# Development of Slug Boiling Liquid Film Thickness Technique Measurement using Infrared Thermometry

Junha Kang [a], Sangmin Park [a], Soonil Kwon [a], and Hyungdae Kim [a*]
[a] *Department of Nuclear Engineering, Kyung Hee University*
*1732 Deogyeong-daero, Giheung-gu, Yongin-si, Gyeonggi-do, 17104, Korea*
[*] *Corresponding author: hdkims@khu.ac.kr*

## 1. Introduction

Downward-facing flow boiling is significant thermal-hydraulic phenomenon in relation to in-vessel retention and external reactor vessel cooling (IVR-ERVC) as a passive severe accident mitigation system of advanced nuclear power plants. The system removes decay heat from molten corium by supplying water through the reactor cavity. The flooded coolant undergoes downward-facing flow boiling on the heated surface of the external reactor vessel with various surface orientations. During the boiling phenomena, discrete bubbles nucleated on the downward-facing wall merge before departing from the wall and form large slug bubbles. In this situation, liquid film is formulated beneath the slug bubbles flowing in contact with the wall. Conduction heat transfer across the liquid film and its evaporation on the top play a role during slug boiling. Hence, thickness of the liquid film is an important parameter for developing slug boiling heat transfer prediction model.

Haramura and Katto [1] made a hydrodynamic model of liquid film thickness using Helmholtz instability between vapor stems and liquid film. They assumed that a number of vapor stems exist under slug bubbles, penetrating liquid film and a liquid film under slug bubbles can exist up to the height of the vapor stems. Then, they calculated the liquid film thickness using the critical wavelength determined by the Helmholtz instability theory. Cheung and Haddad [2] proposed a liquid film thickness model by adjusting a proportional constant to best predict the critical heat flux (CHF) experimental data at various downward inclinations. Later, Park et al. [3] conducted the CHF experiments on a downward-facing wall with different wettability and proposed an additional correction factor to the Cheung and Haddad liquid film thickness model to modify CHF model.

In previous studies, liquid film thickness models have been developed only to predict CHF during downward-facing flow boiling. However, to accurately predict the transient thermal behavior of the reactor vessel during IVR-ERVC in addition to a simple judgement of whether CHF occurs on the external wall, a phenomenologically validated slug boiling heat transfer model incorporated with a sub-model for liquid film thickness needs to be developed. Objective of this study is to experimentally measure liquid film thickness under slug bubbles using wall temperature and heat flux from infrared thermometry at various heat fluxes. The measured liquid film thickness data is compared with prediction by previous theoretical models.

## 2. Experimental Setup

The subcooled downward-facing flow boiling experiment was conducted to obtain wall temperature and heat flux distributions using infrared camera (FLIR SC6000) with a frame rate of 500 Hz. Two high-speed cameras (Phantom v7.3) were synchronized with the infrared camera to visualize bubble coalescences from side and upward views with a frame rate of 5000 Hz.

The test section includes sapphire windows and test sample to adopt the integrated infrared thermometry and high-speed measurement techniques. Each of two sapphire windows was placed at left and right side of the test section and the other at the back, and test sample at the front as shown in Fig. 1. Considering the flow conditions of IVR-ERVC at APR1400, cross sectional area of a rectangular flow channel was 10 mm width and 20 mm height. The dimension of heated wall was 8 mm in width and 130 mm in length to provide enough space for bubbles to merge.

A 400 nm-thick Cr above 100 nm-thick CrN was deposited over 10 mm-thick sapphire plate for the heated surface of the test sample. Since Cr has low emissivity, CrN is added to Cr to work as blackbody. Pt/Ti electrode film was deposited at each end side of Cr/CrN with 150 nm/150 nm thickness.

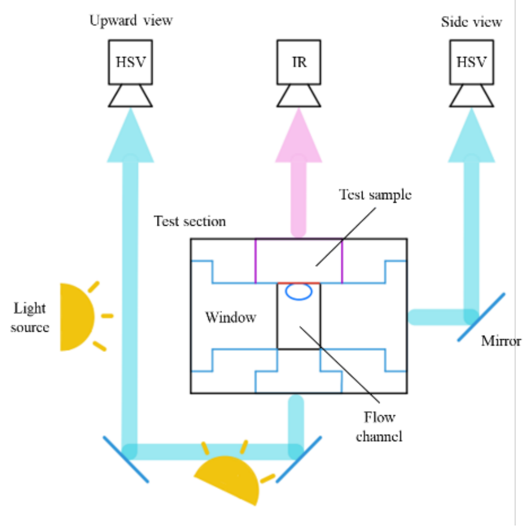


Fig. 1. Schematic diagram of experiment measurement of integrated infrared and high-speed camera

