

The Growth of Vapor Bubbles in the Volume of Superheated Drops, Dispersed in High-Boiling Liquid

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Abstract

The growth of bubbles to the critical size, resulting in a volume of superheated droplets, which dispersed in high-boiling continuous medium liquid emulsion. Based on the first law of thermodynamics analysis of the formation of a new liquid-vapor interface surface and the nature of the phase transitions of the first kind in the closed medium, which is limited to the surface of the droplets of the dispersed phase. Shows the presence of factors associated with the size of the bubbles of vapor with a constant supply of heat through the interface. Presents the dependencies that fundamentally different from those describe boiling in unlimited volume fluid or near the surface of the heated wall.

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

1 Introduction

The formation of a continuous film of vapor near surfaces cooled walls with help homogeneous liquid can completely block heat transfer. An effective way to prevent boiling crisis is the use of liquid emulsions. The transfer process of vaporization in the volume drops low-boiling dispersed phase allows avoiding a sharp reduction in heat transfer [1, 2]. The fact that the high-boiling continuous medium of the emulsion at a high enough concentration drops can inhibit the growth and merging of bubbles of vapor. This is due to excessive capillary pressure inside drops and insulation of vapor bubbles formed in the neighboring droplets. Thus preserves the homogeneity of the structure of non-equilibrium gas-liquid system in the dispersed phase of the emulsion. Subcooled liquid continuous medium eliminates the appearance of film vapor on heating surfaces, which promotes uniform distribution of heat flow in the volume of liquid emulsion.

In general, the unproductive expenses of heat required to move all dispersed liquid in the vapor state, will be relatively high, which creates conditions for increase efficiency of heat transfer to the emulsions. Mechanisms of transfer of heat in emulsion with low-boiling of the dispersed phase, which caused to the efficiency of the process of heat exchange, significantly different from the classical pool nucleate boiling - mechanism of boiling in an unlimited volume of a homogeneous liquid.

Dynamics of nucleate boiling in the droplets of bidistillate at solid wall of the heater was studied [3]. These experiments was carried out on the copper rough surface as well as on the polished solid surface. Marked important differences of vaporization inside of volume droplets from conditions pool boiling. Intensive droplet boiling accompanied by continuous motion of a contact line: the area of droplet base and its shape change, the number of bubbles varies continuously as well as their average diameter and his time of life. Shows that this boiling mechanism fundamentally differs from pool nucleate boiling.

Results of the analysis of the conditions of stable nucleation in the low-boiling disperse phase taking into account the turbulent mode of motion of liquid emulsions presented [4]. Proposed calculated relation for estimating the dependence of the minimum size of drops, whose boiling up can initiated by the resonance mechanism of their destruction by turbulent pulsations on the superheating temperature. Take into account the effect of hydrodynamic factors on the time delay of boiling up of emulsions with the low-boiling dispersed phase. This gives broader understanding of the possible modes of the bubbles boiling.

More complex for the experimental study is boiling inside the droplets of the dispersed phase, separated from the heating surface of the emulsion high-boling continuous environment. In this case, the model representation based on the generalization of the results of studies of the physical processes involved in the composition of the studied phenomenon.

2 Thermodynamic Model the Growth of Vapor Bubbles Within the Volume of Dispersed Drops

Consider the process of formation and growth of the radius R_v bubbles of vapor in the volume of superheated drops with radius R_l dispersed in high-boiling continuous medium liquid emulsion ($R_l > R_v$). Limited to a uniform size distribution, the number of drops of the dispersed phase N in the volume of emulsion V_e determined by the ratio:

$$\frac{4}{3}\pi R_v^3 N = W_d V_e \quad (1)$$

where $V_e = V_d + V_c$, $W_d = V_d / (V_d + V_c)$, and V_d and V_c are the volumes dispersed and continuum phases of liquid emulsion.

Per unit volume of the emulsion, the number of low-boiling droplets dispersed phase is defined as

$$N = 3W_d / (4\pi R_l^3) \quad (2)$$

They correspond to the total area S_{l-l} , representing the surface of the liquid-liquid interface of the continuous and disperse phases $S_{l-l} = 4\pi R_l^2 N = 3W_d / R_l$ and excess surface energy ε_d , associated with the dispersion of droplets in the volume of the continuous medium

$$\varepsilon_d = \frac{\sigma_{l-l}}{R_l} S_{l-l} = \frac{3\sigma_{l-l} W_d}{R_l^2} \quad (3)$$

Surface forces that limit the location of the bubbles within the volume drops and inhibit their growth, cause, on the other hand, aggregate instability of the emulsion, the tendency to coalescence of the dispersed phase [5]. Therefore, consideration is limited to the conditions when the impact can assumed negligible.

