

# Temperature-Insensitive Additives for Conductive Measurements

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**Abstract:** An elaborate measurement technique of void fraction, phasic velocity and phasic temperature helps clarify multi-dimensional and transient boiling flow in nuclear reactor. To quantify void fraction in the gas-liquid flow, the wire mesh sensor is one of the most valuable techniques using an electrode and we employed this method to evaluate the cooling performance of coolant for boiling flow in a heated rod bundle carrying current for the power supply. This paper proposes electric effect and its improving technique, which is caused by methods such as potential gradient, electromagnetic wave and temperature variation. The additional effects of a solute, namely unexpected corrosion, precipitation and other chemical reactions, were also experimentally demonstrated. The aqueous solution, including the solute, increased its electrical conductance and the result had a considerable impact on decreasing the temperature variation of the electrical conductance. This effect suggested that the measurement uncertainty of an equivalent void fraction about temperature in the case of the aqueous solution was smaller than that of pure water. Additionally, it was also clarified that adding solute can increase the ratio between the signal average and its standard deviation without sensor gain and that these ratio values in the case of the aqueous solutions were pursuantly larger than those of pure water. Furthermore, the insulated coating process of the sensor wire except the measuring area increased this effect of improving electric noise.

**Key words:** void fraction, wire mesh sensor, temperature sensitivity of electrical conductance, solute addition effect

## 1. Introduction

The Phase distribution is one of the most crucial points when designing boilers, evaporators and condensers and ensuring nuclear reactor safety. In the present study, we adopted a wire mesh sensor [1] to measure the void fraction in a gas-liquid flow. T. Arai et al. developed a sub-channel void sensor (SCVS) and applied this technique to boiling flow in a heated rod bundle [2-3]. Various electrode techniques, including this method immersed into a coolant media, reveal some useful knowledge, not only of void fraction but also phasic velocity, pH, gas concentration and so on. For particular examples, J. Li et al. developed an NO<sub>2</sub> gas sensor using single-walled carbon nanotubes (SWCN) on an interdigitated electrode (IDE) [4]. A

relative humidity sensor which is made of SnO<sub>2</sub> nanowire was linearly measured to 90% by Q. Kuang et al. [5]. However, although electrode techniques have wide-ranging applications for the purposes of a sensor, they are prone to temperature variation, which affects the electrical conductance of a coolant. Since our experiment generates boiling behavior with Joule heat caused by energization, in some test cases where the thermal flow behavior of a nuclear reactor is simulated, such as a boiling water reactor (BWR), the electric potential gradient and electromagnetic wave are frequently generated in the coolant media. These factors result in critical measuring uncertainties when measuring the void fraction and phasic velocity in the form of electric noise. Furthermore if the test fluid has a temperature sensitivity of electrical conductance, the real-time variation of temperature during a transient boiling phenomenon adds additional uncertainties to the raw signals on the wire mesh sensor.

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In this paper, we propose a tool of solute addition to decrease the electric negative points and demonstrate the effects of decreasing noise of the detected signal and reducing the temperature sensitivity of electrical conductance. Additionally, the insulated coating effect of this devised technique is also demonstrated. Relating to all six solutes, namely unexpected corrosion, precipitation and other chemical reactions, these two effects were experimentally clarified by measuring electric conductivity, pH and dissolved oxygen (DO) and the relative root mean square (relative-RMS) of the sensor signal.

## 2. Material and Methods

This chapter explains our experimental apparatus and six test aqueous solutions. To conclusively confirm the devised effect under current-carrying condition, a single heated rod bundle was set in the center region of a channel box. However, the experiments in this paper involved a non-heating condition to investigate only the properties of aqueous solutions, including solutes. The test samples were selected to avoid the possibility of corrosion, precipitation and chemical reaction because these factors may cause damage and may result in certain properties of the heated rod bundle and coolant varying.

