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Regimes of Heat Transfer During Boiling Emulsions with Low-Temperature Dispersed Phase

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Abstract

Modification of the model of heat transfer during boiling of the emulsion with dispersed low-temperature phase near the solid heating surface performed. Believed, that in the near-wall layer, the energy of deformation of the interfacial surface, supplementing the heat energy stimulates the formation within of droplets the steam embryos of critical size. Established criteria for two characteristic boiling regimes: transition and developed with turbulent mixing. Shown that in superheated near-wall layer of the high-boiling continuum phase of emulsions they correspond to different criterial relationship. A single generalized correlation equation, which takes into account the presence of the border of transition from one regime to another boil, is given.

Keywords: liquid emulsion, heat transfer, low-boiling droplets, initiation of nucleation, vapor bubbles, boiling modes

1 Introduction

The exceptional complexity of the study of multiphase flows because the theory of single-phase turbulent flows is in the stage of its development. Also complicates the flow pattern to add to the turbulent flow of particles or impurities in the form of drops or bubbles [1]. Vaporization in emulsions with a disperse low-temperature phase also is complex, and cannot be swift-imaging character.

Heating surface for drops of the dispersed phase is the deformable surface with a high-temperature continuous phase through which the heats transfer from the heating surface. This facilitates the isolation of drops in the volume of the emulsion, which delays the onset of the crisis leads to a boil and heat transfer efficiency. However, to date there is no clarity with respect to the physical representations of the regimes of boiling in the volume of the dispersed phase droplets, limited interfacial surface.

Theoretical models of such complex processes in multicomponent systems with phase transitions contain empirical constants. Also, remain rather limited experimental studies of heat transfer in liquid emulsions. The basis of the analysis was the results of research in the field of developed nucleate boiling homogeneous fluid at the heating surface belonging Labuntsov [2]. However, proposed an approximate theory of nucleate boiling and the equations for the heat flux density is limited to the region of homogeneous boiling of liquids.

2 Model boiling of emulsions with a low-temperature aqueous dispersed phase from the heated surface

Boiling homogeneous fluid near the heated surface treated by Labuntsov based on the physical analogy with single-phase forced convection. He introduced the concept of the original surface layer, the effective thickness of which determined by the ratio of viscous and inertial forces. Outside of this layer is dominated by pulsating the fluid motion is caused by the growth and movement of vapor bubbles, which is quantitatively characterized by a certain average of the fluctuating velocity $\bar{u}$.

Typical speed was determined based on the balance of its average kinetic energy, and energy associated with increasing of the vapor bubbles at interfacial surface from the following relationship [2]:

$$\rho_s (dR/dt)^2 R^2 n_s^* \sim \rho_s \bar{u}^2 , \tag{1}$$

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

During boiling of the emulsion with dispersed low-temperature phase heat transfer becomes much more complicated. In the boundary layer near the surface heating of the droplets of the dispersed phase are influenced by viscous forces. The energy of deformation of the interfacial surface, supplementing the heat energy stimulates the formation of vapor nuclei of critical size inside drops. In this regard, the boiling is possible only for part of drops, which is located directly at the heating surface [3].

Based on this proposal, it was obtained the relation for the heat flux during boiling of the emulsion with dispersed low-temperature phase:

$$q \sim \lambda_s \bar{u}\Delta T / \nu_s + r\rho_v \bar{u} = \bar{u}(C_1 \lambda_s \Delta T / \nu_s + C_2 r \rho_v), \qquad (2)$$

where ΔT - is the temperature overheating, ν_s, and λ_s - are 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, C_1 and C_2 - are experimental constants.

