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An improved electrical sensor for simultaneous measurement of the void fraction and two-phase flow velocity in the inclined pipe.

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1. Introduction

Two-phase flow is a common phenomenon in various engineering systems including thermal-hydraulic systems. The void fraction and velocity in two-phase flows are most important parameters in system analysis and design. For this reason, many techniques have been proposed to measure them. The electrical signals of the electrical impedance sensor depend on the void fraction as well as the flow structure. Therefore, the information for the flow pattern is also required to measure the void fraction.

In order to solve this problems, Ko et al.[1] proposed the void fraction measurement sensor according to the flow pattern using a three-electrode. The sensor system applied for a horizontal flow loop, and its measured performance for the void fraction was evaluated.

In this study, a dual sensor was suggested to improve the measurement accuracy of the void fraction and the velocity. We applied the sensor to the inclined pipe simulating the PAFS heat exchanger [2] In order to verify the void fraction and velocity measure ments, we used the wire-mesh sensor and the high-speed camera.

2. Numerical analysis for sensor optimization

2.1. Mathematical background

Let us consider staratified flow and annular flow through the conductance sensor as shown in Fig. 1. In each phase, the potential distribution can be described by the following Laplace equations:

$$\nabla \cdot \sigma_g \nabla u_g = 0 \text{ for the gas phase,} \quad (1a)$$

$$\nabla \cdot \sigma_\ell \nabla u_\ell = 0 \text{ for the liquid phase,} \quad (1b)$$

where u_g and u_ℓ represent the potential distribution to be determined for each phase. For convenience, We define the dimensionless conductance as:

$$G^*_{opp} = \frac{G}{G_\ell}. \quad (2)$$

Here, G_ℓ is the conductance value in the opposite electrodes for the sensor measured when the flow channel is filled only with liquid ($\alpha = 0$) and G for a certain two-phase flow.

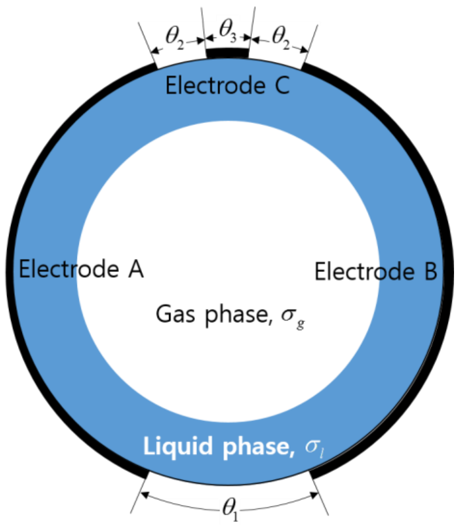

Fig. 1. Schematic of the conductance sensor for annular flow

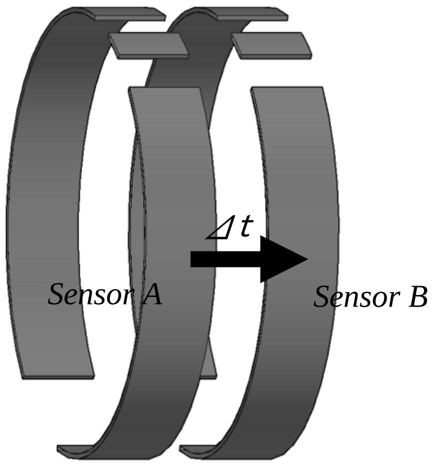

Fig. 2. Improved dual conductance sensor system for velocity measurement

2.2. Numerical calculations for sensor design

Based on the results of Ko et al.[1], the sensor size determined through numerical calculation is as θ_1, θ_2, and θ_3 are 0.5, 0.2, and 0.3 rad, respectively.

In a dual sensor system, the distance between each sensor is very important because the measured electrical signals are affected by the other sensor electrode. Fig 2. shows a concept of a dual sensor system for velocity measurement. To calculate a minimum distance that is not affected by the other sensor, 3D numerical calculation program COMSOL Multiphysics based on the FEM was employed. Table I. is the conditions used for the numerical calculation. On the basis of the results shown in Fig 3. finally, the gap size between the sensor was determined to be 30㎜

Table I. Conditions for numerical calculation

	Condition	
Conductivity (S/m)	Water	0.005
	Air	1,000,000
	Gap	0
Applied voltage (V)	5	
Electrode Thickness (D_e , mm)	15	
Gap size (D_g / D_e)	0.25 ~ 5	

