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MECHANISMS OF BOILING OF AN EMULSION WITH A LOW-BOILING DISPERSE PHASE IN A TURBULENT FLOW OF A HOMOGENEOUS EMULSION

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A theoretical analysis of the time delay in the boiling of overheated drops in a turbulent flow of a homogeneous emulsion with a low-boiling disperse phase has been performed. Model relations determining the influence of the fluctuations of the velocity of a turbulent flow of an overheated emulsion on the formation of critical vapor bubbles in the disperse-phase drops have been derived. The initiation of formation of stable centers of nucleation of the vapor phase in an overheated emulsion by the factors determining the deformation and fragmentation of drops in it has been considered. The results obtained were compared with the corresponding experimental data.

Keywords: *emulsion, turbulent flow, disperse phase, overheated drops, vapor phase, initiation of nucleation.*

Introduction. In turbulent flows of real homogeneous liquids and disperse systems, such as emulsions of immiscible liquids, a momentum transfer arises frequently due to the heat and mass transfer in them. Usually the following physical notion is used. It is assumed that one and the same volumes (moles) of a liquid, participating in its pulsatory motion and in the formation of the turbulent friction, concurrently determine the turbulent heat and mass transfer and other transfer processes in it.

The mechanism of the turbulent transfer in an emulsion is determined by only the individual properties of the substances transferred by its pulsatory motion [1]. At the same time, the motive force of this process is substantially dependent on both the energy and the properties of the turbulent flow of the emulsion. The energy ε and the local properties of a volume of a homogeneous liquid can be determined by its internal pulsation microscale λ_0 with the use of the Kolmogorov model of turbulence of a homogeneous, isotropic liquid. The important characteristics of the disperse phase of a heterogeneous liquid emulsion are the concentration of drops, their size distribution, and the excess energy related to the surface tension of the phases and the interface tension [2].

Under definite initial and boundary conditions of realization of the turbulent-transfer processes in emulsions, the above-indicated interrelated factors form the internal mechanisms of these processes, which eventually determine their efficiency. An important example of this interaction can be the boiling of the overheated drops in a turbulent flow of a homogeneous emulsion with a low-boiling disperse phase [3, 4]. The point is that such emulsions, especially organosilicon liquids with an aqueous disperse phase, are widely used for cooling of cutting tools in the process of thermal treatment of metals because they can substantially intensify the heat-transfer as compared to any other homogeneous emulsions.

The effect of overheating of an emulsion was experimentally investigated in [3–6], and, on the basis of the results obtained, an expression for determining the time delay in the boiling of an emulsion was obtained: $\Delta T_{\text{b}} = T_{\text{liq}} - T_{\text{sat}}$. It was established that the mechanism of this phenomenon is fairly complex. Therefore, not all the experimental results obtained in the indicated works correspond to the qualitative and quantitative explanation of the time delay in the boiling, proposed by their authors.

Clearly the parameters of the heat transfer in emulsions are substantially dependent on the elementary physical mechanisms of formation of stable centers of nucleation of the vapor phase. There is little likelihood that a vapor bubble will appear in an absolutely homogeneous liquid as a result of its accidental pulsations under the conditions where

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external forces are absent. Since, in accordance with the Laplace equation, the capillary pressure within a vapor bubble changes in inverse proportion to its diameter and, in infinitely small nuclei, this pressure can be indefinitely high, an infinitely large overheating is required to attain a saturation pressure.

It is generally believed that the boiling near a heated (or cooled) solid surface is initiated by the pointed microasperities having a small curvature. In the case where a homogeneous heat-transfer agent with a finite temperature exceeding the saturation temperature T_{sat} is used, these asperities become continuously acting stable centers of vaporization. In emulsion systems, the boiling process begins in the near-wall region and continues in the disperse-phase drops of different sizes, distributed in the bulk of the continuous medium. When passing from a heated solid surface to a deformable interphase boundary, new mechanisms of heat transfer appear, and these mechanisms do not act coincidently in space and time.

For example, in the case of a low-boiling disperse phase, boiling centers are formed inside drops where, because of the surface tension, the pressure is higher than the environmental pressure by the value of the capillary component $2\sigma_{\text{liq-liq}}/R$. On the other hand, under the action of an external pressure, an interphase boundary in an emulsion can deform and concentrate small particles of solid impurities, which can also play the role of vaporization centers under the conditions of free motion of the emulsion.

