Unsteady model of wall-adjacent boiling subcooled liquid flow

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Abstract. We discuss an approach to constructing a mathematical model of formation and dynamics of the vapor phase on the heat-releasing surface under conditions of unsteady heat flux. We focus on nucleate boiling, since its predictive model is at present most difficult to design. The nucleate boiling stage is described in the form of a homogeneous model that accounts for the heat fluxes associated with the vapor phase presence. The stage of film boiling takes into account the dynamics of a pulsating vapor layer and its heat exchange with subcooled liquid and the heat-releasing surface.

1. Introduction

Determining the dynamics of boiling in the near-wall liquid layer is one of the relevant problems that has been actively studied in recent years. The rapid growth of computing power and development of commercial computing packages allow for involvement of an increasing number of researchers, who to some extent use numerical approaches for the heat transfer description. A huge variety of experimental techniques, including more and more detailed optical diagnostics, laid the foundation for verification of constantly improving numerical simulation methods. As a result, we need significantly more accurate predictive models to describe such key parameters of boiling as vapor phase geometry, nucleation centers density, surface overheating, and heat flux density.

We find the determining of duration of each stage of unsteady boiling particularly important. The vapor phase volume change can be illustrated using the pressure dynamics, which in the case of unsteady heat release has a highly non-linear form (Fig. 1). There are few certain time limits: $\tau_{ONB}$ is the moment of first nucleation, $\tau_g$ corresponds to the nucleation density large enough for the coalescence regime to start, $\tau_{ind}$ is the moment of explosive boiling begins. The most significant increase in the pressure value occurs at the moment of formation of the vapor film that rapidly increases its volume ($\tau > \tau_{ind}$). The nuclear boiling stage precedes this event ($\tau_{ONB} < \tau < \tau_{ind}$) and takes little time. However, the possible evaporation of the heated volume of liquid is determined precisely by these brief moments of time, during which the number of active evaporation centers and the size of an individual bubble grow dramatically. During the nuclear boiling stage, the vapor mass accumulated in the near-wall layer has a dual influence. On the one hand, the bubbles inside superheated liquid layer of liquid, where $T_w>T_s$, intensify heat transfer due to microconvection and heat conduction. On the other hand, the thickening of the effective hydrodynamic layer and the increase in the area of the coated vapor phase results in an inevitable transition to a degraded heat exchange regime, i.e. to the film boiling. Consequently, numerical simulation even of a short-term stage of nucleate boiling is an important objective when describing explosive boiling.
Figure 1. Pressure dynamics under the unsteady heat release.

On the one hand, the best predictions of the diameter value are given by models based on empirical results and expressed in terms of thermal characteristics. Moreover, predictions for the magnitude of temperature give better results than those based on heat flux. To a large extent, this is due to the substantial dependence of the bubble size on the surface temperature. On the other hand, the abundance of possible conditions, such as thermophysical properties of the liquid and the surface, leads to a large range of possible values of the bubble diameter. Even a small variation of the liquid pressure leads to a drastic change in the bubble geometry. Differences in thermophysical properties, the nature of heat generation, and the convective pattern in the neighborhood of the nucleation zone can lead to a large variation of the temperature field. Therefore, generally, we need a detailed picture of the temperature distribution near the heat-releasing surface.

In this regard, it looks promising to use models based on key parameters, one of which is the thickness of the superheated liquid layer. Here we can mention the works [1–3] that present attempts to describe the dynamics of bubble growth through the definition of its extreme heat balance. The main feature of this approach is the possibility to avoid the determination of mechanical characteristics which has become popular in recent years, but does not allow evaluation of the thermal pattern in the neighborhood of nucleation. Analysis of the experiments with unsteady heat release on the technical surface shows that prediction of the evaporation centers density can be successfully done using general knowledge about the thermal state of the surface. The size of a vapor nucleus is so small that its appearance only indirectly depends on the level of subcooling of the liquid or on the nature of heat generation. Thus, the previously developed and successfully applied dependences for determining the evaporation centers density can be extended to unsteady boiling when the vapor nucleus size is negligible comparing to the temperature gradient.

Analysis of the effect of boiling characteristics (evaporation centers density, maximum bubble size, nucleation frequency, etc.) on heat transfer in the near-wall liquid layer revealed the three most important key parameters: thickness of the overheated liquid layer, temperature gradient near the saturation isotherm, and the specific surface area of the heater involved in the nucleate boiling. This conclusion does not imply that we can avoid calculation of classic characteristics of an individual bubble. In the approach proposed, these values \((D_m, f_0, \text{ etc})\) are minor; therefore they depend on the thermal boiling pattern and can be determined with some admissible error.

