TWO-DIMENSIONAL PROJECTED GAS–LIQUID INTERFACIAL AREA IN BOILING FLOW

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Although the gas–liquid interface in boiling flow is very important, it is difficult to clearly show the relationship between the gas–liquid interface in the channel and heat transfer characteristics. The interfacial area concentration (IAC) is one of them, however its measurement method is not easy. Here, a two-dimensional projected gas–liquid interfacial area (2D-PGIA) is proposed as a simple index. 2D-PGIA is an index obtained by image processing from a video image which is two-dimensional information, and other parameters such as velocity vector of bubbles is not considered. Flow boiling experiments using vertical 4-mm-diameter transparent heated tube were carried out to investigate the relationship between heat transfer characteristics and 2D-PGIA. From the result analyzed images in bubble, slug, and annular flows, it is clear that the 2D-PGIA time profile well follows the temporal change of the inner wall temperature in all flow regimes. Especially in bubble flow, heat transfer increases as 2D-PGIA increases, 2D-PGIA reaches the maximum value just before DNB, and then 2D-PGIA drastically decreases when DNB occurs. From our experimental results, 2D-PGIA will be a useful index for understanding boiling heat transfer in a tube.

KEY WORDS: image analysis, flow boiling, gas–liquid interfacial area

1. INTRODUCTION

In order to analyze two-phase flow phenomena, various models such as homogeneous model, slip model, drift flux model, and two-fluid model have been proposed. Among these models, the two-fluid model (Ishii, 1975) is considered the most accurate model because this model treats each phase separately considering the phase interactions at gas–liquid interfaces. In two-fluid model, averaged conservation equations of mass, momentum, and energy are formulated for each phase. The conservation equations of each phase are not independent of each other and they are strongly coupled through interfacial transfer terms of mass, momentum, and energy through gas–liquid interface. Interfacial transfer terms are characteristic terms in two-fluid model and are given in terms of interfacial area concentration (IAC) as a interfacial area per unit volume of two-phase flow.

IAC is obtained by measuring the radial profiles of the void fraction, and bubble velocity, bubble chord length. These parameters were measured using high-speed photography and digital image processing techniques (Takamasa et al., 2003), or using probe sensor (Hibiki and Ishii, 2000a,b, 2002; Kataoka et al., 1986). Brief review about IAC measurements was reported by Lin and Hibiki (2014). The high-speed photography method can be applied for only low void fraction and needs the transparent test part for observation of flow behavior. Many experimental studies on the local measurements of these parameters in two-phase flow have been carried out. However, most of the studies have been conducted in adiabatic bubbly flow condition. For boiling flow, most of previous works were conducted under subcooled flow boiling conditions. Zeitoun et al. (1994) also measured the void fractions and mean bubble
sizes at various axial locations in subcooled flow boiling. The bubble mean diameter, which can be used to calculate interfacial area concentration, was determined using high-speed photography, and the void fraction was measured by a single-beam gamma densitometer. Based on the measured data, they proposed a correlation for mean bubble diameter. Garnier et al. (2001) performed the measurements of local two-phase flow parameters in R-12 flow boiling in a vertical channel. The void fraction and interfacial area concentration were measured by an optical probe. Lee et al. (2002) measured the radial profiles of local void fraction and velocities of both phases in subcooled boiling flow of water in a vertical concentric annulus with a heated inner tube. A double-sensor conductivity probe was used for the measurements of local gas phase parameters. Situ et al. (2004) and Lee et al. (2008, 2009) measured axial developments of the local void fraction, interfacial area concentration, and bubble Sauter mean diameter in subcooled boiling flow of water in a vertical internally heated annulus using the double-sensor conductivity probe technique. Their experiments were performed under varying conditions of heat flux, inlet liquid velocity, and inlet liquid temperature, and the influence of flow conditions on the profiles of local two-phase flow parameters was discussed.

IAC is a well–known parameter for gas–liquid two-phase system, but is difficult to measure experimentally, because costly measurement devices, complex image analysis, and/or some assumptions such as bubble shape and interfacial velocity are necessary to get IAC information. If there is a qualitative index about gas–liquid interface which is easily measured, it will be possible to use widely as an on-site analysis. From this point of view, here we will propose a new simple index for boiling and two-phase flow.

