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

Kyu-Byoung Lee [a,b], Chi-Jin Choi [b], Jong-Rok Kim [c],
Dong-Jin Euh [c], Goon-Cherl Park [b], Hyoung-Kyu Cho [b]

[a] Korea Institute of Nuclear Safety
[b] Seoul National University
[c] Korea Atomic Energy Research Institute

kblee@kins.re.kr

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2. Design process of liquid film sensor

3. Liquid film flow experiment

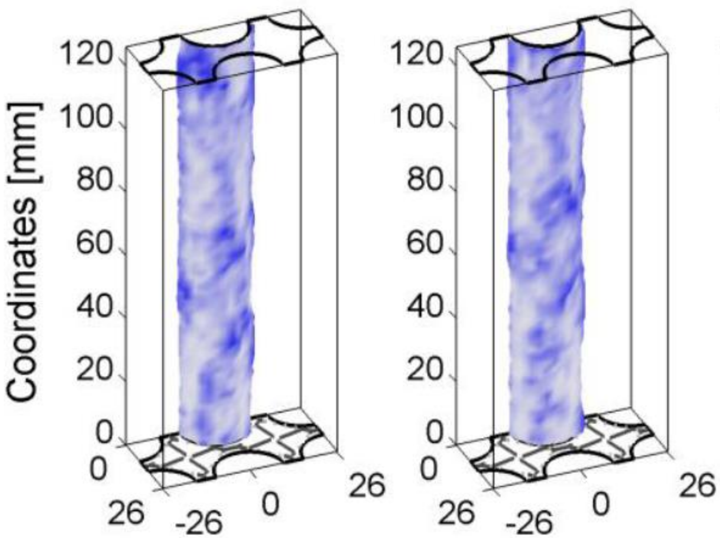
4. Conclusions

High precision two-phase flow experiment

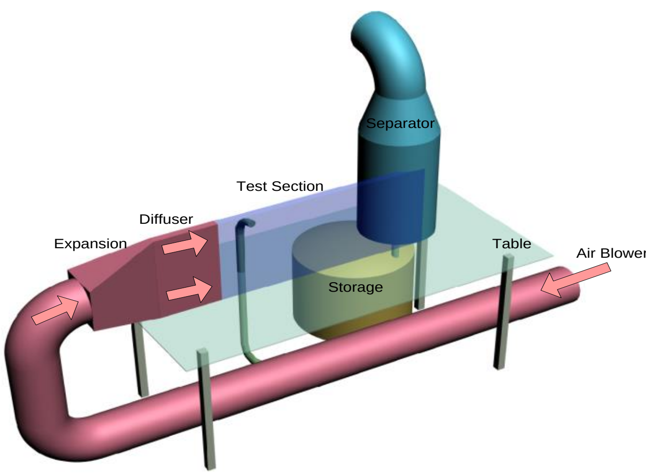
- Various research and experiment have being conducted on the area of annular and pipe flow condition.
- Liquid film flow is one of major concerns in the nuclear safety system.

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

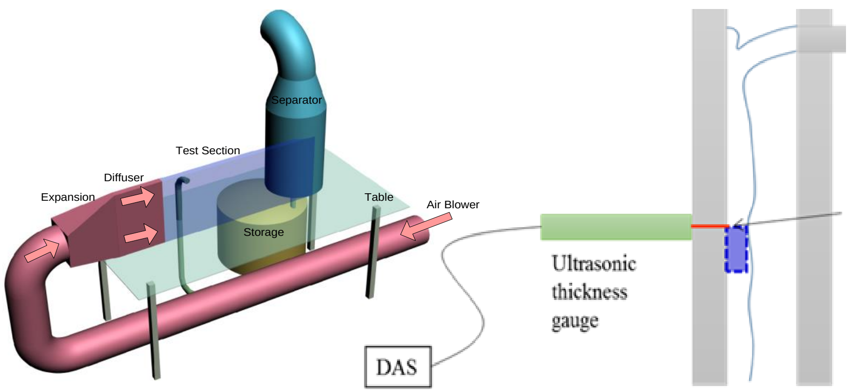


Annular flow (Damsohn et al., 2010)



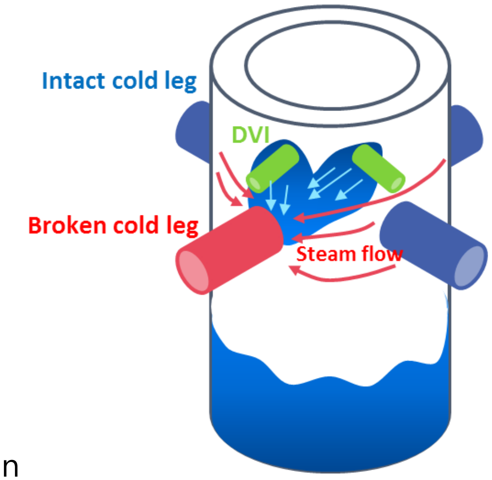
KAERI fluid film experiment (Yang et al., 2015)

❖ Extension for more realistic experiment condition



KAERI Fluid film experiment
(Yang et al., 2014)

Reflood phase in Downcomer



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

- ✓ Steam-water
- ✓ Annulus
- ✓ High 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

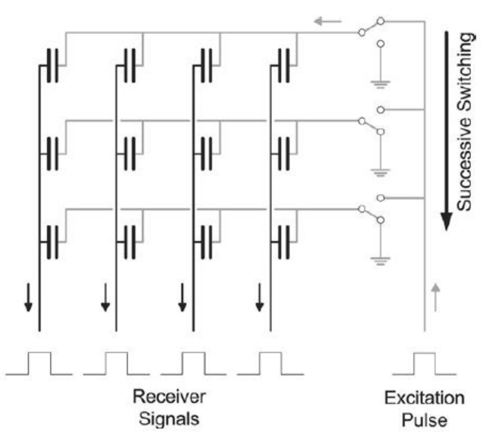
-Developing a new liquid film sensor

❖ Wire-mesh & electrical method (Damsohn et al., 2009)

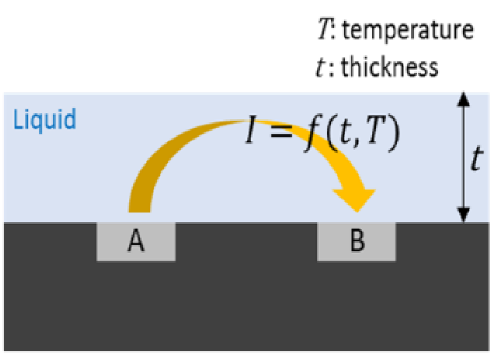
- ✓ High resolution on time and space
- ✓ High flexibility by using the FPCB (flexible printed circuit board)
  - FPCB can endure high temperature condition.
- ✓ Limitation on the temperature varying condition

