

BOILING IN VOLUME OF LOW TEMPERATURE DROPLETS OF DISPERSED PHASE OF LIQUID EMULSIONS

by

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Mechanisms of droplets boiling in dispersed liquid-liquid systems differ significantly from more commonly studied and better understood mechanisms of vaporization in homogeneous fluids. For the analysis of boiling of liquid emulsions with low-temperature dispersed phase the theory of Labuntsov has been used, which was developed for boiling of homogeneous fluid near a solid wall. Model representations of more complex physical phenomena were substantiated using the similarity criteria, corresponding to the character of the heat exchange mechanisms with the dispersed droplets in the analogous conditions. A modified calculated dependence has been obtained for liquid emulsions with the low boiling dispersed phase. The results of the calculations are compared with the data of visual observations and experimental studies from the literature. It turned out that depending on the concentration of dispersed phase heat transfer in emulsions is characterized by two regimes with different nucleate boiling mechanisms. Good agreement was indicated with measured data of heat flux at boiling of emulsions of water-in-oil type.

Key words: heat exchange, liquid emulsion, nuclear boiling, vapours bubbles, low boiling dispersed phase

Introduction

Boiling liquids is a complex physical phenomenon. A variety of boiling regimes and the structures of two-phase mixtures remain the subject of significant experimental and theoretical research up to the present time. This fact is explained by a number of circumstances, such as the development of new technological processes and equipment for them, ensuring the effectiveness and safe operation of the existing power equipment of steam generators or heat exchangers type, and also for control of heat transfer processes when using different homogeneous liquids and mixtures as heat transfer liquid. The most studied process of heat transfer is nucleate pool boiling in homogeneous liquids. In this regard, both analytical and numerical methods are important for practical applications of thermal science. They can not only solve the real problems of heat transfer, but also serve as a paradigm for justification of the solution of more complex problems [1]. Even with the simplification of the thermal differential problem [2], approximate solution of the Dirichlet problem, using the method of thermal heat-integral balance, and the generalized parabolic profile and can be optimized with respect to the required characteristics of a parabolic temperature distribution. However, for solving the problems associated with different geometry, boundary conditions, character of boiling, physical-chemical properties and flow rate, a joint use of different analytical and numerical methods is necessary [3].

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Numerical methods are the most powerful means of solving the complex heat transfer problems, associated with boiling. They use methods of CFD for liquid and vapour in two-phase flow. Equations conservation of mass, momentum and energy are written for each phase, while interface transfer processes are modelled by *closure laws*. For modelling of vapour generation dynamics the relations of the heat flux with the wall superheating and the bubble residence time on the heater's surface are used (the time of bubble growth up to the bubble departure diameter) [4].

Such a detailed formulation of the model pool boiling of homogeneous liquid is possible only with the involvement of the theory-based methods. However, obtaining solutions in an explicit analytical form is currently facing a large number of formal restrictions. Numerical modelling is not connected with them and allows a more complete consideration of the physical conditions of boiling. So in the article [5] this approach was successful for prediction of the heat transfer coefficient for nucleate pool boiling under high heat fluxes, based on results from the temperature distribution on the heater's surface. Numerical simulations have been performed with the model developed for the high heat flux conditions, which lead to the boiling crisis. The boiling crisis and corresponding critical heat flux (CHF) are detected by a rapid increase of the calculated wall surface temperature. In this case no assumptions about the pattern of two-phase mixture on the heater's surface in pool boiling were introduced.

In the study of Khalal *et al.* [6] numerical computations for evaporation of a binary liquid film, composed of mixtures of water-ethanol or water-methanol, were performed. Studies concerning the analysis of the multi-component solutions flows with evaporation were paid far less attention. The main conclusions of the model calculations were in good agreement with the physical models and the experimental data of the other authors. They have demonstrated that the mixture evaporating rate increases when the inlet liquid mass flow rate decreases. In this case exchange of heat and mass are more enhanced in mixtures with a higher concentration of more volatile component.

However, it is clear that only experimental data can give a complete picture of the diversity and specific characteristics of the complex heat transfer processes even in homogeneous liquids. Semi-empirical methods complete not sufficiently studied numerical calculations patterns in the form of empirical correlations. A particular one is the prediction of the onset of nucleate boiling (ONB). The ONB demarcates the boundary between single-phase and two-phase heat transfer in the flow channel. Thus, identifying the exact location of the ONB constitutes the first step to evaluation of the subcooled flow boiling heat transfer. The current CFD models designate the point where the local wall temperature reaches the saturation temperature as the location of the ONB. For this, priori in composition of the CFD models several basic parameters of boiling heat transfer should be postulated, such as the active nucleation site density, frequency and bubble departure size. Experimental investigation needed to develop reliable models of the basic mechanism of boiling parameters which can be taken for the adaptation of CFD models to the given real conditions [7].

