Development of Methodology for Measuring Liquid Film Thickness Based on Three-ring Conductance Method

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Contents

1. Introduction
2. Design process of liquid film sensor
3. Liquid film flow experiment
4. Conclusion
1. Introduction

2. Design process of liquid film sensor

3. Liquid film flow experiment

4. Conclusions
High precision two-phase flow experiment

✓ Various research and experiment have being conducted on the area of annular and pipe flow condition.

✓ Liquid film flow is one of major concerns in the nuclear safety system.

Two-dimensional film flow experiment (KAERI)

✓ To evaluate Interfacial & wall friction factors for two-dimensional film flow

✓ Scaled down (1/10 & 1/5) test sections of the unfolded downcomer

Annular flow (Damsohn et al., 2010)  KAERI fluid film experiment (Yang et al., 2015)
Extension for more realistic experiment condition

- Air-water
- Duct (plane)
- Low resolution

To measure the film thickness, a liquid film sensor is demanded to have...

1. Temperature varying condition
2. High resolution (time & space)
3. High flexibility
4. High temperature condition

Conventional sensor cannot satisfy.

Purpose of the research
- Developing a new liquid film sensor
Wire-mesh & electrical method (Damsohn et al., 2009)

- High resolution on time and space
- High flexibility by using the FPCB (flexible printed circuit board)
  - FPCB can endure high temperature condition.
- Limitation on the temperature varying condition

Three-ring conductance method (Kim et al., 2013)

- Liquid film sensor on the temperature varying condition
- Limitation on the curved surface and high temperature
1. Introduction

2. Design process of liquid film sensor

3. Liquid film flow experiment

4. Conclusions
Design process of liquid film sensor

**Design of sensor electrodes (Ring type)**

- Previous design of three-ring sensor
  - Limitation in large scale integration (patterning)
- Range of the detectable film thickness
  - 0.5 ~ 3.0 mm (based on KAERI experiments)
- Electrical potential analysis for the sensor design
  - COMSOL ver. 5.1

![Potential analysis result](image)

![COMSOL calculation result](image)

Three-ring conductance meter (J. R. Kim et al., 2013)
**Parallel circuitry system**

- Parallel circuitry system for effective data acquisition
  - Analogous with wire-mesh circuitry system (Prasser et al., 1997)
    - Individual circuit layer of transmitter and receivers
  - Reducing the number of signal lines effectively ($3 \times N \times N_{(Array)} = 3N^2 \rightarrow 3 \times N$)

![Parallel circuitry system](image1)

![Prototype sensor](image2)
1. Introduction

2. Design process of liquid film sensor

3. Liquid film flow experiment

4. Conclusions
Liquid film flow experiment

**Experiment condition**

- Identical flow condition with the KAERI experiment (1/10 scale, w/o air blowing)
  - Nozzle to plane: 25 mm
  - Pipe diameter: 21 mm
- Measurement section dimensions: 360×180 mm
  - FPCB sensor: 24×12 array (total 288 sensors)

Schematic diagram of the experimental apparatus

- Conductance meter (C)
- Thermocouple (T)
- Water tank
- Temperature control
- Cooler
- Heater
- Flow meter
- Pump
- Signal processor
- Injection nozzle
- Test section
- Liquid film sensor
- Calibration device
- Test section

Liquid film flow experiment loop
Liquid film flow experiment

- **Calibration experiment**
  - **Calibration range**
    - 0.0 ~ 3.5 mm (0.5 mm step)
    - 17°C, 20 μS/cm filtered water
  - **Repeatability test**
    - Accuracy: 1.6% (~1.5 mm), 4.0% (~3.5 mm)
  - **Isothermal & non-isothermal test**
    - Using 20°C and 40°C water

![Schematic diagram of calibration apparatus](image)
Liquid film flow experiment

* Liquid film sensor characteristics
  
  ✓ Available measurement thickness
    - 0.0 ~ 3.5 mm
  ✓ Parallel circuitry with switch board
    - Inducing channel is switched automatically with trigger signal.

Test section

FPCB sensor

Water injection

Diagram:

- Function generator
- Switching trigger signal
- DAS ($V_1/V_2$)
- Circuit board
- Inducing signal
- Switch board
- Receiver 1
- Receiver 2
- Transmitter
- FPCB

13/18
Liquid film flow experiment

- **Liquid film flow measurement - 1**
  - Steady-state measurement
    - Averaged value for 5 seconds (1000 data)
  - Water inlet velocity: 0.46, 0.84 m/s
Liquid film flow experiment

- **Liquid film flow measurement - 2**
  - ✓ Transient measurement
    - • Experiment with decreasing the flow rate
  - ✓ Time resolution: 0.48s
  - ✓ Comparison with film flow video

Film flow video

Film thickness contour
Liquid film flow measurement - 3

- Steady-state measurement with different temperature conditions
  - Temperature variation test
  - 20 ~ 40°C measurement based on 20°C calibration data
1. Introduction

2. Design process of liquid film sensor

3. Dynamic liquid film flow experiment

4. Conclusions
Conclusions

1. Feasibility of liquid film sensor was confirmed.
2. Ring type sensor was proposed for patterning.
3. Switching circuitry was devised for large sensor system.
4. Dynamic & steady film flow measurement was conducted by applying FPCB sensor and switching system.
5. Further study will be followed to extend temperature range.
Thank You!
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Coupling with wire-mesh circuitry

- Wire-mesh circuitry
  - Bi-polar DC
  - High speed switching

- Current problem using bi-polar DC

Steady state does not appear.

(Damsohn, 2009)

(Prasser, 1997)
Appendix

- Preliminary test of three-ring method on FPCB
  - Conventional design of the three-ring conductance method (Kim et al., 2013)
  - Fabricating on the FPCB
Calibration result

- Test condition
  - Inducing voltage: AC 10V (1 kHz)
  - Water condition: 22°C & 5 μS/cm
- 36 different calibration curves

Verification of calibration result

- Repeatability was confirmed.
- Comparison with the ultrasonic thickness gauge

![Schematic diagram of the calibration experiment](image)
FPCB

- IT (information technology) & MEMS (micro electro mechanical systems) field
- Great flexibility and tolerance on relatively high temperature condition
- Integrated multi-layer fabrication

Various measurement technique

Temperature & strain sensor (D. J. Lichtenwalner et al., 2006)
Local pressure sensor (E. Pritchard et al., 2008)
Flexible flow sensor (M. Shikida et al., 2012)
Specific design of the sensor

- The electrode design was determined by the parametric study.
Appendix

**Modified FPCB sensor for experiment**

- Additional shielding plane to prevent the cross-talk effect
- Cross-talk: undesired effect in another circuit or channel
  - Electromagnetic interference from one unshielded twisted pair to another twisted pair, normally running in parallel.
  - Induced current could interfere the measurement of current ratio.

<table>
<thead>
<tr>
<th>Crosstalk effect</th>
<th>Main receiver ($I_1$)</th>
<th>Near receiver ($I_2$)</th>
<th>Far receiver ($I_3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prototype</td>
<td>-</td>
<td>3.13%</td>
<td>2.36%</td>
</tr>
<tr>
<td>Modified model</td>
<td>-</td>
<td>0.96%</td>
<td>0.71%</td>
</tr>
</tbody>
</table>
Test for condensation experiment condition

- Steam condensation on the surface of the FPCB sensor
  - Drop wise condensation