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

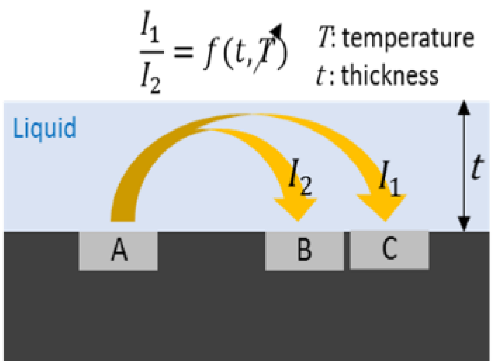
- ✓ Liquid film sensor on the temperature varying condition
- ✓ Limitation on the curved surface and high temperature



Wire-mesh circuitry
(H. M. Prasser et al., 1997)



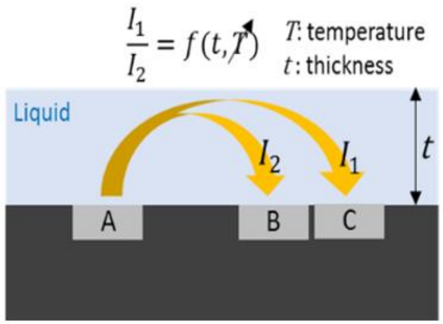
Liquid film sensor on PCB
(M. Damsohn et al., 2007)



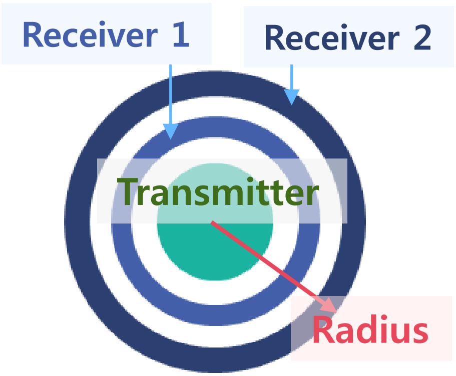
Three-ring conductance meter
(J. R. Kim et al., 2013)

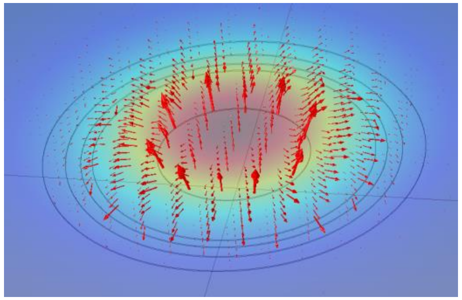
❖ Design of sensor electrodes (Ring type)

- ✓ 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

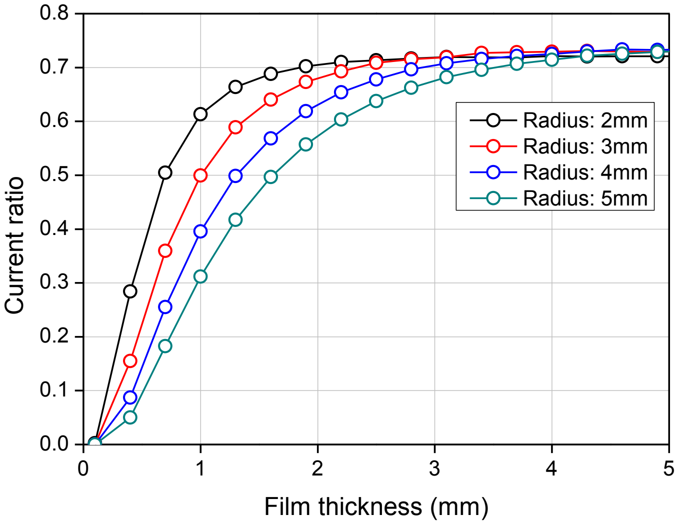


Three-ring conductance meter
(J. R. Kim et al., 2013)





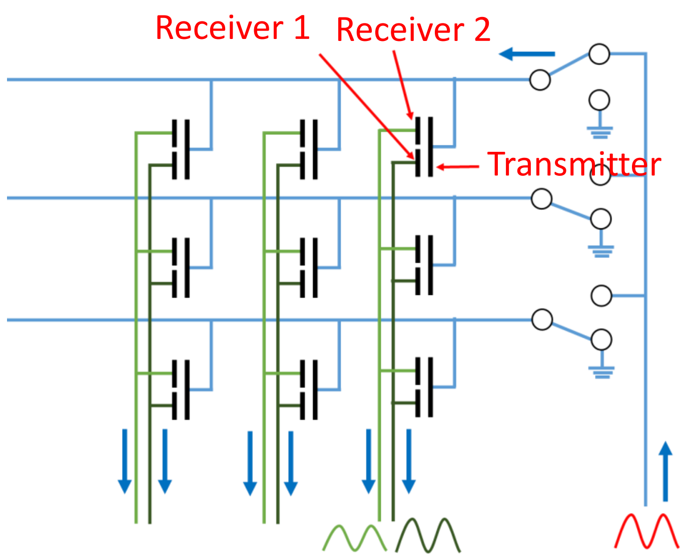
Potential analysis result



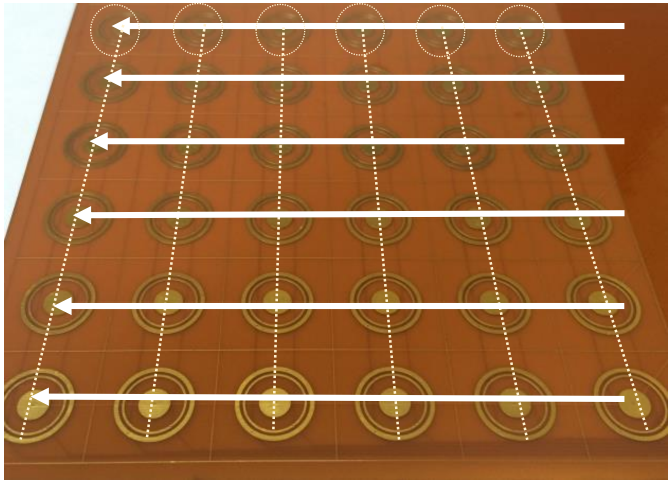
COMSOL calculation result

❖ 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 ($3 \times N \times N_{(Array)} = 3N^2 \longrightarrow 3 \times N$)