Table 1. Experimental conditions

| Parameter | Range/Value |
|---|---|
| Mass flux [kg/m$^2$s] | 300 |
| Heat flux [kW/m$^2$] | 500 - 1100 |
| Inclination angle [°] | 30 |

The test section including the test sample was connected to a flow loop during the experiment. The experiment was conducted with mass flux of 300 kg/m$^2$s to set Reynolds number over 9,000 and keep flow laminar as in IVR-ERVC. The heated wall inclination was kept as 30° for a preliminary test of the liquid film thickness measurement method explained in the following section. Heat flux is applied to the wall with a range of 500-1100 kW/m$^2$ that slug bubbles could be examined. The experimental conditions are summarized in Table 1.

### 3. Liquid Film Measurement Method

IR count data are obtained from the above experiment and are converted into the wall temperature using a fitting equation from IR calibration experiment. Heat transfer coefficients (HTCs) are obtained using Newton's cooling law, $q''_{app} = h\,(T_w - T_{sat})$ where $q''_{app}, h,\ T_w, T_{sat}$ each refers to applied heat flux, HTC, wall temperature, and saturation temperature. HTC and wall and saturation temperature are further used in 3-D Fluent analysis to measure wall heat flux considering heat loss from sapphire sample plate.

From the wall heat flux distribution data, dryout areas are examined with particularly low heat flux compared to surround regions. As the liquid film under a slug bubble evaporates, dryout areas occur, hence the region should be neglected in the process of calculating the film thickness. Therefore, typically low heat flux value of dryout area from heat experimental data is set to be a threshold and areas with heat flux lower than threshold value are eliminated and are turned into *NaN* as shown in Fig. 2. Corresponding areas in wall temperature data underwent the same process.

Conduction is the main heat transfer between the heated wall and the liquid film in slug boiling. Therefore, 1-D conduction is assumed to be dominant heat transfer phenomenon. Liquid film thickness, $\delta_m$, is calculated with the 1-D conduction equation,

$$\delta_m = k_l \frac{T_w - T_{sat}}{q''_w} \quad (1)$$

Where $k_l$, $T_w$, $T_{sat}$, and $q''_w$ each refers to the working fluid thermal conductivity, wall temperature, saturation temperature, and wall heat flux.

Calculated liquid film thickness data are synchronized with high-speed visualization images to precisely determine liquid film are under the slug bubble. From the backward visualization result, slug bubbles do not cover the entire heating wall in width, hence the total 10 % of the liquid film thickness data in width, each 5% of side, is cropped. From the high-speed side images, bubbles merging into slug bubbles are visualized as shown in Fig. 3. The area A, B, and C each refer to the nucleate boiling, bubble coalescence, and a complete slug bubble. Finally, the film thickness and the complete slug bubble images are synchronized considering a frame rate and the actual length and consequently, the average liquid film thickness under the slug bubble is measured.

