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Characteristics of a liquid microlayer formed by a confined vapor bubble in micro gap boiling between two parallel plates

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ABSTRACT

The microlayer thickness formed between an elongated bubble and the heating surface during boiling in a parallel microchannel was measured directly using the laser extinction method. Microchannels with gap sizes of $s = 0.15$, 0.30, and 0.50 mm were used as test channels. Water, ethanol, toluene, and HFE7200 were used as testing fluids. The effects of gap sizes, the velocity of the bubble forefront, and the distance from the bubble inception site were investigated. Furthermore, the progress of bubble growth in two dimensions with acceleration was simulated by the volume of fluid (*VOF*) method using the computational fluid dynamics (CFD) package of FLUENT12.1. The microlayer thickness calculated from the simulation results shows relatively good agreement with the experimental results. The effects of the physical properties on the configuration of the microlayer were analyzed, and the characteristics of the microlayer in low- and high-velocity regions were qualitatively clarified. An empirical correlation for the microlayer thickness as the function of the Capillary number, the Weber number, and the Bond number in parallel mini/microchannels was proposed using dimension analysis. The present correlation predicts the experimental results within an accepted error range.

1. Introduction

Boiling in mini-/microscale channels is becoming increasingly important in various applications because this technique is capable of removing large amounts of heat over small areas. However, phase-change heat transfer mechanisms and characteristics at the microscale are distinctly different from those at the macroscale. In microchannels, bubbles nucleate and quickly grow to the channel size such that elongated bubbles that are confined by the channel walls are formed, and these bubbles grow very quickly in length, with a dynamic tip. A microlayer is formed between the bubbles and the inner heating plate walls after the dynamic tip of the bubble. The bubble inside the microchannel is confined such that the tip is an extremely small part, whereas most of the bubble is surrounded by a microlayer that is approximately parallel to the heating plate. The transient evaporation of the microlayer underneath the elongated bubbles is considered to be a major heat transfer mechanism. As such, the microlayer formed by the movement of the vapor–liquid interface has been investigated theoretically and experimentally in numerous studies.

Taylor [1] conducted experiments on a glass tube with a diameter of 2–3 mm filled with a glycerin–water solution that could be varied to cover a wide range of capillary numbers and measured the amount of liquid remaining on the tube wall after an air bubble propagated through the glass tube. The thickness of the film deposited on the wall by the propagating bubble was demonstrated to increase with an increase in capillary number. Bretherton [2] theoretically derived a prediction method for the microlayer thickness based on a lubrication approximation for the limit of $Re \ll 1$ while neglecting gravitational forces. Bretherton suggested that the liquid layer thickness could scale with the capillary number. For the limit of slow flow, Aussillous and Quere [3] proposed a first-order analysis using scaling arguments. Based on their experimental results, a correlation of microlayer formation at the steady high-velocity region was proposed as $\delta/r = 1.34Ca^{2/3}/(1 + 1.34 \times 2.5Ca^{2/3})$, where δ is the thickness of the microlayer; r is the radius of the microtube; Ca is the Capillary number ($=\mu_L V_L/\sigma$), where σ, μ_L, and V_L are the surface tension, viscosity, and velocity of the bubble forefront, respectively, and coefficient 1.34 was derived by Bretherton [2]; and the coefficient 2.5 is empirical. The mechanism of microlayer formation under steady, adiabatic conditions has nearly been clarified. Under a slow-motion limit of bubbles with negligible inertia, the microlayer thickness is determined by the balance between the viscous and capillary forces near the bubble tip; thus,

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the microlayer thickness (normalized by the tube radius or gap size) is only dependent on the capillary number Ca and approaches a finite value as Ca increases. As the steady propagation speed of a bubble increases, the inertial effects cannot be neglected in the problem. The inertial term has to be taken into account, and we must employ the steady Navier–Stokes equation instead of the Stokes equation to describe the problem [4]. Aussillous and Quere [3] also investigated the inertia effect using low-viscosity liquids and found that above a threshold of Ca, the microlayer is thicker than the correlation derived from the Stokes equation. They analyzed the problem by scaling the steady Navier–Stokes equation and found that the nondimensional microlayer thickness could be correlated as

$$\frac{\delta}{r} \sim \frac{Ca^{2/3}}{1 + Ca^{2/3} - We} \tag{1}$$

which agrees with the trend that the inertia thickens the film thickness; however, it seems that the coefficient and exponent require modification based on the experimental or numerical results. Otherwise, this is only valid for $We < 1$.