2. Mathematical model of unsteady boiling of subcooled liquid

The differential equation for the vapor volume has the form:

\[
\rho_v \frac{dV_v}{d\tau} = \dot{m}_{ev} - \dot{m}_{ad},
\]

where \(\dot{m}_{ev}\) correspond to the evaporation and \(\dot{m}_{ad}\) correspond to the condensation of the vapor volume due to the contact with subcooled liquid. The heat transfer equation comprises terms that correspond to heat fluxes associated with the surface boiling and other energy sources. Such fluxes can include
conduction through the superheated liquid layer $q_{csl}$, microlayer evaporation $q_{eml}$, and microlayer conduction $q_{cml}$. It was shown in [4] how they can be used to the homogenous model. Therefore, the liquid temperature can be found from the following equation:

$$\rho_l C_l \frac{\partial T_l}{\partial t} + \rho_l C_l u \nabla T_l = k_l \nabla \cdot \nabla T_l + q_+ , \quad (2)$$

where $q_+$ is a volume heat source and may include other components that account for mechanisms of energy transfer, for example, from laser emission. The size of the heat release region should be calculated on the basis of the current understanding of the mechanics of a particular sub-process. For example, in the case of cumulative jets formation after the laser generated bubble released from the fiber, a region of the heat release could be at least 2 times bigger than the maximum bubble diameter.

![Figure 2. Scheme of the bubble releasing from the surface with formation of the cumulative jet.](image)

The cumulative jets of a size of a bubble sometimes act as a powerful source of heat transfer during nucleate boiling. Figure 2 shows a schematic representation of a cumulative jet penetrating the vapor bubble. Its occurrence is stipulated by a rupture of vapor-surface "bridge" and the subsequent acceleration of interlocking masses of liquids in the lower part of the bubble. After the bubble collapses, a submerged jet of hot liquid is produced, which has a significant velocity. Due to this mechanism, additional mixing of the subcooled deep layers and removal of the saturated liquid from the heat-releasing surface occurs.

The laminar fluid flow problem:

$$(\rho_l \mathbf{u} - \rho_l (\mathbf{u} \cdot \nabla) \mathbf{u} = \nabla \cdot \left[ -p I + \mu (\nabla \mathbf{u} + (\nabla \mathbf{u})^T) \right] , \quad (3)$$

$$\rho_l (\mathbf{u} \cdot \mathbf{u}) = 0 . \quad (4)$$

From the viewpoint of the near-wall liquid boiling dynamics, the most important values determined from equation (2) are the thickness of the superheated liquid layer, defined as the distance between the heat-releasing wall and the saturation isotherm:

$$\delta_s = r_{T_r = T_s} \quad (5)$$

as well as the temperature gradient in the area of the saturation isotherm $dT_l / dr \bigg|_{r=\delta_s}$, since its value determines the intensity of heat transfer in the neighborhood of condensing vapor structures. Based on
the density of nucleation $N_a$ and the average diameter of the bubbles $\bar{d}$, we can determine the specific surface area covered with vapor as:

$$F_v = \bar{d}N_a$$

(6)

In turn, the volume of vapor determines the boiling mode. Once the surface is covered with vapor bubbles to a certain extent, $F_v = F_{tg}$, the bubbles begin to stick together forming a close-packed layer. For the range $F_{tg} < F_v < 1$, it is necessary to use the components of the nucleate boiling heat flux proportionally. Following this, as the heater surface temperature rises, a layer of bubbles turns into a vapor film that does not let cold liquid enter.

Thus, the calculation of unsteady explosive boiling and the dynamics of the vapor phase is carried out step by step:

1. Heat the surface to $T_{ONB}$. The calculation is carried out by solving equations (2)–(4). The appearance of the first bubble. $F_b = 0$.
2. Boiling with single bubbles occurs. The calculation of this stage has no particular difficulties and requires the solution of equations (1)–(6). $F_b > 0$.
3. Mixed mode. The surface is partially covered with coalescence bubbles, forming zones of reduced heat transfer. $F_b > F_{tg}$.
4. The surface is completely covered with bubbles, $F_b = 1$, which evolve into the vapor film that does not let cold liquid enter. The next mode is accompanied by a cyclic increase and drop in pressure due to the pulsation of the vapor film. Detailed modeling of the pressure dynamics of this stage is described in [5].

Conclusion

We have presented an approach that makes it possible to consider all the key stages of unsteady explosive boiling of subcooled liquid as part of the calculation of a single mathematical model: heating, formation of individual bubbles, developed nucleate boiling and transition to film boiling. Further development of this approach will include effects of the vapor film rupture in case of instability on the interface surface and mixed boiling modes (for example film boiling with short periods of nucleate boiling).

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