary of the particle itself, the possible instabilities caused by them cannot destroy the given boundary of the particle;

2) if the acceleration (velocity) vector of the interface itself is unidirectional with the acceleration vector acting on the particle boundary from the neighboring one, then the resultant vector is equal to the vector acting on the boundary from the side of the neighboring drop.

Taking into account these assumptions, the acceleration tending to destroy the interface of the drop No. 1 equals

$$g_{p_1}=\begin{cases}\sum\limits_{i=1}^{2} g_i;k_1\ge 0,k_2\ge 0,\\ -\sum\limits_{i=1}^{2} g_i;k_1\le 0,k_2\le 0,\\ g_2;k_1<0,k_2>0,\\ -g_2;k_1>0,k_2<0,\end{cases} \tag{10}$$

where

$$g_i=k_i\frac{R_i(x_i-R_1)}{\rho_M d_i^3};\quad d_i=\left|x_i-R_1\right|;$$

$$k_i=p_{R_i}-p_\infty+0.5w_i^2\rho_\infty-\frac{2\rho_\infty w_i^2R_i^2}{d^3}.$$

Then the force due to acceleration or slowing down of the flow is

$$F_{Bo_1}=4\pi\rho_\infty g_{F_1}R_1^3. \tag{11}$$

Similarly, we can write down for velocity

$$w_{p_1}=\begin{cases}\sum\limits_{i=1}^{2} w_i;w_{R_1}\ge 0,w_{R_2}\ge 0,\\ -\sum\limits_{i=1}^{2} w_i;w_{R_1}\le 0,w_{R_2}\le 0,\\ w_2;w_{R_1}<0,w_{R_2}>0,\\ -w_2;w_{R_1}>0,w_{R_2}<0,\end{cases} \tag{12}$$

where

$$w_i=w_{R_i}R_i^2\frac{(x_i-R_1)}{d_i^3}$$

is the velocity of motion of the vapor bubble boundary.

Then the force of the dynamic head

$$F_{We_1}=6\pi\rho_\infty R_1^2\left|W_{p_1}\right|^2. \tag{13}$$

As is known, the capillary force F_σ regardless the shape of the deformed droplet always restores the spherical shape and the minimum Gibbs surface energy (steady state) is reached. Therefore, if the drop is deformed in the direction of its motion to a flattened ellipsoid, the capillary force counteracts the external force. But if the drop is deformed to an elongated ellipsoid, then the capillary force coincides in direction with the external force. It follows that the shape of the elongated ellipsoid is unstable in the process of deformation whereas the shape of the flattened ellipsoid can be quasi-stable.

A minimum of this capillary force is possible. We will assume that the minimum is determined by the Laplace force and the corresponding force is

$$F_{\sigma_1}=8\pi\sigma R_1. \tag{14}$$

Thus, if the force F_σ is exceeded by an external force, deformation of a given volume will occur: equilibrium when

the forces are equal and repulsion of a given volume without deformation if $F_\sigma > F_{BoWe}$.

The differences between F_{BoWe} and F_σ are equal to

$$\Delta F_{Bo} = F_{Bo} - F_\sigma; \quad \Delta F_{We} = F_{We} - F_\sigma. \tag{15}$$

For the example of the force induced by flow acceleration or deceleration, one can write down the following conditions: $F_{Bo} \ge F_{Bo}^{cr}$ (fragmentation); $\Delta F_{Bo} > 0$ (deformation); $\Delta F_{Bo} = 0$ (equilibrium); $\Delta F_{Bo} < 0$ (transfer).

