Influence of the thermal parameters on the bubble heat balance at transient boiling of subcooled water

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Abstract. This paper considers the development of the approach presented [1–3] to the determination of heat transfer in subcooled boiling flow additively from the components of forced convection and heat fluxes associated with the presence of bubbles on the surface. The case of non-stationary heat release in a vertical channel with an uprising fluid was numerically studied on the basis of the experimental data from [5]. We have studied the effect of the fluid subcooling and the heat flux on the characteristics of transient boiling.

1. Introduction
The subcooled liquid is widely used in heat transfer and cooling devices, since it allows removing heat with greater intensity than in case of saturated flow. The formation, growth and collapse of bubbles on the heater surface contribute to the heat transfer enhancement, creating additional heat fluxes. Recently, many papers have been published [3,4] that address calculations of such fluxes based on new experimental data on the bubble growth dynamics and nucleation density. When constructing numerical models of boiling, many authors obtained highly reliable results, but for a limited range of conditions. The reason for this is a large number of closure relations included in the models that describe such key parameters such as the bubbles lifetime, their maximum or lift-off diameter, the size of dry spots and thickness of the superheated liquid layer etc. Given the high variability of the wall boiling conditions (temperature of the flow and heat wall, flow rate, pressure in the system, heat flux, surface wettability etc.), we can hardly expect that the use of semi-empirical models will be successful. Therefore, in recent years, researchers are motivated to focus their studies on the influence of boiling conditions on the simplest individual submodels of heat transfer and/or mechanical equilibrium. In this paper, we consider such components of an individual bubble heat flux as heat flux of the bubble initial evaporation, \( q_{ei} \), microlayer evaporation heat flux, \( q_{eml} \), heat flux of the heat conduction through the microlayer, \( q_{cml} \), heat flux of the heat conduction through the superheated layer, \( q_{cs} \), and their sum, \( q_b \). We study the influence of such parameters such as subcooling, \( \Delta T_{\text{sub}} \), heater surface temperature, \( T_w \), overall heat flux, \( q_{\text{tot}} \), and wall heating rate \( \partial T/\partial t \) on the calculation of heat fluxes. When calculating the heat fluxes, we used the experimental data presented in Levin and Khan [5].
2. Heat transfer model for transient boundary layer

In this paper, we further elaborate on the application of the numerical model presented in [6]. The system of differential equations describing the coupled problem of heat transfer under conditions of forced convection is complemented by closing relations for the heat exchange with bubbles on the surface. The bubble heat flux consists of the thermal fluxes of the initial evaporation of the bubble, \( q_{ei} \), the evaporation of the microlayer, \( q_{eml} \), the thermal conductivity of the microlayer \( q_{cml} \) and the thermal conductivity of the superheated layer, \( q_{cs} \):

\[
q_b = q_{ei} + q_{eml} + q_{cml} + q_{cs}.
\] (1)
Here, the heat balance components are defined as:

\[ q_{ei} = h_l \rho_l \frac{\pi D_{ml}^3}{6} f N_a \]

(2)

\[ q_{eml} = h_l \rho_l \delta_{ml} \frac{\pi D_{ml}^2}{6} f N_a \]

(3)

\[ q_{cml} = \frac{N_a \pi k_l (T_{w} - T_{s}) D_{ml}^2}{4 \delta_{ml}} \]

(4)

\[ q_{cs} = N_a \int_{r_{w}+\delta_{s}}^{r_{w}+\delta_{ml}} k_l (T_{w} - T_{s}) \pi \left( \frac{D_{ml}}{r - r_{w}} - 2 \right) dr, \]

(5)

where \( D_{ml} \) is the diameter of the microlayer; \( h_l \) – latent heat; \( T_w \) – surface temperature; \( T_s \) – saturation temperature; \( D_m \) – maximum bubble diameter; \( k_l \) – thermal conductivity; \( N_a \) – nucleation density; \( f \) – nucleation frequency; \( \rho \) – density; \( \delta_s \) – thickness of superheated liquid layer; \( \delta_{ml} \) – thickness of microlayer.

Figure 3. Individual components of the heat balance in the wall liquid layer under unsteady heat generation depending on the surface overheating.