Thus, to predict the characteristics of the homogeneous pool boiling of liquids and solutions of miscible liquids, there are well-founded model representations. They are supplemented, when necessary, by correlation dependences, allowing detailing of the features of the subject area of research, based on experimental data. This progress creates preconditions for the simulation of heat transfer in more complicated boiling conditions of heterogeneous systems of immiscible fluids. But a number of issues, associated with the local structure of two-component mixtures of liquids in the presence of a vapour phase in one of them and also with the identification of boiling regimes, require further investigation. The purpose of this article is to bring

new views of thermal and related sciences, to detail the complex physical phenomena in liquid emulsions. The analysis is limited to the nuclear boiling regime near the solid surface heating of the emulsions of immiscible fluids, and the published data of experimental studies.

Model representations of complex processes of heat exchange in liquid emulsions

A much more complex physical process is the boiling of non-homogeneous liquid emulsions in which the characteristics of mass, momentum, and energy transfer depend not only on the conditions of heat exchange, but also on the physical-chemical properties, volumetric concentration, and size of droplets of the dispersed phase. The reason for the complex thermodynamic behaviour of emulsions is the formation of cross-processes [8], due to exchange of energy and matter in non-equilibrium conditions in which the gradient of one physical quantity causes the transfer of another one. The mutual influence of transfer processes in heterogeneous systems complicates the allocation of boundary regimes and composition of physical mechanisms of boiling. This explains most of the problems associated with the model representations that arise when performing as analytical, numerical and experimental studies of heat transfer in emulsions.

One of the first known publications, devoted to the experimental study of the characteristics of heat transfer from a horizontal wire stationary during pool boiling of emulsions of the oil-in-water- and water-in-oil type is, apparently, the work of Mori *et al.* [9] and Mori [10]. For the first time the author of these works considered the majority of factors that do not exist in homogeneous liquids [9]:

- proportions of two liquids constituting the emulsion,
- which of these fluids is continuous medium and which is dispersed phase,
- size distribution of droplets dispersed phase, and
- stability of the emulsion.

Boiling curves, established in these studies, indicate the presence of modes corresponding to the nucleate, transition and film boiling regimes, determined at the usual homogeneous liquids boiling. Noted, that it is impossible to identify a model of boiling for these modes using visualization, because of the opacity and heterogeneity of the emulsions. In another work of Mori [10] the configuration *two-phase bubble* is considered, consisting of gas-phase and liquid-phase in the volume of immiscible with them continuous medium of the emulsion. They are classified into three types: inclusion of gas bubbles within the volume of the droplet, partial coalescence of gas bubbles, and liquid droplets with the formation of three phase contact line or formation of aggregates of gas bubbles, and droplets of dispersed liquid. Simple criteria are proposed by which a possible configuration within the system is predicted. Experiments, using some combinations of liquids and air, indicate the overall relevance of the criteria. Of course, insoluble gas-phase (air) simplifies the situation greatly as compared to the steam phase, formed during boiling in the emulsion of the continuous medium or the dispersed phase. But here, apparently, an overall approach to the classification of the structures of the liquid-vapour mixtures is first formulated, formed when boiling emulsions with low boiling and high boiling dispersed phase. Also in [9] the importance of the differences in the boiling points of the phases of the emulsion and the influence of type on heat transfer were established. Thus, almost all the basic tasks were formulated by Nicolis and Prigogine [8] and Mori *et al.* [9], associated with pool boiling liquid emulsions, which are solved nearly complete enough up to the present moment.

Extensive, multifaceted research in this area was continued by Bulanov *et al.* [12]. They studied the effects of practically all of the factors on heat transfer that distinguishes the emulsion from homogeneous liquids. Experimental studies were conducted using improved

Mori-techniques on horizontal and vertical platinum wires with a diameter of 50-100 μm . The nature of the boiling centres formation in emulsions with low boiling disperse phase is poorly understood. Studies [11-14] allowed us to obtain new information about the mechanism of their formation (activation). When boiling of the emulsions with low boiling disperse phase, heating surface is wetted with high boiling continuous medium. This hinders the emergence of the boiling centres on the surface, even if these centres appear, they do not have a significant impact on the process of boiling of the dispersed phase. As a result, the emulsion boils at temperatures of the heat transfer surface exceeding considerably the temperature of the saturated vapour of the dispersed phase. Typically, the delay factor at the beginning of the boiling point for pure liquids and solutions does not exceed 1-5 $^{\circ}\text{C}$. The authors found that heat transfer to emulsions in a bubble boiling regime has the delay at the beginning of the boiling, which can reach the value of about 100 $^{\circ}\text{C}$. They also obtained experimental results on the dependence of the delay at the beginning of boiling on the concentration of the emulsion and droplet size of the dispersed phase. The influence of the droplet diameter of the dispersed phase on the nature of heat transfer at bubble boiling and boiling crisis of the emulsion is investigated [15].

Experimental investigation of heat transfer during boiling of emulsions in the pipe [15] and on the surface of the thin steel band [16] also showed the presence of the delay at the beginning of the boiling. The boiling of the emulsion starts on the heating surface and the boiling-up of superheated droplets in the thermal boundary layer only at large densities of heat flow because there is no connection between the delay at the beginning of boiling and boiling of superheated droplets of the dispersed phase in the volume of the emulsion. The delay in the onset of boiling can not reach such temperatures.