And discusses the growth of vapor bubbles in interfacial surface inside the dispersed droplets, which are superheated near-wall layer high boiling continuous medium of the emulsion in a solid heating surface. It is believed that this process is similar to the growth of vapor bubbles, which are formed in a homogeneous liquid on the heating surface [2]:

$$R \sim \sqrt{\lambda_s \Delta T / (r\rho_v)} \sqrt{t}\ . \qquad (3)$$

Taking into account the gradient of the mechanism of initiation of vaporization in the volume of low-boiling droplets of the dispersed phase, bounded by a spherical surface section, it is determined by the following formula [4]:

$$\bar{u} \sim \left(\lambda_s / (r\rho_v)\right)^{\frac{1}{(1-\delta-\beta)}} \left(\rho_s d / \sigma\right)^{\frac{\delta}{2(1-\delta-\beta)}} \left(\rho_s d^3 / W_0(\Delta T, p)\right)^{\frac{\delta}{2(1-\delta-\beta)}} \cdot \left(\sqrt{n_s} \Delta T\right)^{\frac{1}{(1-\delta-\beta)}}, \qquad (4)$$

where σ - is surface tension, d - is the droplet diameter, n_s - is the number of drops per unit area of heating surface in the thermal boundary layer, δ, β – experimental constants, $W_0(\Delta T,p)$ - work is necessary for the formation of vapor embryo of critical size [4]

To convert to dimensionless form of the basic model according to (1) used the criterion Nusselt Nu and the Reynolds number Re. Given that $q = \alpha \Delta T$, this equation can be written as

$$Nu = C_1 \,\mathrm{Re} + C_2 \frac{\bar{u} r \rho_v D}{\Delta T \lambda_s}\ , \qquad (5)$$

where $Nu = \frac{\alpha D}{\lambda_s}$, $\mathrm{Re} = \frac{\bar{u} D}{\nu_s}$, α - is the heat transfer coefficient, D - is a characteristic geometric size.

In the particular case, a limited review of the emulsion with low-temperature aqueous dispersed phase, the expression (4) fair valuation of the constants $\delta \to 0$, $\beta \to 0$. Then, the modified terms of fluctuating velocity (4) will be as follows:

$$\bar{u} \sim \frac{\lambda_s}{r\rho_v} \sqrt{n_s} \Delta T\ . \qquad (6)$$

To compare the model equation to the experimental data under comparable conditions the total number of drops n_s present in the form $n_s = N \cdot n_{s1}$, were N – number of "layers" drops, and n_{s1} - the number of droplets in a "layer" per unit surface area of the heat. Then the Reynolds number can be written as $Re = Re_1 \sqrt{N}$.

С учётом соотношения (6), уравнение (5) для эмульсий с водной фазой принимает следующий вид

$$Nu = C_1\sqrt{N}\,Re_1 + C_2 D\sqrt{N}\sqrt{n_{s1}}\ . \tag{7}$$

Equation (7) defines the heat transfer liquid emulsions when boiling occurs inside the droplets of the dispersed phase deformed directly from the heating surface.

3 Comparison of the model equation of heat exchange with the data of experimental studies

In experimental studies [6, 7, 8] presented the results of research of boiling water emulsions with a disperse low-temperature phase on a heated platinum wire with a mean droplet size of 35 - 40 microns. However, heat transfer boundary conditions appeared different from the model representations where boiling considered in a two-dimensional solid surface.

For comparison, the theoretical model with experimental data transform formula (7) for the number of the boiled emulsion droplets n_s, per unit dimensional surface of the heated wire. The number of superheated droplets are in superheated heated layer wire the length *l* corresponds to $n_l = N\sqrt[3]{nl}$.

Then the number of drops per unit surface of the heated wire corresponds $n_s = N\dfrac{\sqrt[3]{nl}}{Dl} = N\dfrac{\sqrt[3]{n}}{D} \sim N\dfrac{\sqrt[3]{C}}{Dd}$, where *D*, *d* - is the diameter of the wire and drops, respectively, *C* - volumetric concentration of water droplets.