### 2.1 Test Loop with a Heater Pipe

Fig. 1 illustrates a schematic image of the experimental apparatus, which comprises a pre-heater, a test section including a heated rod bundle, a separator tank, a condenser and a circulation pump. The system pressure is atmospheric and a bypass flow line is set to provide a stable flow to the test section. The single heated rod bundle, with diameter and length of 11.2 and 310 mm respectively, is inserted in the acrylic resin container and heated by direct current-carrying. A cross-sectional image of the measuring section in the apparatus is illustrated in the framed area by a dotted line regarding Fig. 1. The inside length of the flow channel of the container is 25

mm square. Wire mesh sensors were inserted nearby the heated section. The transmitter and receiver wire electrodes are 200  $\mu$ m in diameter and made of stainless steel (SUS304). The transmitter wire electrodes, which are configured with 2 in total, are placed parallel to each other at 3 mm intervals. On another front, the receiver wire electrodes are placed parallel to each other perpendicular to those of the transmitter wire at intervals of 1.6 mm. To compare the insulated coating effect of the sensor wires, both transmitter and receiver wires were set as coated and non-coated, respectively. In this experiment, coating- and non-coating cases were compared. Here, the coating case means that both transmitter and receiver wires are coated, while conversely, the non-coating case means that neither transmitter nor receiver are coated. The coating specification is explained in more detail in the next section.

The test liquid selected was ion-exchanged water to stabilize the signal level of the wire mesh sensor before adding some solute. The experiment was conducted under a non-boiling (no bubbles in solution) condition to quantify only the electric effect of each aqueous solution because bubbles directly affect the signal levels due to the principle of the wire mesh sensor [1].

### 2.2 Insulated Coating of Sensor Wire

A cross-sectional structure of the wire mesh sensor is illustrated in the central position of Fig. 1. The four measuring spots were set where the transmitter and receiver wires intersected. An insulated coating covered with Teflon except for the measuring spot was also attempted to decrease electric noise and cross talk as far as possible, while the coating wires were exfoliated using laser abrasion with an ultra-violet wavelength region. After this process, the conduction of the exfoliated area was confirmed before installing in the test section. An observation photograph of the abrasion area and a cross-sectional surface of the coating wire with scanning electron microscope (SEM)

are illustrated in Fig. 2. The absorption length is proportional to the sensor signal value, which is related to the electrical conductance of the area sandwiched between the transmitter and receiver wires. In this experiment, the abrasion length was defined as

approximately 2 mm and the coating thickness was about 40 μm to maintain a comfortable signal level under all test conditions for the liquid temperature, solute type, insulated-coating and current-carrying.

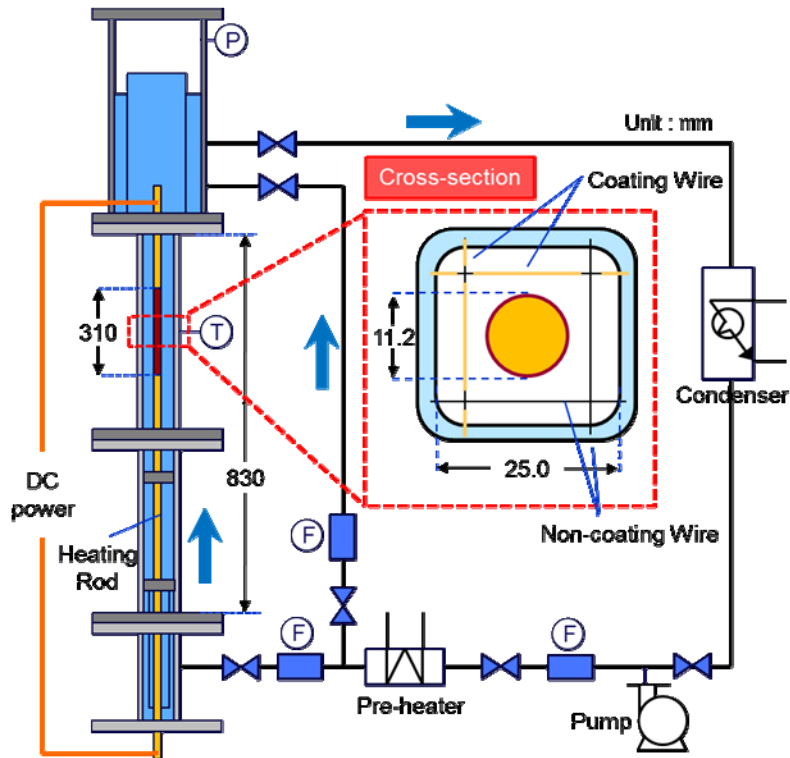


Fig. 1 Experimental setup with a heated rod bundle and cross-sectional wire mesh sensor structure in the test section.

