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Three-Electrode Conductance Sensor Based on Flexible Printed Circuit Board for Measuring Wide Ranges of Liquid Film Thickness

Chi-Jin Choi [a], Hyoung-Kyu Cho[a*], and Goon-Cher Park [a]
[a]*Nuclear Thermal-Hydraulic Engineering Laboratory, Seoul National University*
Gwanak 599, Gwanak-ro, Gwanak-gu, Seoul, Korea
[*]*Corresponding author: chohk@snu.ac.kr*

1. Introduction

In nuclear power plants, the liquid film behavior on heat exchanger surfaces or fuel rods is a crucial factor in terms of heat transfer. Besides, under an accident condition, the liquid film behavior in two-phase flow on reactor downcomer is closely related with how much amount of Emergency Core Cooling (ECC) water is needed. Accordingly, these facts have motivated the studies about techniques of measuring liquid film using various methods. Among them, an electrical method that uses electrical conductivity of water has widely used due to its advantage of having high time resolution.

Damsohn et al. [1] developed a liquid film sensor which has a pair of electrodes, so called transmitter and receiver mounted flush to the wall. The electrodes were fabricated on a Flexible Printed Circuit Board (FPCB) to apply on a fuel rod. The dimension of a measuring point is 2 mm × 2mm for measuring the liquid film thickness in the range between 0 and 1 mm. Kim et al. [2] adopted three-electrode method which was initially developed by Coney [3] for compensating the conductivity variance of water. The electrodes were fabricated on a PCB which is not available on a curved surface. Recently, Lee et al. [4] designed a ring-shaped electrodes based on three-electrode method, and they were fabricated on a FPCB.

In this study, a new pattern of electrode fabricated on a FPCB was developed to measure the liquid film thickness in the range between 0 and 3.5 mm. The newly developed sensor is based on three-electrode method, however it is not for compensating the conductivity variance, but for improving the measurement accuracy in thin film region. In order to confirm the feasibility of the sensor, the liquid film flow experiment was performed with the calibrated sensor.

2. Sensor Design

2.1 Electrode Design

The electrode was designed to measure the liquid film thickness in the ranges from 0.5 mm to 3.5 mm. Figure 1 shows the arrangement of the electrodes based on three-electrode method, where T, R, and G represent transmitter, receiver, and ground respectively. The dimension off a measuring point is 6 mm × 12 mm. The ground electrodes play an important role in improving measurement accuracy by increasing the sensitivity of the electrical signal and minimizing the cross-talk effect. The receiver electrodes are classified by the distance from the transmitter electrode in a same measuring point, and they are called near receiver (R1) and far receiver (R2). The COMSOL Multiphysics code was used to analyze the electrical potential field around the electrodes and the calculated current to two receivers with increasing film thickness are presented in Fig. 2. The results show that the trends of two curves are different from each other. The current at R1 is more sensitive in thin region (~1.5 mm) compared with the current at R2, but it becomes nearly saturated at 3.0 mm. Therefore, if the electrical signal can be used selectively according to the liquid film thickness, the measurement accuracy of the sensor can be enhanced compared to that of a sensor which has a same electrode dimensions.

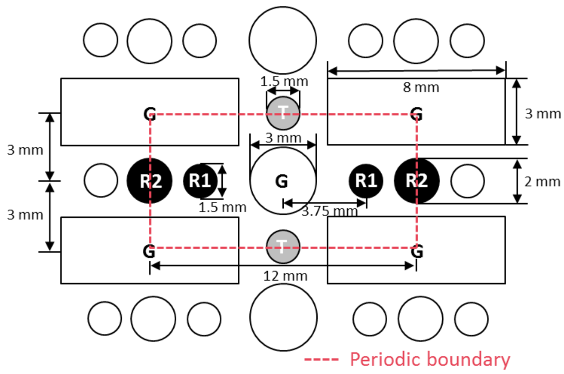

Fig. 1. Geometry of electrodes with periodic boundary

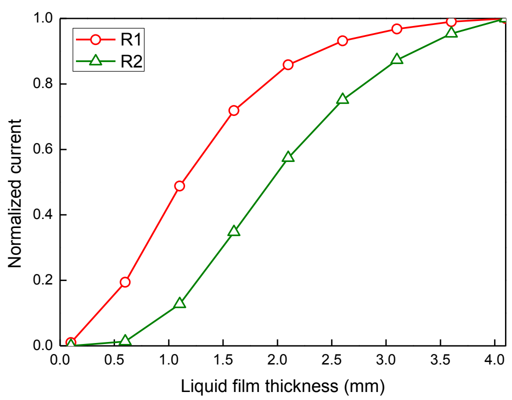

Fig. 2. Electrical potential analysis result using COMSOL

The designed electrodes were fabricated on a Flexible Printed Circuit Board (FPCB) with 24 × 24 array of the measurement points as shown in Fig. 3. The dimension of the total measurement part is 144 mm × 288 mm.

