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Features of the Breakage Drops Low Boiling Dispersed Phase in Gradient Flow Near the Heated Surface

Alexander K. Rozentsvaig * and Cheslav S. Strashinskii

Kazan (Volga region) Federal University, Naberezhnye Chelny Institute
Tatarstan, Russian Federation

*Corresponding author
423823, Naberezhnye Chelny, street Shamil Usmanov
dom 76/39 (45/15/01), kvartira 50, Russian Federation

Abstract

The mechanisms of the formation of vapor bubbles of a critical size in deformable droplets of the dispersed phase in liquid emulsion been studied. The model is proposed breakup of the droplets in gradient flow of the emulsion near the surface heating under the combined action of viscous shear stresses and thermal overload. Was the dependence of the heat flux density at boiling of dispersed drops of low-temperature liquid phase in a gradient flow of the emulsion near hard surface. Comparison with the data of experimental studies shows the validity of the proposed model concepts that are different from the usual boiling of homogeneous fluids at surface heating.

Keywords: liquid emulsion, gradient flow, heat transfer, low-boiling droplets, initiation of nucleation, vapor bubbles, breakage mechanisms

1 Introduction

The presence of excess thermal energy of the emulsion contributes to the destruction of superheated droplets under the influence of turbulent fluctuations of velocities of the continuous medium [1]. This complicates the nature of heat transfer in emulsions of immiscible fluids in comparison with homogeneous fluids. An increase in the frequency breakage of drops is a consequence not only of the influence of hydrodynamic factors [2, 3]. Turbulent pulsations of the continuous medium generate local pressure pulsations in the droplets of the dispersed phase, constrained deformable interface surface. They, in turn, initiate the formation of viable bubbles of vapor phase [4]. This results in the increased effective volume of the dispersed liquid, which enhances evaporation and breakage of the droplet reaches a critical size.

Isothermal destruction of droplets in a homogeneous turbulent flow of immiscible fluid with them related to the local structure of the velocity fluctuation. Stability drops in accordance with the theory of A. N. Kolmogorov - Hinze determined by the ratio of interfacial tension forces and external forces [5, 6]. Depending on the size of the droplets can dominate the dynamic forces caused by turbulent velocity fluctuations

$$d_{max} \approx \left(\sigma / (\rho_c \bar{\mathrm{v}}^2)\right),\ d_{\max} > \lambda_0 , \tag{1}$$

or viscous forces, shear forces, due to their gradient

$$d_{max} \approx \left(\sigma / (\mu_c\, \partial \bar{\mathrm{v}} / \partial r)\right), \qquad d_{\max} < \lambda_0 , \tag{2}$$

where σ - is the interfacial tension, ρ_C - is the density of the continuous medium, and $\bar{\mathrm{v}}$ - is the averaged velocity of turbulent pulsations.

Energy of turbulence, sufficient to direct destruction of drops in non-isothermal conditions is only enough for education within their local areas of low negative pressures [7]. This energy may be sufficient to reduce the critical size of a viable steam bubbles. Thus the formation in a volume of superheated deformable drops of steam bubbles, the magnitude of which is greater than the critical size been stimulated. The condition of formation of bubbles of critical size we assume a sufficient level of energy viscous forces of the turbulent fluctuations, interacting containing buried drop-mi. It must exceed the energy of formation of critical bubble size $W_0(\Delta T, p)$, which is a function of the superheat temperature of ΔT and "negative" pressure p inside the droplet [8].

The total result of the temperature factor in the breaking model drops formally presented to the replacement of the original diameter d_{max} drops in the ratio for gradient mode (2) $d(\Delta T)_{max}$ corresponding to hydro-thermodynamic destruction of the drops in non-isothermal conditions:

$$d(\Delta T)_{\max} = d_{max}\left(A_{темп} / A_{\mathrm{grad}}\right)^{\gamma} , \tag{3}$$

where γ - is an empirical constant power. $A_{темп} \sim W_0(\Delta T, p)$ - work necessary for the formation of vapor embryo of critical size in the deformed drop. The work of the viscous forces due to the gradient of the averaged velocity fluctuations is recorded as follows in $A_{grad} \sim \mu_c \left(\partial \bar{v}/\partial r\right) d^3 (\Delta T)_{\max}$ if $d(\Delta T)_{max} < \lambda_0$.