In the nucleation models proposed in [4, 6], as the main elements, the bubbles of the impurity gas (air) dissolved in a liquid as well as the surface-active substances and the solid microscopic particles found in it are considered. However, these external factors are static and do not explain the physical mechanisms of formation of continuously acting stable centers of vaporization. Their role is undoubtedly important for the maintenance of the conditions favorable for the boiling process and the formation of vaporization centers of critical size.

The influence of external actions on the initiation of the boiling processes was investigated in [7]. The authors of this work explain the formation of nucleation centers by the "pressure impulse"; however, they do not explain the physical nature of this phenomenon. Therefore, in the present work we considered the physical effects that are due to the pulsatory motion of moles of a continuous medium and are favorable for the formation of critical-size vapor bubbles in disperse-phase drops. Prominence is given to the study of the dynamic interaction of low-boiling drops with a turbulent homogeneous flow of a continuous medium, which serves to initiate the nucleation process in these drops.

A peculiarity of the heat transfer in an emulsion with a low-boiling disperse phase is that liquid drops with a deformable elastic surface are heated through the continuous medium of the emulsion. In the case of highly disperse micron-size drops, the total area of the interphase boundary can exceed the area of the surface bounding the emulsion flow by several orders of magnitude. Under these conditions, the role of the ordinary boiling centers found on the most solid surface of heating is fairly small as compared to the developed interphase boundary in the bulk of the continuous medium.

It is known that the disperse-phase drops found in turbulent and laminar flows can break down under the action of the dynamic and viscous forces of the emulsion flow. The size of the small drops can increase as a result of their coalescence under the action of the turbulent pulsations and the shear viscous stresses to the value determined by the surface-tension forces [8]. A large disperse-phase drop in a turbulent flow can deform and break down into two or several parts. Moreover, even in the case of motion of an emulsion in the laminar regime, the boiling of even one drop leads to local turbulization and activation of the emulsion flow.

The mechanisms of coalescence and fragmentation of liquid drops in disperse systems moving in the turbulent regime were investigated in detail in [2, 9]. It was noted that the turbulence energy of the continuous medium in such systems is sufficient for the deformation of the dispersed drops and their complete breakdown. The interaction of drops with turbulent vortices can lead to their deformation depending on the relation between the characteristic sizes of the drops. For example, local convexities and concavities, similar to the asperities on a solid boundary wall, can form on the spherical surface of drops. They can change the curvature in the process of deformation of the drops, which leads to a local decrease in the capillary pressure. The turbulent pulsations, as the internal factors of the nucleation, can form, with a stable frequency, local rarefaction zones with a decreased pressure, initiating the formation of vapor nucleation centers in the bulk of large drops.

Consequently, the duration of the metastable state of an emulsion and the degree of its overheating because of the physical nature of the interphase boundary are substantially determined by the characteristics of turbulence of the continuous medium. In particular, a prerequisite for the realization of the mutual mechanisms of nucleation is the increase in the pressure fluctuations in the process of resonance deformation of the disperse-phase drops [10–12].

Initiation of the Boiling of Disperse-Phase Drops by the Fluctuations of the Velocity of a Turbulent Continuous-Medium Flow (Resonance Regime). We now consider the relation between the conditions of a stable nucleation with hydrodynamic parameters of a diluted emulsion under the conditions of resonance interaction of a pulsating turbulent homogeneous flow and large disperse drops of size $d_{\text{min}} > \lambda_0$ [8, 10]. Hereafter we used model representations restricted by the following assumptions.

First, emulsion drops are metastable; however, they are not heated to the temperature at which spontaneous nucleation of fluctuation nature can arise with a marked frequency. More precisely the energy of turbulent flow of an emulsion is so high that the velocity fluctuations can not only dominate over the other nucleation factors but also cause the breakdown of drops into stable fragments of limiting size d_{max} [11–13].

Second, the characteristic size d_{min} of drops capable of boiling under the action of the above-considered initiation factors exceeds the microscale of turbulence λ_0. This is a region of universal dynamic equilibrium, where the collisions of drops of size $d_{\text{min}} > \lambda_0$ with turbulent vortices remain inelastic.