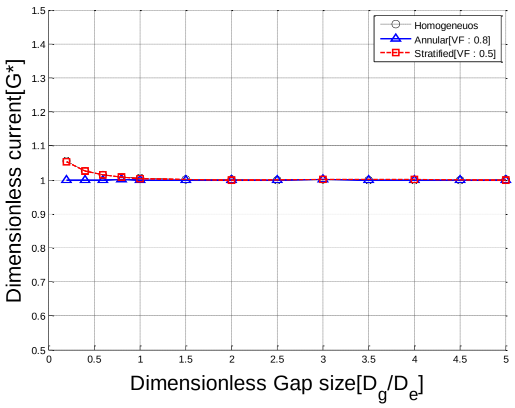

Fig. 3. The calculation results according to the distance between the sensors

2.3. Sensor system setup

For measurement, an LCR meter was adopted for voltage sources to the electrodes and a NI instruments was employed to shift the voltage sources and data acquisition. The specifications of the measurement instruments involved in the experiments are summarized in Table II. In the experiments the applied voltage was set to 5 V with 10 kHz signal frequency. In this frequency range the electrical response is nearly conductive [2]. The switch and sampling frequencies of the dual conductance sensor system were set to 2 kHz and 8 kHz, respectively. With this setup, 4 electrical conductance values are first measured in the adjacent electrode pair and those are consecutively recorded in the opposite pair. This measurement procedure is repeated at a rate of 2 kHz.

Table II. Specifications of measurement instruments used for experiments

Instruments	Accuracy	Signal range	Time definition
Agilent 4284A LCR meter	0.05 ~ 0.5%*	Up to 20 V with 1 MHz	N/A
NI PXI-2536	N/A	Up to ±12 V and 100 mA	50,000 cross-points/sec
NI PXIe-6368	3 mV for ±10V range	Up to ±10 V	2,000,000 samples/channel

* The accuracy is determined depending on the magnitude of the applied voltage. For 1 ~ 10 V range, for example, the basic accuracy is given by 0.1%.

3. Experimental results and discussions

For the loop experiments, various superficial velocities ranging from 0.1 to 3.0 m/s for water ($j_\ell = 0.1 \sim 3.0$ m/s) and from 0.1 to 18.0 m/s for air ($j_g = 0.1 \sim 18.0$ m/s) were considered. Some selected flow conditions discussed here are given in Table II and these are illustrated on the experimental flow pattern map of Taitel & Dukler [3] as shown in Fig. 4.

In the experiments the switch and sampling frequencies of the conductance sensor were set to 2 kHz and 2 MHz and the measurement frame of the wire-mesh sensor and high-speed camera was set to 1 kHz. These two sensor systems and high speed camera were synchronized by a customized clock box.

Table III. Specifications of measurement instruments used for experiments

Case	j_ℓ (m/s)	j_g (m/s)	Flow pattern
01–05	0.1	0.1, 0.5, 1.5, 10, 12	Stratified
06	0.3	18	Stratified
07-11	0.5	0.1, 0.5, 1.5, 10, 12	Stratified
12-16	1	0.1, 0.5, 1.5, 10, 12	Intermittent
17-21	2	0.1, 0.5, 1.5, 10, 12	Intermittent
22-25	3	0.1, 0.5, 1.5, 10	Intermittent

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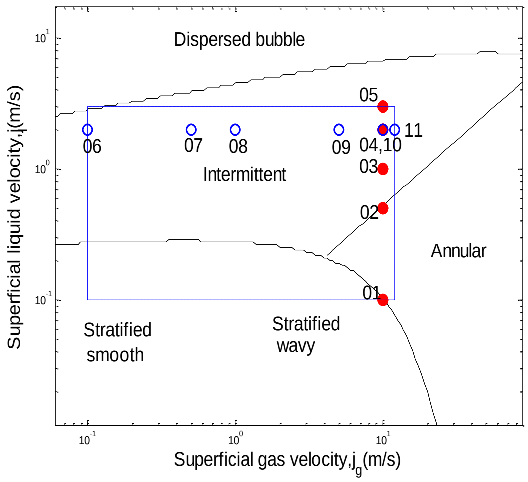

Fig. 4. Some selected flow conditions on the flow regime map of Taitel & Dukler [3]

Criteria for the flow pattern in the inclined pipe were determined based on the existing research [4]. In the present work three flow patterns (stratified flow, annular flow and intermittent flow) are considered.

The criteria for flow pattern classification in this study are summarized as Table VI.