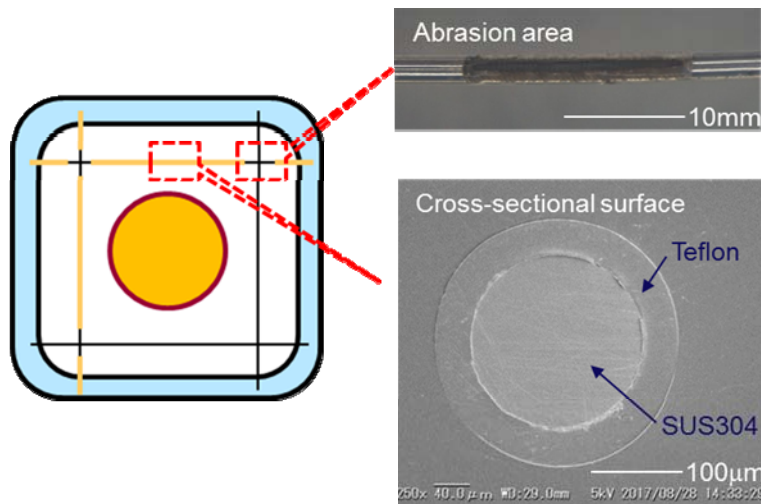


Fig. 2 Observation photographs of abrasion area and its cross-sectional surface of insulated coating of the wire mesh sensor.

2.3 Concentration of Sample and Calibration Processes

The test samples are diluted aqueous solutions with

pure water, the additives to which are vitriolic solutes ( $K_2SO_4$  and  $Na_2SO_4$ ), nitric solutes ( $KNO_3$  and  $NaNO_3$ ) and fluorescence (Rhodamine-B and Uranine)

which are ordinarily used in particle imaging velocimetry (PIV) [6], laser-induced fluorescence (LIF) [7] which are velocity measurement techniques with laser light source. These solutes were selected to prevent corrosion, precipitation and chemical reactions in the test section, including the heated rod bundle. The experimental procedures are tabulated as follows:

Sensor signals of water, which are proportional to the electric impedance at the non-coating measuring spot, were measured using ion-exchanged water at intervals of 10°C from 30 to 100°C. Using the time-averaged value under each temperature condition, equivalent void fractions caused by temperature variation of water with the calculation equation of void fraction (1), were detected in Fig. 3. Here,  $V_{TMP}$  is the time-averaged electric impedance under each temperature condition and  $V_{100^\circ C}$  is that at 100°C.

This figure expresses the relationship between the equivalent void fraction with subcooling from 0 to 70°C. Additionally in this figure, the temperature dependence of the coolant on the electric conductivity, which is proportional to the electric impedance of the sensor, was expressed.

$$\alpha_{CAL.} = 1 - V_{TMP} / V_{100^\circ C} \quad (1)$$

The equivalent void fraction rises under a lower temperature condition because the electrical conductance between the transmitter and receiver wire declines inversely proportional to the liquid temperature. Although this measuring error should be minimized to measure void fraction in a two-phase flow, sensor gain manages to increase electric noise, so adding some solutes to the coolant is an appropriate technique to increase sensor signal relative to noise.