Thus, the original expression (2), the generalized dependence (3), takes the following form:

$$d(\Delta T)_{max} \approx \left(\sigma/\mu_c\left(\partial\bar{v}/\partial r\right)\right)/\left(W_0(\Delta T,p)/(\mu_c\left(\partial\bar{v}/\partial r\right)d(\Delta T)^3_{max})\right)^{\gamma} \qquad (4)$$

Equation (4) represented as a dimensionless criterion of the temperature dependence for the maximum stable droplet size:

$$\left(\mu_c\left(\partial\bar{v}/\partial r\right)d(\Delta T)_{max}/\sigma\right)^{\alpha}\left(\mu_c\left(\partial\bar{v}/\partial r\right)d(\Delta T)^3_{max}/W_0(\Delta T,p)\right)^{\beta}, \qquad (5)$$

where $\beta/\alpha = \gamma$ - is an empirical constant associated with the two factors of breakage - hydrodynamic and thermodynamic.

This criterion characterizes the probability of preserving the continuity of two-phase vapor-liquid droplets of the dispersed phase, which provides the energy of surface tension in a non-isothermal turbulent flow of the emulsion.

2 The Model of Breakup Drops in Gradient Flow with Boiling in the Emulsion near the Heated Surface

The homogeneous boiling of the liquid on the heated surface Labuntsov considered, using the analogy of single-phase forced convection [9]. He introduced the concept of the original surface layer, the effective thickness of which is determined from the condition of commensurability effective viscous and inertial forces. Outside of this layer dominated by pulsating current, the intensity of mixing which is proposed to quantitatively characterize some average pulsation rate.

During boiling of the emulsion with dispersed low-temperature phase is assumed in the boundary layer near the surface of the heating drops are deformed through viscous forces. The oscillation energy of the interfacial surface stimulates the formation of vapor nuclei of critical size. Limited to the assumptions that boil only the "surface" drop [10], it proposed that the ratio of the heat flux during boiling of the emulsion with dispersed low-temperature phase:

$$q \sim \lambda_s \bar{u}\Delta T/\nu_s + r\rho_V \bar{u} = \bar{u}(C_1\lambda_s \Delta T/\nu_s + C_2 r\rho_V), \qquad (6)$$

where C_1 and C_2 are experimental constants, ΔT - temperature overheating, ν_s, λ_s - is the kinematic viscosity and the thermal conductivity of the continuous medium, r is the specific heat of vaporization of the dispersed phase, ρ_v - is the density of the vapor phase.

The characteristic speed is determined so that the calculated on the basis of the average kinetic energy of the fluctuating motion meet growing energy on the heating surfaces of steam bubbles, the following relation:

$$\rho_s \left(dR/dt \right)^2 R^2 n_s^* \sim \rho_s \bar{u}^2 , \tag{7}$$

where R is the current radius of the vapor bubble, n_s^* - the number of active centers in boiling droplets from the heating surface.

Discusses the sustainable growth of a vapor bubble generated in the droplets that are in the superheated layer high-boiling continuous medium of the emulsion near the heating surface. It is believed that in many respects it is similar to the growth of vapor bubbles, which are formed in a homogeneous liquid on the heating surface [9]:

$$R \sim \sqrt{\lambda_s \Delta T / (r \rho_v)} \cdot \sqrt{t} \quad , \tag{8}$$

The number of embryos in drops critical size near the surface of the heating taking into account the effect of viscous force continuous medium is defined as follows:

$$n_s^* = P(d_{max}) \cdot n_s , \tag{9}$$

where n_s is the number of droplets at the surface of a single surface layer, $P(d_{max})$ is the probability of nucleation of a critical size in a single drop, which will be determined from the relation (5):

$$P(d_{max}) \approx \left(\mu_c \left(\partial \bar{v} / \partial r \right) d_{maxt} / \sigma \right)^{\alpha} \left(\mu_c \left(\partial \bar{v} / \partial r \right) d_{maxt}^3 / W_0 (\Delta T , p) \right)^{\beta} . \tag{10}$$

For "wall" area in the conditions of developed turbulence rightly ratio [11]

$$\tau_w = \left(\mu_s \, \partial \bar{v} / \partial r \right)_w = \rho_s \bar{u}^2 , \tag{11}$$

where τ_w is the shear stress at the wall.