Table IV. Specifications of measurement instruments used for experiments

G^*_{opp}	G^*_{adj}	Flow pattern
< 0.01		Stratified
≥ 0.01	$< 0.32(\alpha > 0.76)$	Annular
	$\geq 0.32(\alpha \leq 0.76)$	Intermittent

Figure 5 and 6 show the comparison result of measurement between the dual conductance sensor (CS) and the wire-mesh sensor (WMS). The number 'ST', 'INT', and 'AN' on the y axis of the bottom figures represent the distinguished flow pattern for stratified flow, intermittent flow, and annular flow, respectively. The measurement results of the proposed sensor are generally good agreements with those of the wire-mesh. Figure 7 shows the comparison results for the time-averaged void fraction. Very good agreements between the proposed sensor and the wire-mesh sensor are observed. For all flow rate conditions the maximum deviation between two instruments is 5.6%.

Table V. show the velocity measurement results between conductance sensor and high-speed camera. Both measurement techniques between the comparison results are in good agreement, and can also check the effect of the increased gas superficial velocity. Although the measurement performance of the proposed sensor is proved to comparable to those of the wire-mesh sensor and high-speed camera, its limitations observed in the experiments have to be further improved in future works.

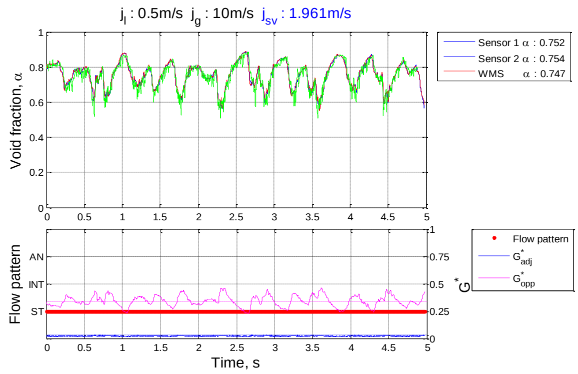

Fig. 5. Comparison in instantaneous void fraction between CS and WMS for superficial liquid velocities (case 4).

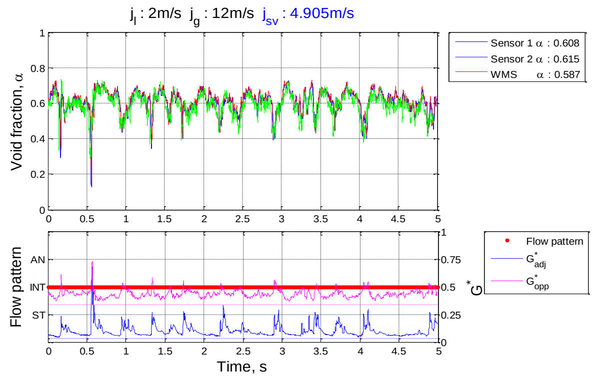

Fig. 6. Comparison in instantaneous void fraction between CS and WMS for superficial liquid velocities (case 21).

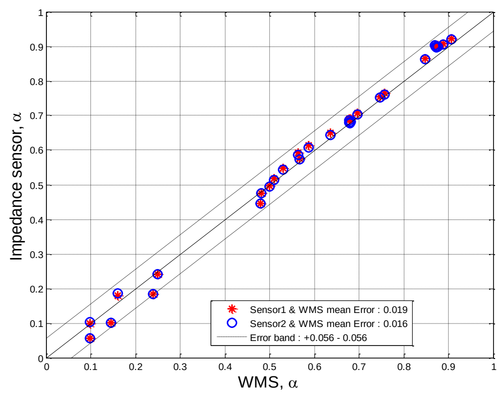

Fig. 7. Comparison in time-averaged void fraction between CS and WMS

Table V. Comparison in velocity between CS and high-speed camera

Case	j_l **(m/s)**	j_g **(m/s)**	j_{sv} **(m/s)** sensor	j_{sv} **(m/s)** HSC
01	3.0	0.5	3.19	3.16
05	3.0	1.0	3.66	3.66

4. Conclusion

In this study, an improved electrical conductance sensor for void fraction and velocity in inclined pipes has been designed. For minimizing between the sensor electrode interference, the numerical analysis has been performed. The loop experiments were conducted for several flow conditions and the experimental results for the void fractions and velocity measured by the proposed sensor were compared with those of a wire-mesh sensor and high-speed camera. Both measurement techniques between the comparison results are in good agreement. However, due to the limitations of measurement condition using a high-speed camera, the measurement accuracy of the flow velocity was not sufficiently validated yet. Therefore, additional comparison experiments will be performed. In order to reduce the void fraction error, further experiments will be performed applying the temperature correction.

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