Later Roesle *et al.* [17] have formulated a prospective plan to create a new set of boiling mechanisms of emulsions and to show how they can be integrated into the Euler-Euler model of multi-phase flows. The results of further studies [18-20] have shown how far the proposed representation is from the real complexity and ambiguity of the physical heat transfer processes in heterogeneous systems. A critical attitude to the model assumptions of Bulanov does not reduce a high value of their experimental results. More likely, the difficulties are associated with the objective complexity of the formalization of the heat transfer mechanisms in boiling emulsions. Only one of the methods of CFD, which showed the effectiveness of predicting the characteristics of heat transfer in homogeneous fluids, is insufficient for analyses of the behaviour of emulsions. The droplets behaviour of the dispersed phase, their consolidation and splitting when movement of the continuous environment, require the involvement of discrete equations of population balance (DPB). In turn, the interaction of steam and two liquid phases of the emulsion are not limited only to the interfacial friction, intensity of condensation and evaporation rate. For forecasting it is necessary to provide joint CFD and DPB models using a new semi-empirical closure laws. Therefore, an effective approach is possible only for some particular application tasks under certain restrictions [21] or using real data of experimental studies [22].

Experimental studies in other related technical applications enrich significantly physical ideas of modes and characteristics of heat transfer. They are performed and interpreted on the basis of the specifics of a particular subject area. So in [23] an analysis of the initial indices of emulsion mist generation in the process of machining under the conditions of the method of minimum quantity cooling lubrication was carried out, such as the size and *distribution* of droplets, surface wettability, nozzle distance and flow velocity. The investigation of the oil release mechanism of oil-in-water emulsions at temperatures, exceeding the boiling point of emulsions was presented by Januszkiewicz *et al.* [24].

Boiling crisis and evaporation of droplets of ethanol water solution on a horizontal ceramic heating surface were studied experimentally in [25]. The interaction of water droplets with a heated wall in the mode of film boiling is detailed viewed. It was found that the liquid vapour interface loses its stability and oscillates, and thus extends the transitional zone of boiling crisis. In work [26] a simulation of the oil mist impingement behaviour on a smooth surface is presented. This challenging problem used complex models including a motion reference frame (for the tool rotation velocity), Lagrangian particle tracking in a eulerian continuous phase (oil mist in pressurized air), and a special wall interaction model (fluid film formation). The results contribute to the providing an overall understanding of the oil mist behaviour and fluid film formation for different configurations. Numerical simulations were performed using STAR CCM+ commercial software considering multi-phase flow physics with incompressible and isothermal liquid and gas-flow.

The results of such diverse studies can be useful for modelling of the complex physical heat transfer processes, for understanding of the role of each of the mechanisms and their interactions.

Modification of homogeneous liquid boiling model for liquid emulsions with low boiling dispersed phase

Evaporation in emulsions with low boiling dispersed phase is complex by nature, rapid and non-susceptible for visualization phenomenon. A high boiling medium serves as a heating surface for the droplets of the dispersed phase, by means of which the heat transfers from the heating surface. This contributes to the isolation of the droplets in the volume of the emulsion, which delays the onset of boiling crisis. However, up to now there is no clarity with regard to the physical concepts of the boiling mechanisms in the volume of the droplets of the dispersed phase, limited by the interfacial surface. Therefore, the reliability of analytical models of liquid emulsions can only be judged by their comparison with the data of experimental studies [27, 28].

The following analysis is based on highly reliable and informative data of the experimental measurements by Bulanov *et al.* [12] and Gasanov and Bulanov [13, 15] of nucleate boiling emulsions with low boiling (water) dispersed phase. As a starting point for structure selection criterion, theoretical concepts are used for the region of developed nucleate boiling of homogeneous liquid at the flat surface of the heat got by Labuntsov [29]. As a result of generalization of a large number of experimental data during boiling of homogeneous fluids with different physical-chemical properties Labuntsov [29] obtained in criteria form the following relationship:

$$\text{Nu}_* = C \text{Re}_*^n \text{Pr}^{1/3} \quad (1)$$

where $\text{Nu}_* = \frac{\alpha L_*}{\lambda}$, $\text{Re}_* = \frac{w_* L_*}{\nu}$, and $\text{Pr} = \frac{\nu}{a}$.

The parameters, included in the dimensionless criteria, are:

$$n_s^* \sim \frac{1}{R_*^2}, L_* = R_* \frac{\rho c_p}{2 \rho_v r} \Delta T \sim \frac{1}{\sqrt{n_s^*}} \frac{\rho c_p}{2 \rho_v r} \Delta T, \alpha = \frac{\lambda}{\rho c_p}, w_* = \frac{1}{R_*} \frac{\lambda \rho c_p}{(\rho_v r)^2} \Delta T^2 \sim \sqrt{n_s^*} \frac{\lambda \rho c_p}{(\rho_v r)^2} \Delta T^2 \quad (2)$$

where ρ is the density of the liquid, ρ_v – the vapour phase density, c_p – the specific heat liquid at constant pressure, r – the specific evaporation heat, ΔT – the overheating temperature, R_* – the radius of vapour embryo of critical size, L_* – the large-scale embryonic size, n_s^* – the surface density of nuclei on the heating surface, and α – the coefficient of heat transfer.