Parallel circuitry system



Prototype sensor

1. Introduction

2. Design process of liquid film sensor

3. Liquid film flow experiment

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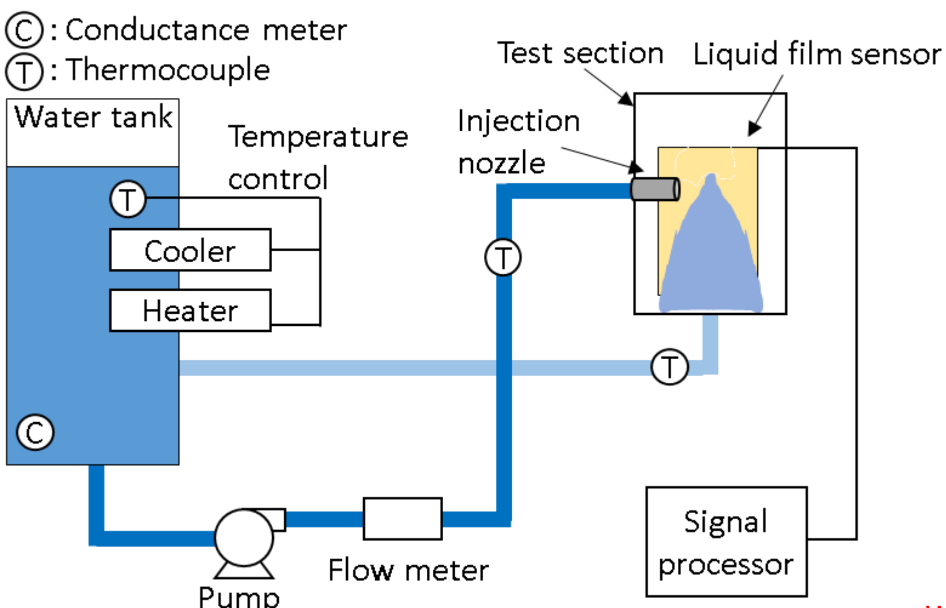
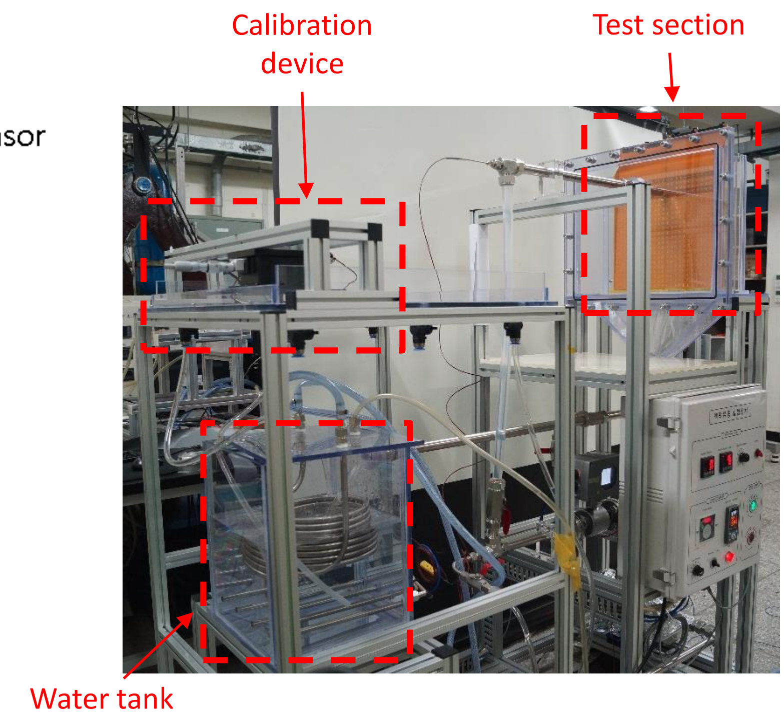
Experiment condition

- ✓ 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)



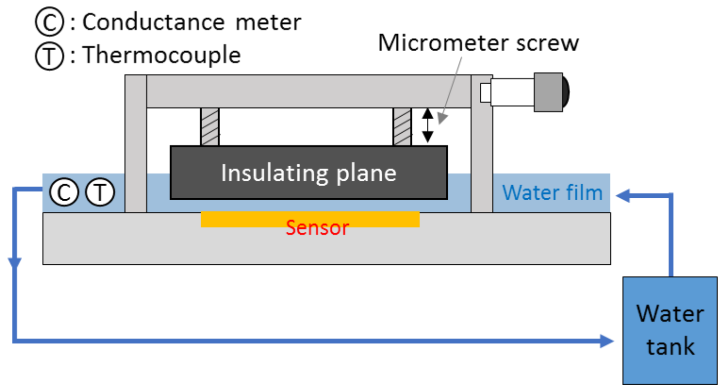
Schematic diagram of the experimental apparatus



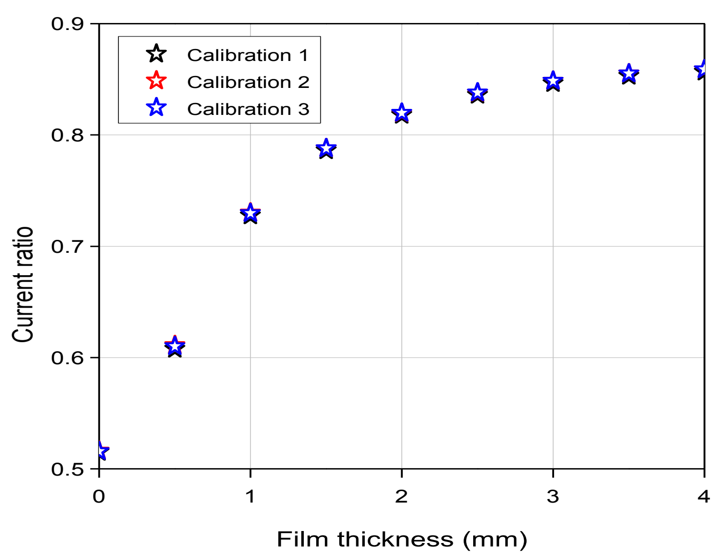
Liquid film flow experiment loop

Calibration experiment

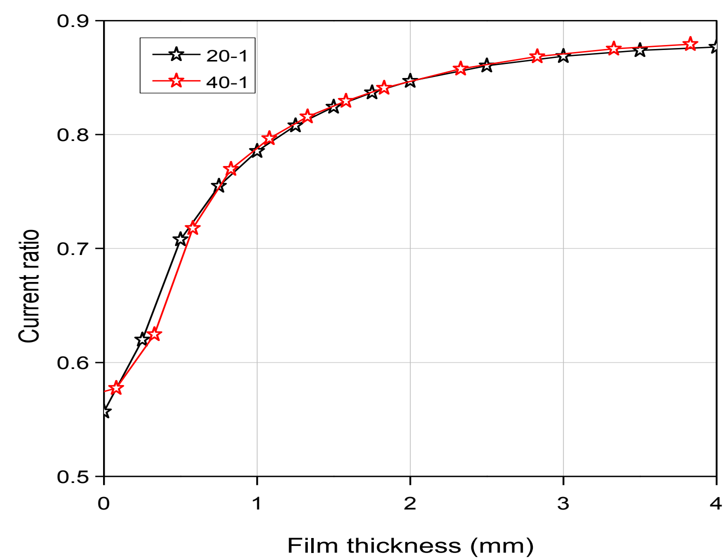
- Calibration range
  - 0.0 ~ 3.5 mm (0.5 mm step)
  - 17℃, 20 μS/cm filtered water
- Repeatability test
  - Accuracy: 1.6% (~1.5 mm), 4.0% (~3.5 mm)
- Isothermal & non-isothermal test
  - Using 20℃ and 40℃ water



