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Design and Fabrication of Liquid Film Sensor Using Flexible Printed Circuit Board Based on Three-Ring Conductance Meter

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1. Introduction

Two-phase flow is frequent phenomena in some industrial environments. Especially gas-liquid flow is common in nuclear industry, understanding the two-phase flow is an important part of the analysis on safety and performance of nuclear safety system. As the liquid film thickness is one of key factors, a lot of research has been conducted for measuring liquid film thickness. Recently, electrical methods have been widely applied for many years. Damsohn[1] developed a high speed liquid film sensor that has high resolution for time and space by combining conductance method with wire-mesh signal processing unit. However, since the electric conductivity of liquid can be affected by its temperature, the conventional electrical conductance methods have limitation on applying for varying temperature conditions where a heat transfer is involved. Coney[2] proposed three-ring conductance method that can compensate the change of conductivity of the liquid. Kim[3] and Lee[4] showed the feasibility of the three-ring conductance meter by fabricating it on printed circuit board (PCB) and flexible printed circuit board (FPCB) individually. In this study, the three-ring conductance meter is fabricated on FPCB. The FPCB can tolerate relatively high temperature (400K). And thanks to the high flexibility, it has applicability on a curved surface. This paper introduces the design procedure of liquid film sensor and calibration result in order to confirm its feasibility.

2. Three-ring conductance meter

2.1 Principle of three-ring conductance meter

The specific theory of the three-ring conductance meter is described on Coney[2] and Kim[3]. There is an assumption in three-ring conductance meter. That is the liquid film has only conductance property on electrical point of view. The three-ring conductance meter measures liquid film thickness using three electrodes as shown in Fig. 1. The currents are developed by electrical potential difference between transmitter (A) and receivers (B and C). If the electrical path of A-B and A-C have equal potential difference, the currents are determined by the liquid film thickness and the conductance of liquid. Because of the conductance, the currents are varied by change of temperature. However, the current ratio (I_2/I_1) is independent of the temperature by compensating the changing conductivity effect. So, Measurement of the film thickness is possible regardless of temperature change.

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2.2 FPCB characteristics

FPCB is composed of cooper layer and polyimide film layer. Thanks to the properties of polyimide, it can be applied on curved surface and relatively high temperature (400K), which is higher than the saturation temperature of the steam under the atmospheric pressure.

Also, the possibility of delicate and multi-layer fabricating allows the manufacturing sensors that has complicate structure.

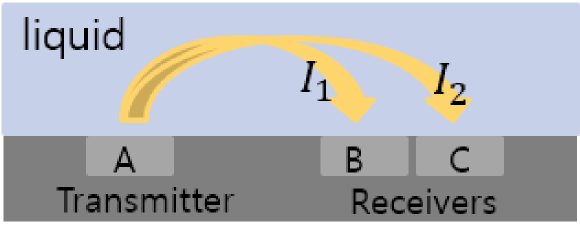

Fig. 1. Current flow between transmitter and receivers of three-ring conductance meter (Kim [3])

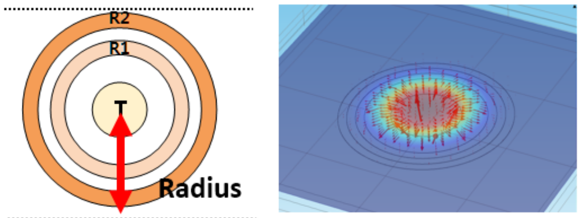

Fig. 2. Geometry of electrodes and electrical potential field calculation by using COMSOL 5.1.

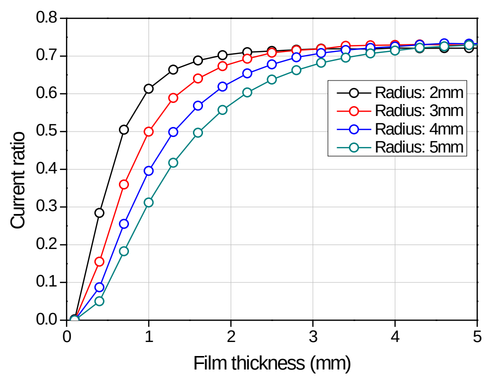

Fig. 3. Electrical potential field calculation result according to radius size of probe.

3. Design of liquid film sensor

To design and optimize the geometry of the sensor electrodes, the electrical potential field simulation was conducted by using COMSOL 5.1 (Fig. 2). The target of maximum measurable film thickness was 3 mm. The geometry concept of electrodes is presented in Fig. 2. The transmitter and receivers are concentric circles. Fig. 3 describes the measurable film thickness according to the radius of probe, and it indicates that large probe can measure thicker film than small probe. Also, in order to prevent the cut-off phenomenon, the length of pitch was set to 15 mm and ground electrode was added. Square lattice shaped ground electrode was deposed as shown in Fig. 4. Electrical potential analysis was conducted to determine the proper width of ground electrode (Fig. 5).