Let us assume that the vapor bubbles of critical size d_{cr} are formed in the disperse-phase drops in the case where the energy of the turbulent vortices is sufficient to provide, through the resonance mechanism, a stable nucleation. Such conditions are realized due to the fluctuations of the velocity of the continuous medium, leading to the formation of standing capillary waves on the surface of a drop, or in the case where the energy of the collision of a turbulent vortex with a drop is comparable with the energy of its surface forces. As a result, the turbulent pulsations in the bulk of a drop generate local compression and rarefaction regions near the interphase boundary. A decrease in the pressure in the bulk of a drop, in turn, can initiate the formation of vapor-nucleation centers of critical size in it.

The resonance effect providing an efficient turbulent-energy transfer and the formation of turbulent pulsations, under the action of which drops break down, was investigated in [11, 12] on the basis of an analysis of the standing capillary waves on the surface of a liquid sphere. In the case where the characteristic frequency of the turbulent pulsations of a continuous medium is equal to the eigenfrequency of vibrations of a drop, the drop becomes unstable. The natural vibrations of an ideal-liquid drop are characterized by the frequency f_k [11]:

$$(2\pi f_k)^2 = \frac{8\,(k-1)\,k\,(k+1)\,(n+2)\,\sigma_{\text{liq-liq}}}{[(k+1)\,\rho_{\text{d}} + k\rho_{\text{c}}]\,d^3}\,, \tag{1}$$

where $k = 2, 3, \ldots$.

The vibrational motion of a sphere is realized at the following frequencies beginning with the highest-energy frequency at $k = 2$:

$$f_k = C_1\sqrt{\frac{(k-1)\,k\,(k+1)\,(k+2)\,\sigma_{\text{liq-liq}}}{[(k+1)\,\rho_{\text{d}} + k\rho_{\text{c}}]\,d^3}}\,. \tag{2}$$

We now consider a scheme of interaction of metastable disperse-phase drops with a turbulent flow of a continuous medium. In the process of collisions of turbulent vortices with overheated drops, an energy sufficient for the boiling of the drops can be transferred to them from the vortices. It is assumed that the boiling of overheated drops is initiated as a result of the inelastic collisions of them with the turbulent vortices.

Thus, in order that the boiling of the disperse phase be initiated, it is necessary that the energy released as a result of the collision of a vortex with a drop be larger or equal to the work expended on the formation of the vapor-phase nucleation centers of size d_{cr} in this drop. The condition of boiling of overheated drops as a result of the turbulization of the continuous medium is as follows:

$$m_{\text{c}}\overline{V}^2 \geq \sigma_{\text{v-liq}} d_{\text{cr}}^2\,. \tag{3}$$

The minimum size d_{min} of the drops, the boiling of which can be initiated by the energy of a turbulent flow, is assumed to be equal to the scale of the energy-carrying vortices:

$$\rho_c \overline{V}^2 d_{\min}^3 \geq \sigma_{\text{v-liq}} d_{\text{cr}}^2 . \tag{4}$$

To relate $\overline{V}^2$ to the kinetic energy of turbulence, we will use the theory of local isotropy of the structure of turbulent flows developed by A. N. Kolmogorov [14]. In accordance with this theory, the energy of the pulsations, the scale of which exceeds λ_0, obeys an asymptotic law. For pulsations of this scale, the averaged square of the difference between the velocity fluctuations is determined only by the energy expended for a unit mass in a unit time ε:

$$\overline{V}^2 \approx (\varepsilon d_{\min})^{2/3} . \tag{5}$$

Using relation (5), we eventually obtain the following expression for the diameter of such a drop:

$$d_{\min} \left(\frac{\rho_c}{\sigma_{\text{v-liq}} d_{\text{cr}}^2} \right)^{3/11} \varepsilon^{2/11} = C_2 . \tag{6}$$

For a flow of a liquid in a pipeline, the rate of dissipation of the energy of the liquid per unit of its mass is determined from the following balance equation:

$$\frac{\pi D^2 l \rho_c \varepsilon}{4} = \tau_w \pi D l U , \quad \tau_w = \lambda \rho_c U^2 / 8 . \tag{7}$$