Schematic diagram of calibration apparatus



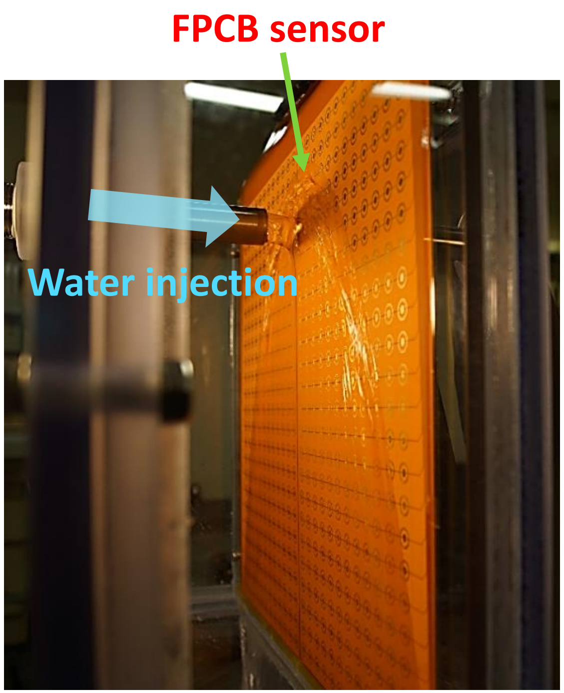
X: Film thickness
Y: Current ratio



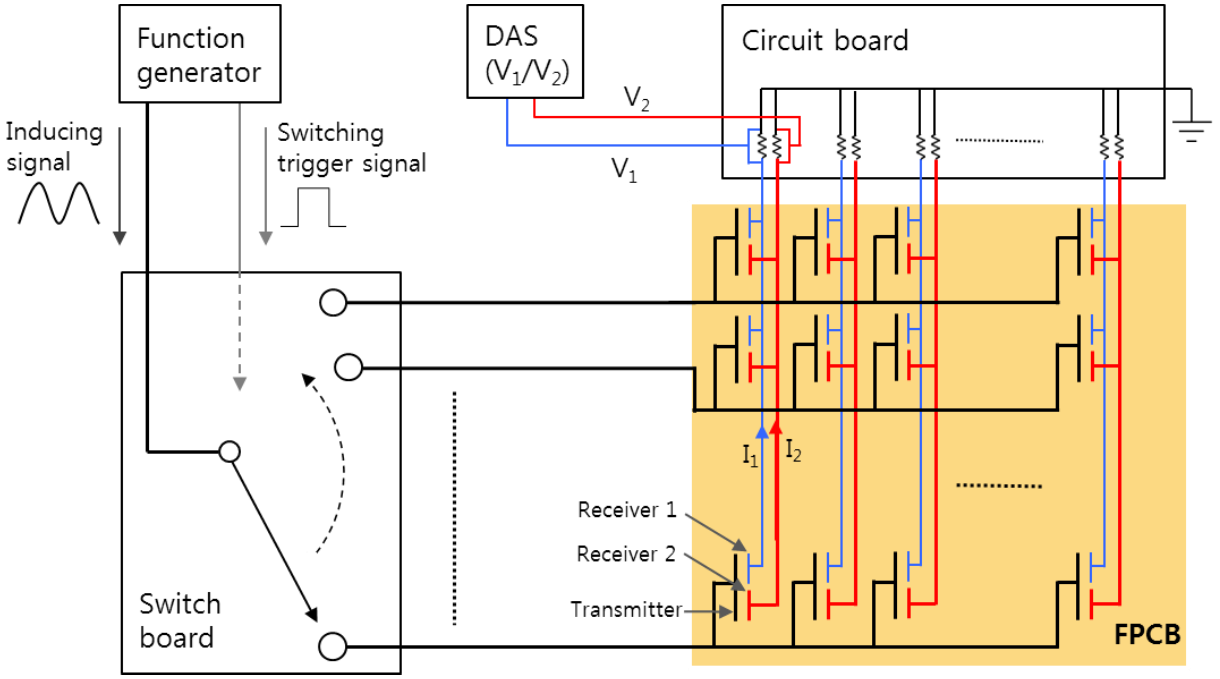
X: Current ratio
Y: Film thickness

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.

