Hydrodynamics of single departing slug on downward-facing nucleate boiling with various orientation

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1. Introduction

In this study, dynamics of a single slug in nucleate boiling on downward-facing surface, i.e. mushroom, were investigated via quantitative analysis using high speed visualization method. Slug formation and departure were main heat transfer mode until critical heat flux (CHF), so its behavior is supposed to have close relation with boiling performance, i.e. boiling heat transfer coefficient (BHTC) and CHF. In this reason, its understanding is a key issue in order to explain dramatic deterioration of boiling performance on downward-facing surface; i.e. how and when the slug departs from the surface and how fast and big the departing slug is. Synchronized two high speed camera were employed to capture the three-dimensional shape of the slug according to time, so its departing frequency, diameter, speed, and evaporation rate were quantitatively measured according to surface orientation and heat flux condition by volume-based analysis.

2. Methods and Results

2.1 Pool boiling experiments

Nucleate pool boiling experiments were conducted at atmospheric pressure corresponding to orientation angles of the heater in the downward-facing range: 120, 135, 150, 160, and 170°. Fig. 1. shows schematics of the experimental apparatus [1]. The system consisted of a container vessel, a main heater mount, and a data acquisition system. The container vessel could maintain saturated distilled (DI) water of 27 L without water level loss at atmospheric pressure, using a cartridge heater of 700 W and a reflux condenser open to the air. Via visualization windows in its front and back sides, bubble dynamics was visualized using two high-speed cameras. The main heater mount had a mirror-polished silicon wafer heater (20 mm × 25 mm × 475 μm), and its orientation was controlled by a worm gear. The silicon heater had an electrical insulation layer of 500 nm SiO_2, and a platinum film heater (10 mm × 15 mm) was deposited on its bottom side and connected to a DC power source. The platinum film generated heat by Joule heating. We measured wall temperature as an RTD (resistance temperature detector), by measuring the voltages applied to the Pt film and reference resistance with the data acquisition system.

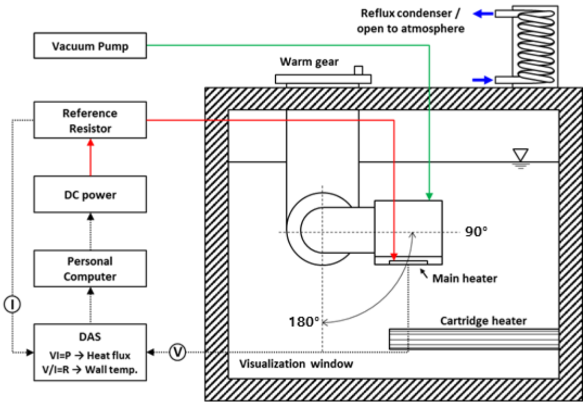

Fig. 1. Experimental apparatus

2.2 Image analysis

As shown in Fig. 2., two synchronized high speed camera captured the slug from side view (fig.2-a) and top view (fig.2-b) with 1,000 frame per second. From the images, thickness and width of slugs were measured with respect to the slug flow direction, and by integration (fig.2-c), the volume of slug were quantitatively measured for each time.

Volume generation rate by evaporation could be calculated by differentiation of slug volume. Accordingly, departing speed of slug could be calculated by differentiation of center of mass of slug. Moreover, mean departing frequency could be counted from captured images, and using frequency data, the departing volume of slug could be calculated.

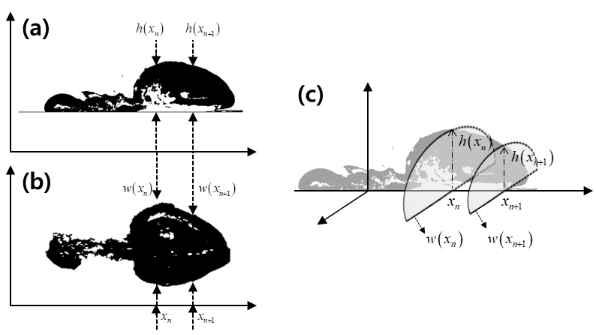

Fig. 2. Image reduction process; by coupling (a) side view image and (b) top view image, volume of slug was measured by integration according to each times