The relation for this quantity in the explicit form is as follows:

$$\varepsilon = \frac{\lambda U^3}{2D} . \tag{8}$$

The final expression for the rate of the energy dissipation can be written with the use of the Blasius formula for the hydraulic resistance

$$\lambda = 0.3164 / \text{Re}^{0.25} , \quad \text{Re} = \frac{UD}{\nu_c} = \frac{UD\rho_c}{\mu_c} , \tag{9}$$

in the following form:

$$\varepsilon = \frac{0.158 \mu_c^{0.25} U^{2.75}}{D^{1.25} \rho_c^{0.25}} , \tag{10}$$

whence Eq. (6) can be written as

$$d_{\min} = C_3 \frac{D^{0.23}}{\rho_c^{0.23} U^{0.5}} \Delta W_{\text{cr}}^{0.27} \mu_c^{-0.05} , \tag{11}$$

where $\Delta W_{\text{cr}} = \frac{\pi}{3} \sigma_{\text{v-liq}} d_{\text{cr}}^2$ [15].

The dependence of the dynamic viscosity of a continuous medium on the temperature is determined by the Andrade relation

$$\mu_c = A_0 \exp \left(\frac{B_0}{T} \right) \tag{12}$$

with the parameters A_0 and B_0, and the dependence of the surface-tension coefficient on the temperature is determined by the analogous relation with parameters A_1 and A_2 [16]:

$$\sigma_{\text{v-liq}} = A_1 - A_2 T \, . \tag{13}$$

Let us also estimate the dependence of the work of formation of a critical-size nucleation center on the temperature [15]:

$$\Delta W_{\text{cr}} = \frac{16\pi^3 \sigma^3_{\text{v-liq}}}{3\,(p_{\text{sat}} - p^*)^2\,(1 - v^*/v^{**})^2} \, , \tag{14}$$

where p_{sat} is determined by the Antoine equation with approximation constants B_1, B_2, and C_4 [16]:

$$p_{\text{sat}} = C_4 \exp\left(-\frac{B_1}{T + B_2}\right) . \tag{15}$$

Away from the critical point, where the ratio $v^*/v^{**} << 1$, formula (14) simplifies:

$$\Delta W_{\text{cr}} \cong \frac{16\pi^3 \sigma^3_{\text{v-liq}}}{3\,(p_{\text{sat}} - p^*)^2} \, , \tag{16}$$

and, with the use of the temperature dependences, is written as

$$\Delta W_{\text{cr}} \cong \frac{16\pi^3\,(A_1 - A_2 T)^3}{3\left(\exp\left(-\frac{B_1}{T + B_2} - p^*\right)\right)^2} \, . \tag{17}$$

Using expressions (12), (13), and (17), we obtain, on the basis of Eq. (11), the relation for the resonance regime of initiation of the boiling of large disperse drops

$$d_{\text{min.res}} = C_5 \frac{(A_1 - A_2 T)^{0.81}}{\left(\exp\left(-\frac{B_1}{T + B_2} - p^*\right)\right)^{0.54}} \exp\left(-\frac{0.05 B_0}{T}\right), \quad C_5 = C_3 \frac{D^{0.23}}{\rho_{\text{c}}^{0.23} U^{0.5}} \, . \tag{18}$$

Initiation of the Boiling of Small Disperse-Phase Drops (Gradient Regime). We will now consider the case where the characteristic sizes of disperse-phase drops in an emulsion satisfy the condition $d_{\text{min}} < \lambda_0$. In this region, the viscous forces of a turbulent flow of the emulsion are dominant, and the interaction between the continuous medium and the small disperse drops and the attendant redistribution of the kinetic energy between them ceases to be dynamic in character. The velocity fluctuations cannot cause direct collisions of particles found in the continuous medium and in the drops because the sizes of these particles are small as compared to the internal scale of turbulence λ_0 restricting the minimum size of the energy-carrying vortices.

The model representations of the initiation of the boiling of overheated drops in a homogeneous turbulent flow should be related to the work of the viscous forces of the shear stresses of the small-scale pulsations. The corresponding physical mechanism of the energy transfer is determined by the deformation of the interface by the averaged gradient of the vortex motion of the continuous medium. In order that the disperse phase comes to the boil, the work of the external shear stresses must not be smaller that the energy expended for the formation of a critical vapor bubble of size d_{cr} in a drop.

