

# Liquid Film Thickness Measurement Using Electrical Conductance Method in 1/10 Scale Air-Water ECC Bypass Experiment

Chi-Jin Choi<sup>a</sup> and Hyoung Kyu Cho<sup>a\*</sup>

<sup>a</sup>Nuclear Thermal-Hydraulic Engineering Laboratory, Seoul National University  
Gwanak 599, Gwanak-ro, Gwanak-gu, Seoul, Korea

\*Corresponding author: chohk@snu.ac.kr

## 1. Introduction

Liquid film wetting the surfaces such as fuel rod, reactor downcomer and heat exchanger can be a crucial factor for safety analysis of nuclear reactor. Due to the fact that using a computational fluid dynamics (CFD) code for reactor safety analysis has been emphasized, several CFD studies have been carried out to investigate the liquid film behavior or the heat transfer with it. However, since there were not enough data which had measured locally in the experiment, CFD results have had a difficulty of being properly validated.

In the present study, the focused phenomenon is the ECC (Emergency Core Coolant) bypass during a LOCA (Loss-Of-Coolant Accident) in a pressurized water reactor. If a break occurs in a primary coolant system, ECC is injected to the reactor downcomer. However, the injected water which is in the form of liquid film on the wall is influenced by the circumferential steam flow. Thus, the interfacial friction acting on two-phase leads some of the injected water to be bypassed out to the broken region. Because the portion of the bypassed water is an important parameter for the safety of the nuclear reactor, it needs to be predicted accurately. Therefore, this motivated the experimental work to investigate the liquid film behavior in an upper downcomer and obtain the local measurement data for the CFD validation. In order to measure the liquid film thickness in the experiment, a sensor was developed based on electrical conductance method. By fabricating the sensor on the Flexible Printed Circuit Board (FPCB), it was applicable to the curved surface.

This paper presents the development procedure of the sensor to measure the liquid film thickness. Subsequently, the local measurement of liquid film thickness in air-water ECC bypass experiment are presented. The results of CFD simulation and validation with the experiment results were also included in the paper.

## 2. Development of liquid film sensor

### 2.1. Sensor design

The developed sensor is a type of using electrodes mounted flush to the wall. In order to measure the liquid film thickness, an electrical potential difference between the transmitter and receiver electrode is obtained, because it changes according to the thickness of the liquid film covering both electrodes.

In the present work, for the maximum thickness of 3.2 mm, the size of a measuring point was set to  $6 \times 12 \text{ mm}^2$ . The arrangement of electrodes was shown in Fig 1. In the figure, there are two different types of electrodes, R1 (near receiver) and R2 (far receiver) in a measuring point. The distance between the transmitter electrode and far receiver is directly related to the span of the sensor. However, in thin film region, the result based on far receiver may not be accurate because the relation between the voltage drop and the film thickness is non-linear. This weakness of far receiver motivated to introduce the near receiver. Compared to the far receiver, near receiver has better sensitivity of the signal in thin film region. The designed electrodes were fabricated on FPCB with an array of  $24 \times 24$  measuring points (Fig. 2).

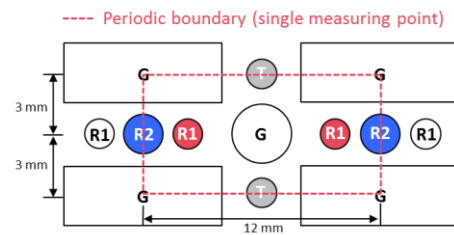


Fig. 1. Geometry of electrodes

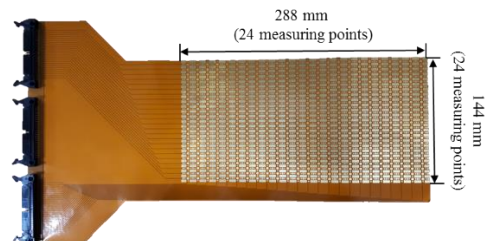


Fig 2. Fabricated FPCB sensor

In order to improve the efficiency of the acquiring the signal, the reticular structure of the circuit wires was applied to the sensor. In this circuit system which was firstly suggested by Prasser et al. [1], transmitter electrodes were connected in a vertical sequence and receiver electrodes were connected in a horizontal sequence. Since each receiver wire is connected to multiple electrodes, the thickness at whole measuring points can be obtained by switching the transmitted signal in order.