Taking into account (10) and (11) equation (9) takes the form

$$n_s^* \sim \left(\rho_s \bar{u}^2 d / \sigma \right)^{\alpha} \left(\rho \bar{u}^2 d^3 / W_0 \, (\Delta T, p) \right)^{\beta} \cdot n_s . \tag{12}$$

On the basis of equations (7) and (8) is the characteristic velocity $\bar{u}$:

$$\bar{u} \sim \sqrt{n_s^* \Delta T \, \lambda_s / (r \rho_v)} \, . \tag{13}$$

The final expression for takes the form:

$$\bar{u} \sim \left(\lambda_s / (r \rho_v) \right)^{\frac{1}{(1-\alpha-\beta)}} \left(\rho_s d / \sigma \right)^{\frac{\alpha}{2(1-\alpha-\beta)}} \left(\rho_s d^3 / W_0 (\Delta T, p) \right)^{\frac{\beta}{2(1-\alpha-\beta)}} \cdot \left(\sqrt{n_s} \Delta T \right)^{\frac{1}{(1-\alpha-\beta)}} . \tag{14}$$

The heat flux density from equation (6) can be written as follows

$$q = \left(\lambda_s / (r\rho_v)\right)^{\frac{1}{(1-\alpha-\beta)}} \left(\rho_s d/\sigma\right)^{\frac{\alpha}{2(1-\alpha-\beta)}} \left(\rho_s d^3 / W_0(\Delta T, p)\right)^{\frac{\beta}{2(1-\alpha-\beta)}} \cdot \left(\sqrt{n_s}\,\Delta T\right)^{\frac{1}{(1-\alpha-\beta)}} \cdot (C_1 \lambda_s \Delta T / \nu_s + C_1 r\rho_v) \quad . (15)$$

The value of the exponents α and β is obtained by matching with the experimental data of boiling emulsions from the heated surface.

3 Comparison of Model Calculations with the Data of Experimental Studies

The results of the study of boiling of the emulsion near the surface of the heated platinum wire with a diameter of D with the low-temperature dispersed phase presented in [12]. For comparison the theoretical model (15) with the experimental data determined the number of emulsion droplets n_s per unit of the flattened surface of the heated wire. The number of superheated droplets in superheated layer of the heated wire of length *l* corresponds $n_l \sim \sqrt[3]{n} \cdot l$. Then the number of drops per unit area of the heated wire will fit $n_s \sim \sqrt[3]{n}l/(Dl) = \sqrt[3]{n}/D$. The ratio of the heat flux density, after substitution number concentration n on volume - *Cd* : $C_d \sim d^3 n$, can be written as

$$q = \left(\lambda_s / (r\rho_v)\right)^{\frac{1}{(1-\alpha-\beta)}} \left(\rho_s d/\sigma\right)^{\frac{\alpha}{2(1-\alpha-\beta)}} \left(\rho_s d^3 / W_0(\Delta T, p)\right)^{\frac{\beta}{2(1-\alpha-\beta)}} \cdot \left(\sqrt[6]{C}\,\Delta T / \sqrt{Dd}\right)^{\frac{1}{(1-\alpha-\beta)}} (C_1 \lambda_s \Delta T / \nu_s + C_2 r\rho_v) \quad . \quad (16)$$

Fig. 1 shows experimental measurements of the heat flux at boiling water emulsion/silicone liquid PES-5 [12]. Was that an acceptable approximation of the data by means of model dependence (16) is achieved when α → 0 and β = 0. It shows an insignificant influence of viscous forces on the nature of heat transfer.

This fact may be explained by that in drops of water already exist dissolved gas bubbles of critical size [13]. Therefore, the boiling drops of aqueous emulsions do not require additional energy and occurs when they are relatively "small" deformations.

In addition, you can see that the experimental points are grouped around two different curves. Curve 1 corresponds to the experimental of points with low volume concentrations of *Cd* = 0.001 - 0.01%. Curve (2) approximates the points corresponding to higher concentrations of *Cd* = 0.1 - 4%.