The condition of boiling of the drops, the diameter of which does not exceed the microscale of turbulence λ_0, is as follows:

$$\mu_c \frac{\partial \overline{V}}{\partial r} d_{\min}^3 \geq \sigma_{\text{liq-liq}} d_{\text{cr}}^2 . \tag{19}$$

Using the local-isotropy assumption, Batchelor obtained an expression for the averaged gradient of turbulent pulsations [17, 18]:

$$\frac{\partial \overline{V}}{\partial r} = \sqrt{\frac{2\varepsilon}{15\nu_c}} . \tag{20}$$

With the use of this expression, relation (19) can be rearranged in the following way:

$$d_{\min} (\mu_c \rho_c \varepsilon)^{1/6} \geq (\sigma_{\text{v-liq}} d_{\text{cr}}^2)^{1/3} . \tag{21}$$

Equation (21) can be written, with the use of expression (10) for the energy ε, in the form

$$d_{\min} = C_6 \frac{D^{0.21}}{\rho_c^{0.13} U^{0.47}} \Delta W_{\text{cr}}^{0.33} \mu_c^{-0.21} . \tag{22}$$

Using the temperature dependences for the viscous and surface tension (12) and (13) as well as the temperature dependence for the energy expended for the formation of a critical-scale nucleation center (17), we obtain a computational dependence for the gradient regime of initiation of the boiling of small drops:

$$d_{\text{min.grad}} = C_7 \frac{A_1 - A_2 T}{\left(\exp\left(-\frac{B_1}{T + B_2} - p^* \right) \right)^{0.66}} \exp\left(-\frac{0.21 B_0}{T} \right), \quad C_7 = C_6 \frac{D^{0.21}}{\rho_c^{0.13} U^{0.47}} . \tag{23}$$

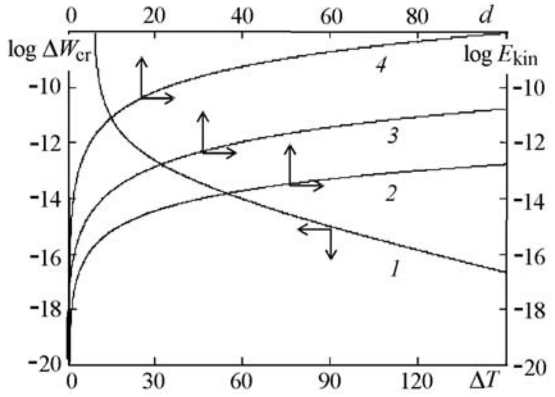
The nucleation-initiation mechanisms considered are important from the practical standpoint because they are naturally determined by the internal structure of a turbulent flow and do not call for special equipment and additional power for their realization. Passing to the characteristic sizes at which only a part of the factors acts, we obtain models of elementary physical phenomena, constructed on the basis of clear and theoretically substantiated physical notions. On the basis of these models, the efficiency of transfer processes can be estimated and the power expended for them can be compared and minimized, which makes it possible to develop energy-conserving structures of these processes in accordance with the features of their mechanisms [19].

Analysis of the Results Obtained. Investigations of the mechanisms of the elementary phenomena occurring in the transfer processes in complex disperse systems of immiscible liquids are important from the standpoint of decreasing the power expended for the turbulent flows of heat carriers. It has been established that the mechanisms of the transfer processes in real polydisperse emulsions including drops of different sizes are interrelated. The contribution of these mechanisms to the formation of the characteristics of heat-transfer processes depends on the distribution of the disperse phase, which substantially complicates the interpretation of the results of experimental investigations.

The above conclusion is illustrated in Fig. 1, where the dependences of the work ΔW_{cr} expended for the formation of a critical nucleation center in an overheated water drop on the overheating temperature ΔT, calculated by formula (17), and the dependence of the kinetic energy of the energy-carrying vortices in the continuous medium E_{kin} on the diameter of the disperse-phase drops d are shown. The calculations were carried out at different velocities of an emulsion flow; only vortices of size exceeding the microscale of turbulence λ_0 were considered. The physicochemical parameters of the PÉS-5 water–organosilicon liquid emulsion were used in the calculations [3, 4].