The increase in the temperature of the emulsion creates conditions for vaporization in the volume of low-boiling liquid inside the droplets of the dispersed phase. Interfacial surface, separating it from the high-boiling continuous medium, becomes like a solid surface during heating of a homogeneous liquid. As the warm above the temperature of saturated vapor of the liquid drops inside the droplet at the interface conditions for the formation of a critical vapor bubble, able to exist and grow in size. The temperature of the vapor in the bubbles assumed equal to the saturation temperature. It will provided by the constant supply of heat through the interface surface S_{v-l} , that separates steam phase in volume of the droplets of the dispersed phase.

Depending on the concentration of the dispersed phase and thermal conditions boiling drops may fail not only complete or partial evaporation of them, but also the reverse process of condensation when lack a energy from outside.

Heat spent for evaporation, formation of new liquid-vapor interface surface within volume of drops, and the change of the surface area of the drops themselves.

It is believed, that the source of heat for the drops of the dispersed phase is surrounding their continuous medium of the emulsion, the amount of which is to simplify the modeled complex migration process relies unlimited. Further consideration is also limited to changing the size of the vapor bubble radius for a fixed volume of the droplets of the dispersed phase

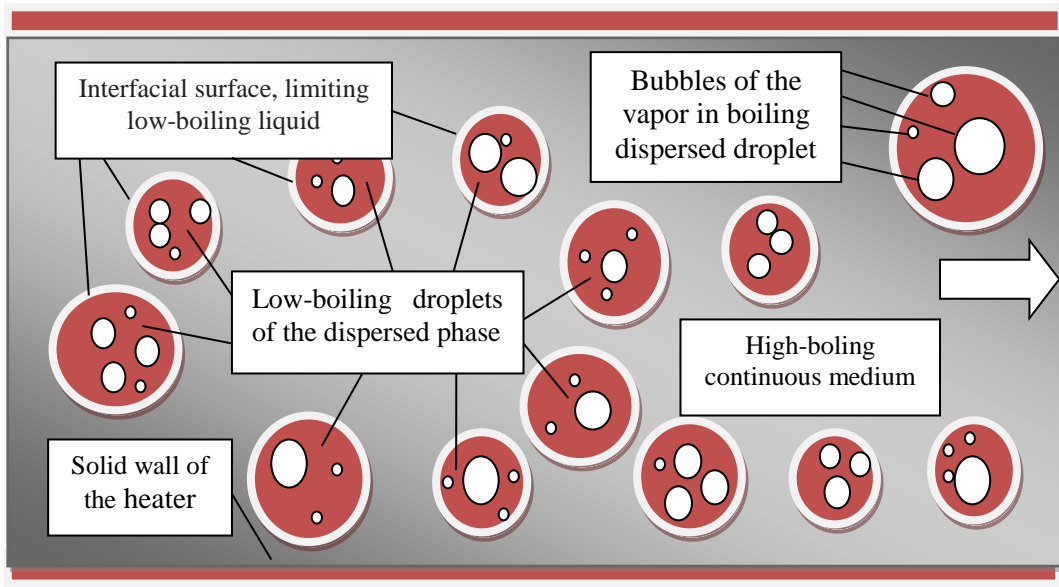


Figure 1: The scheme for nucleate boiling in volume low-boiling dispersed phase limited by the interfacial surface

We write the first law of thermodynamics for vapor bubbles formed in the volume of each droplet of the dispersed phase liquid emulsion with radius R :

$$dQ = dI - V_v dp \quad (4)$$

where dQ is the heat input from the continuum phase to the drops of the dispersed phase, dI is the change of enthalpy of the phase transition, $V_v = 4\pi R_v^3 n / 3$ - total volume of bubbles of vapor phase, the number of which n depends on the level of heat energy input, dp is the pressure change inside of the bubbles.

Express the amount of the energy required for the formation of bubbles of steam in each of the droplets of the dispersed phase, as

$$dQ = q S_{v-l} dt \quad (5)$$

where q is the specific heat flow from the superheated layer interfacial surface bubbles with radius R_v , $S_{g-l} = 4\pi R_v^2 n$ is the total interfacial area of all vapor bubbles in a single drop of the dispersed phase.