The system of equations (10)–(15) for particle No. 2 located at a distance h from the first particle will take form

$$g_{p_2} = \begin{cases} -\sum_{i=1}^{2} g_i; k_1 \ge 0, k_2 \ge 0, \\ \sum_{i=1}^{2} g_i; k_1 \le 0, k_2 \le 0, \\ g_1; k_1 < 0, k_2 > 0, \\ -g_1; k_1 > 0, k_2 < 0, \end{cases}$$

$$w_{p_2} = \begin{cases} -\sum_{i=1}^{2} w_i; w_{R_1} \ge 0, w_{R_2} \ge 0, \\ \sum_{i=1}^{2} w_i; w_{R_1} \le 0, w_{R_2} \le 0, \\ w_1; w_{R_1} < 0, w_{R_2} > 0, \\ -w_1; w_{R_1} > 0, w_{R_2} < 0, \end{cases} \tag{16}$$

where

$$g_i = k_i \frac{R_i (x_i - j)}{\rho_\infty d_i^3}; \; w_i = w_{R_i} R_i^2 \frac{(x_i - j)}{d_i^3};$$

$$d_i = |x_i - j|; \quad j = h - R_2.$$

$$F_{Bo_2} = 4\pi\rho_\infty g_{F_2} R_2^3, \tag{17}$$

$$F_{We_2} = 6\pi\rho_\infty R_2^2 \left| W_{p_2} \right|^2, \tag{18}$$

$$F_{\sigma_2} = 8\pi\sigma R_2. \tag{19}$$

As an example, consider two drops of emulsion with R_{10}=100 μm and R_{20}=10 μm which are at different distances h from each other at an initial temperature of 180 °C (130 °C) and the corresponding saturation pressure. At some point in time, the pressure is lowered to atmospheric, thereby causing intensive growth of the vapor phase at the oil-water interfaces and further growth of the oil-vapor interface. Let us study how the forces causing displacement, deformation or fragmentation of the vapor volume in time vary at different distances between the drops, on the surfaces of the large and small drops. The results of calculations by equations (16)–(19) are shown in Fig. 3, 4. In equations, the time is taken into account in the radius derivative. The values of radius, velocity and acceleration are variable and time-dependent. It can be seen from these figures that instability of the Rayleigh-Taylor type brings about the greatest effect in the destruction of drops.

In all the cases shown, it plays a decisive role while instability of the Kelvin-Helmholtz type is observed as well (Fig. 4, *a*) but only after its dynamic effect leads to a destruction of the large drop (from the comparison of Fig. 3, *c*) and, as a consequence, fragmentation of a small drop will not occur. At small distances h (Fig. 3, *d*), fragmentation of the vapor volume of the large drop will occur almost immediately after the pressure drop. As the distance increases (Fig. 3, *a*, *b*), the time to fragmentation also increases, which is to be expected, passing to infinity in the limit if the force interaction between the drops as they approach and touch the surfaces is not considered.

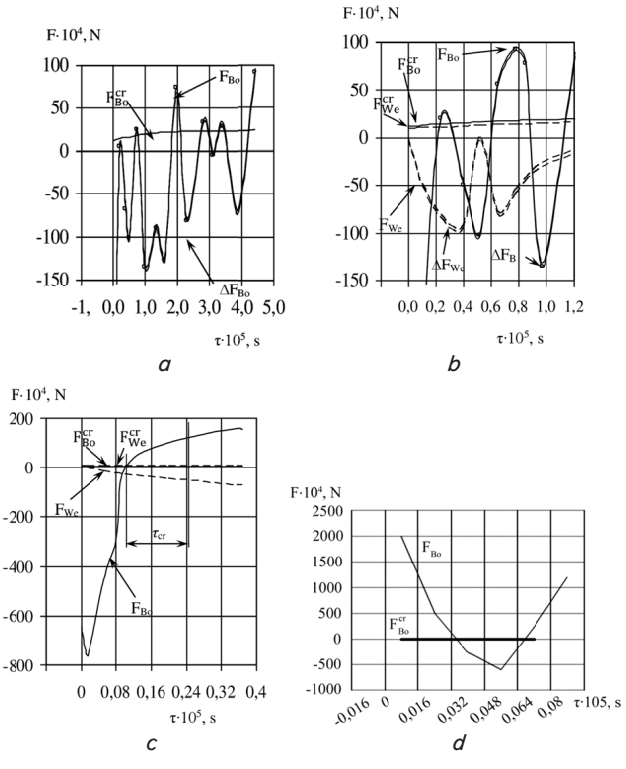

Fig. 3. Change in time of the forces acting on drop No. 1 (Fig. 1) at R_{10}=100 μm, R_{20}=10 μm, t_0=180 °C, ρ_∞=1 atm. and the distance between the drops: h=250 μm (*a*), h=200 μm (*b*), h=150 μm (*c*), h=120 μm (*d*)