The numerical values of the constant in eq. (1), when boiling of non-metallic liquids, correspond to the following values: $C = 0.0625$ and $n = 0.5$, when $Re_* \leq 0.01$ and $C = 0.125$ and $n = 0.65$, when $Re_* > 0.01$. The dependence determined criteria values $Re_* = 10^{-5}$ - 10^4 and $Pr = 0.86$ - 7.6 .

For emulsion formal generalization of the Labuntsov-theory of homogeneous liquid boiling at a solid wall is restricted by the following assumptions [30, 31]:

- in more difficult conditions of boiling of emulsion water-in-oil type, the droplets of low boiling dispersed phase of the emulsion at the heating surface become centres of nucleation of the vapour phase. Their initiation is due to the elastic interaction of the droplets surface with the pressure pulsations in the high boiling continuous medium,
- pulsations result from the effervescence of the neighbouring drops in the near-wall layer of the heating surface, and
- dilute emulsions with the volume concentration of water droplets $F \ll 1$ are considered, since at moderate pressures vapour phase increases greatly the amount of boiling of the dispersed phase.

On the basis of the assumptions, the boiling of water droplets in the emulsion from the heating surface is considered. In the Labuntsov-model the parameter (the number of centres boiling per surface heating unit) is replaced by its analogue for the emulsion (the number of boiling drops of thin superheated layer per heating surface unit). Thermophysical parameters of a homogeneous liquid are replaced by the parameters of the continuous medium of the emulsion. When the heat flow from the heating surface is taken aside by a high boiling continuous medium, the nuclei of the vapour phase appear inside the overheated droplets of the dispersed phase.

Under these assumptions the consequences of hypothetical identity processes, caused by boiling at the heating surface, and uniform liquid water droplets in the emulsion are considered. First, in the Labuntsov-model the parameter n_s^* (the number of boiling centres per heating surface unit) is replaced by an analogue for emulsions n_{se}^* (including superheated droplets boiling thin layer per heating surface unit). Then thermophysical parameters of a homogeneous liquid are replaced by the parameters of the continuous medium of the emulsion. Finally, the heat flow under these conditions is only given to high boiling continuous medium from the heating surface. Overheated droplets of the dispersed phase become the source of the nuclei of vapour phase, and the emergence and collapse of bubbles promote a uniform distribution of heat. It is known, that there are always drops of water in a gas, in particular air bubbles of critical size [32]. In this case, the boiling of overheated drops of the dispersed phase does not require a lot of external influences.

A more general form of relations (1) and (2) can be obtained if instead of parameter n_s^* we use a more overall parameter n_{se}^* , that takes into account the effect of pulsations continuous medium, which are caused by the boiling water droplets [33]:

$$n_{se}^* = n_{se} \quad (3)$$

where n_{se} is the number of droplets in a thin superheated layer of emulsion per surface unit.

As a result, the modification of eq. (4) for the boiling of emulsions can be represented in the form:

$$Nu_{*e} = Re_{*e}^n Pr_S^{1/3} \quad (4)$$

where Nu ———, $Re_{*e} = \frac{w_{*e} L_{*e}}{\nu_S}$, and $Pr_S = \frac{\nu_S}{a_S}$.

The parameters included in the dimensionless criteria are determined from the following relations:

$$L_{*e} = \frac{1}{\sqrt{n_{se}^*}} \frac{\rho_s c_{ps}}{2\rho_v r} \Delta T, \quad a_s = \frac{\lambda_s}{\rho_s c_{ps}}, \quad w_{*e} = \sqrt{n_{se}^*} \frac{\lambda_s \rho_s c_{ps}}{(\rho_v r)^2} \Delta T^2 \quad (5)$$

where the index *s* corresponds to the parameters of the continuous medium.

Characteristics of experimental set-up and materials

Validation of the generalized model in criterial form (3) was performed using published data of boiling emulsions with low temperature (water) dispersed phase on a heated platinum wire of length, $l = 56$ mm and a diameter, d , of about 100 microns and the average droplet size of 35-40 μm (fig. 1) [12]. Years of experience have enabled the authors to work out a method of obtaining reliable and accurate measurement data of such a complicated object as an unstable liquid emulsion.

They used platinum wires which can be manipulated to determine simultaneously and with high accuracy both the power taken off the wire surface and the wire temperature. The experiments began with the temperature calibration of the wire using a reference platinum resistance thermometer which was installed in place of the thermocouple 9.

Prior to the experiments with emulsions, for example, with water/PES-5 emulsion, measurements were performed of the coefficient α of heat transfer to PES-5 pure dispersion medium. After these measurements, the preassigned batch of dispersed phase (water) was added to the PES-5 liquid (to the thermostat-1). As a result of intensive stirring of the mixture, the emulsion of desired concentration was prepared in the thermostat. Thus, the experiments started with low concentrations of the dispersed phase (0.1 wt.% and less). The concentration was then increased from experiment to experiment owing to the introduction of new portions of dispersed phase into the heat transfer agent. The size distribution of emulsion was determined by the microscopic method using a P111 Polam microscope.

The other thermophysical parameter values were taken at saturation temperature from the reference materials [34, 35] (tab. 1).

