非定常沸騰熱伝達の数値シミュレーション

Numerical Simulation of Boiling Heat Transfer by Transient Heating

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A numerical simulation for transient pool boiling heat transfer was carried out in this study. Combining transient heat conduction with macrolayer model of Maruyama, we simulated the transient boiling curve for water and fluorinert FC-72(C_6F_{14}). The results are: (1) For lower transient heating rates, the boiling curve in the nucleate boiling regime remains the same as the steady-state curve. For higher transient heating rates, the nucleate boiling curve deviates from the steady-curve. (2) The critical heat flux increases with increasing heating transients. Th changes of macrolayer and void fraction were also investigated. The results imply that the evaporation of macrolayer may have an important effect on the increase of critical heat flux under transient heating.

Key Words: Transient Boiling, Macrolayer, Critical Heat Flux, Numerical Simulation

Introduction

Transient boiling processes are very important in steel production and safety evaluations in nuclear reactors. A large number of experimental studies on transient pool boiling have been conducted. Most of these boiling processes were carried out with linear or exponential power increasing. Recently, Hohl et al performed pool boiling experiments with controlled wall temperature transients. They obtained transient boiling data using a cylindrical copper block of 10-mm thickness and 34mm in diameter in a pool of saturated liquid FC-72. The experiment revealed that the characteristics of the transient boiling curve changed with wall temperature transients. The critical heat flux increases with increasing heating transients and decreases with cooling transients.

The theoretical treatments of the problem have been reported by Pasamehmetoglu et al and Zhao et al. Pasamehmetoglu et al provided a model for predicting transient CHF in saturated pool boiling. The developed model includes the analysis of thermal energy conduction within the heater coupled with a macrolayer-thinning model. The prediction indicated favorable agreement with the experimental data except the fast transient when the exponential period of heat generation rate t_m is less than 20ms. However, the prediction was just compared to that of the heater of small diameter wires. In fact, the analytical model is based on the assumption that for the critical heat flux, the vapor bubble departs only when the macrolayer is dried out completely. This is inconsistent with the experiment by Kirby & Westwater. Zhao et al recently put forward a model for transient pool boiling heat transfer basing on the microlayer model by themselves. In their model, the evaporation of the microlayer below the individual bubbles were considered to play an important role in the nucleate boiling heat transfer. For the transient heating, they assumed that the population of individual bubbles increases with time and in each time-step a new group of bubbles with the same size form and grow up. Although the prediction showed the same tendency with the experimental data, it employed too high heating rate to be realized in practical experiments for a horizontal surface.

In this paper, in order to investigate the mechanism of transient boiling, we developed the macrolayer model for steady state by introducing the analysis of transient heat conduction within the heater. The transient boiling curves for water and FC-72 were predicted. The transient behavior of pool boiling may be understood in some degree through this simulation. First, we will explain the macrolayer model for transient pool boiling.

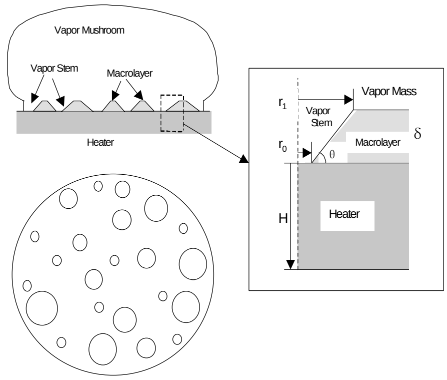

Fig.1 Model of heat conduction and evaporation near the liquid-vapor interface

Method of Numerical Simulation

Fig. 1 shows the schematic of the top and side views of a vapor bubble over a heated surface. In this study, we assumed that the macrolayer evaporation model could be extended to the transient pool boiling. The macrolayer forms cyclically. While the vapor mass departed from the surface, the macrolayer replenished immediately without a transition period between the departures of two vapor masses. From the heater surface, heat is conducted into the macrolayer and is utilized in evaporation at macrolayer-bubble interface. Therefore, the thickness of macrolayer is written as

$$\delta(t) = \sqrt{\delta_0^2 - 2\frac{\lambda \Delta T}{\rho_l H_{fg}} t} \tag{1}$$

For the liquid-vapor stem, we suppose that the heat from the heated surface is conducted into the sloped area and is applied in the evaporation at the stem-liquid interface. Therefore, the growth