2.3 Boiling performance

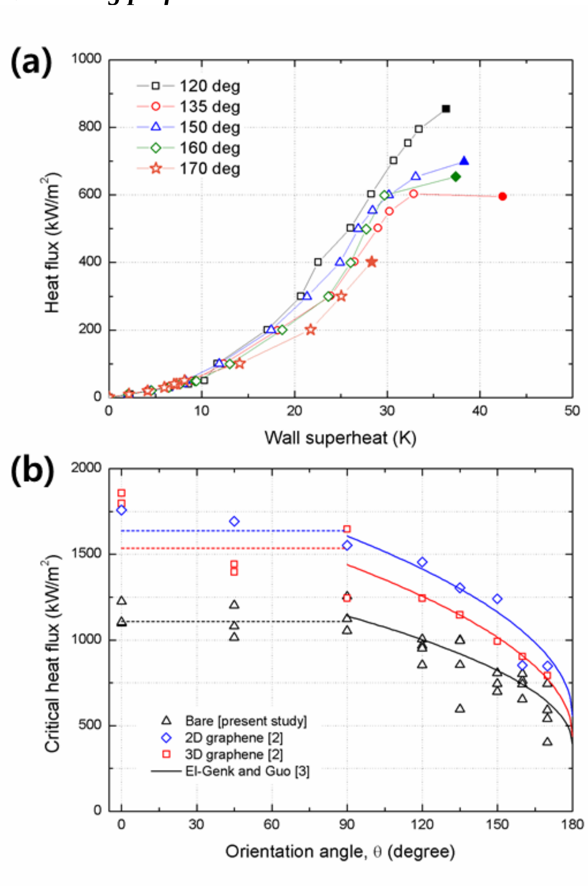

Fig. 3. (a) Boiling curve, and (b) CHF vs orientation

Fig. 3-a shows boiling curves according to surface orientation. The filled symbols indicate CHF points at each orientation. As orientation angle increased, BHTC and CHF performance were deteriorated, which was consistent with previous reports [2-4]. Fig. 3-b shows CHF performance with respect to orientation angle. From vertical (90°) to downward (180°), the CHF dramatically decreased even when the surface was modulated with graphene for CHF enhancement, and their CHF deteriorations were known to have a trend with orientation angle, as a form of following correlation [2, 3].

$$q''_{CHF} = C_{CHF}(\theta) \times \rho_g h_{lg} \left[\frac{\sigma(\rho_l - \rho_g) g}{\rho_g^2} \right]^{1/4} \quad \text{Eq. (1)}$$

$$C_{CHF,bare}(\theta) = A + B(180 - \theta)^{0.5} \quad \text{Eq. (2)}$$

where ρ_g, ρ_l, h_{lg}, and σ are vapor density, liquid density, latent heat, and surface tension, respectively. Here, A and B are fitting factors.

Eq.(2) indicates that the effect of surface modification and the effect of orientation angle act on CHF performance independently, so that the orientation effect could be analyzed focusing on bubble dynamics in far-field region, which could be distinguished from macrolayer in near-field region.