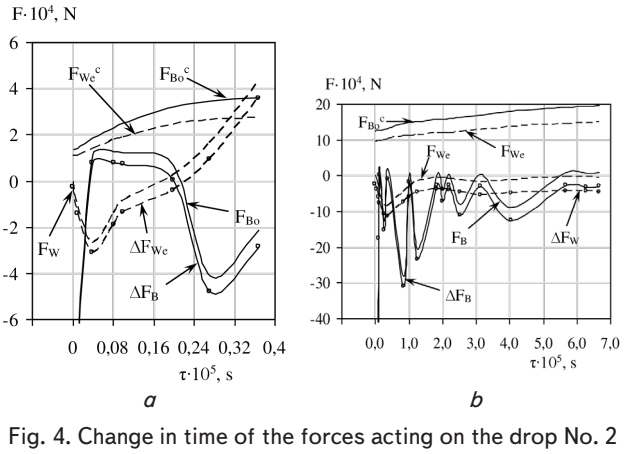

Fig. 4. Change in time of the forces acting on the drop No. 2 (Fig. 1) at R_{10}=100 μm, R_{20}=10 μm, ρ_∞=1 at, h=150 μm, at the superheat temperatures: *a* – t_0=180 °C, *b* – t_0=130 °C

If the distance between the drops is equal to 250 μm (Fig. 3, *a*), i. e. 2.5 times the initial radius of the large drop, fragmentation will be observed at the second peak of the force F_{Bo} oscillations while this will be the first peak at shorter distances. At $\Delta F_{BoWe} > 0$, ΔF_{BoWe} shows that displacement or deformation of the volume is possible at the given time moment. It is interesting that at a distance of 150 μm (Fig. 3, *c*,

Fig. 4, *a*), a small drop deforms before it breaks up a large drop while a large drop will not even be deformed before this time. This can be explained by the fact that the processes of acceleration and deceleration of the interface in a small drop proceed much faster, and this peak of the deformation force (Fig. 4, *a*) is caused by a sharp slowing down of its interface while the oil-vapor interface of the large drop is still accelerating. It is also necessary to take into account the fact that a larger surface area (larger droplet radius) creates larger vicinity of its impact.

As shown in Fig. 4, *b*, with a decrease in the initial temperature to 130 °C, even at a distance of 150 μm, the effects of fragmentation or deformation are not observed at all. As a result of calculation, it was found that a decrease in the initial temperature from 180 °C to 130 °C leads to a ≈3-fold decrease in the maximum distance at which fragmentation is still possible when the pressure is released from the value of saturation to atmospheric for these droplet radii.

5. Discussion of the results obtained in investigation of the processes of boiling up metastable liquids

In the study of the velocity and pressure fields, data were obtained that indicate that in the inter-bubble space of the ensemble, even at a monotonous expansion of bubbles, there are sharp jumps of pressures and velocities characteristic of turbulent flow. This type of flow contributes to intensification and stimulation of heat and mass exchange and hydrodynamic processes in the liquid phase of the bubble system.

Collapse of vapor caverns and individual bubbles in a metastable liquid is characterized by anomalously high values of pressure pulses. Initiation of such powerful dynamic effects with a subsequent control of their degree of influence can be used to intensify the technological operations of emulsification, dispersion and homogenization in liquid multicomponent media. In this paper, we studied the effect of mode parameters on the bubble dynamics from which it was established that the degree of underheating of the liquid has the greatest effect: at a weak underheating, the process takes a smooth condensation mode when the bubble size decreases monotonically without noticeable pulsations. The change of the external pressure does not affect dynamical characteristics of cavitation bubbles so much: the amplitude values of characteristics decrease with a decrease in external pressure and as the pressure increases, the more intensive compression is compensated by slowing down of the collapse speed due to the higher initial vapor content in the bubble. With an increase in the initial radius of the bubble, duration of the energy transformation increases and, accordingly, the amplitude values of the dynamic parameters decrease. The degree of steam superheating has no significant effect on the bubble dynamics.