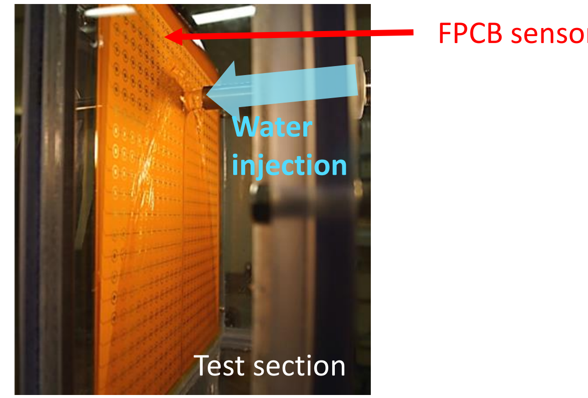


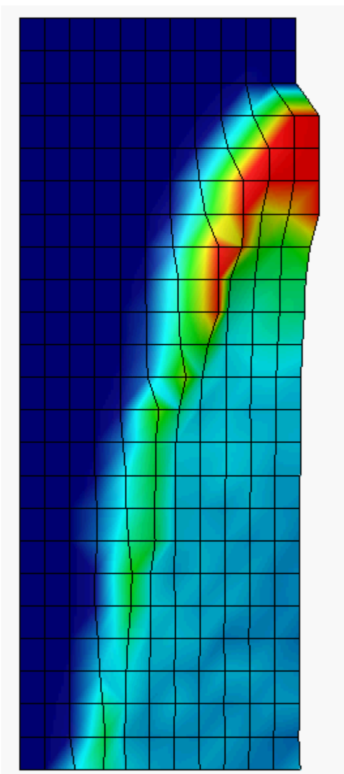
Test section

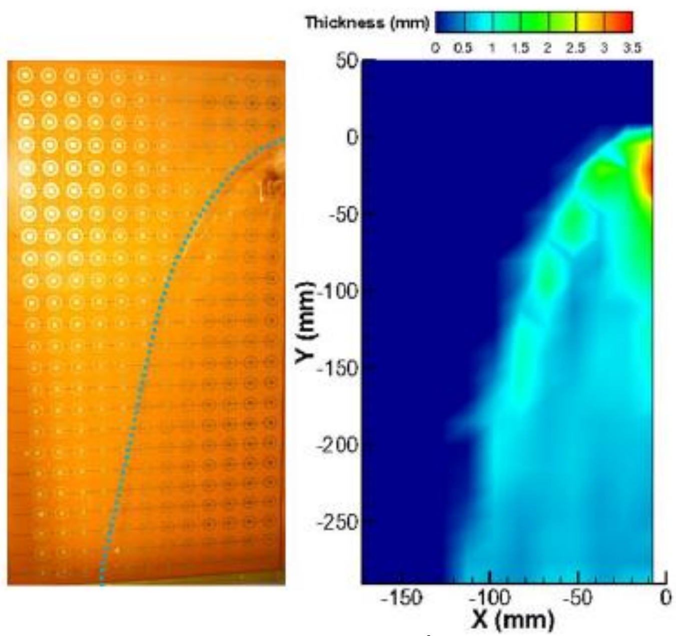


Liquid film flow measurement - 1

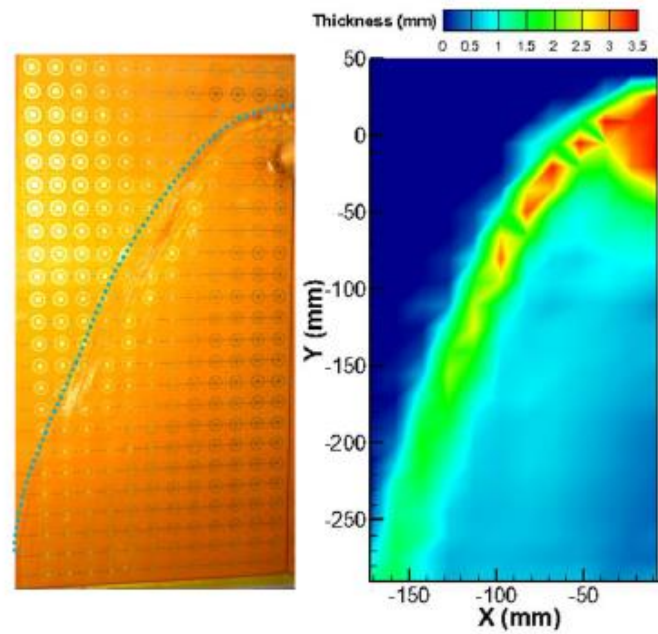
- Steady-state measurement
  - Averaged value for 5 seconds (1000 data)
- Water inlet velocity: 0.46, 0.84 m/s







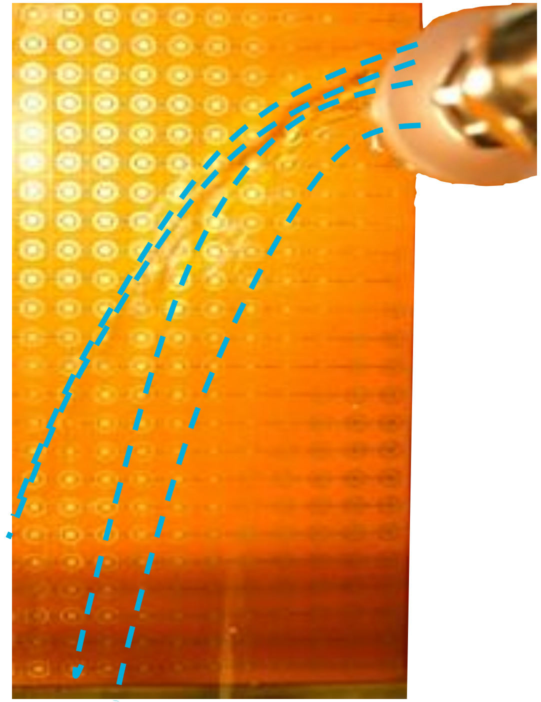
V_{in}=0.46 m/s



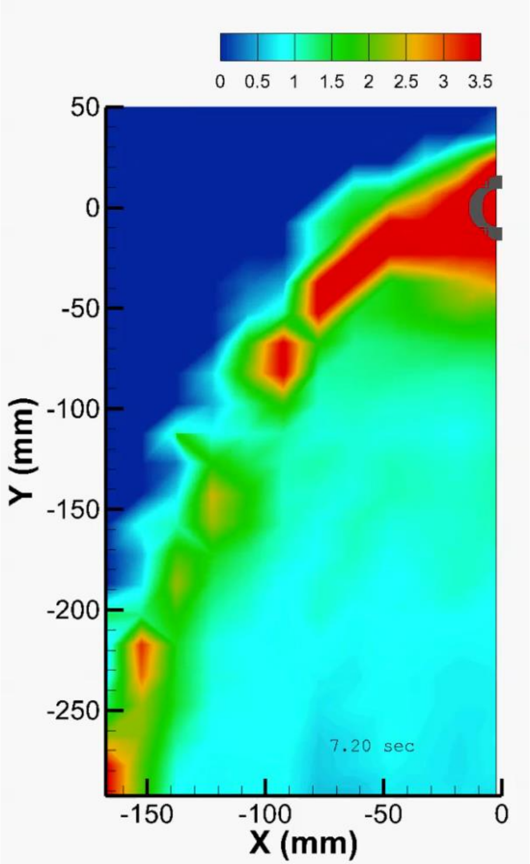
V_{in}=0.84 m/s

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

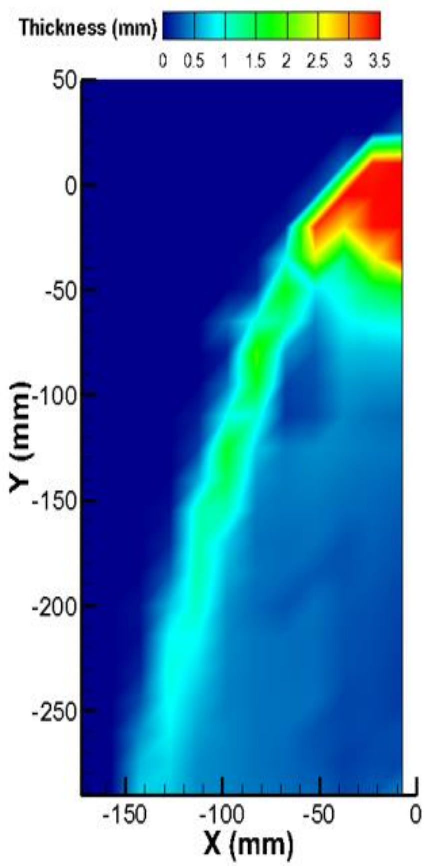


Film thickness contour

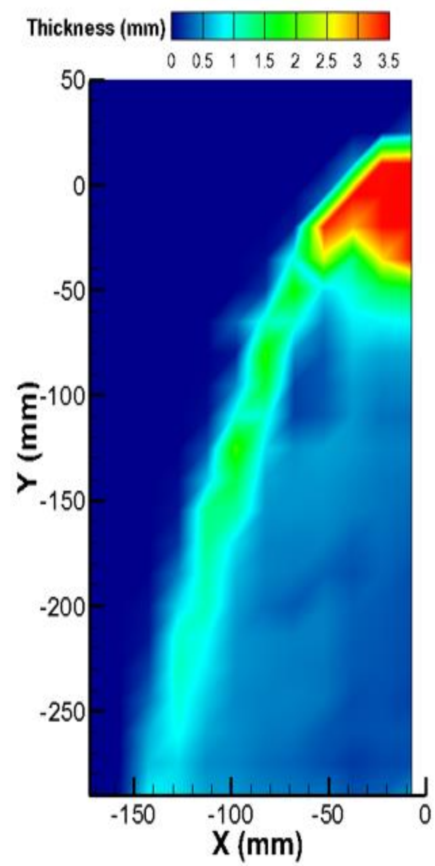
❖ Liquid film flow measurement - 3

✓ Steady-state measurement with different temperature conditions

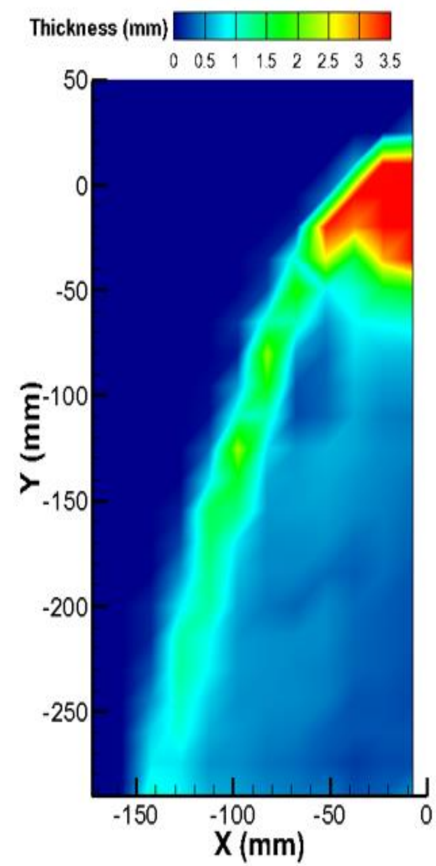
- Temperature variation test
- 20 ~ 40℃ measurement based on 20℃ calibration data