Therefore, in this case the equation (7) takes the form

$$Nu = C_1\sqrt{N}\,\mathrm{Re}_1 + C_2\sqrt{N}\sqrt[6]{C}\sqrt{\frac{D}{d}}\ . \tag{8}$$

The results of statistical processing of the raw data of experimental studies [6] dedicated a boil emulsions: a) water / PES-5 and c) water / PMS-300 shown in Figure 1. Consider the nature of correlation data points based on their graphic distribution. It was found that the graphs could be isolated line sections, wherein the concentration of the dispersed phase was irrelevant. Apparently, they are developed for mode boiling of emulsions with turbulent mixing, which is described by equation (8)

From the data in Fig. 1a it is seen that there is separation of homogeneous solid baseline data of experimental measurements in two different shapes of the group. Obviously, this phenomenon is due to the fundamental difference in the nature of the boiling emulsion from a homogeneous liquid [3].

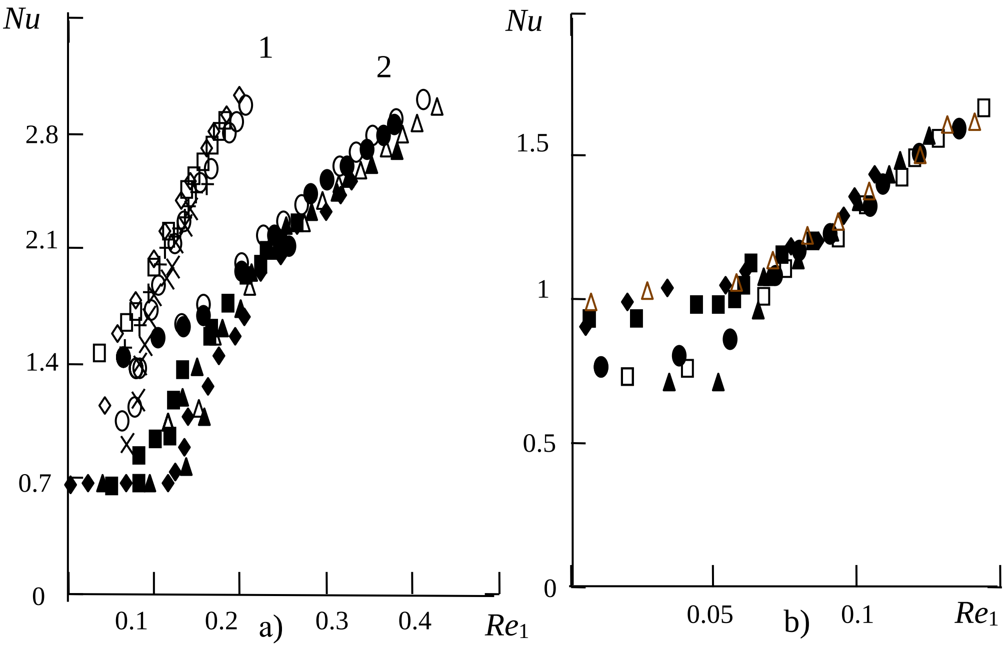

Figure 1: The experimental data [6] to study the boiling of the emulsion: a) water / PES-5. (1 - *C* = 0.001% - 0.01% 2 - 0.1% to 1%.); b) water / / PMS - 300. *C* = 0.1% - 2%).

The set of all experimental data can be divided into two characteristic regions boiling emulsions. Using the analogy with the transition from laminar to turbulent flow regime determine the two modes boil [9]. One mode in $Re_1 < Re_{1cr}$ is transient by boiling a homogeneous liquid to a boil concentrated emulsions. It is obvious effect of the concentration of the dispersed phase and the dependence is a complex, non-linear.

Another mode, with $Re_1 > Re_1cr$ boiling regime is developed, similar to the turbulent hydrodynamic regime. The peculiarity of it is the lack of concentration of the dispersed phase when the emulsion behaves like a homogeneous fluid. The distribution of the experimental data takes a simple linear.

Figure 1b presents the results of the study treated with boiling water emulsion / PMS-300, obtained in [6] for the bulk concentration of the dispersed phase $C > 0.1\%$. It stores the same character according to the boiling emulsions, as in the previous case 1a.