The proposed mathematical model of dynamics of a single vapor bubble takes into consideration all physical factors controlling the bubble behavior without limiting the degree of influence of this or that factor at different stages of the process. This model makes it possible to obtain information about the laws of boiling processes but it does not allow us to take into account the effect of surfactants on the heat exchange and boiling processes. Computational experiments with the help of this model showed good agreement of the results with experimental data for particular problems, for example, for determination of the force action of the water drop boiling in oil. In order to determine parameters that characterize the process of growth of the vapor phase at the interface between liquid emulsions of the water-oil type, an experimental setup was designed (Fig. 5).

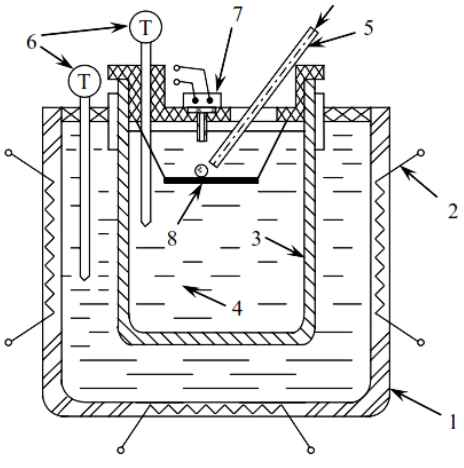

Fig. 5. Diagram of the experimental setup for determining the pressure pulses produced by the steam volume during emulsion boiling-up (see the text for designations)

The experimental setup includes an oil thermostat 1 for setting the required temperature and maintaining it by heaters 2. A flask 3 filled with oil 4 is placed in the thermostat. The temperature regime data in the thermostat and the flask are taken with thermocouples 6. Water is fed through the capillary 5 in a form of a drop of a certain size to the stand 8. To take data on the pressure pulses that arise when the water drops boil (appearance of a vapor interlayer on the oil-water interface), a low-inertia pressure sensor 7 (hydrophone) is used. The inlet opening for the pressure sensor 7 is at a fixed distance from the surface of the stand 8. The water drop is fed directly to the axis formed by the sensor 7 hole. Thus, the distance between the surface of the water drop and the sensor opening which is found as the difference between a known distance from the sensor 7 opening to the surface of the stand 8 and the diameter of the water drop under consideration.

To read the data, a virtual oscillograph and Velleman functional generator were used.

The principle of operation of such oscillographs consists in gating the input signal by extracting short cut-samples from it. They are digitized using a high-speed analog-to-digital converter and the sample codes are transmitted to a PC via a communication port for external devices.

The experimental setup (Fig. 5) enables detection of the change of pressure (force) in time at a certain distance from the surface of the boiling water drop by the use of a low-inertia pressure sensor connected to a virtual oscillograph and the Pc-Lab 2000 program to process the obtained data.

In this experiment, a drop of water with an initial diameter d_0=0.5 mm was taken and placed by means of a capillary into the volume of the heated oil. The resulting diameter of the water drop was previously measured with a laboratory microscope when discharged from the capillary. The distance between the inlet opening of the sensor 7 (Fig. 5) and the surface of the stand 8 was Δh=2.5 mm. Without considering the surface wettability phenomenon for small droplets in which the surface forces tending to return the droplet shape to the spherical are large enough, it can be assumed

that the distance between the sensor inlet opening and the surface of the water drop is Δl=2 mm.