The prototype of liquid film sensor is presented in Fig. 6. It is composed of 6×6 array, and the length of width and height is 90 mm. The width of ground is 0.2 mm and the outer radius of probes is set to 5 mm.

4. Calibration experiment and result

The manufactured prototype sensor was conducted calibration procedure. The conductivity and temperature of water was 24μS/cm and 24℃. AC 10V voltage signal was induced to the transmitter with 1 kHz. In fact, the unique signal with characteristic frequency should be applied in respect of conductance method. However, due to the limitation on speed of data acquisition system, 1 kHz signal was adopted in this research.

To verify the characteristics of the sensor, calibration procedure was conducted. The calibration method used a micrometer stage to maintain the uniform liquid film thickness (Fig. 7). The calibration result is shown in Fig. 8. By repeating the calibration, the reproducibility of the sensor was confirmed. Through the calibration, it was possible to identify the different characteristic curves of each probe. This result is considered of mechanical manufacturing tolerance. Because of the different characteristics of every probe, 36 different calibration were conducted.

In order to confirm the accuracy of the sensor, additional test was carried out. The needle was connected to micrometer and by controlling the micrometer, measuring the moment that needle tip contact the free surface was carried out (Fig. 9). The result is described in Fig. 10. Though the sensor has relatively high error in thin film region, considering its maximum film thickness, this error thought to be acceptable level.

The temperature independency test was performed in another probe with two different temperature conditions (27℃ and 37℃) with identical water. Fig. 11 presents the result of two test. As the temperature of water increased, the current outputs of receiver were increased. However, the current ratio did not changed significantly (Fig. 12). With some modification in Eq. (1), the current ratio of two tests was maintained with almost same value (Fig. 13).

$$Ratio = \left(\frac{I_2 - 0.35}{I_1}\right)^{1.05} \qquad (1)$$

5. Conclusions

Through the electrical potential analysis, liquid film sensor was designed. Calibration procedure was conducted with the manufactured film sensor. By the result of calibration result, it was confirmed that this sensor can measure the film thickness up to 3 mm. In addition to this calibration, study on sensitivity of the sensor and optimum signal processing are needed for applying in dynamic measurement of various two-phase flow experiment.

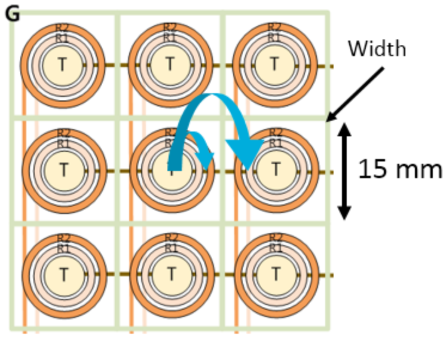

Fig. 4. Geometry of ground electrode and probe array of prototype.

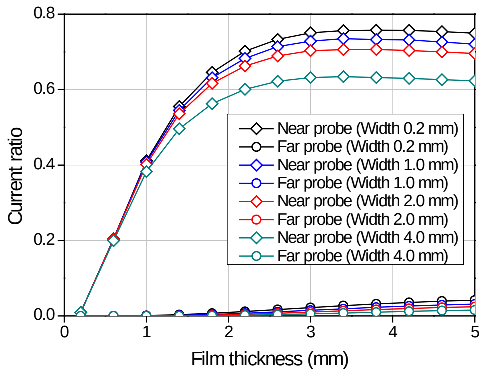

Fig. 5. Electrical potential field calculation result according to width size of ground electrode.

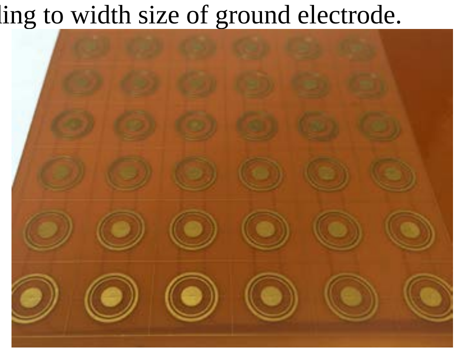

Fig. 6. Prototype of liquid film sensor fabricated on FPCB.