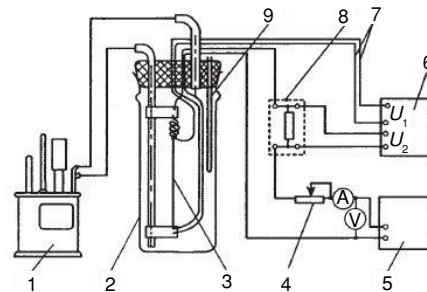


Figure 1. Schematic of experimental apparatus [12]

1 – thermostat, 2 – glass cylinder, 3 – platinum wire, 4 – resistance box, 5 – electric current source, 6 – digital voltmeters, 7 – potential leads, 8 – reference resistance coil, 9 – thermocouple

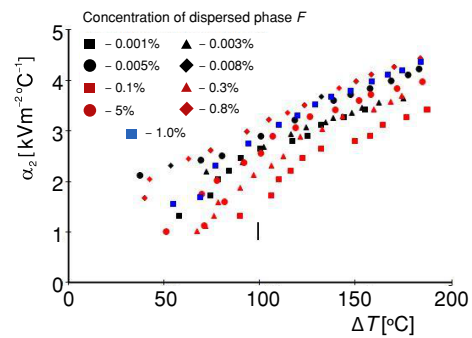


Figure 2. Raw results of the measurement of the heat transfer coefficient α from overheating DT for emulsion water-PES-5 [12]

Table 1. Thermal and physical properties of boiling emulsion [12]

Oil specification	λ_s , [$\text{m}^{-1}\text{K}^{-1}$]	c_{ps} , [$\text{Jkg}^{-1}\text{ }^\circ\text{C}^{-1}$]	ν_s , [m^2c^{-1}]	ρ_s , [kgm^{-3}]
PES-5	0.146	$1.73 \cdot 10^3$	$32.9 \cdot 10^{-6}$	943
PMS-300	0.150	$1.62 \cdot 10^3$	$83 \cdot 10^{-6}$	903
PES-4	0.131	$1.85 \cdot 10^3$	$7.80 \cdot 10^{-6}$	907

For illustrative purposes only fig. 2 shows part of the raw experimental data in the original dimensional variables. It is obvious that conventional methods of treating them on the analogy of similar liquids do not give a complete picture about the features of physical processes of nucleate boiling in emulsions.

Detection of the experimental data with the aid of model concepts

Model representation of Labuntsov-theory is obtained for a flat heating surface. The results of an experimental study of the emulsions boiling with a low temperature dispersed phase are obtained by heating the emulsion on a platinum wire [12]. For a comparison of theoretical models with the experimental data it is necessary to transform eq. (4) for the conditions of linear heating surfaces. Instead of the original number n_s^* appears the number of emulsion droplets per surface unit of the heated 1-D wire. The total number in the line layer of the heated wire of length, l , is respectively equal to $n_l \sim n^{1/3} \cdot l$. Then the number of droplets within the layer per surface unit of the heated wire will correspond to $n_s = (n^{1/3} \cdot l) / \pi d l = n^{1/3} / \pi d$. Consequently, the number of at the boiling surface unit will be equal to $n_{se}^* = (n)^{1/3} / \pi d$. On the basis of the relationship between number droplets of n and the volumetric concentrations of droplets of the dispersed phase F obtain:

$$n_{se}^* = \sqrt[3]{\frac{3}{4\pi}} \frac{\sqrt[3]{F}}{\pi R_0 d} \quad (6)$$

The parameters included in the dimensionless eq. (5), in this case for aqueous emulsions, the equation will take the form:

$$L_{*e} = \sqrt[6]{\frac{4\pi}{3}} \frac{\sqrt{\pi R_0 d}}{\sqrt[6]{F}} \frac{\rho_s c_{ps}}{2\rho_v r} \Delta T, \quad w_{*e} = \sqrt[6]{\frac{3}{4\pi}} \frac{\sqrt[6]{F}}{\sqrt{\pi R_0 d}} \frac{\lambda_s \rho_s c_{ps}}{(\rho_v r)^2} \Delta T^2 \quad (7)$$

For the conditions of emulsions boiling, which occurs at relatively large overheating, they take the value of $n = 0.65$.

In fig. 3 for emulsions: water – silicon-organic liquid PES-5, water – silicone-organic fluid PMS – 300, and water/silicone-organic fluid PES-4 shows the calculated curves for the dependence $Nu_{*e}, Pr_s^{-1/3}$, and $Re_{*e}^{0.65}$, obtained by the eq. (4) at various concentrations. The dots mark the experimental data published in the literature [12]. The presented results of analysis show that the distribution of experimental points is non-uniform. They formed two separate groups, which were approximated by two model curves. The curve 1 with constant $C = 0.43$ was in good accordance with experimental points with low volume concentrations of 0.001-0.01% of the emulsion water/PES-5, and the curve 2 with high volume concentrations – from 0.1 to and more – for all the emulsions.