The entire circuit system including the sensor was shown in Fig 3. A function generator transfer 10V AC voltage to the switching board at a frequency of 1kHz.

Then the transmitted signal excites the transmitter electrode in the FPCB sensor via the switching board. The voltage drop between the transmitter and receiver electrodes were delivered to op-amp, which makes output signal 100 times greater in amplitude. Finally, the signal is acquired by data acquisition system (DAS).

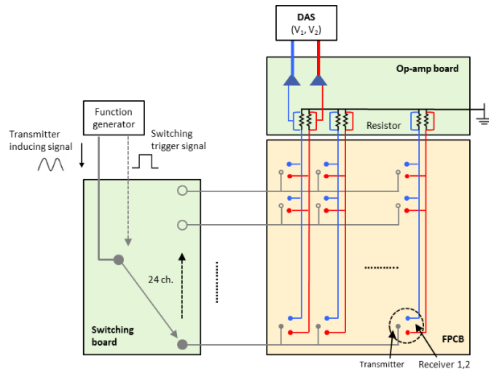


Fig. 3. Circuitry system

### 2.2. Sensor calibration

The developed sensor was calibrated using the method suggested by Ito et al. [2]. In this method, the plates which is cut to the calibration thickness (0.2 mm, 0.7 mm, 1.2 mm, 2.2 mm, 2.7 mm, 3.2 mm) were used for calibration device. The principle of the calibration is illustrated in Fig. 4. When the curved plane is on the calibration plate sunk under water, a uniform thickness of liquid film formed in the gap between the sensor and the calibration plate. Because the length of the gap is the minimum thickness that each measuring point can measure, the minima of the signal were obtained by rolling the curved plane to left and right. The calibration results in the range of 0.2 mm ~ 3.2 mm film thickness are shown in Fig. 5. The results at near receiver shows that the sensitivity of the signal is high in thin film (0.2 ~ 1.2 mm), but the increment of the signal nearly saturated at 3.2 mm. In the case of far receiver, the signal shows good linearity in thick film (1.2 ~ 3.2 mm), though the sensitivity of it is low in thin film region. These results led to an idea for obtaining the liquid film thickness by using two sets of calibration results selectively with the reference film thickness of 1.2 mm. If the two thicknesses decided by two receivers are less than 1.2 mm, the thickness from the near receiver is selected as a precise value, and if they are more than 1.2 mm, the thickness from the far receiver is only used. This method has an advantageous in improving the accuracy of the sensor.