2. TWO-DIMENSIONAL PROJECTED GAS–LIQUID INTERFACIAL AREA

2.1 Concept

Due to heat and mass transfer being performed through the gas–liquid interface, the interface is very important for heat transfer in gas–liquid two-phase flow. Here we propose the two-dimensional projected gas–liquid interfacial area, 2D-PGIA, as a simple index for two-phase flow heat transfer. Figure 1 shows the concept of 2D-PGIA. Bubbles in the tube are projected onto the screen of a charge coupled device (CCD) camera by the backlight. At that time, the gas–liquid interface around the bubble is projected dark due to the difference in refractive index between gas and...
liquid. Therefore, by calculating the darker part than a certain threshold value, the gas–liquid interface area can be calculated. In this case, since the gas–liquid behavior projects three-dimensional information in two dimensions, it is not able to separate overlapping bubbles and to distinguish bubbles on the tube wall from intratubular bubbles. The above-mentioned concept of 2D-PGIA is really simple and expresses information of gas–liquid behavior in a tube as a simple and objective index. 2D-PGIA does not need interfacial velocity, bubble velocity, bubble shape and size, any vectors, and sensors except a camera to observe the flow behavior.

2.2 Image Analysis Procedure

The procedure of image analysis of 2D-PGIA consists of three steps: brightness smoothing, binarization, and calculation, as shown in Fig. 2. Each step is illustrated in detail below.

2.2.1 Brightness Smoothing

To cancel the brightness difference due to the location of the circular tube, we take the difference of brightness of the images between the liquid single-phase flow and the gas–liquid two-phase flow. The image of the single-phase flow takes before each experiment. The region of the image analysis is set 1–2 pixels inner of the projection area of the tube to remove noise near the projected inner wall of the tube. Then brightness differential image is obtained.

2.2.2 Binarization

For binarization of the image, Otsu’s method (Otsu, 1976) is used. Otsu’s method is a kind of discriminant analysis method, and this is an exhaustive search for the threshold that maximizes separation metrics, defined as a ratio
between-class variance to the within-class variance. When the brightness of the image is separated, two classes 1 and 2 by a threshold $t$, $\omega_1 / \omega_2$ and $\sigma_1 / \sigma_2$ and $\mu_1 / \mu_2$ are number of pixels, variances, means of these two classes, respectively. The number of pixels, variance, mean of the classwide are $\omega_t$, $\sigma_t$, and $\mu_t$. The within-class variance $\sigma^2_w$ and the between-class variance $\sigma^2_b$ are as follows:

\[
\sigma^2_w = \frac{\omega_1 \sigma^2_1 + \omega_2 \sigma^2_2}{\omega_1 + \omega_2},
\]

\[
\sigma^2_b = \frac{\omega_1 (\mu_1 - \mu_t)^2 + \omega_2 (\mu_2 - \mu_t)^2}{\omega_1 + \omega_2} = \frac{\omega_1 \omega_2 (\mu_1 - \mu_2)^2}{(\omega_1 + \omega_2)^2}.
\]

Here, total variance $\sigma^2_t$ can be easily verified:

\[
\sigma^2_t = \sigma^2_w + \sigma^2_b.
\]

Then the separation metrics $S$ can be written

\[
S = \frac{\sigma^2_b}{\sigma^2_w} = \frac{\sigma^2_b}{\sigma^2_t - \sigma^2_b}.
\]

Because $\sigma^2_t$ is a constant value independent of the threshold, $\sigma^2_b$ should be maximized in order to take the maximized value of the separation metrics $S$. Thus, the threshold $t$ can be derived by iterative calculation to get the maximum value of the numerator of $\sigma^2_b$ in eq. (2).

2.2.3 Calculation of 2D-PGIA

After binarized processing, the number of pixels having a brightness not less than the threshold value are counted as a gas–liquid interface area, and the two-dimensional projected gas–liquid interface area is calculated.