The enthalpy change is:

$$dI = \rho_v L dV_v, \quad (6)$$

where ρ_v - density bubbles formed pair, L is the specific heat of vaporization.

The pressure inside the vapor bubbles, which are formed inside of volume the droplets of the dispersed phase, is formed of the following components:

$$p = p_0 + \frac{\sigma_{v-l}}{R_v} + \frac{\sigma_{l-l}}{R_l}, \quad (7)$$

where p_0 is the pressure in the continuous medium of the emulsion, σ_{v-l} - coefficient of surface tension at the interface of vapor and liquid phases in volume drops dispersed phase, σ_{l-l} is the coefficient of surface tension at the interface of the dispersed phase and the continuous medium of the emulsion.

Substituting (5) - (7) in (4) and assuming spherical symmetry of the process of evaporation in a drop of low-boiling liquid, get

$$qS_{v-l} dt = \rho_v L dV_v - V_v dp, \quad dV_v = 4\pi R_v^2 n dR_v, \quad dp = -\frac{\sigma_{v-l}}{R_v^2} dR_v - \frac{\sigma_{l-l}}{R_l^2} dR_l, \\ qdt = \rho_v L dR_v + \left(\frac{\sigma_{v-l}}{R_v} dR_v + \frac{R_v}{R_l} \frac{\sigma_{l-l}}{R_l} dR_l \right). \quad (8)$$

To determine the relationship between R_v and R_l use the law of conservation of mass of separate drops during evaporation:

$$\rho_l V_0 = \rho_v V_v + \rho_l (V_l - V_v), \quad (9)$$

where ρ_l - density liquid phase drops, V_0 and V_l - initial and current volume drops.

The condition of conservation of mass of each droplet with initial radius R_0 , after the formation of n vapor bubbles, having a spherical shape

$$\rho_l R_0^3 = \rho_v n R_v^3 + \rho_l (R_l^3 - n R_v^3) \quad (10)$$

Away from the critical point will $\rho_v \ll \rho_l$. Then due to the change in volume of the dispersed phase due to the formation of bubbles of vapor phase inside the low-boiling droplets are

$$R_l \approx \sqrt[3]{(R_0^3 + n R_v^3)} \quad (11)$$

Taking into account expressions for R_l and dR_l obtained from (11), equation (8) can written as follows:

$$qdt = \rho_v L dR_v + \frac{1}{R_v} \left[\sigma_{v-l} + \frac{n\sigma_{l-l}}{(n + (R_0/R_v)^3)^{4/3}} \right] dR_v \quad (12)$$

The differential equation (12) relative to the size of the vapor bubbles R_v is nonlinear. It is rather greatly simplifies the real situation, to serve as a basis for exact or numerical solutions, like a deeper understanding situations [6]. Equally important is the qualitative analysis of the mechanisms of heat transfer, which considered favorable thermal conditions [7].

Further mechanisms evaporating like steam explosion [8, 9], excluded consideration of the relatively low and constant level of heat flux density in the volume of the continuous medium liquid emulsion. In a first approximation, the number of bubbles n in each individual drop is considered equal to one, assuming the heat flux is insufficient for growth of other viable embryos vapor phase, which potentially also can grow under more favorable conditions.

3 Analysis of the Mechanisms of Growth of Bubbles Within the Volume of Drops Limited Interfacial Surface

Let us consider some limiting cases, when the equation (12) reduced to the linear mind and integrates without the use of numerical methods. So of coarse emulsions, when vapor bubbles notably smaller droplet size of the fluid in which they are formed, i.e. by $R_0 \gg R_v$, equation (12) is substantially simplified:

$$qdt = \rho_v L dR_v + \frac{1}{R_v} \sigma_{v-l} dR_v \quad (13)$$

With sufficiently large size bubbles of steam, when the increase in their linear dimension small compared with the increase in the vapor phase and the second summand in the right hand side can neglected, equation (13) takes well known from the works of other authors form [10-12]:

$$qdt = \rho_v L dR_v, \quad dR_v / dt = q / (\rho_v L) \quad (14)$$

Obviously, in this case, the growth of vapor bubbles limited only by the supply of heat, required for the process of vaporization, and does not explicitly depend on their size. This model corresponds to the conditions boiling in unlimited volume of stationary fluid, where there is no need to consider the availability of the developed interfacial surface.