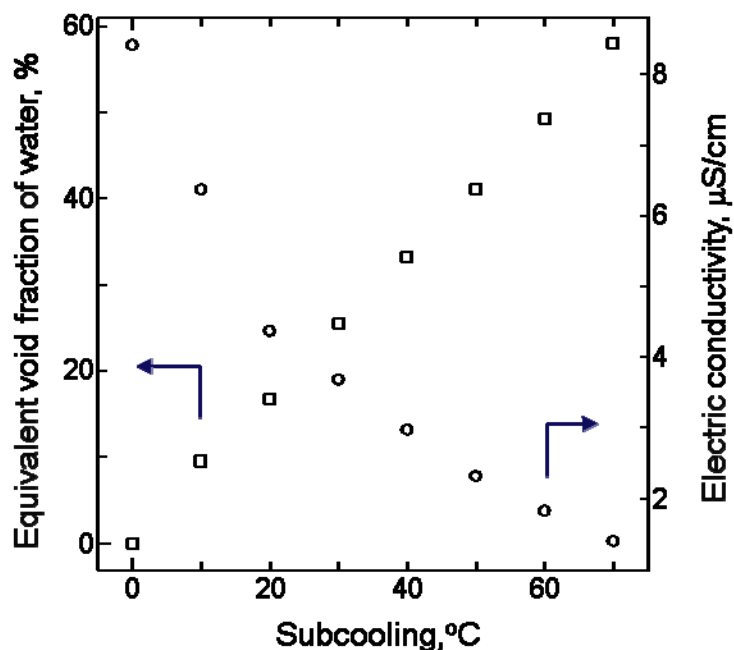


Fig. 3 Equivalent void fraction caused by temperature variation of water in single liquid phase flow.

In this experiment, these target measuring spots are both the insulated-coating and non-coating points, which are illustrated at the top left and lower right measuring points of the enclosed area by a dotted line in Fig. 1, respectively. Here, to expand the dynamic range of the sensor signal as far as possible, the electric

impedance at 90°C was regulated to approximately 95% of the maximum value in the detector specification using the sensor gain. In this experiment, a  $\pm 5V$ -bipolar pulsed signal was sent to the transmitter wire and the resolution performance of the detector was 12 bits. Conversely, in the case of all-aqueous solutions,

including each additive, this dynamic range was controlled using only solutes without the sensor gain, which means the detector gain was set to 1 to inhibit some electric noise and evaluate only the effect of adding solute. The configured concentration of each of the additives was controlled from a pre-determined rule with the case of ion-exchanged water. The regulation results were indicated in Table 1 with solute concentrations within the range of 0.01 ~ 0.08 wt%.

### 3. Results and Discussion

This chapter experimentally demonstrates the verification of the devised solute addition effect. Quantifications of the temperature sensitivity and the ratio are indicated in detail in the following steps:

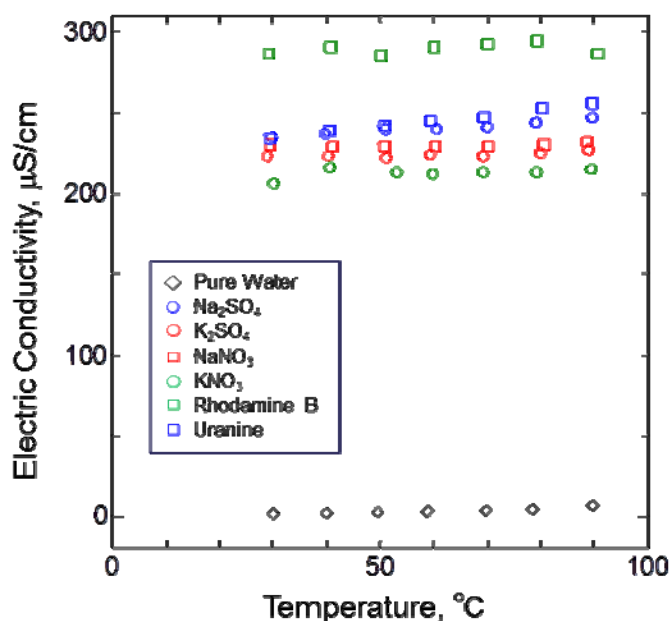
#### 3.1 Thermo-reactive Properties of Test Aqueous Solutions