20℃



30℃



40℃

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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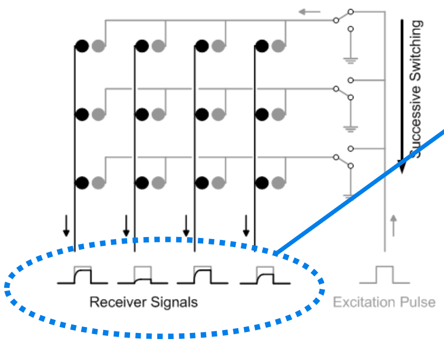
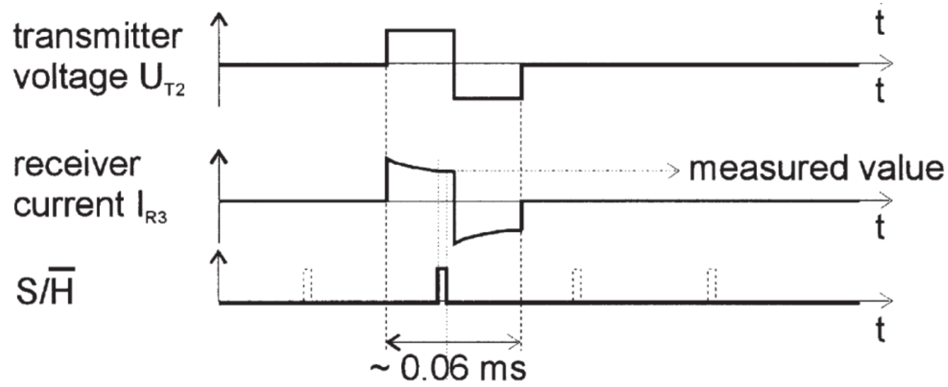
Coupling with wire-mesh circuitry

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

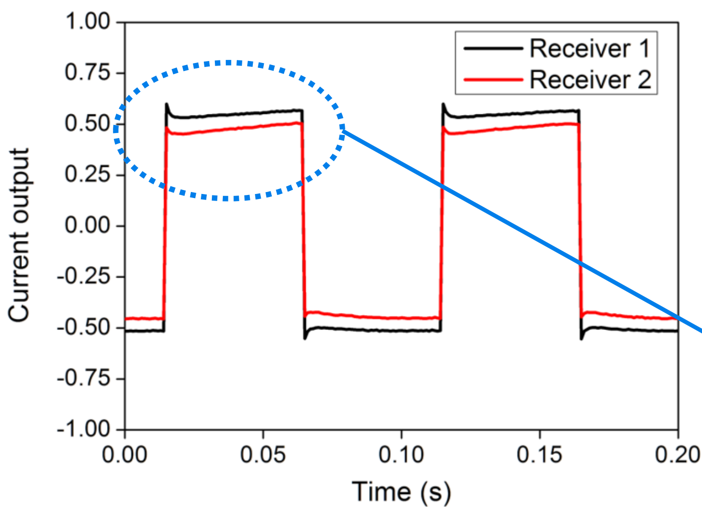


(Damsohn, 2009)



(Prasser, 1997)

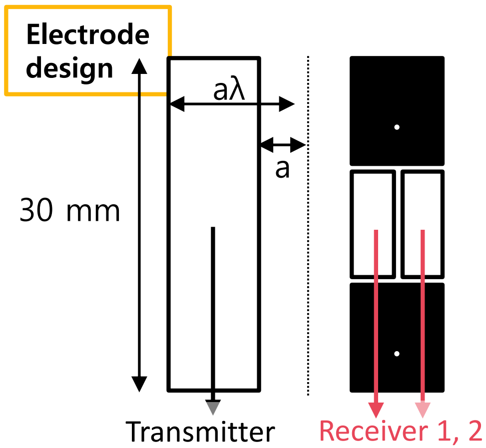
- Current problem using bi-polar DC

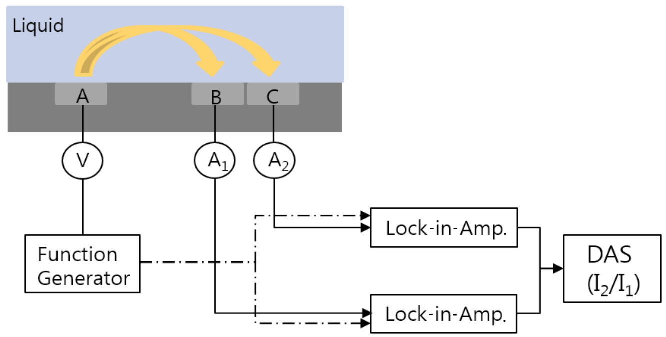


Steady state does not appear.

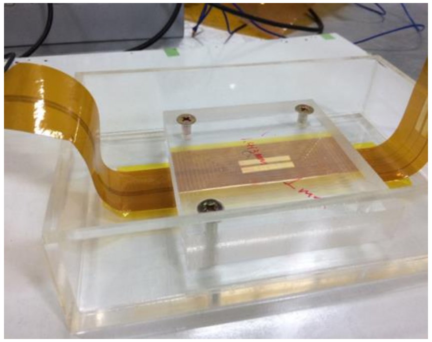
Preliminary test of three-ring method on FPCB