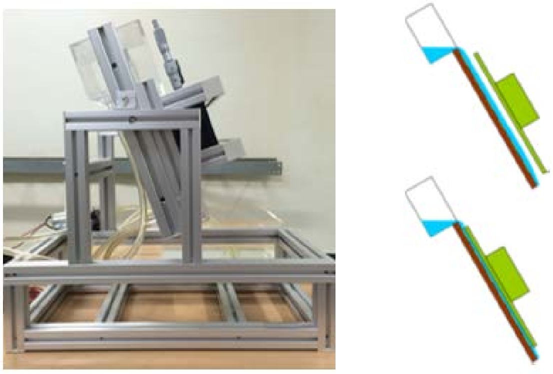

Fig. 7. Calibration apparatus to confirm liquid film sensor using micrometer.

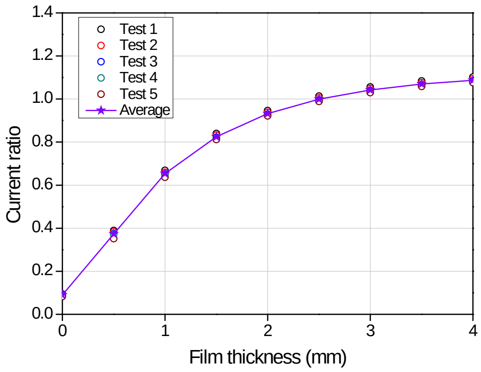

Fig. 8. Calibration result of single probe with changing liquid film thickness.

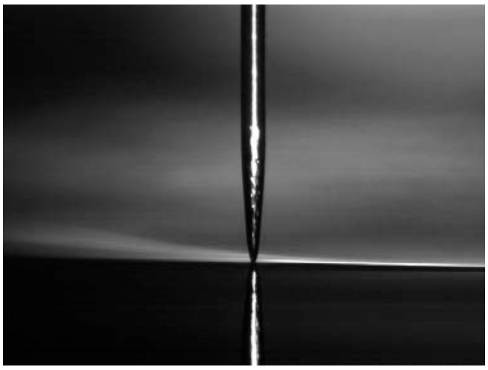

Fig. 9. Calibration result of single probe with changing liquid film thickness.

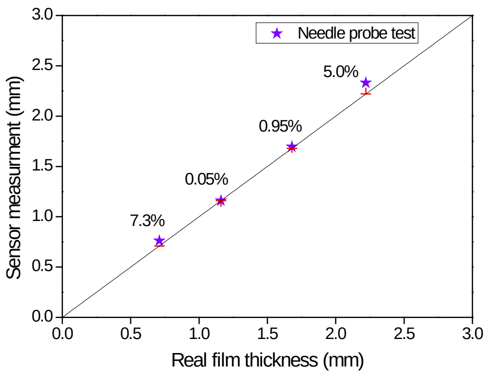

Fig. 10. Comparison liquid film sensor and needle probe.

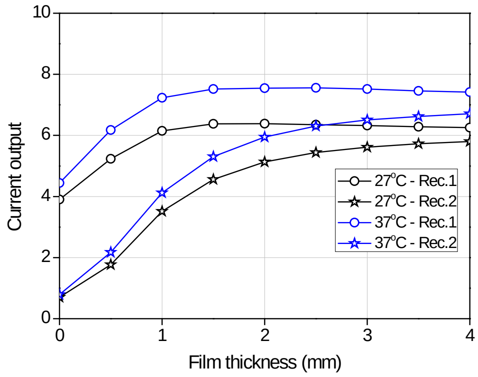

Fig. 11. Current output signals of two different temperature conditions.

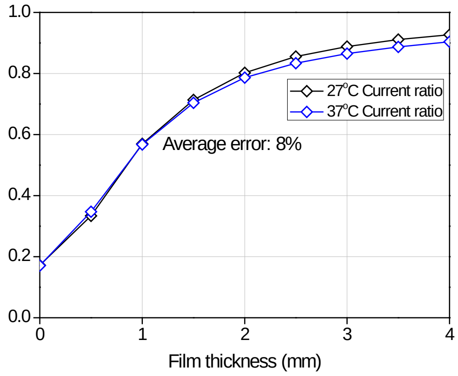

Fig. 12. Current ratio of two different temperature conditions.

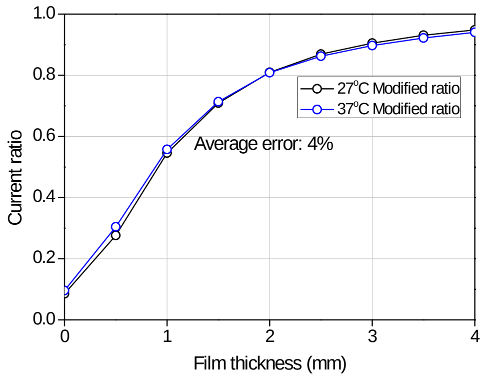

Fig. 13. Modified current ratio of two different temperature conditions.

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