Appearance and growth of the vapor phase were initiated by placing a drop of water in the oil heated to 140 °C. Thus, the water was in the medium with temperature higher than the saturation temperature of water at atmospheric pressure (the pressure at which the experiment was carried out). As a result, water boiled accompanied by appearance of vapor bubbles at the interface between the oil and water phases due to the fact that there was a low interfacial tension at this boundary since oil is a surfactant with respect to water.

To exclude influence of the stand material on the process of water boiling, a cork plate was used as a stand which has a heat transfer coefficient lower than that of the oil used. The presence of gas cavities on the surface of the cork itself, which can lead to an inaccurate measurement result, since they will be sources of dynamic forces during their heating (sources of gas formation), was eliminated by heating them in oil and, as a consequence, ascending to the surface of the oil. As a result, oil occupied those pores of the cork plate which were freed by gas.

The results of the experiment are shown in Fig. 6. It can be seen from this figure that appearance of a new phase (vapor) initiates a sharp pressure growth in the vicinity of the boiling water drop. At the initial stage of boiling, several significant pressure growth peaks (τ=0...0.1 ms) were seen on the virtual oscillograph screen which indicates formation of a large number of vapor bubbles subsequently merging with each other which was well observed visually at a further growth of the vapor phase.

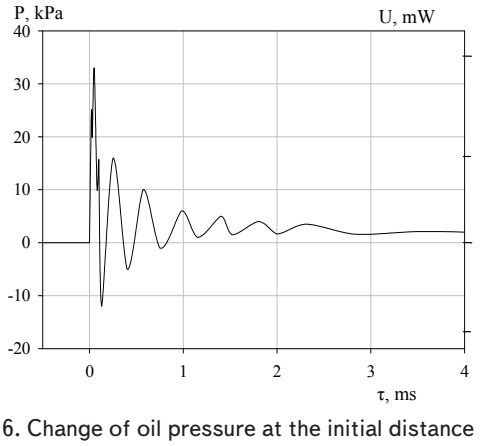

Fig. 6. Change of oil pressure at the initial distance from the surface of the water drop to the measuring point of 2 mm with the growth of the vapor phase resulting from water boiling

The further pressure change in time indicates its oscillatory character. In this case, the amplitude of the resulting oscillations decreases and the period increases, that is, damping oscillations take place. Existence of rarefaction is also possible with maximum value reaching ≈12 kPa. In general, after several characteristic oscillations with a large amplitude, the pressure tends to establish a certain value which is slightly higher than the ambient pressure. The time of achievement of this equilibrium pressure is ≈4 ms.

Thus, as a result of the experiment, a qualitative and quantitative picture of the pressure (force) change at a certain distance from the growing vapor cavity was obtained. The discrepancy between the calculated and experimental data was 14 %.

6. Conclusions

1. A mathematical model of the dynamic effect of boiling drops of a multicomponent liquid (for example, an emulsion) was created. The model characterizes the dynamic effects arising from spontaneous boiling of the thermolabile component of the mixture and also takes into account the laws of heat and mass exchange in thermodynamically unstable liquids in a state of their quasi-stationary thermodynamic equilibrium (superheated fluids).

2. The level of dynamic effects was estimated from the point of view of the possibility of fragmentation of the drops of the primary mixture taking into account their size and amount of thermal energy supplied to the mixture. Dependences have been obtained that enable a qualitative estimation of the critical forces sufficient for the thermodynamic fragmentation of the secondary phase, for example, in the liquid homogenizing processes. Equations take into account the regularities of motion of the boundary of the boiling liquid drop (vapor), its velocity and acceleration. The calculated values of these parameters make it possible to determine critical values of the hydrodynamic forces at which the unevaporated part of the drop can be fragmented.

3. Equations were proposed for calculating critical values of the forces that arise in a mixture of liquids when metastable equilibrium is violated sufficiently for fragmentation of the liquid drops. An experimental estimation of accuracy of the calculated parameters was made. The proposed technique for determining basic thermodynamic parameters of superheated liquid and vapor can be used to predict energy parameters of thermodynamic homogenization technology.

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