Thus, the critical Reynolds number Re1cr defines the transition to the regime of "turbulent" boiling, stirring characterized by the development of the emulsion under the influence of vaporization. For a water / PES-5 at $C \leq 0.01\%$ the value of $Re_{1cr1} \cong 0.1$ ($Nu_{cr1} \cong 1.8$), and at of $C \geq 0.1\%$ the value $Re_{1cr2} \cong 0.23$ ($Nu_{cr2} \cong 2$). For a water / PMS 300 at $C \geq 0.1\%$ the value $Re_{1cr} \cong 0.06$ ($Nu_{cr} \cong 1$).

4 Presentation of boiling regimes in the generalized equation

The obtained typical values of the criteria Re_{1cr} and Nu_{cr} allow us to represent heat transfer in boiling of the emulsion using a single correlation ratio. We write the general equation (8) for the critical values

$$Nu_{cr} = C_1\sqrt{N}\,Re_{1cr} + C_2\sqrt{N}\sqrt[6]{C}\sqrt{\frac{D}{d}}\,. \tag{9}$$

It allows you to convert the equation (9) to a more general form

$$Nu - Nu_{cr} = C_1\sqrt{N}(Re_1 - Re_{1cr})\,. \tag{10}$$

Transformation of the experimental data presented in Figure 1, with the new dimensionless variables $Nu^* = \dfrac{Nu}{Nu_{cr}}$ and $Re^\bullet = \dfrac{Re_1}{Re_{1cr}}$, corresponds to a generalized dependence

$$Nu^* = C_1\sqrt{N}\,\frac{Re_{1cr}}{Nu_{cr}}(Re_1^* - 1) + 1\,. \tag{11}$$

At $Re^* = 1$ value $Nu^* = 1$.

Fig. 2 presents processed according to equation (11), experimental data for emulsions of water / PES - 5 and water / PMS - 300. We see that at $Re^* > 1$ there is a linear dependence of Nu^* from Re^*, which, according to equation (11) corresponds to the development of the "turbulent" boiling emulsions. Number Re_{1cr} defines the beginning of the developed turbulent boiling emulsion.

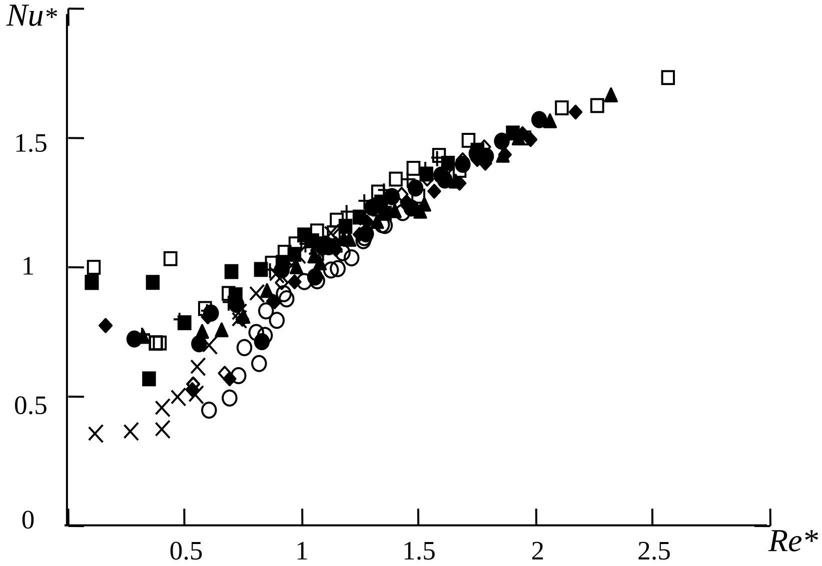

Figure 2: Statistical analysis of experimental data [6] to emulsions water / PES-5 and water / PMS-300.