2.4 Slug dynamics

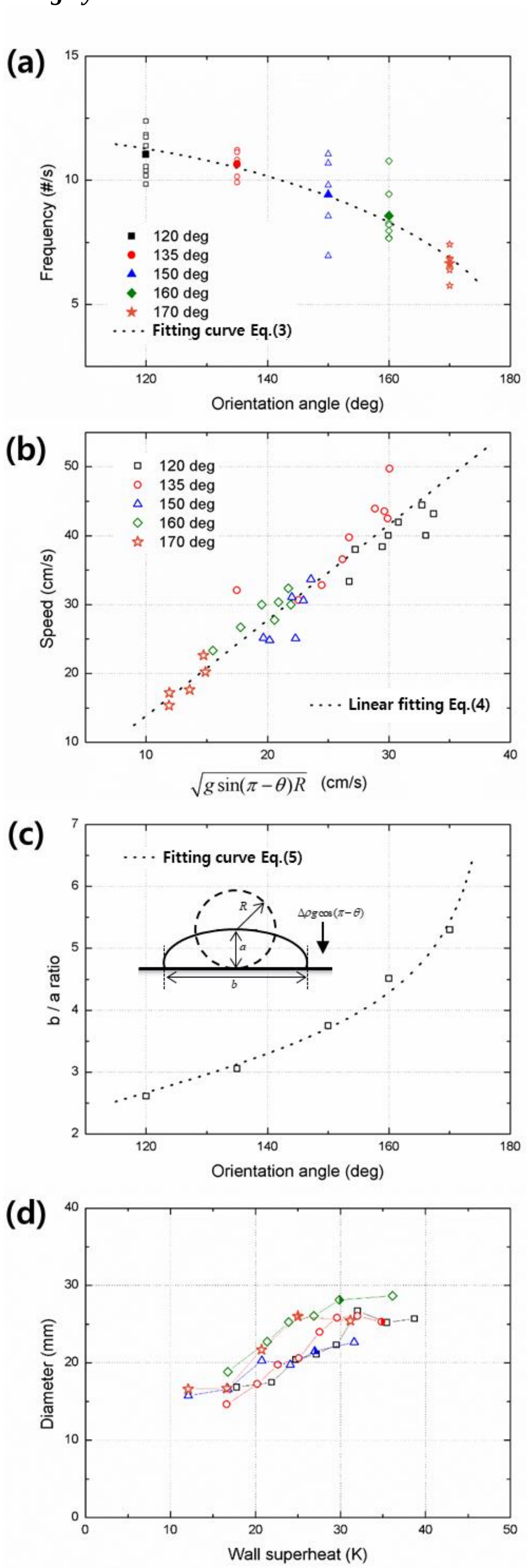

Fig. 4. Departing slug dynamics [1]; (a) frequency and (b) speed, (c) deformation ratio, and (d) equivalent diameter

In our previous work [1], the dynamics of departing slug were measured, i.e. frequency, speed, deformation ratio, and equivalent diameter, as shown in Fig. 4. And their trend with orientation angle could be expressed, as follows.

$$f = 8.552\sqrt{\sin(\pi-\theta)} + 3.313 \qquad \text{Eq. (3)}$$

$$v = 1.387\sqrt{g\sin(\pi-\theta)R} \qquad \text{Eq. (4)}$$

$$\frac{b}{a} \sim \frac{\cos(\pi-\theta)}{\sqrt{\sin(\pi-\theta)}} \qquad \text{Eq. (5)}$$

where, f, θ, v, g, R, and b/a are departing frequency, orientation angle, speed of slug, gravitational acceleration, equivalent radius of slug, and deformation ratio, respectively.

Eq.(3) indicates that hovering time of slug before departure from the heating surface become longer with higher orientation angle. Many researchers reported that increased hovering time might cause CHF trigger by dryout of macrolayer between slug and heating surface. Interesting point is similarity of trend between CHF and departing frequency, i.e. Eq.(1) and Eq. (3).

Accordingly, we postulated that if the frequency is derived analytically from slug dynamics, a CHF model could be developed to predict its deterioration on downward-facing surface. Focusing on a cross section of slug perpendicular to its flow direction, one could set the cross section area as an escaping channel of vapor generated from heating surface. Then, the slug departure could happen only when the translation speed become larger than vapor inflow speed via the cross section. The terminal speed of departing bubble and the cross section area are closely related with orientation angle, i.e. Eq. (4) and Eq. (5), so that the frequency could be expressed as a function of orientation angle and heat flux. Here, we leave this task as our further research, and we are expecting to discuss this topic in the conference.

In this study, the heating area was fixed with 10x15mm^2. However, the area was also supposed to be considered for the analysis of equation (3) to (5), wherein the departing bubble diameter would be enlarged when the heating area increased. Accordingly, one could expect that the terminal speed of equation (4) would become faster, but departing frequency of equation (3) and deformation ratio of equation (5) would need to be further analyzed. In real application of downward vessel of reactor, the situation could be supposed as infinite heating area, compared with slug diameter. The size effect of heating surface on slug dynamics could be distinguished into translation and width directions of slug. Accordingly, we have a plan to investigate above issues using arrayed individual heaters for translation and width directions.

3. Conclusions

Slug dynamics in nucleate boiling regime on downward-facing surface were investigated via quantitative analysis. The deterioration of CHF performance according to orientation could be derived by solving slug dynamics for departure, in which its speed, deformation ratio, and vapor generation rate are supposed to determine the frequency of slug departure, i.e. hovering time.

4. Acknowledgments

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