The thermo-reactive properties of all test liquids were determined in this section. Electric conductivity is the most crucial, because a wire mesh sensor detects the electrical conductance of the sandwiched area

between the transmitter wire with the receiver wire [1]. Fig. 4 illustrates the temperature sensitivities of electric conductivity for aqueous solutions dissolved with the solute into each other with a pre-determined concentration in Table 1. Fig. 4 is the raw data, the upper stage of Table 2 shows the temperature gradients of the properties based on the value at 30°C to confirm the temperature dependence of this property. Here,  $\sigma$  means electric conductivity and it can be confirmed that adding solute affects the increasing electrical conductance of all liquid samples based on the result of the absolute values. The properties of the aqueous solutions were indicated at 20 to 30 times those of water under all temperature conditions. From 30 to 90°C in Table 2, the temperature gradient of the water indicated over 100 times that of other aqueous solutions. In fact, the electric conductivities of aqueous solutions except that of uranine correlated effectively to each other to within  $\pm 10\%$  for all samples in the temperature range, which clarified that the temperature sensitivities may be quite small when adding solute compared to those

**Table 1** Concentration of test solutes.

|             | K <sub>2</sub> SO <sub>4</sub> | KNO <sub>3</sub> | Na <sub>2</sub> SO <sub>4</sub> | NaNO <sub>3</sub> | Rhodamine-B | Uranine |
|-------------|--------------------------------|------------------|---------------------------------|-------------------|-------------|---------|
| Conc. [wt%] | 0.0140                         | 0.0161           | 0.0140                          | 0.0170            | 0.0800      | 0.0604  |



**Fig. 4** Temperature dependence of test aqueous solutions on electrical conductivity.

**Table 2** Temperature gradients of electrical conductivity  $\sigma$ , pH and DO normalized by its value at 30°C.

|                                 | Water | K <sub>2</sub> SO <sub>4</sub> | KNO <sub>3</sub> | Na <sub>2</sub> SO <sub>4</sub> | NaNO <sub>3</sub> | Rhodamine-B | Uranine |
|---------------------------------|-------|--------------------------------|------------------|---------------------------------|-------------------|-------------|---------|
| $d\sigma/dT \times 10^{-3}$ [-] | 55.2  | 0.30                           | 0.40             | 0.80                            | 0.30              | 0.20        | 1.50    |
| $dpH/dT \times 10^{-3}$ [-]     | -3.20 | 2.70                           | 2.00             | 0.70                            | 0.10              | -3.00       | -0.30   |
| $dDO/dT \times 10^{-3}$ [-]     | -18.7 | -18.8                          | -18.8            | -19.1                           | -18.7             | -18.6       | -18.1   |

of water. Additionally, the electric conductivity of ion-exchanged water is not stabilized because this property depends on the performance of ion-exchanged resin, which provides for measuring uncertainty of void fractions. This may be an important merit for solute additives to regulate and fix electric impedance, which is proportional to electric conductivity.

Other parameters which have the potential to affect the electric signal of the wire mesh sensor, were rechecked. The measuring results of the temperature sensitivity of pH and the dissolved oxygen level (DO) are shown in Figs. 5 and 6, respectively. As with the electric conductivity, Fig. 5(a) shows the raw data and the middle stage of Table 2 shows the temperature gradients of properties based on the value at 30°C to estimate the effect of these properties on the sensor signal. In Fig. 5(a), both uranine and rhodamine-B indicated alkaline and acidic properties respectively, while the other four solutes show approximately equivalent trends to water, which indicates a neutral pH. As with the electric conductivity, some difference in the absolute value can be corrected for void fraction measurement through a calibration process if its difference is pre-clarified. However as shown in Table 2, if the parameter has a dominantly different temperature dependence such as K<sub>2</sub>SO<sub>4</sub> and KNO<sub>3</sub>, not only does this affect measuring uncertainty for void fractions, it may also prevent measurement due to overlapping measurement sensitivity between electric conductivity with pH. Here, the key factor involves detecting only the difference from water. In other words, it is perfect if this experiment has a sensitivity trend equivalent to that of water, except electric conductivity, which means no sensitivity to the sensor signal, because it only involves evaluating

the decreasing effect of temperature sensitivity on electric conductivity. Consequently, rhodamine-B is the most appropriate solute for all test samples because it has the same sensitivity trend of pH with water due to non-ionization. Conversely, the solutes which have an inverse trend with both water and rhodamine-B, act to increase the measuring uncertainty of the void fraction. The results of the DO value were also illustrated in Fig. 6. As with electrical conductivity and pH, Fig. 6(a) is the raw data and the lower stage of Table 2 is the temperature gradients of the properties based on the value at 30°C to estimate the effect of these properties on the sensor signal. There are thought to be little or no effects on this parameter, because the temperature trends of all solutes match the trend of water well.