3. EXPERIMENTAL SET-UP AND PROCEDURE

3.1 Test Loop

The flow boiling experimental loop used in this study is configured to investigate high-speed visualization approach and heat transfer measurement of FC-72. The test loop is shown in Fig. 3. The loop consists of several primary components; a reservoir tank, a pump, a Coriolis mass flow meter, a plate heat exchanger (pre-heater 1), metal heated tube as a second pre-heater (pre-heater 2), a heated tube as a boiling test section, a condenser, a buffer tank, pressure and temperature measurement instrumentations. The test loop is filled with well-degassed FC-72. The temperature is measured by using K-type thermocouples except inner wall temperature of the heated tube in the test section. The absolute pressure at the entrance of the metal heated tube and the pressure drop between the metal heated tube and the test section are measured by pressure transducer. For the heated tube in the test section, the transparent heated tube (Kawanami et al., 2007; Ohta, 1997, 2003) is applied. This tube is made by Pyrex glass coated by 10–50 nm gold film on the inner wall of the tube. Simultaneous acquisition of inner wall surface averaged temperature, heating of fluid, observation of flow behavior are possible by using this tube. This tube is 5 mm in heated length, 4 mm of the inner diameter, and 6 mm of the outer diameter as shown in Fig. 4. Detailed instruction about the transparent heated tube was reported in our previous paper (Okubo et al., 2016).

A high-speed camera is used to observe flow behavior. The shutter speed and frame rate of the high-speed camera are 1/2,000 s and 1,000 fps, respectively. The observation area of the heated tube is 5 mm × 4 mm as shown in Fig. 4, which corresponds to 83 pixels × 70 pixels. Therefore, the spatial resolution of the image is about 60 µm. 2 s recording of flow behavior at each experimental conditions is conducted by using this camera. Other data such as temperature, pressure, mass velocity are measured by data logger (DU1040-H, Takasago Ltd.) with 100 Hz. The time lag between image and other data taken by data logger is less than ± 0.02 s.
The experimental conditions are listed in Table 1. $G = 50–1000$ kg/m$^2$s, $P_{in} = 95–105$ kPa, $q_{in} = 0–700$ kW/m$^2$ and flow direction is vertical upward. The inlet condition as subcooling temperature $\Delta T_{sub}$ or quality $x_{in}$ is set by pre-heaters.
TABLE 1: Summary of experimental conditions and accuracy

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Experimental conditions</th>
<th>Unit</th>
<th>Degree of accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass velocity, $G$</td>
<td>50-1000</td>
<td>kg/m$^2$s</td>
<td>± 5 kg/m$^2$s</td>
</tr>
<tr>
<td>Inner wall temperature, $T_{iw}$</td>
<td>20–125</td>
<td>$^\circ$C</td>
<td>± 0.029$^\circ$C (Relative error)</td>
</tr>
<tr>
<td>Temperature (Thermocouple), $T$</td>
<td>20–125</td>
<td>$^\circ$C</td>
<td>± 0.25$^\circ$C</td>
</tr>
<tr>
<td>Inlet pressure, $P_{in}$</td>
<td>95–105</td>
<td>kPa</td>
<td>± 0.3 kPa</td>
</tr>
<tr>
<td>Heat flux, $q_{in}$</td>
<td>0–700</td>
<td>kW/m$^2$</td>
<td>± 0.05%</td>
</tr>
</tbody>
</table>

3.2 Data Derivation of Heat Transfer Characteristics

For evaluating the inner wall temperature averaged over the entire temperature measurement length of the tube $T_{iw}$, the electric resistance of the gold film $R$ is measured, and then $T_{iw}$ can be calculated as the linear function of the resistance of the tube $R$ (Okubo et al., 2016):

$$R = aT_{iw} + b,$$

where $a$ and $b$ are the constant values, and these constant values can be determined by non-heating calibration test before boiling experiment. Heat flux $q_{in}$ is

$$q_{in} = \frac{Q_{total} - Q_{loss}}{A} = \frac{IV - Q_{loss}}{\pi DL},$$

where $Q_{loss}$ is defined by the functions of temperature difference between outer wall temperature and air temperature.

4. RESULTS

4.1 Bubble Flow

Figure 5 shows the time variations of inner wall temperature and 2D-PGIA under the conditions of $q = 189$ kW/m$^2$s, $G = 400$ kg/m$^2$s, and $\Delta T_{sub} = 28$ K during 1 s. The flow regime is bubble flow, and a regular fluctuations of the 2D-PGIA and the inner wall temperature, are observed. The period of fluctuation of the inner wall temperature which has the range of 0.5 K, is about 0.1 s, it is almost periodic. At a sharp peak of 2D-PGIA, the inner wall temperature decreases. If the 2D-PGIA as the gas–liquid interfacial area increases, the heat transfer from heated wall to liquid via the interface increases, so the inner wall temperature decreases. After the 2D-PGIA peak, the 2D-PGIA decreases and the inner wall temperature rises to coincide with a decline in 2D-PGIA.