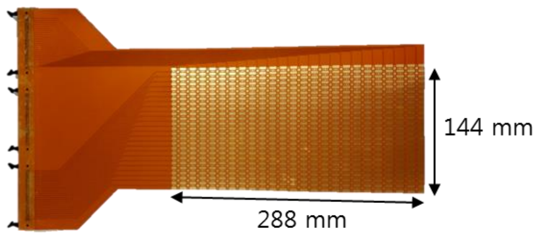

Fig. 3. Liquid film sensor based on FPCB with 24 × 24 array of the measurement points

2.2 Circuitry System

In order to obtain a large number of signals effectively, the circuitry system was installed. It is nearly identical with the system used in Lee et al. [4], but the operational amplifier (op-amp) was added to amplify the voltage signal to Data Acquisition System (DAS). The reticular signal wire system applied on the sensor has an advantage of reducing the number of wire with high temporal resolution.

3. Sensor Calibration

The developed sensor aims to be applied on an experiment which describes liquid film flow on a reactor downcomer. Then, the sensor should be calibrated on a curved plane considering the electrical field distribution which is affected by the geometry. The calibration method used in this study is similar with Ito's [5] method and it is shown in Fig. 4. The two sensors attached on the curved plate which height and dimeter are 390 mm and 400 mm respectively were calibrated on the calibration plate. The inner region of calibration plate is cut to a uniform thickness *t*, and the minimum voltage ratio is measurable when the distance between the sensor and the calibration plate becomes the length of *t* while the test section is rolled. In the calibration tests, the water temperature and electrical conductivity are about 22℃ and 17 μS/cm respectively. The induced signal from function generator was 10V AC voltage with 1 kHz.

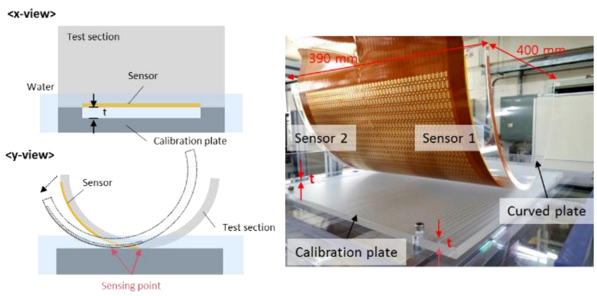

Fig. 4. Calibration method

The calibration results with different *t* at a measuring point are presented in Fig. 5. The calibration curve at R1 was more sensitive in thin region and less sensitive in thick region than that at R2. The voltage ratio (R2/R1) was also proportional to the liquid film thickness and it shows good linearity except for very thin and thick region. Based on the results, the procedure of obtaining the liquid film thickness was developed by selecting a calibration curve according the reference thickness which is 1.5 mm calculated from the voltage ratio curve.

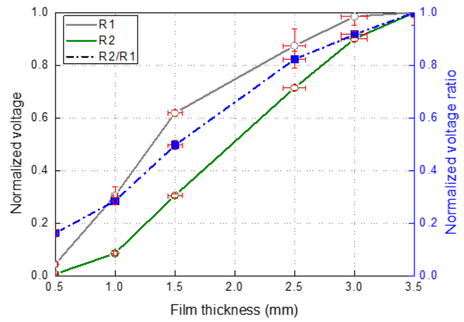

Fig. 5. Calibration results

4. Liquid Film Flow Experiment

The calibrated sensor was applied on the liquid film flow experiment. The experimental facility is nearly same with that from Lee et al. [4], but one difference is that the curved test section was used instead of flat one. At the test section, the water from a nozzle is injected to the sensor. After being impinged on the sensor, water falls down and goes back to the water tank.

Figure 6 shows the time-averaged film thickness with different inlet velocities. In all cases, at the impingement position, the thickest film was measured, and a relatively thick film near the edge was obtained due to the hydraulic-jump phenomenon. As increasing the inlet velocity, the parabolic shaped edge was expanded, which is well matched with the visual observation.

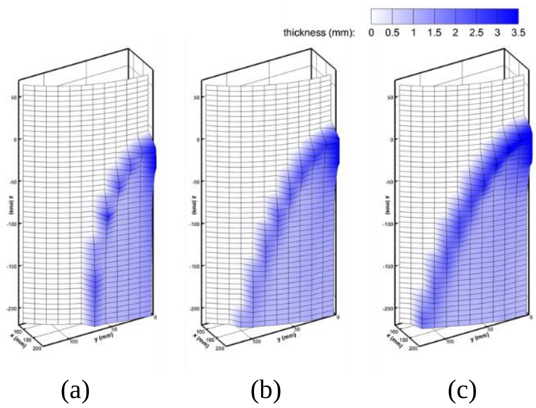

Fig. 6. Measurement of liquid film thickness: (a) V_{in} = 0. 39 m/s; (b) V_{in} = 0.51 m/s; (c) V_{in} = 0.63 m/s

5. Conclusions

The newly designed sensor based on three-electrode method was devised. With two different types of receivers, R1 and R2, the data acquisition method which uses calibration curves selectively according to the film thickness was presented. The sensor was calibrated on the curved test section, and then the feasibility of it was confirmed with the liquid film flow experiment.

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