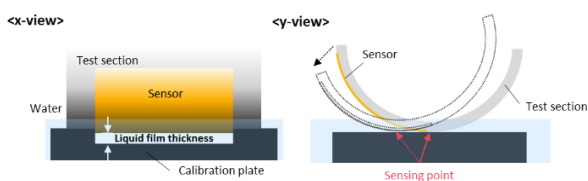


Fig. 4. Calibration method

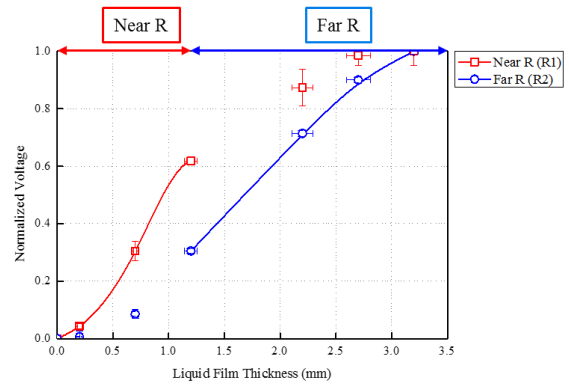


Fig. 5. Calibration curve

## 3. Local measurement in air-water ECC bypass experiment

### 3.1. Experimental facility and test conditions

The air-water ECC bypass experiment facility was designed to describe the ECC bypass phenomenon in the reactor vessel downcomer during large-break LOCA. The facility is 1/10 reduced scale of APR1400, and the schematic of it is shown in Fig. 6. By using two blowers, the air is injected to the test section through two pipes corresponding to the intact cold legs. The ECC water is also injected to the test section through a nozzle, and the valve to control the water level in the test section was installed at the drain pipe connected to the lower part of the test section. The test section describing the reactor vessel downcomer is a half of the annulus channel which inner diameter is 400 mm. In the middle of it, two FPCB sensors were attached to measure the film thickness on the inner wall of the test section. The detailed view of the test section are in Fig. 7. The broken cold leg below the water nozzle is connected to the air-water separator, which separate two-phase mixture into water and air. The air exits through the top of the separator, and the water returned to the water tank through the drain pipes at the bottom of the test section and separator.

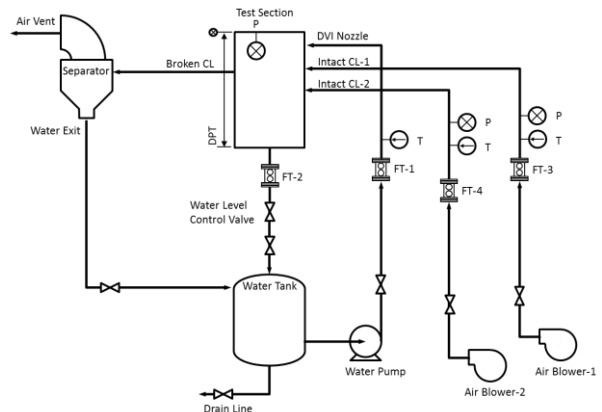


Fig. 6. Schematic of experiment facility

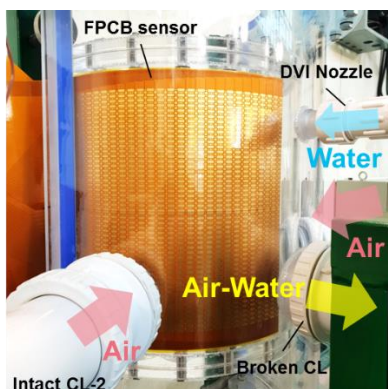


Fig 7. Annulus test section

The experiment conditions were determined based on the transient analysis result of APR1400 during the cold leg break LOCA [3]. Then, the parameters were scaled down according to the modified linear scaling method [4], which preserves the Wallis parameter as follows.

$$j_k^* = \frac{\dot{m}_k}{\rho_k A_{flow}} \left[ \frac{\rho_k}{(\rho_f - \rho_g) g D_{gap}} \right]^{1/2} \quad (1)$$

The non-dimensionalized air and water velocities as the Wallis parameter is presented in Table I.

Table I. Test conditions

$j_f^*$	0.026		0.037			
$v_f$ (m/s)	0.63		0.89			
$j_g^*$	2.37	3.40	3.74	4.08	4.43	4.78
$v_g$ (m/s)	14	20	22	24	26	28

### 3.2. Local measurement of liquid film thickness

Under various flow conditions, the time-averaged film thicknesses for 10 seconds were obtained. In the case of no air injection, the measured results were compared to the visual observation in Fig. 10. The injected water makes jet impingement on the wall and thick film can be observed near the impinging area due to the hydraulic jump. Then the liquid film falls along the wall by the gravitational force. As increasing the inlet water velocity, the liquid film width becomes wider. From the measurement results, it was confirmed that the sensor properly reflect the real flow behavior.