However, in the case of the very small bubbles, rapidly increasing radius with the increase volume of the vapor phase, on the contrary, the first term of the right side of equation (13) will prevail over the latter. In this limiting case, the rising steam bubbles will be described another equation:

$$qdt = \frac{\sigma_{v-l}}{R_v} dR_v \quad (15)$$

Equation (15) corresponds to a fundamentally different model view, when the growth of fine bubbles within the volume of the droplets of the dispersed phase liquid emulsions limited only by the energy of surface tension forces. Moreover, under these conditions, the role of surface forces with decreasing bubble radius becomes all the more important that, accordingly, there available physical concepts [11].

There are many theoretical and experimental studies [10], that are connected with the initial stage of the phase transition of the liquid - vapor. It is established, that in the superheated liquid can evolve over time, only vapor bubbles, the radius of which exceeds the critical value R_{cr} . For the vapor bubbles of smaller size exist a very high probability of returning them to the liquid phase.

This a priori information corresponds to the initial condition $R_v \Big|_{t=t_0} = R_{cr}$,

which must satisfy the solution of the model equation (15) for the case of vaporization in the limited interfacial surface volume of the superheated fluid.

The model equation (15) is integrated in an analytical form for the stationary flow of heat $q(t) = q_0$, its solution is non-linear:

$$R_v(t) = R_{kp} \exp\left(\frac{q_0}{\sigma_{v-l}} t\right) \quad (16)$$

It is true to a certain bubble size, R^* , when the rate of growth is dependent on increasing the volume of the vapor phase. The dependence of the growth of the steam bubbles exceeding this limit, takes linear:

$$R_v(t) = R^* + \frac{q_0}{\rho_v L} t \quad (17)$$

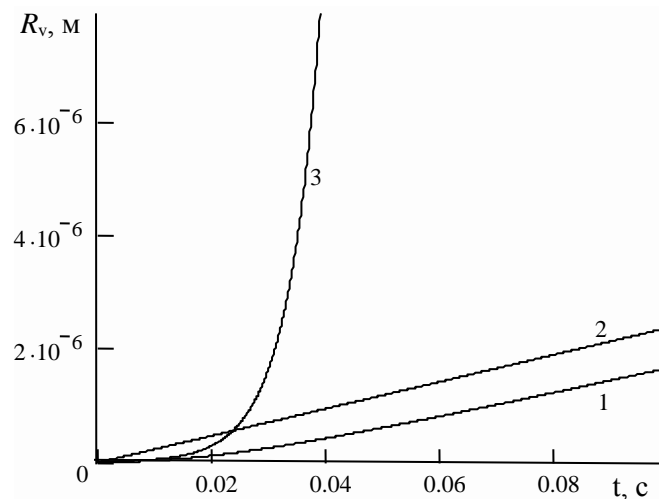


Figure 2: The dependence of the radius of the vapor bubble from time to time with a constant supply of heat to the drop of water with a specific flow $q_0 = 10 \text{ W/m}^2$, corresponding to different model views: 1 - (13), 2 - (14), 3 - (15).

The fig.2 presents the results of numerical solutions of the model equations (13) - (15), thermophysical parameters correspond to conditions when the high-boiling continuous medium dispersed relatively large drops of water. Note that the curve (1), summarizing the growth of vapor bubbles corresponds to the exponential dependence on time, based on the experimental data [12-14].

A comparison of the curve (1) with the curves (2) and (3) shows that the scope is rather narrow and restricted by the size of the bubbles close to the size of critical vapor bubbles under conditions of the fluctuation of formation vapor phase [12]. Conditions initiated by the vaporization meet a wider range of external factors, which are not included in the model equation (12).

4 Conclusions

1. Thermodynamic model of vaporization in the limited volume of the droplets of the dispersed phase liquid emulsion comprises in the range of thermophysical factors are characteristics of interfaces between immiscible liquids forming the emulsion, and between liquid and vapor of the dispersed phase.

2. Mechanisms of heat transfer in the presence of well-developed interfacial surface significantly enhance the physical understanding of the processes of vaporization in an unlimited volume of stationary fluid. Therefore, for the radius of the vapor bubbles close to the critical value obtained exponential relationship between

them and the surface tension coefficient between the vapor and the liquid phase within a volume of low-boiling droplets of the emulsion.

3. The proposed model of growth of vapor bubbles in superheated emulsion (13) with a low-boiling dispersed phase to justify additional physical view for explaining the delay of the boiling.

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