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

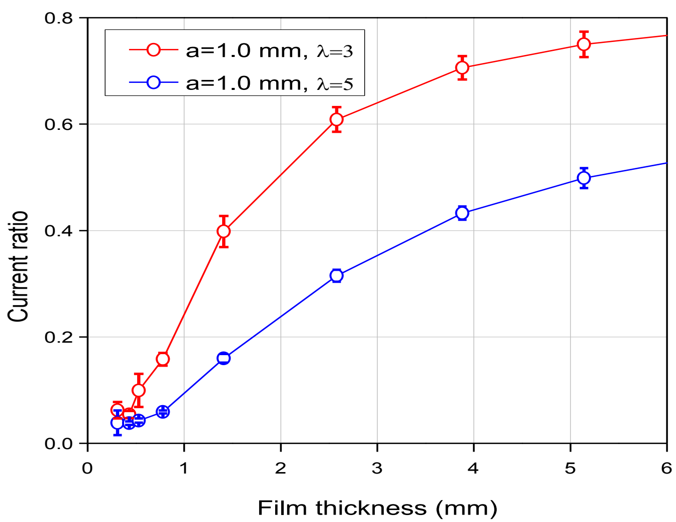


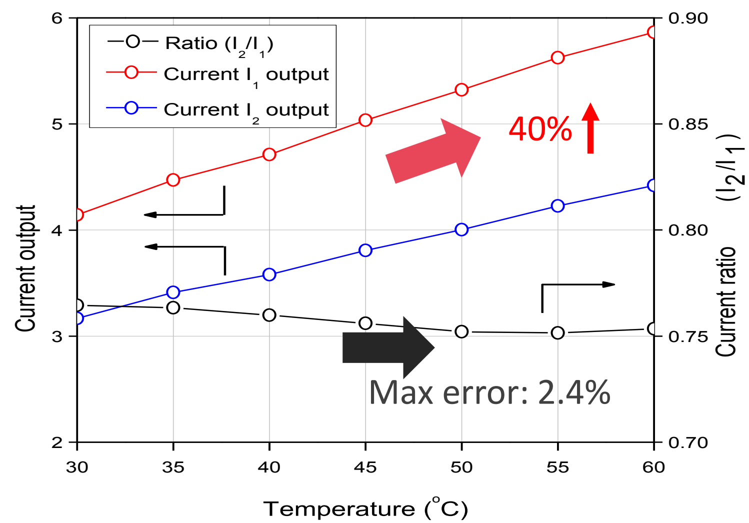


Three-ring method circuitry



Preliminary experiment



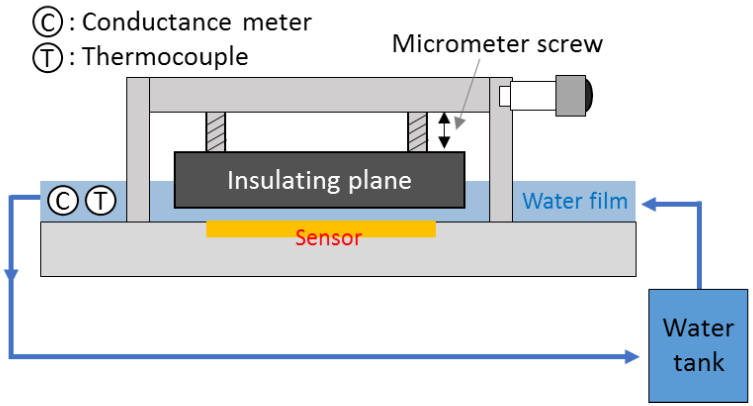


Calibration result

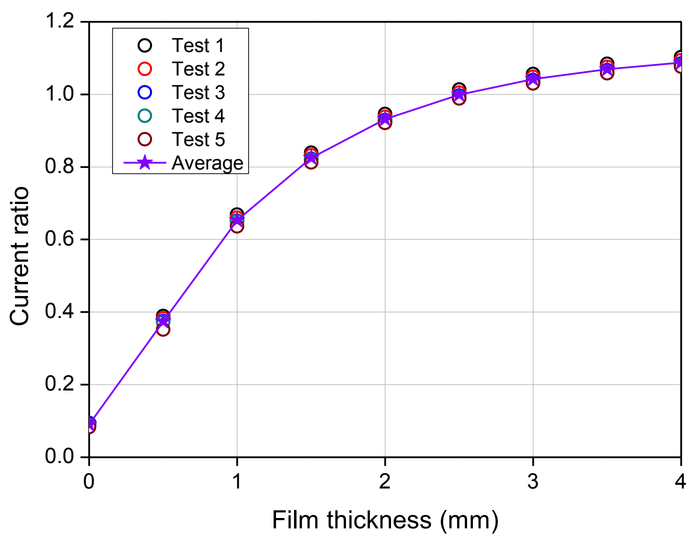
- Test condition
  - Inducing voltage: AC 10V (1 kHz)
  - Water condition: 22℃ & 5 μS/cm
- 36 different calibration curves

Verification of calibration result

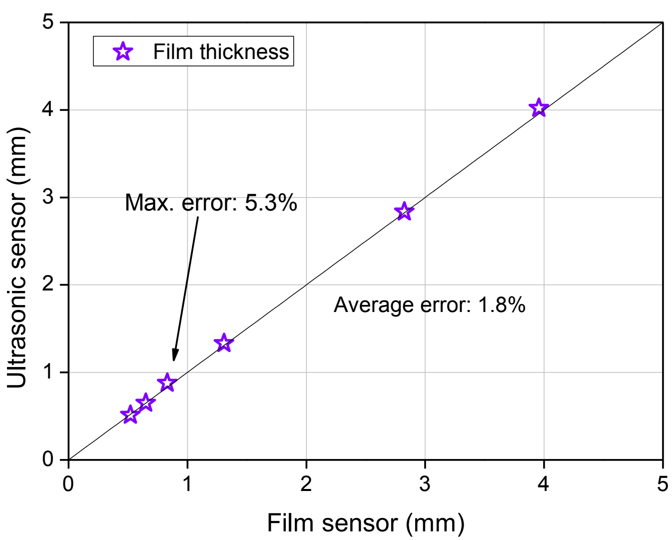
- Repeatability was confirmed.
- Comparison with the ultrasonic thickness gauge



Schematic diagram of the calibration experiment



Calibration experiment
- Repeatability test

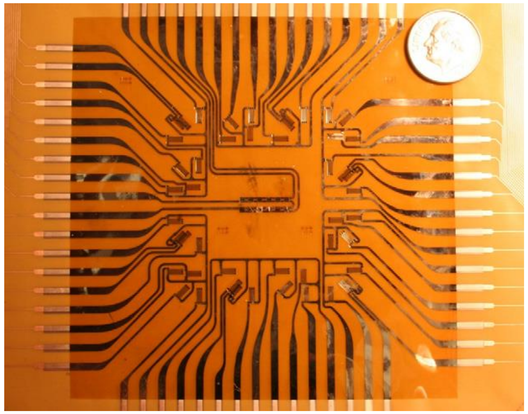


Calibration experiment
- Comparison with ultrasonic sensor

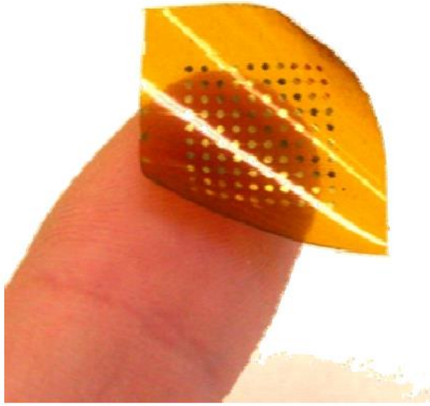
❖ FPCB

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

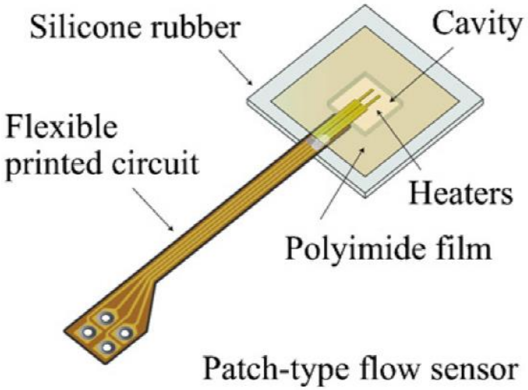
❖ Various measurement technique



Temperature & strain sensor
(D. J. Lichtenwalner et al., 2006)