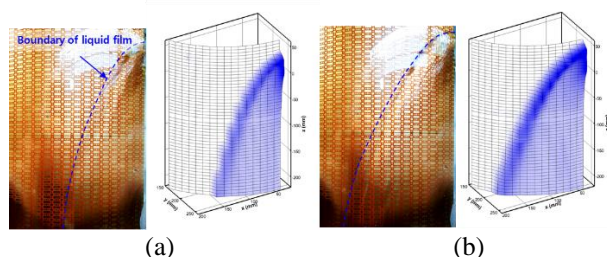


Fig 8. Local measurement of liquid film thickness without air injection: (a)  $j_f^* = 0.026$  (0.63 m/s); (b)  $j_f^* = 0.037$  (0.89 m/s)

Figures 9~10 are the measurement results with different air velocities. The lateral air flow toward the broken cold leg interacts with the downward liquid film, and the thick boundary region of the liquid film was shifted toward the broken cold leg. When the air velocity at each cold leg reached about 20 m/s, the entrainment could be observed and some part of the liquid film began to bypass in the form of droplet. In the case of air velocity of 28 m/s, the thick liquid film just below the break was observed in the measurement results. This can be observed because of the hanging liquid film created by the balance of the gravitational force and interfacial friction force.

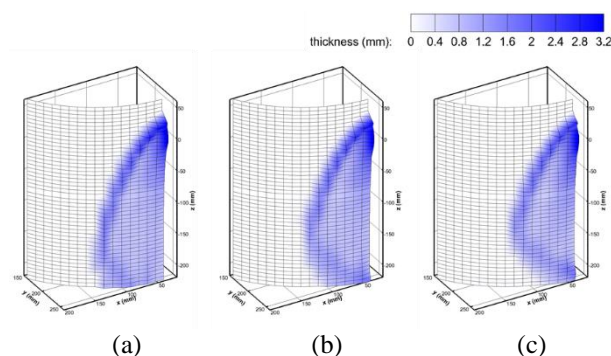


Fig 9. Local measurement of liquid film thickness with  $j_f^*$  of 0.026: (a)  $j_g^* = 3.40$  (20m/s); (b)  $j_g^* = 4.08$  (24 m/s); (c)  $j_g^* = 4.78$  (28m/s)

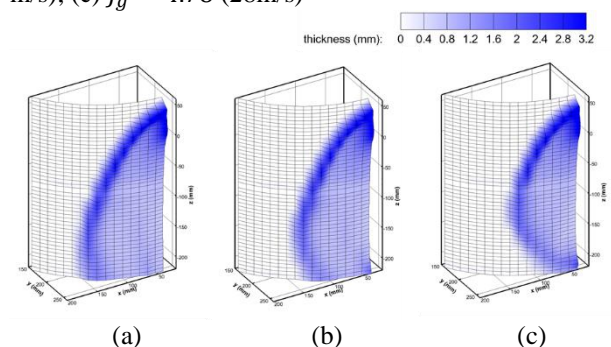


Fig 10. Local measurement of liquid film thickness with  $j_f^*$  of 0.037: (a)  $j_g^* = 3.40$  (20m/s); (b)  $j_g^* = 4.08$  (24 m/s); (c)  $j_g^* = 4.78$  (28m/s)

## 4. CFD simulation

The air-water ECC bypass experiment was simulated using a commercial CFD code, STAR-CCM+ [5]. The calculated local variables in the simulation can be used to investigate the liquid film behavior and improve physical models concerned with the film behavior. In this study, only the case of no air injection was simulated as a preliminary analysis. Figure 14 shows analysis domain of the test facility with applied boundary conditions. The water inlet velocity at the nozzle is 0.63 m/s, and for the interface tracking in two-phase flow, volume of fluid (VOF) method was used in the simulation. The  $k-w$  based shear stress transport (SST) turbulence model was applied for turbulence closure. The hexahedral meshes

were used and the total number of the elements is approximately 12,860,000. The unsteady simulation was carried out with the time step of  $10^{-4}$  sec.