Using a laser focus displacement meter, Han and Shikazono [5] measured the thickness of a microlayer formed in adiabatic slug flow in microtubes with diameters of 0.3, 0.5, 0.7, 1.0, and 1.3 mm. They confirmed that the liquid microlayer thickness is determined only by the capillary number at a small Ca and the effect of the inertial force on the microlayer thickness is negligible. However, as Ca increases, the effect of inertia is not neglected. Based on the measurement results, a correlation was obtained as

$$\frac{\delta}{D_i} = \begin{cases} \dfrac{0.67Ca^{2/3}}{1+3.13Ca^{2/3}+0.504Ca^{0.672}Re^{0.589}-0.352We^{0.629}} & (Re < 2000) \\ \dfrac{106.0\left(\frac{\mu^2}{\rho\sigma D_i}\right)^{\frac{2}{3}}}{1+497.0\left(\frac{\mu^2}{\rho\sigma D_i}\right)^{\frac{2}{3}}+7330\left(\frac{\mu^2}{\rho\sigma D_i}\right)^{0.672}-5000\left(\frac{\mu^2}{\rho\sigma D_i}\right)^{0.629}} & (Re > 2000) \end{cases} \tag{2}$$

With regard to microchannel boiling, bubbles nucleate and quickly grow to the channel size such that elongated bubbles are formed; these are confined by the channel walls and grow nonlinearly in length owing to the rapid evaporation of the microlayer (see Fig. 1 by Utaka et al. [6]). This requires using the full Navier–Stokes equations rather than the Stokes equations or steady Navier–Stokes equations that neglect local acceleration. However, there are not sufficient published studies on microlayer formation under accelerated motion [4] (see Fig. 1).

Moriyama and Inoue [7] reported that the microlayer thickness follows one of two trends as the interface traveling velocity increases. They considered that a transition in the controlling mechanism occurred in the range of their experimental conditions.

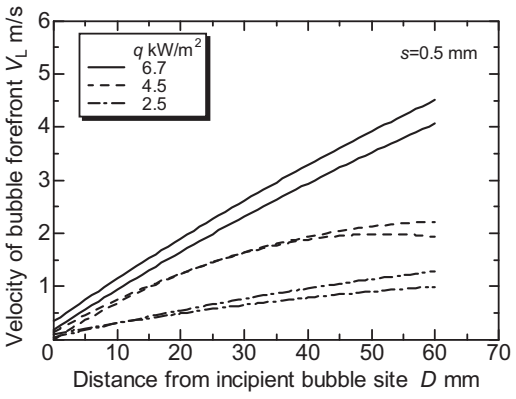

Fig. 1. Velocity of bubble forefront increasing with distance from bubble site by Utaka et al. [6].

Two regimes for microlayer formation in their experimental study were identified according to whether the Bond number, $Bo = \frac{\rho D_i^2}{\sigma}\left(\frac{U^2}{2D}\right)$ (which is calculated using the approximately constant acceleration of interface movement rather than gravity) is greater than 2 as Eq. (3),

$$\frac{\delta}{s} = \begin{cases} 0.07Ca^{0.41} & (Bo \leqslant 2) \\ 0.10\left[\frac{1}{s}\sqrt{\frac{\mu_L t_g}{\rho_L}}\right]^{0.84} & (Bo > 2) \end{cases} \tag{3}$$

where s is the distance between the two parallel plates; D is the distance from the bubble forefront to the incipit site; t_g is the bubble growth time; and μ_L and ρ_L are the viscosity and density of the liquid, respectively. Han and Shikazono [8] assumed that under accelerated conditions, the bubble nose curvature is affected by the viscous boundary layer. Based on the measured results of the microlayer thickness under adiabatic conditions affected by the acceleration for the circular tube, a modification coefficient $f = 0.692Bo^{0.414}$ was obtained by least-squares fitting of the data at $Bo > 1$. Then, a correlation using the Bond number, Bo, for the data at $Bo > 1$ is proposed as

$$\frac{\delta}{D} = \frac{0.968Ca^{2/3}Bo^{-0.414}}{1 + 4.838Ca^{2/3}Bo^{-0.414}} \tag{4}$$

Based on a review of the literature, an insufficient number of studies have examined the accelerated motion of bubbles confined in mini-/microchannels with respect to boiling when the bubble grows nonlinearly due to rapid evaporation of the microlayer. In the present study, to clarify the formation mechanism of the microlayer, the initial microlayer thickness—which is defined as the thickness of the microlayer just after the bubble tip at the location at which the interface between the vapor and the liquid is approximately parallel to the heating plate, as shown in Fig. 2—was measured directly using a laser extinction method for the test fluid of water, ethanol, toluene, and HFE7200. In addition, the progress of bubble growth in two dimensions with acceleration was also simulated by the volume of fluid (*VOF*) method using the computational fluid dynamics (CFD) package of FLUENT12.1. Furthermore, a nondimensional correlation was obtained based on the measurement data and numerical studies.

2. Nomenclature

A	extinction coefficient (m^{-1})
a	acceleration (m/s^2)
D	distance from bubble inception site (mm)
I	laser intensity
I_0	incident laser intensity
s	gap size (mm)
V_L	local bubble forefront velocity (m/s)
δ	microlayer thickness (μm)
δ_0	initial microlayer thickness (μm)
δ_{0n}	nondimensional initial microlayer thickness $\delta_{0n} = \delta_0/s$
δ_V	viscous boundary layer thickness (μm)
μ	viscosity (Pa s)
σ	surface tension coefficient (N/m)
ρ	density (kg/m^3)
Ca	capillary number $\frac{\mu_L V_L}{\sigma}$
We	Weber number $\frac{\rho s V_L^2}{\sigma}$
Bo	Bond number $\frac{\rho s^2 a}{\sigma}$