Nucleate density for the unsteady case was satisfactory predicted by following correlation [6]:
\[ N_a = 10^6 \cdot [\exp(0.14(T_w - T_{ONB}) - 1)]. \]  

Relative influence area \( F_b \), within which equation (1) is responsible for taking into account the heat balance in the wall liquid layer, is defined as a part of the heating surface fully covered by bubbles of diameter \( D_m \):

\[ F_b = \frac{2}{3} N_a D_m^2. \]  

Figure 1 presents the influence of the liquid temperature and the heater surface on the surface area with nucleate boiling. The increase of \( \Delta T_{sub} \) from 12 K to 72 K leads to decrease of \( F_b \) from 80 to 20%. The exponential nature of the dependence of the area influencing the wall temperature is reflected by formula (6). A significant decrease in the share of the heater surface covered with steam should diminish the role played by the components of the heat balance (2)–(5) when we reduce the initial liquid temperature \( T_0 \).

The dependence of the calculated values of the heat flux \( q_{tot} \) on the temperature head \( \Delta T_w \) demonstrates an increase in the intensification of heat transfer with a decrease in the liquid temperature of the liquid \( T_0 \) (figure 2). The influence of the liquid subcooling on the heat flux exceeds the results obtained by other authors for stationary boiling. This can be explained by the significantly smaller thickness of the superheated liquid layer in the case of a rapidly increasing surface temperature.
Analyzing the influence produced by the heat releasing surface temperature and the total value of the heat flux into the liquid on the components of the heat balance in the boundary liquid layer (figures 3 and 4), we can observe some common features: the greatest contribution to the overall heat transfer from heat conduction through the overheated layer of fluid $q_{cs}$; the second most important (about 80% of $q_{cs}$) term in the balance is the heat transfer associated with the final condensation of the vapor bubble ($q_{ei}$); the thermal conductivity through the liquid microlayer under the bubble $q_{cml}$ is about 50% of $q_{ei}$; the heat of evaporation of the liquid microlayer $q_{eml}$ is approximately equal to 25% of $q_{ei}$. As expected, an increase in the liquid subcooling leads to a significant decrease in the components $q_{eml}$, $q_{cml}$, $q_{cs}$, $q_{ei}$ under the increase of the general heat flux $q_{tot}$, because the area covered by bubbles $F_b$ decreases.

Using empirical estimates for such nucleate boiling characteristics such as the maximum bubble diameter, nucleation frequency, and nucleation site density, the heat balance components can be written as follows:

\[
q_{ei} = C_i(e^{0.14\Delta T_{w}} - 1)\Delta T_{w}^2 \quad (8)
\]
\[
q_{eml} = C_{eml}(e^{0.14\Delta T_{w}} - 1)\Delta T_{w} \quad (9)
\]
\[
q_{cml} = C_{cml}(e^{0.14\Delta T_{w}} - 1)\Delta T_{w}^2 \quad (10)
\]
\[
q_{cs} \approx C_{cs}(e^{0.14\Delta T_{w}} - 1)\Delta T_{w}^2 \ln \Delta T_{w} \quad (11)
\]

where $\Delta T_{w} = T_w - T_{ONB}$, and $C_i$ are the values that do not depend on the wall overheating. It follows from (8)–(11) that the heat balance components can be ordered with the respect to the increase in the heat flux growth when the wall overheating increases: $q_{eml}$ has the smallest size, then $q_{ei}$ and $q_{cml}$ follow, while $q_{cs}$ has the biggest growth rate. Estimating the influence of factors from equations (8)–(11), we can also conclude that the nucleation site density dominates the heat transfer process in the wall liquid layer.

**Conclusions**

Under the conditions of unsteady heat release into a subcooled liquid flow, variations of the wall temperature, the initial temperature and the value of the heat flux, the density nucleation centers are influenced more than the size of bubbles. We can assume that this effect will become stronger with the increase in pressure. The increase in the total heat flux from the wall into the liquid under increasing subcooling is caused by a significant decrease in the superheated layer thickness. In this case, the values of heat flux components associated with the presence of the vapor phase are significantly reduced, since a decrease in nucleation density has a greater effect on heat transfer in general than an increase in heat transfer in the neighborhood of a single bubble. It is worth noting that our research does not cover coalescence nucleate boiling, for which a more complex heat transfer model should take into account the mutual influence of the nucleation spots.

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