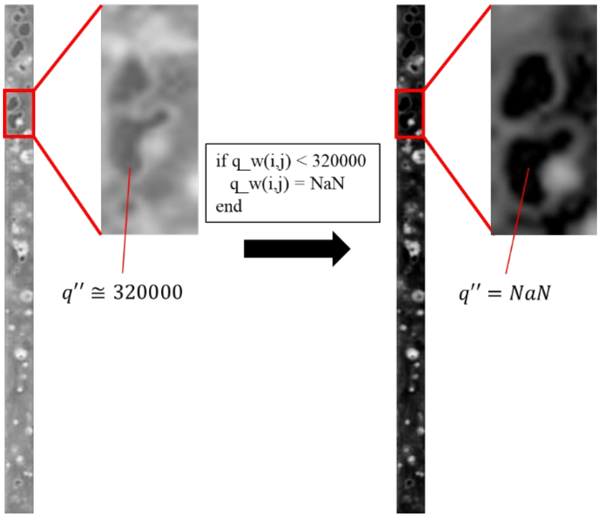


Fig. 2. Removing process of dryout area with threshold heat flux

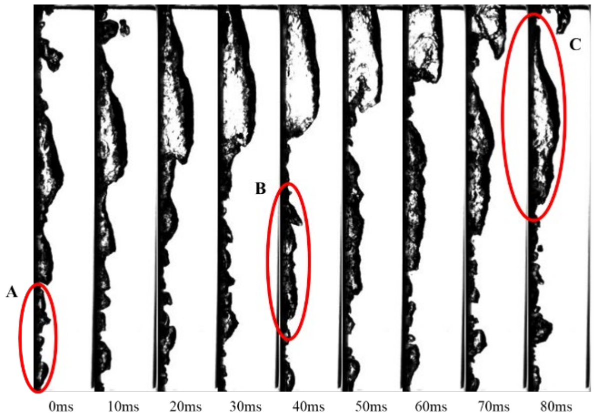


Fig. 3. High-speed side view images of slug bubble formation

### 4. Result and Discussion

Liquid film thickness was measured at the surface inclination angle of 30° as shown in Fig. 4. The slug bubble was barely seen at the low heat flux range of 100-400 kW/m$^2$, therefore the thickness is measured from 500 kW/m$^2$ to 1100 kW/m$^2$, which is just before CHF. As the wall heat flux increases, the thickness decreases. This is because the increases in heat flux will affect evaporation of the liquid film under slug bubble. Liquid film evaporation will be more occurred at the higher heat flux, causing the thickness of it to decreases.

Validation of the experimental data is also shown in Fig. 4 by comparing data with other four liquid film thic-

Table 2. Constant value of liquid film thickness models (G: Mass flux [kg/m$^2$s])

| Model | $C_m$ value |
|---|---|
| Haramura and Katto [1] | 0.00535 |
| Cheung and Haddad [2], | 0.00079 |
| Park et al. [3] | 0.014 |
| Hu et al. [4] | 0.00999 / (0.004365G + 1.296) |

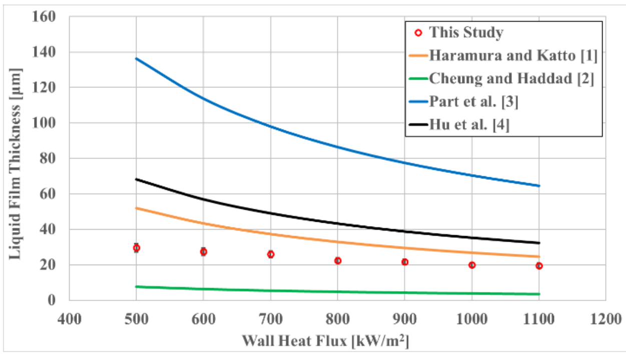


Fig. 4. Liquid film thickness result at inclination angle 30°, compared with previous models

kness models. These models are all based from Haramura and Katto [1] liquid film thickness correlation in function of fluid properties, Eq. (2).

$$\delta_m = C_m \sigma \rho_g \left(1+\frac{\rho_g}{\rho_f}\right)\left(\frac{\rho_g}{\rho_f}\right)^{0.4}\left(\frac{h_{fg}}{q''_w}\right)^2 \qquad (2)$$

The term $\delta_m$ refers to the film thickness, $C$ to a proportionality constant, $\sigma$ to surface tension, $\rho$ to density, $h$ to enthalpy, and $q''_w$ to the wall heat flux. The subscripts $m$ refers to mean value, $f$ and $g$ each to the fluid and vapor. Values of the constant $C$ for each model is empirically obtained as shown in Table 2. Fluid properties from the experimental conditions are used to compare the correlation with this study data. In the heat flux range of 500-1100 kW/m$^2$, likewise other model, experimental result of this study tends to decrease with increasing heat flux. However, the thickness magnitudes are different with others, especially with the Park et al. [3] model.

### 5. Conclusion

This paper presented the indirect measurement method of liquid film thickness under slug bubble using infrared thermometry technique. The thickness could be measured using 1-D conduction equation since the corresponding heat transfer is dominant between the heated wall and the liquid film. Experimental setup to measure the thickness becomes simpler using this method. Moreover, measuring liquid film thickness in various heat flux and surface orientations will improve slug boiling phenomena prediction particularly related with IVR-ERVC.

However, accuracy and reliability improvement of the experiment and its result is required. More experimental data including not only thickness, but slug bubble parameters effecting the thickness such as bubble length, velocity, and frequency are also needed at various heat flux and surface orientation conditions. These improvements are expected to improve thermal-hydraulics analysis of wall boiling phenomenon at IVR-ERVC.

### ACKNOLEDGEMENT

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