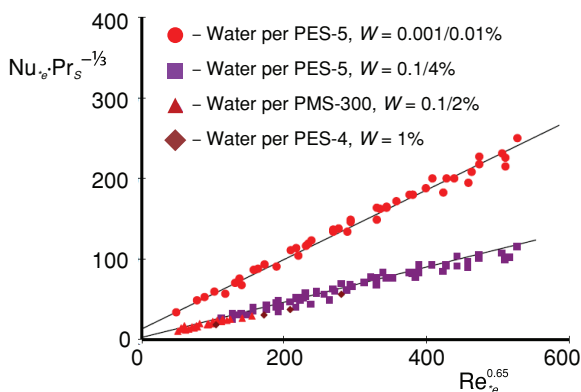


Figure 3. Generalization of experimental data on heat exchange at boiling of aqueous emulsions with low boiling dispersed phase

The character of grouping of experimental points obviously shows the changing nature of boiling point with the increasing concentration of the dispersed phase. It is obvious that in the transition from the first nucleate boiling regime ($F \approx 0.0001 - 0.01\%$) to the second regime with formation of chains from vapour bubbles (concentration of more than 0.1%) the nature of the boiling changed due to the change in the mechanisms of the elementary physical phenomena. Boiling, limited to liquid emulsions with a volume of low boiling disperse phase, is not uniform, which resulted in two modes of heat exchange. This feature can be associated with the fact that vaporization occurs not on the heating surface, as in boiling a homogeneous liquid and at some distance from it. But, nevertheless, the volume of the vapour phase at a certain concentration of droplets can behave similarly to the vapour film and can block the flow of heat to the more remote droplets. As a result, this flow of heat is insufficient for boiling of those droplets that are behind a veil of steam formed in front of the heating surface.

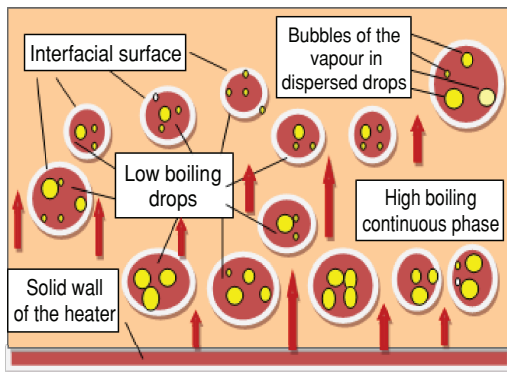


Figure 4(a). Mode bubble boiling of emulsion with the formation of chains from vapour bubbles

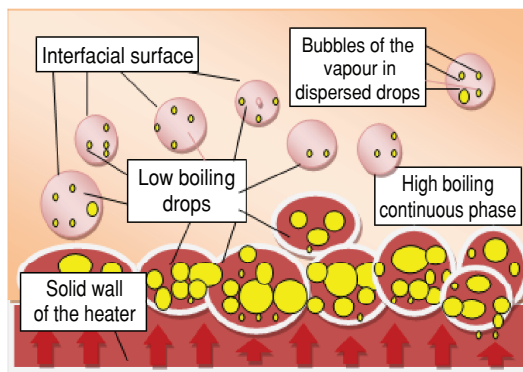


Figure 4(b). Mode boiling of emulsion with the formation blanket of vapour

Figure 4 presents the physical content of the process of boiling emulsions with low temperature dispersed phase in graph form. It is in good agreement with observations of the CHF during boiling of a homogenous liquid at the heating surface. In [36, 37] it was found that there are no data about chains of bubbles of vapour over the vapour layer at the heating surface exposed to high heat fluxes. It was concluded that these structures of boiling two-phase mixture at the onset of boiling crisis are missing. Also visual observation of Bang *et al.* [38] did not confirm the presence of chains of vapour bubbles and instabilities Kelvin-Helmholtz as the cause of CHF. Photos with a high speed camera showed that CHF occurs when the evaporation of a liquid film on the heating surface occurs under the vapour layer. The vapour layer is formed due to coalescence of bubbles under an intense heat exchange. The existence of chains of vapour bubbles was observed in the studies, carried out by Chung and No [39]. Instead of this, the existence of local nucleate boiling under big steam film or on its border was observed.

For the vapour film formation it is necessary that the bubbles in the complete evaporation of droplets of dispersed low boiling liquid can be able to come in contact with each other. For this ratio $F_{\max} = \rho_v / \rho_d \approx 0.0006 = 0.06\%$ a limit value of volumetric concentration of drops is defined. It corresponds to the separating boundary of boiling modes shown in fig. 3. The constant for the curve 2, obtained using linear regression analysis of experimental for data groups, which differ from the first group, was equal to 0.218. Experimental data, corresponding to the second mode of emulsion water-in-oil-type is also well approximated by the dimensionless eq. (5), as in the case of a homogeneous fluid. But in this case it is the boiling of a single layer

of droplets on the surface heating, when $F > F_{max}$. The value of the constant for the modified curve 2, fig. 3, was close to the value of the constant $C = 0,43$, which characterizes the boiling single-phase liquid at a solid heating surface.

Conclusion

The modification for emulsions with a dispersed phase of low temperature criterion equations for homogeneous liquid obtained by Labuntsov was in good agreement with the experimental data for boiling around the heating surface. Statistical processing of measurement data using the criteria of the generalized model showed the existence of common mechanisms of heat transfer during boiling of a homogenous liquid or emulsion water-in-oil type near the heating surface. The presence of two regimes of boiling of emulsions with low temperature dispersed phase was detected: normal regime with chains of vapour bubbles and regime with the vapour film formation. It enhances understanding of the boiling mechanisms of emulsions of immiscible liquids and contributes to the improvement of the forecasting methods of characteristics of heat transfer using numerical methods.