Curves 1 and 2–4 show that the energy of the vortices in an emulsion is sufficient to initiate, in a wide temperature range, the formation of vapor nucleation centers of critical size in the disperse-phase drops. Thus, the model dependences obtained correspond to both the physical notions adopted and the experimental data [5–7].

Figure 2 presents the dependences of the change in the relative diameters of the drops on the temperature of the overheating of the PÉS-5 water–organosilicon liquid emulsion, reduced to the overheating temperature ΔT = 10 K.



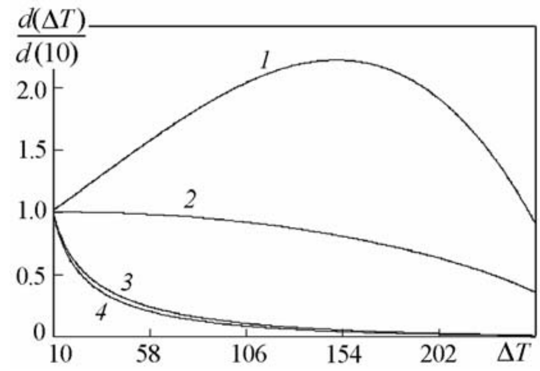


Fig. 1. Dependence of the work expended on the formation of a critical-size nucleation center in an overheated water drop ΔW_{cr} on the overheating temperature ΔT (curve 1) and dependence of the kinetic energy of the pulsations of a turbulent vortex E_{kin} on the diameter of a drop d (PÉS-5 water–organosilicon liquid emulsion): u_0 = 0.01 (2), 0.1 (3), and 1 m/sec (4). ΔW_{cr}, J; E_{kin}, J; d, μm; ΔT, K.

Fig. 2. Dependence of the relative change in the characteristic diameters of the drops in the PÉS-5 water–organosilicon liquid emulsion on their overheating temperature ΔT: 1) $d_{\max.\mathrm{grad}}(\Delta T)/d_{\max.\mathrm{grad}}(10)$; 2) $d_{\max.\mathrm{res}}(\Delta T)/d_{\max.\mathrm{res}}(10)$; 3) $d_{\min.\mathrm{res}}(\Delta T)/d_{\min.\mathrm{res}}(10)$; 4) $d_{\min.\mathrm{grad}}(\Delta T)/d_{\min.\mathrm{grad}}(10)$. ΔT, K.

As the upper boundary of the region where vapor-phase nucleation centers can form, the maximum diameter of the drops resistant to the fragmentation $d_{\max}$ was used [20]. Drops cannot retain their integrity and break down into small fragments in the case where $d > d_{\max}$. In [2, 10], the regimes of fragmentation of drops were analyzed, the computational dependences of $d_{\max}$ on the temperature were obtained, and these dependences were compared with the corresponding experimental data.

The Kolmogorov–Hinze relation was used for the resonance regime of fragmentation of large drops in a turbulent flow of an emulsion in a pipeline:

$$d_{\max.\mathrm{res}}\left(\frac{\rho_c}{\sigma_{\mathrm{liq\text{-}liq}}}\right)^{3/5}\varepsilon^{2/5}=C_8\,. \tag{24}$$

For the gradient regime of fragmentation of small drops, the interaction of which with the turbulent flow is determined by the viscous shear stress, relation (24) takes the form

$$d_{\max\mathrm{grad}}\,\frac{(\mu_c\rho_c\varepsilon)^{1/2}}{\sigma_{\mathrm{liq\text{-}liq}}}=C_9\,. \tag{25}$$

The values of the constants C_8 and C_9, reflecting the differences between the conditions of formation of turbulent emulsion flows are determined experimentally. For example, it is known that C_8 = 0.725 for the flows in pipelines. In the present work, we considered only the influence of the temperature of overheating of drops on the possible change in their limiting size $d_{\max}$, all things being equal. Therefore, these constant were not used in the calculation of the ratio between the diameter of the drops $d(\Delta T)$ and the value of $d(10)$ at a fixed overheating temperature ΔT = 10 K. Relations (12), (13), and (15) were used for calculating the temperature dependences of the dimensional parameters in (24) and (25).