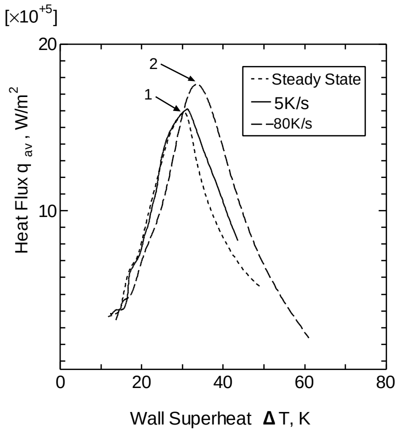

Fig. 2 Transient Boiling Curve of Water

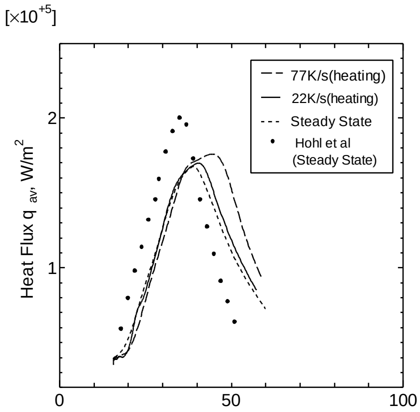

Fig. 3 Transient boiling curves of FC-72

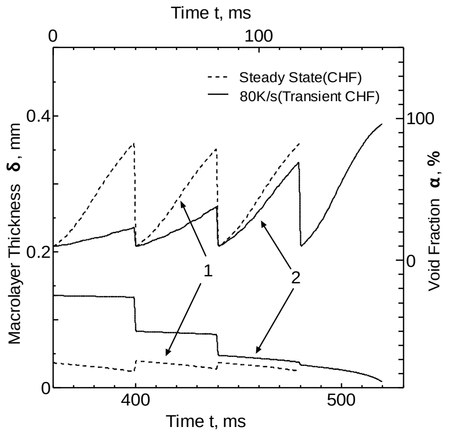

Fig. 4 Changes of Macrolayer and Void Fraction for Steady and Transient Heating

rate of vapor stems can be expressed as

$$\frac{dr_s}{dt} = \frac{1}{\rho_l H_{fg}} \frac{\lambda \Delta T}{\delta}\left[1 + \log\left(\frac{\delta}{\delta_m}\right)\right] \tag{2}$$

where dr_s/dt is related to the change rate of void fraction $d\alpha/dt$. δ_m is the minimum thickness of macrolayer which can be obtained through the upper limit heat flux q_m. It's given by

$$q_m = \frac{\rho_l}{\rho_l - \rho_v}\frac{\rho_v H_{fg}}{T_{sat}}\frac{H_{fg}}{(2\pi RT)^{1/2}}\Delta T \tag{3}$$

With above parameters, the instantaneous heat flux is formulated as

$$\begin{aligned} q_k &= \rho_l H_{fg}\left(-\frac{dw}{dt}\right) \\ &= \rho_l H_{fg}(1-\alpha_1)\left(-\frac{d\delta}{dt}\right) + \rho_l H_{fg}\,\delta\frac{d\alpha_1}{dt} \\ &= q_{\alpha_1} + q_\delta \end{aligned} \tag{4}$$

the initial macrolayer thickness is estimated according to Haramura & Katto's hypothesis, i.e.

$$\delta_0 = 0.0107\,\sigma\rho_v\left(1+\frac{\rho_v}{\rho_l}\right)\left(\frac{\rho_v}{\rho_l}\right)^{0.4}\left(\frac{H_{fg}}{q_{av}}\right)^2 \tag{5}$$

Where q_{av} is referred to as the averaged surface heat flux the departed vapor mass takes off. The input heat rate from the bottom was set to increase linearly. In addition, one-dimensional transient heat conduction within the heater was also considered. The equation is

$$\frac{\partial T}{\partial t} = a\,\frac{\partial^2 T}{\partial x^2} \tag{6}$$

subjecting to the following initial and boundary conditions

$$t = 0,\ q_k = q_{in0},\ T_w = T_0 \tag{7}$$

$$x = 0,\ -\lambda\frac{\partial T}{\partial x} = q_k \tag{8}$$

$$x = H,\ -\lambda\frac{\partial T}{\partial x} = q_{in} \tag{9}$$

Employed explicit FDM, the instantaneous surface temperature can be obtained. Therefore, the instantaneous heat flux can be calculated by applying surface temperature into the macrolayer model. The averaged heat flux increases with the time and reaches the peak value. Because the initial thickness of macrlayer was supposed to be determined by the averaged heat flux the vapor mass takes off, the averaged heat flux will decrease automatically. Therefore, we considered the peak value as the critical heat flux. There're few available data about initial macrolayer in the transition boiling regime, thus, we employed the extrapolated value of the obtained nucleate boiling curve to determine the initial thickness of macrolayer.

Results

The incipient boiling superheats of water and FC-72 were set at 10K and 15K respectively. The simulated area is 10mm in diameter and the heater is copper with 10mm in thickness. The bubble departure periods of water and FC-72 are calculated as 40ms and 30ms respectively. Fig.2 shows the transient boiling curves of water. The boiling curves of FC-72 are plotted in Fig. 3. From these two figures, we can see that the boiling curves change with the heating rates. For lower transient boiling curves almost remain the same as the steady-state curve. Beyond the steady-state CHF, the nucleate boiling curves extend until the transient CHF is reached. For higher transient heating rate, the boiling curves deviate from the steady-state curve and the CHF becomes much higher. The experimental data by Hohl et al are also plotted in Fig. 3. As can be seen, the simulated results are reasonable and compared to experimental data. Fig.4 shows the changes of macrolayer thickness and void fraction of point 1 and point 2. We can see that the macrolayr thickness of point 2 is thicker than that of point 1, whereas the changes of void fraction α of point 1 and point 2 have little difference. This may suggest that because of the thicker macrolayer, the transient CHF becomes higher than the steady-state CHF.

Nomenclature

g	gravitational acceleration, m/s^{-2}
H_{fg}	Latent heat of vaporization, J/kg
q_k	instantaneous heat flux, W/m^2
q_{av}	time averaged heat flux, W/m^2
r_s	radius of a vapor stem, m
r	radial coordinate from the center of a vapor stem, m
α_1	void fraction
δ	macrolayer thickness, m
δ_0	initial thickness of macrolayer, m
q_m	Gambill-Lienhard upper limit heat flux, W/m^2
δ_m	macrolayer thickness corresponded to q_m, W/m^2
α	thermal diffusivity, m^2/s
σ	surface tension, N/m
τ	bubble departure period, s
λ	thermal conductivity, W/mK
θ	contact angle
ρ_l	density of liquid, kg/m^3
ρ_v	density of vapor, kg/m^3
t	time, s
T_w	surface temperature, °C

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