Nomenclature

a – thermal diffusivity, [m^2s^{-1}]
 C, n – constants, eq. (1), [–]
 c_p – liquid specific heat, [$Jkg^{-1}K^{-1}$]
 d – diameter droplet of dispersed phase, [m]
 D – diameter of the pipeline, [m]
 F – volumetric concentration droplets, [–]
 g – gravitational acceleration, [ms^{-2}]
 l – length, [m]
 L – large-scale of embryonic size, [m]
 n – volume number density of embryos, [m^{-3}]
 Nu – Nusselt number, ($= ad/\lambda$), [–]
 Pr – Prandtl number ($= \nu/a$), [–]
 R – radius of vapor embryo of critical size, [m]
 r – specific heat of vaporization, [$J kg^{-3}$]
 Re – Reynolds number ($= wD/\nu$), [–]
 T – temperature, [K]
 ΔT – temperature overheating, [K]
 W – concentration of dispersed phase, [%]
 W_0 – energy of formation of a critical bubble, [J]

w – liquid velocity, [ms^{-1}]

Greek symbols

α – heat exchange coefficient, [$Wm^{-2}K^{-1}$]
 λ – thermal conductivity, [$Wm^{-1}K^{-1}$]
 ν – kinematic viscosity, [m^2s^{-1}]
 ρ – density, [kgm^{-3}]

Subscripts

d – dispersed phase
 e – thin superheated layer emulsion
 $*$ – homogeneous liquid
 0 – initial value
 s – volume of the continuous medium
 v – vapour phase

Superscript

$*$ – modified value

References

- [1] Cui, Q. N., et al., Analytical and Numerical Methods for Thermal Science, *Thermal Science*, 20 (2016), 3, pp. 9-14
- [2] Hristov, J., An Approximate Analytical (Integral-Balance) Solution to a Non-Linear Heat Diffusion Equation, *Thermal Science*, 19 (2015), 2, pp. 723-733
- [3] Sahu, S. K., et al., Analytical and Semi-Analytical Models of Conduction Controlled Rewetting. A State of Art Review, *Thermal Science*, 19 (2015), 5, pp. 1479-1496
- [4] Pezo, M. L., Stevanovic, V. D., Numerical Prediction of Critical Heat Flux in Pool Boiling with the Two-Fluid Model, *International Journal of Heat and Mass Transfer*, 54 (2011), 15, pp. 3296-3303
- [5] Pezo, M. L., Stevanovic, V. D., Numerical Prediction of Nucleate Pool Boiling Heat Transfer Coefficient under High Heat Fluxes, *Thermal Science*, 20 (2016), Suppl.1, pp. S113-S123
- [6] Khalal, L., et al., Numerical Study of Heat and Mass Transfer during Evaporation of a Turbulent Binary Liquid Film, *Thermal Science*, 19 (2015), 5, pp. 1529-1540
- [7] Yang, L. X., et al., Experimental Investigation of Subcooled Vertical Upward Flow Boiling in a Narrow Rectangular Channel, *Experimental Heat Transfer*, 29 (2016), 2, pp. 221-243