FIG. 5: Time variations of 2D-PGIA and inner wall temperature in bubble flow ($G = 400$ kg/m$^2$s, $q = 189$ kW/m$^2$s, $\Delta T_{sub} = 28$ K, $P_{in} = 103$ kPa)
Some example images of the flow behavior from 0.556∼0.668 s were shown in Fig. 6. At \( t = 0.556 \) s, many bubble are generated; 2D-PGIA has a peak value. Then, density of bubbles in the tube is decreased obviously by images from \( t = 0.595 \sim 0.668 \) s in Fig. 6. The density of bubbles increases again after the case of the 2D-PGIA falls down to less than about 3.5.

### 4.2 Slug Flow

Figure 7 shows the time variations of inner wall temperature, 2D-PGIA, and film thickness at the center of the heated tube under the conditions of \( q = 22 \) kW/m²s, \( G = 44 \) kg/m²s, and \( x_{in} = 0.11 \) during 1 s. Images of flow behavior at (a)–(f) during 1 cycle of the 2D-PGIA are shown in Fig. 8. The bubble shape is a Taylor bubble with a flat tail. When the front of the slug enters the heated tube at the point (a) in Figs. 7 and 8, 2D-PGIA increases. Then, the front of the slug reaches the end of the heated part, 2D-PGIA takes a peak value (b). From (a) to (b) the inner wall temperature increased gradually, corresponding to the 2D-PGIA increasing. After the front surface of the slug passes through the heated tube, the 2D-PGIA decreases because the gas–liquid interface at the front part of a bubble passed away. During, the tube wall is covered with the liquid film of the slug. 2D-PGIA and inner wall temperature keep almost constant values (c). The film thickness at the center of the heated tube as pointed out in Fig. 8 is calculated from the images. The film thickness is about 0.25 to 0.5 mm in region (c). At the end of region (c), 2D-PGIA increases again, since the rear part of a slug is coming to the heated tube. The flow in the rear region of a slug is disturbed, and some small bubbles accompany with the rear of a slug. Those small bubbles have a large gas–liquid interface compared to the liquid film region (c), so 2D-PGIA takes a peak (d). When the rear part of the slug passes through the tube, the 2D-PGIA decreases (e) and becomes the minimum value (f). In this region (e)–(f), the inner wall temperature is...
decreasing continuously. Although the liquid film thickness is linked roughly with the inner wall temperature in the region (c), the thickness cannot deal with the inner wall temperature rise in the region (a) and fall in the region (e).

In the case of the bubble flow as illustrated in the previous Section 4.1, the inner wall temperature is decreased with increasing of the 2D-PGIA. The same trend found between (b) and (d) in slug flow. However, for the slug flow, inner wall temperature is increased with increasing of 2D-PGIA between (a) and (b), and decreased with decreasing of 2D-PGIA between (d) and (f). As the result, the turbulent flow just behind a Taylor bubble has a larger influence on enhancement of heat transfer than the gas–liquid interface area in this regions (d)∼(f). Similar observations were reported by Scammell (2016); Scammell and Kim (2015). In addition, in the liquid film region such as (c), even if the thickness of the liquid film is changed, the value of 2D-PGIA keeps almost constant in principle. This means that it does not correspond to the increase in heat transfer coefficient due to the liquid film thickness decrease. How to incorporate the change in the liquid film thickness into the 2D-PGIA is a future work.