The data obtained show that, in the gradient regime of boiling (curve 1), the relative value of the characteristic size $d_{\max.\mathrm{grad}}$ increases by almost a factor of 2.5, reaches a maximum, and then decreases. In the resonance regime of boiling (curve 2), the relative value of the characteristic size $d_{\max.\mathrm{res}}$ decreases. Consequently, the mechanism

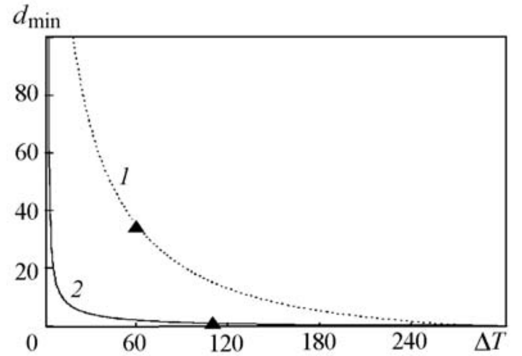


Fig. 3. Dependence of the minimum diameter of the drops in the PÉS-5 water–organosilicon liquid emulsion on their overheating temperature in the cases of the resonance and gradient mechanisms of initiation of the boiling: 1) resonance regime; 2) gradient regime; the points denote the experimental data of [3].

of fragmentation of drops can be judged from the temperature dependence of the maximum size of a drop. The characteristic sizes of drops $d_{\min.\text{res}}$ and $d_{\min.\text{grad}}$ decrease when the overheating temperature increases (curve 3, 4), and this decrease is more rapid for the gradient regime of boiling (curve 4) than for the resonance one.

Thus, independently of the boiling regime, the width of the range of change in the sizes of the drops, determined by $d_{\min}$ and $d_{\max}$, increases, beginning with the instant of their overheating, reaches a maximum, and then decreases. This means that, in both cases, as the overheating temperature increases, the number of disperse-phase drops capable of boiling increases, reaches a maximum at any value of the overheating, and then decreases, which leads to an increase in the heat absorption in the bulk of the emulsion due to the boiling of drops at the initial stage of the overheating. However, when the overheating temperature increases, the rate of increase in the heat transfer decreases and the tendency for a decrease in its intensity becomes dominant.

Figure 3 presents the calculated values of the minimum diameters of the drops $d_{\min.\text{res}}$ and $d_{\min.\text{grad}}$ in the PÉS-5 water–organosilicon liquid emulsion in the resonance and gradient regimes of boiling. The values of the constants C_5 and C_7 in the formulas for the minimum diameter of the drops (18) and (23) were estimated with the use of the experimental data of [7]. The calculated curves represent the boundaries of the region of delay in the boiling of a monodisperse emulsion, determined by two different mechanisms of boiling: the gradient mechanism and the resonance one. The combined mechanism of boiling in the indicated region is characteristic of polydisperse emulsions including drops characterized by a wide range of sizes, at which their boiling can be initiated by the both mechanisms. In this figure, the experimental data on the delay in the boiling, obtained in [3, 21], are also presented.

The correspondence between the experimental data and the results of the model calculations can be interpreted in the following way. The small disperse-phase drops (of size of the order of 1–2 μm) in an emulsion boil by the gradient mechanism under condition (19). Small drops are heated to a boiling temperature in the thermal boundary layer for the time of their movement in it, come to the boil, and are deformed due to the viscous shear stresses in the boundary layer.

Longer time delays in the boiling of emulsions including large disperse-phase drops were detected in the case of very small concentrations of drops in them, where the boiling was initiated, evidently, by the resonance mechanism. The size of the disperse-phase drops in such an emulsion exceeds the size of the thermal boundary layer and, therefore, these drops are not necessarily heated to the boiling temperature near the heating surface. When the small disperse-phase drops are heated, some of them come to the boil and cause a turbulization of the flow, which, accordingly, leads to an increase in the thickness of the boundary layer. This is favorable for heating of the larger drops coming to the boil by the resonance mechanism due to the increase in the energy of the turbulent vortices defined by the right side of relation (4) determining the value of $d_{\min.\text{res}}$.