- [8] Nicolis, G., Prigogine, I., *Exploring Complexity: An Introduction*, W. H. Freeman & Co Ltd, New York, USA, 1989
- [9] Mori, Y. H., *et al.*, Pool Boiling Heat Transfer to Emulsions, *Trans. ASME. J. Heat Transfer*, 100 (1978), 4, pp. 613-617
- [10] Mori, Y. H., Configurations of Gas-Liquid Two-Phase Bubbles in Immiscible Liquid Media, *International Journal of Heat and Mass Transfer*, 4 (1978), 4, pp. 383-396
- [11] Bulanov, N. V., An Analysis of the Heat Flux Density under Conditions of Boiling Internal Phase of Emulsion, *High Temperature*, 39 (2001), 3, pp. 462-469
- [12] Bulanov, N. V., *et al.*, Results of Experimental Investigation of Heat Transfer with Emulsions with Low-Boiling Disperse Phase. *High Temperature*, 44 (2006), 2, pp. 267-282
- [13] Gasanov, B. M., Bulanov, N. V., Heat Transfer under Conditions of Boiling of Emulsion on the Thin Wire Surface, *High Temperature, Vol. 48*, (2010), 3, pp. 456-459
- [14] Gasanov, B. M., Boiling of Emulsions with a Low-Boiling Disperse Phase High Speed Filming, *International Journal of Heat and Mass Transfer*, 94 (2016), 3, pp. 66-74
- [15] Gasanov, B. M., Bulanov N. V., Effect of the Droplet Size of an Emulsion Dispersion Phase in Nucleate Boiling and Emulsion Boiling Crisis, *International Journal of Heat and Mass Transfer*, 88 (2015), 9, pp. 256-260
- [16] Roesle, M. L., *et al.*, Boiling Heat Transfer to Dilute Emulsions from a Vertical Heated Strip. *Trans. ASME. Journal of Heat Transfer*, 137 (2015), 4, 041503
- [17] Roesle, M. L., *et al.*, Boiling of Dilute Emulsions – Toward a New Modelling Framework, *Ind. Eng. Chem. Res.*, 49 (2010), 11, pp. 5188-5196
- [18] Roesle, M. L., *et al.*, An Experimental Study of Boiling in Dilute Emulsions, Part A – Heat Transfer, *International Journal of Heat and Mass Transfer*, 55 (2012), 7-8, pp. 2160-2165
- [19] Roesle, M. L., *et al.*, An Experimental Study Of Boiling in Dilute Emulsions, Part B – Visualization, *International Journal of Heat and Mass Transfer*, 55 (2012), 7-8, pp. 2166-2172
- [20] Roesle, M. L., *et al.*, Boiling Heat Transfer to Dilute Emulsions from a Vertical Heated Strip, *J. Heat Transfer*, 137 (2015), 4, 041503
- [21] Wenzel, E. A. *et al.*, Modelling and Simulation of Liquid-Liquid Droplet Heating in a Laminar Boundary Layer, *International Journal of Heat and Mass Transfer*, 97 (2016), June, pp. 653-661
- [22] Rozentsvaig, A. K., Strashinskii, C. S., Modelling of Heat Transfer Conditions in Cooling Lubricant Emulsions with Low-Boiling Continuous Media in Narrow Gaps, *International Journal of Heat and Mass Transfer*, 102 (2016), Nov., pp. 555-560
- [23] Maruda, R. W., *et al.*, A Study on Droplets Sizes, their Distribution and Heat Exchange for Minimum Quantity Cooling Lubrication (MQCL), *International Journal of Machine Tools and Manufacture*, 100 (2016), 1, pp. 81-92
- [24] Januszkiewicz, K. R., *et al.*, High Temperature Tribological Behavior of Lubricating Emulsions, *Wear*, 256 (2004), 11-12, pp. 1050-1061
- [25] Misyura, S., Wall Effect on Heat Transfer Crisis, *Experimental Thermal and Fluid Science*, 70 (2016), Jan., pp. 389-396
- [26] Cerqueira, R., *et al.*, A Computational Study of the Interfacial Heat or Mass Transfer in Spherical and Deformed Fluid Particles Flowing at Moderate *Re* Numbers, *Chemical Engineering Science*, 138 (2015), Dec., pp. 741-759
- [27] Rozentsvaig, A. K., Strashinskii, C. S., Hydrodynamic Aspects of Boiling up of a Disperse Phase in a Homogeneous Turbulent Flow of an Emulsion, *High Temperature*, 49 (2011), Feb., pp. 143-146
- [28] Rozentsvaig, A. K., Strashinskii, C. S., Identification of Models of Transfer Processes in Complex Disperse Systems, *Appl. Math. Sci.*, 10 (2016), Mar., pp. 1151-1161
- [29] Labuntsov, D. A.. *Physical Principles of Energy. Selected Works on Heat Transfer, Fluid Mechanics*, (in Russian), Thermodynamics, MPEI, Moscow, 2000
- [30] Rozentsvaig, A. K., Strashinskii C. S., The Growth of Vapour Bubbles in the Volume of Superheated Drops Dispersed in High-Boiling Liquid, *Applied Mathematical Sciences*, 8 (2014), 151, pp. 7519-7528
- [31] Rozentsvaig, A. K., Strashinskii, C. S., Regimes of Heat Transfer during Boiling Emulsions with Low-Temperature Dispersed Phase, *Applied Mathematical Sciences*, 9 (2015), 112, pp. 5593-5601
- [32] Zeigarnik, Yu. A., *et al.*, The Nature of Microbubble Emission under Subcooled Water Boiling, *High Temperature*, 50 (2012), 1, pp. 78-83
- [33] Zeigarnik, Yu. A., *et al.*, Behavior of Air Bubbles during Subcooled Water Boiling, *High Temperature*, 50 (2012), 3, pp. 407-411

- [34] Vargaftik, N. B., *Handbook of Thermal Conductivity of Liquids and Gases*, CRC Press, Boca Raton, Fla., USA, 1994
- [35] Reid, R. C., et al., *The Properties of Gases and Liquids*, McGraw-Hill, New York, USA, 1977
- [36] Theofanous, T. G., et al., The Boiling Crisis Phenomenon. Part I – Nucleation and Nucleate Boiling Transfer, *Experimental Thermal and Fluid Science.*, 26 (2002), 6-7, pp. 775-792
- [37] Theofanous, T. G., et al., The Boiling Crisis Phenomenon. Part II – Dryout Dynamics And Burnout, *Experimental Thermal and Fluid Science*, 26 (2002), 6-7, pp. 793-810
- [38] Bang, I. C., et al., Visualization of a Principle Mechanism of Critical Heat Flux in Pool Boiling, *International Journal of Heat and Mass Transfer*, 48 (2005), 25-26, pp. 5371-5385
- [39] Chung, H. J., No, H. C., A Nucleate Boiling Limitation Model for the Prediction of Pool Boiling CHF, *International Journal of Heat and Mass Transfer*, 50 (2007), 15-16, pp. 2944-2951