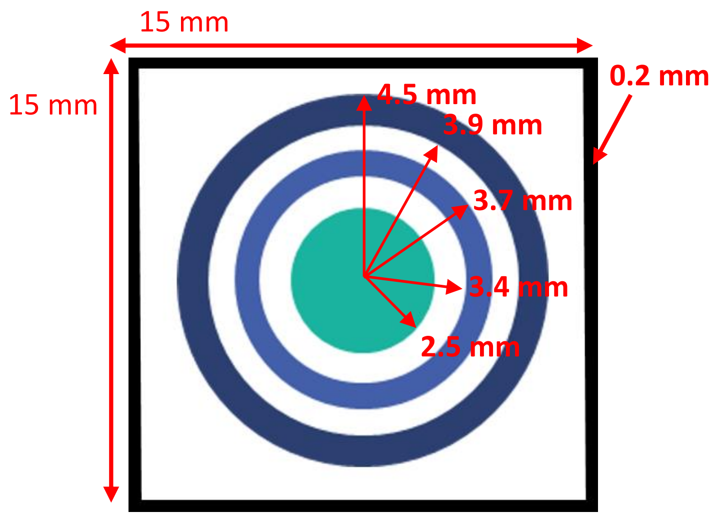
Local pressure sensor
(E. Pritchard et al., 2008)



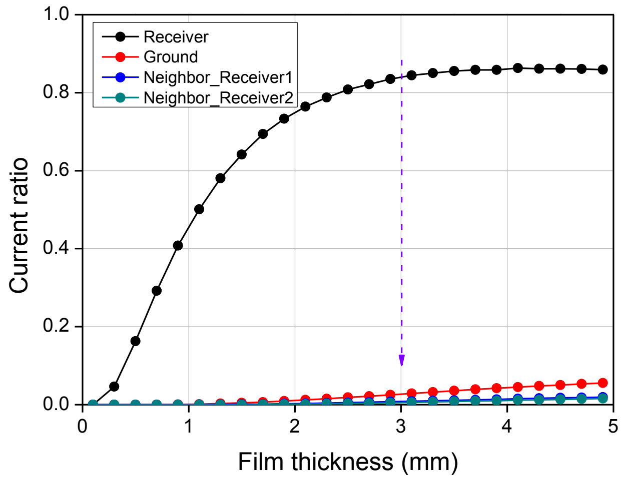
Flexible flow sensor
(M. Shikida et al., 2012)

Specific design of the sensor

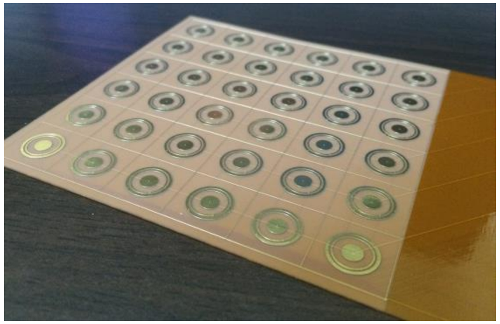
- The electrode design was determined by the parametric study.

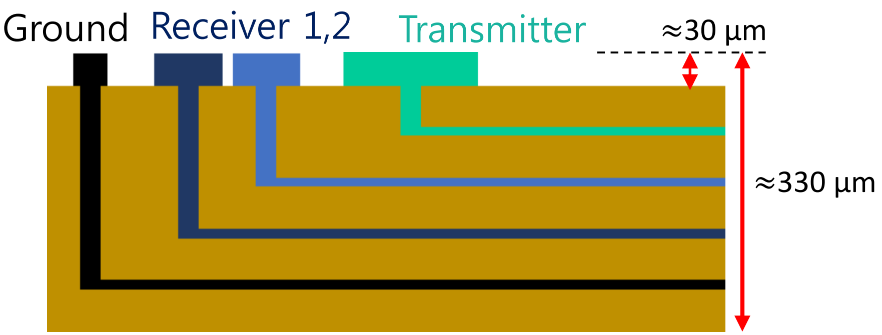


Specific dimensions



Characteristic curve


Prototype FPCB sensor

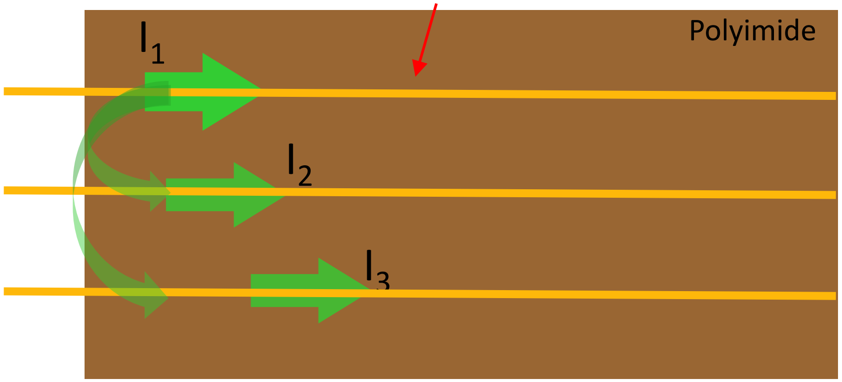


Cross sectional of FPCB

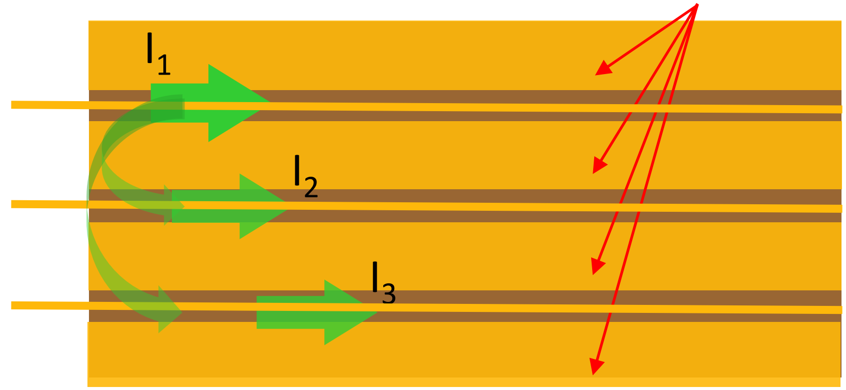
Appendix

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.



Prototype circuit



Modified model circuit

Prototype circuit

Modified model circuit

Crosstalk effect	Main receiver (I_1)	Near receiver (I_2)	Far receiver (I_3)
Prototype	-	3.13%	2.36%
Modified model	-	0.96%	0.71%

❖ Test for condensation experiment condition

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