### 4.3 Annular Flow

Figure 9 shows the time variations of inner wall temperature and 2D-PGIA under the conditions of $q = 112 \text{ kW/m}^2\text{s}$, $G = 44.8 \text{ kg/m}^2\text{s}$, and $x_{in} = 0.48$ during 1 s. Gas–liquid behaviors are shown in Fig. 10. The disturbance wave is clearly found at $t = 0.108 \text{ s}$ in this figure. At the same time, the value of 2D-PGIA takes a large peak value, and the inner wall temperature takes the small value corresponding at this 2D-PGIA peak. The values of 2D-PGIA except at the disturbance wave has large fluctuations compared to the liquid film region (c) in slug flow in Fig. 7. The surface of the liquid film of the region (c) in slug flow is extremely smooth, but the surface of the annular flow is markedly disordered. Assuming that the thickness of the liquid film is nearly constant, it can be said that the fluctuations of the 2D-PGIA in the liquid film region indicate the disordered level of the surface of the liquid film. However, the inner wall temperature of the tube in the annular flow does not correspond to the fluctuation of 2D-PGIA. It is considered that since the inner wall temperature by using the transparent heated tube is measured as the average value of the entire heating section, the influence of the surface disturbance of the liquid film has a low impact on the inner wall temperature.

**FIG. 8:** Example images of slug flow at the times as pointed in Fig. 7

**FIG. 9:** Time variations of 2D-PGIA and inner wall temperature in annular flow ($G = 112 \text{ kg/m}^2\text{s}$, $q = 44.8 \text{ kW/m}^2\text{s}$, $x_{in} = 0.48$, $P_{in} = 96.4 \text{ kPa}$)
4.4 Effects of Heat Flux from Nucleate Boiling to DNB

The average value of 2D-PGIA during 1 s in stable condition under various heat fluxes and flow rate are shown in Fig. 11. Experimental conditions except in heat flux are as follows: $\Delta T_{sub} = 28–30$ K, $P_{in} = 98–103$ kPa, $G = 50$, 400, 1000 kg/m$^2$s. Under such high subcooling condition, bubbly flow continues until just before critical heat flux (CHF), and CHF by departure of nucleate boiling (DNB) is observed.

Flow behaviors under various heat fluxes and mass velocities are shown in Fig. 12. Bubble flow is observed for all mass velocities under the heat flux range from 150 to 284 kW/m$^2$s. From those images in this figure, it is obviously found that bubble density increases with increasing heat flux for all mass velocities conditions. In such a heat flux region, the trend of 2D-PGIA values coincides with increasing in bubble density. When the heat flux becomes larger than CHF, bubbles disappear in “after CHF” images, that is, the transition from nucleate boiling to film boiling is completed. At this point, 2D-PGIA value is sharply decreasing. Taking the case of 1,000 kg/m$^2$s as an example, the value of 2D-PGIA at 630 kW/m$^2$s is 11.8 mm$^2$; it goes down to 3.6 mm$^2$ at 640 kW/m$^2$s. This decline trend of 2D-PGIA after CHF is found in other mass velocities as well. As a result, 2D-PGIA takes a peak value before CHF caused by DNB. Although it is still an open question, 2D-PGIA might be possible to be used for the prediction of DNB.

5. CONCLUSIONS

In this study, 2D-PGIA, which is really simple and expresses information of gas–liquid behavior in a tube as a simple and objective index, is proposed. When bubbles in the tube are projected onto the screen of the CCD camera by the backlight, the gas–liquid interface around the bubble is projected dark due to the difference in refractive index between gas and liquid. So, the projected gas–liquid interface area, named 2D-PGIA, can be calculated by calculating the darker part than a certain threshold value. In this case, since the gas–liquid behavior projects three-dimensional information in two dimensions, it is not able to separate overlapping bubbles and to distinguish bubbles on the tube wall from intratubular bubbles. However, some important information for boiling heat transfer is included in the 2D-PGIA.

From the results of analyzed images in bubble, slug, and annular flows, it is clearly found that the 2D-PGIA time profile well follows the temporal change of the inner wall temperature in all flow regimes. Especially in bubble
flow, heat transfer increases as 2D-PGIA increases, 2D-PGIA reaches the maximum value just before DNB, and then 2D-PGIA drastically decreases when DNB occurs.

From the point of view in the actual system, the heated channel is made by metal normally, so it is not visible. In this case, measurement of 2D-PGIA is possible by installing a glass observation part at the exit of the heating section. Although the value of 2D-PGIA in the non-heating glass part probably becomes small compared to the heating part, the characteristic of 2D-PGIA will not change. There is room for further study of 2D-PGIA, but in the future it will be possible to use for detection of DNB in an actual system.

Although 2D-PGIA still has several open questions, it will be a useful index for understanding boiling heat transfer in a tube from our experimental results.

REFERENCES


Interfacial Phenomena and Heat Transfer