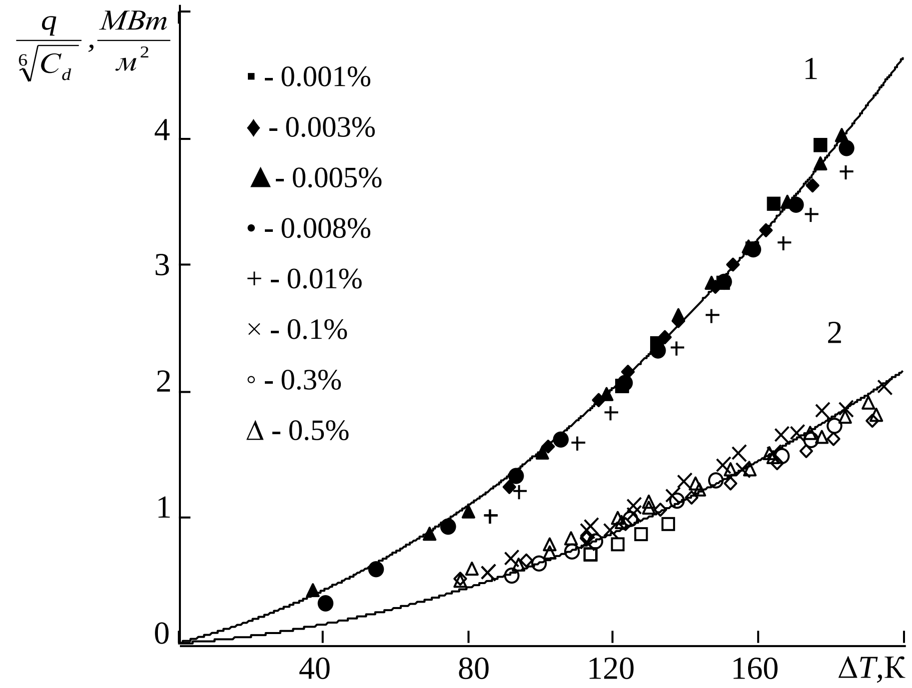

Fig.1. Generalization of experimental data on heat transfer during boiling of the emulsion water / silicone liquid PES-5.

In emulsions of organic liquids, according to [13] gas bubbles are absent, which may hinder the formation of nucleation from the vapor phase.

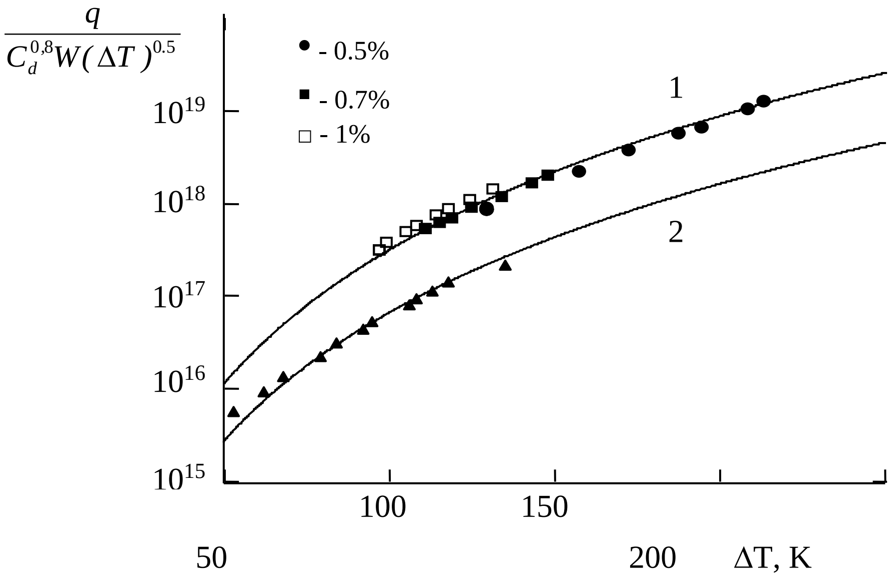

Fig.2. Generalization of experimental data on heat transfer during boiling of the emulsion n-pentane/glycerin

In Fig. 2 shows the results of applying formula (16) for processing the experimental data obtained in [12] for the emulsion of the organic liquid n-pentane/glycerin

This grouping corresponds to previously established modes of boiling: the first bubble (0.0001 - 0.01%) and the second bubble, but with a steam film (concentration of more than 0.1%), modes [10]. It is obvious that there are two bubble boiling regime. However, curves are obtained, well approximate the experimental data at $\alpha = 1$, $\beta = - 0, 21$. This suggests that during boiling of the emulsion of organic heat transfer fluids associated with breaking drops occurring due to the joint action of viscous forces and energy overheating.

4 Conclusions

Heat transfer in emulsions of immiscible liquids is more complex compared to homogeneous fluids. In particular, in emulsions with low-boiling disperse phase embryos vapor phase are formed not only due to thermal overheating, but under the influence of hydrodynamic factors of flow of the emulsion.

The velocity fluctuations and viscous shear stress continuum deforms the elastic surface and interfacial exchange energy with a low-boiling dispersed liquid. In the gradient flow of the emulsion, even this can be enough to break the droplets of the dispersed phase. Otherwise, the thermal energy supplements energy of viscous forces to the level necessary for the formation of the vapor phase. The increase in the boiling drops, in turn, contributes to their breaking.

Test model (16) revealed significant differences in density of the heat flow of emulsions with aqueous and organic liquids based on experimental data processing. It was set in the interrelated influence of formation of the vapor phase and the velocity gradient in the near-wall zone on the fragmentation of droplets of the organic liquid.

Model gradient breakup superheated droplets of the dispersed phase from the heated wall of the cooling emulsion for the temperature of the overheating greatly expands the range of interrelated physical phenomena that determine the nature of the boil and the efficiency of heat transfer from heated surface.

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