Based on all the results of thermo-reactive properties, it was appropriate to inhibit the temperature sensitivity of electrical conductivity as far as possible and that of pH indicates a trend equivalent to that of water such as rhodamine-B.

### 3.2 Temperature Sensitivity

From Fig. 4 and Table 2, it was clarified that adding solute affects coolant liquid to inhibit temperature sensitivity. Furthermore, other parameters have to show temperature trends equivalent to water such as Rhodamine-B, because then there is potential for negative impact on void fraction measurement with a wire mesh sensor.

Void fraction is generally calculated by the difference of electric impedance with calibration data, whereby the measured electric impedance is compared with the calibrated data of a coolant. Therefore, as shown in Fig. 3, pure water with exceptionally low electrical conductivity generates an enormous

measuring error in void fractions due to variation in the liquid temperature. However, by adding an appropriate solute such as Rhodamine-B, the

uncertainty due to temperature variation can be reduced with other thermo-reactive properties unchanged.

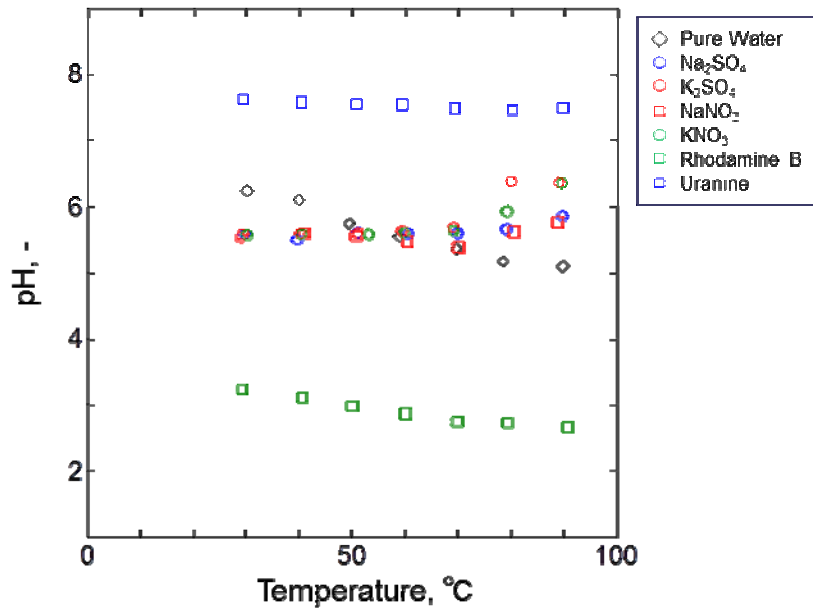


Fig. 5 Temperature dependence of test aqueous solutions on pH.

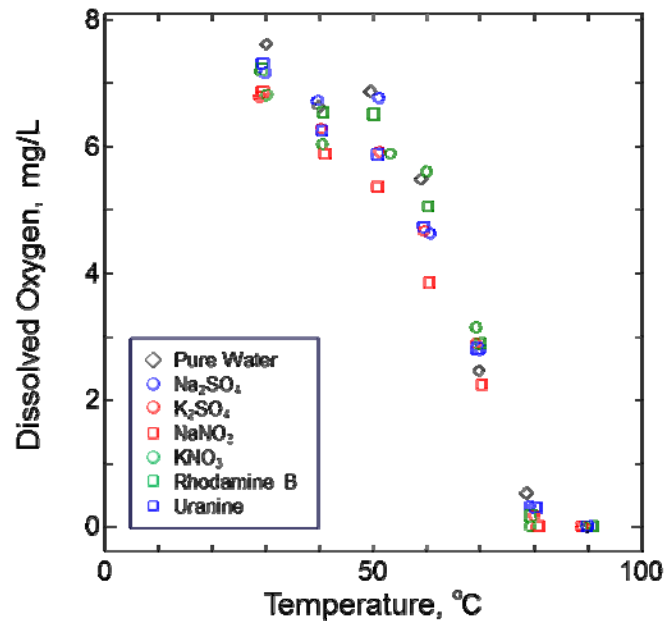


Fig. 6 Temperature dependence of test aqueous solutions on dissolved oxygen (DO).