It was shown in [3, 21] that, in the case where the concentration of drops in an emulsion containing large disperse-phase drops exceeds 0.5%, this emulsion comes to the boil by the combined mechanism because an increase in the concentration of the disperse phase leads to an increase in the number of vapor bubbles that cause turbulization of the boundary layer. This, in turn, increases the microscale of turbulence λ_0 and, consequently, the number of drops coming to the boil by the gradient mechanism. Thus, in the experiments carried out with a heated wire, the two boiling mechanisms of boiling of drops in an emulsion are realized simultaneously.

Conclusions. The energy expended for the transfer processes in complex unstable systems of heat-transfer media representing immiscible liquids can be controlled. The value of this energy is determined by such characteristics of the heat-transfer medium as the concentration and size of the disperse-phase drops, determining the area of the heat-transfer interphase. Clearly the size distribution of the drops most completely reflects the characteristics and interaction of the physicochemical and regime parameters of real transfer processes in liquid emulsions.

Relations for the minimum diameter of the drops (18) and (23), the resonance and gradient regimes of boiling of which are initiated by a turbulent flow depending on the heating temperature, were obtained. These relations allow one to determine the conditions necessary for initiation of the boiling and the time delay in the boiling of different emulsion systems with a low-boiling disperse phase as well as to estimate the heat flows arising in the process of boiling of such systems.

Along with the determination of the boundaries of different regimes of boiling, a no less important result is the widening of the range of factors initiating the vaporization of disperse-phase drops. The dependences obtained allow one to control the time delay in the boiling of emulsions and the regimes of their nucleate boiling by the characteristics of an emulsion turbulent flow.

The combined consideration of the heat transfer in a turbulent flow of an emulsion and its energy structure makes it possible to decrease the energy expended for the transfer processes in it. In particular, for a heat-exchange system, the transfer processes can be represented in the form of a set of elementary physical processes.

NOTATION

A_0–A_2, B_0–B_2, C_1–C_9, empirical constants; D, diameter of a pipeline, m; d, current diameter of the disperse-phase drops, m; d_{min}, minimum diameter of the overheated drops capable of initiating the boiling, m; d_{max}, maximum diameter of the drops resistant to the fragmentation, m; d_{cr}, critical size of the vapor-phase nucleation centers, m; $\partial\overline{V}/\partial r$, averaged gradient of turbulent pulsations, sec^{-1}; E_{kin}, kinetic energy of the turbulent pulsations of the continuous medium, J; f_k (k = 1, 2, 3, ...), eigenfrequencies of the vibrations of a drop, Hz; l, length of a pipeline, m; m_{c}, mass of the energy-carrying vortices of the continuous medium, kg; p_{sat}, pressure of the saturation vapor, Pa; p^*, pressure of the liquid phase, Pa; r, radial coordinate; R, radius of the disperse-phase drops, m; $\text{Re} = UD\rho_{\text{c}}/\mu_{\text{c}}$, Reynolds number; T, current temperature, K; T_{liq}, temperature of a liquid, K; T_{sat}, temperature of the saturation vapor, K; ΔT, overheating temperature, K; ΔT_{b}, time delay in the boiling, K; U, average rate of the flow in a pipeline, m/sec; $\overline{V}^2$, average square of the difference between the velocities of pulsatory flows at a distance d (diameter of a drop), m^2/sec^2; v^*, v^{**}, specific volumes of the liquid and vapor phases, m^3/kg; ΔW_{cr}, work expended on the formation of a critical-size vapor nucleation center; ε, turbulent-flow energy expended for a unit mass in a unit time, J/(kg·sec); λ, coefficient of hydraulic resistance; λ_0, microscale of turbulence, m; μ_{c}, dynamic viscosity of the continuous medium, Pa·sec; ν_{c}, kinematic viscosity, m^2/sec; ρ_{c}, density of the continuous medium, kg/m^3; ρ_{d}, density of a disperse-phase drop, kg/m^3; $\sigma_{\text{liq-liq}}$, surface-tension coefficient at the boundary between the emulsion phases, N/m; $\sigma_{\text{v-liq}}$, surface-tension coefficient of a bubble, N/m; τ_{w}, viscous-friction stress at the walls of a pipeline, N/m^2. Subscripts: c, continuous medium; d, disperse phase; w, wall; liq, liquid; cr, critical; max, maximum; min, minimum; res, resonance; grad, gradient; b, boiling; sat, saturation.

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