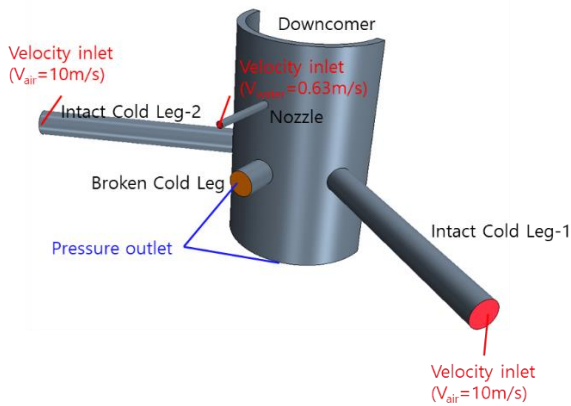


Fig 11. Analysis domain in STAR-CCM+

The calculated liquid film thickness after 3.2 seconds was obtained from the iso-surface of void fraction at 0.5, and the front view of it is plotted in Fig. 12. Compared to the Fig. 8 – (a) which was obtained in the same condition, it can be confirmed that the liquid film width and thickness were reasonably calculated. Then the profiles of the liquid film thickness along two lines ( $x=-8$  mm,  $x=-44$  mm) were compared to the experiment results (Fig. 13). The point where the  $z$ -coordinate is zero indicates the region where water is injected. Both show the decreasing tendency of the liquid film thickness as the film falls along the wall. In general, the calculated film thicknesses were comparable with the experiment results, though the CFD slightly overestimates the thickness at the center line ( $x=-8$  mm).

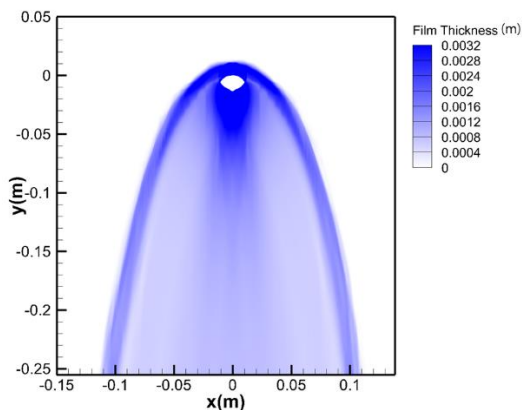


Fig 12. Calculated liquid film thickness without air injection ( $j_f^* = 0.026$ )

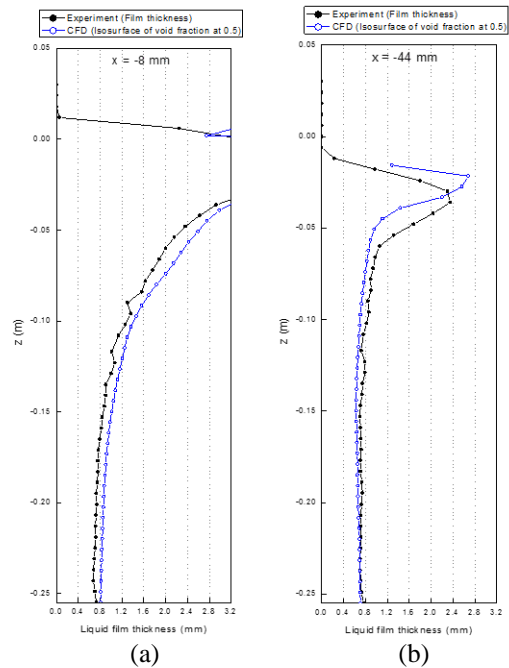


Fig 13. Comparison of the liquid film thickness: (a)  $x = -8$  mm; (b)  $x = -44$  mm

#### 4. Conclusion

In the present work, the liquid film thickness sensor based on electrical method was developed to obtain the local measurement data. The fabricated sensor was demonstrated by the calibration and the air-water ECC bypass experiment. As a preliminary simulation, CFD analysis was performed in the case of no air injection. The local thickness of liquid film in the experiment was used to validate the CFD code.

#### Acknowledgement

This work was supported by National R&D program through the Ministry of Education of the Republic of Korea and National Research Foundation of Korea (NRF). (No. NRF-2017M2A8A4018490)

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