Based on the linear nature of the model dependency ratio can be designated, as $\sqrt{N}\,\dfrac{\mathrm{Re}_{1kp}}{Nu_{kp}} = C_3$. This allows you to make the following replacement:

$$\sqrt{N} = C_3\,\frac{Nu_{kp}}{\mathrm{Re}_{1kp}}. \tag{12}$$

Therefore, the equation (11) takes the simple form

$$Nu^* = C_4(\mathrm{Re}_1^* - 1) + 1, \tag{13}$$

were $C_4 = C_1 C_3$.

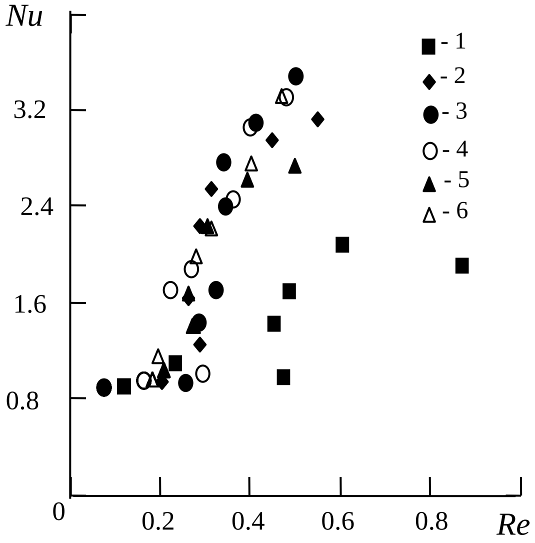

Figure 3: The experimental data [7] for values *C*,%: 1 - 0.1, 2 - 0.5, 3 - 1, 4 - 0.1%, 5 - 0.5, 6 – *C* = 1% with the addition of 0.01 wt % polyethylene glycol PEG-400.

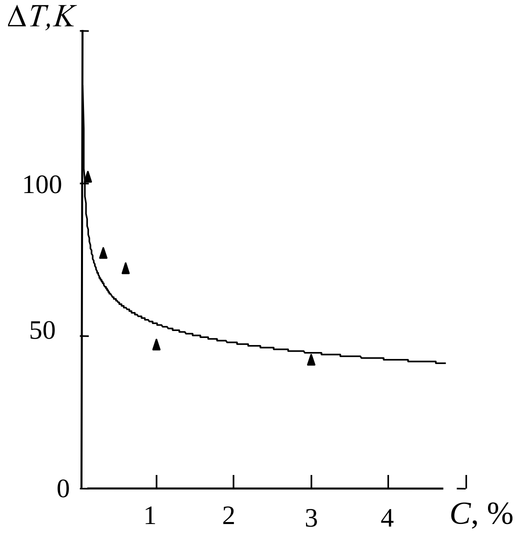

Figure 4: The boundary of occurrence of the development of "turbulent" boiling.

Further, if similarly considered presented in [7], the experimental data for water / oil emulsions VM-1A on the vertical platinum wire at atmospheric pressure (Figure 3), then it is possible to determine the critical Reynolds number Re_{1cr}. For values of concentration greater than 0.1%, it is approximately equal to 0.35.

Using equation (12), we obtain the relationship between the temperature overheating ΔT_{cr} and volumetric concentrations C_{cr}, defines the boundary of this turbulent boiling emulsion (Figure 4)

$$\Delta T_{cr} = 0.35\,\frac{\nu_s r \rho_v}{\lambda_s}\sqrt{\frac{d}{D}}\,\frac{1}{\sqrt[6]{C_{cr}}}. \tag{14}$$

Experimental points obtained by statistical processing of the data for emulsions of water / oil VM-1A to a vertical platinum wire at atmospheric pressure [8].

5 Conclusions

A statistical analysis of experimental study of boiling water emulsions with a disperse low-temperature phase. It revealed two modes of boil - transition and developed turbulence, for which a single criterion equation (11). Correlation equation (14), defining the border of the developed turbulent boil. The possibilities of further detailing of model representations of heat transfer processes, which are associated with boiling disperse phase liquid emulsions.

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