### 3.3 Ratio of Sensor Signal to Electric Noise

From The method of adding solute without detector gain provides improves the electric noise effect on the ratio between the time-averaged value of the sensor signal with its standard deviation. In this section, the

effect  $V_{EFF}$ . was quantified in detail using the following defined Eq. (2). Here,  $V_{AVE}$ . is the time-averaged voltage of the sensor signal and  $V_{STD}$ . its standard deviation. This experiment evaluates the electric noise of the sensor using this equation.

$$V_{EFF.} = V_{STD.} / V_{AVE.} \quad (2)$$

Both insulating conditions indicated that the  $V_{EFF.}$  values of the aqueous solutions were improved less than those of pure water. Regardless of the insulated coating condition, it was clarified that the method of adding solute reduces the signal noise variation in electrode measurement. The detail is as follows:

Table 3 shows the  $V_{EFF.}$  values under both non-coating and coating conditions at 90°C. Electrical conductivity increases with rising electrical conductance of measurement volume under a higher temperature condition, whereupon it can be considered that the effect of the electric cross talk

among each measuring point under coating condition becomes smaller than that when under a non-coating condition. In this experiment, the highest temperature condition was only focused on evaluating both the effect of the insulated coating on increasing the  $V_{EFF.}$  value with solute addition and electric cross talk. Electric noise is more acceptable when the effect of electric cross talk is larger. In Table 3, the  $V_{EFF.}$  values under a non-coating condition exceeded those under a coating condition, which suggested that an inversely larger effect of cross talk under the non-coating condition. Additionally, the improved level of electric noise from that of water under a coating condition was larger than that under a non-coating condition.

**Table 3** Root mean square value (to its average) of the wire mesh sensor signal at 90°C for coating and non-coating of electric insulation.

unit: %

|             | Water | K <sub>2</sub> SO <sub>4</sub> | KNO <sub>3</sub> | Na <sub>2</sub> SO <sub>4</sub> | NaNO <sub>3</sub> | Rhodamine-B | Uranine |
|-------------|-------|--------------------------------|------------------|---------------------------------|-------------------|-------------|---------|
| Coating     | 0.94  | 0.67                           | 0.49             | 0.49                            | 0.55              | 0.48        | 0.51    |
| Non-coating | 2.31  | 1.09                           | 0.95             | 1.01                            | 1.19              | 0.89        | 0.80    |

To decrease electric noise for electrode measuring techniques such as wire mesh sensor, processing of insulated coating and adding solute are effective techniques.

#### 4. Conclusions

We devised a solute addition technique for wire mesh sensors to decrease the measurement uncertainty of void fractions due to temperature variation and improve the ratio between the time-averaged value of the sensor signal with its standard deviation under a current-carrying experimental condition. The electrical conductivity, pH and dissolved oxygen (DO) of six aqueous solutions with pre-determined concentrations were measured to confirm the effect of the sensor signal on the electrical conductance of the measurement area. It was confirmed that solute addition provides for decreasing temperature sensitivity of electrical conductivity. Consequently, the signal thermo-variations of the aqueous solutions also were smaller than those of a calibration liquid (water)

without detector gain. The result suggested that this effect helps ensure that the equivalent uncertainty of void fraction of solute addition becomes smaller than that of water. The additional effect of solute addition was clarified by comparing the ratio of the sensor signal between the time-averaged value with its standard deviation. This ratio value was improved with solute addition more than with detector gain and it was also clarified that the insulated coating technique assisted this effect in the higher temperature region. It was considered that this effect helped reduce the cross-talk effect among each of the measuring points.

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