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Study on Quality Measurement Using Multiple Small Holes

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ABSTRACT

Quality measurement of two-phase refrigerant is sometimes required in vapor compression refrigeration cycles to monitor and control the cycle properly. In a previous research, a new quality measurement was proposed based on a concept that the velocities of liquid and gas became almost the same in a narrow tube with flow pattern of plug flow. With applying many narrow tubes in a test section, the quality of the flow through the test section was obtained by liquid flow rate through pipes where only liquid phase flows, gas flow rate through pipes where only gas phase flows and gas-liquid flow rates through a pipe where the two-phase flow flows. Although the quality measurement was successfully achieved within a reasonable accuracy, applicable flow rate range was not enough for actual refrigeration cycles.

In this study, many small holes were adapted instead of the narrow tubes for the application to the larger flow rate and simplicity. When the two-phase flow is separated into the gas phase and the liquid phase in an upstream header and the number of holes through which two-phase flow flows is a few at the gas and liquid interface, the flow rate of the two-phase flow through those holes is negligible compared to the liquid-phase flow rate through lower holes and the gas-phase flow rate through upper holes. Therefore, only the number of holes through which the gas phase or liquid phase flows and the pressure difference across the holes are needed to obtain the flow rates of both phases and consequently the quality of whole two-phase flow. In the experimental setup, detection of liquid level in the upstream header was done to obtain the number of holes for the liquid-phase flow. The quality measurement applying the many small holes was examined by air-water two-phase flow by measuring the liquid level in the header and the pressure difference. It was confirmed that quality measurement with an error of about ±3% was achieved. Besides, when the pressure difference across the holes is larger than the liquid head in the upstream header, quality measurement without measuring the pressure difference was possible.

1. INTRODUCTION

In refrigeration cycles, there are many portions where the condition of refrigerant is gas-liquid two-phase flow. Quality measurement or quality control of the two-phase refrigerant is sometimes required especially at an injection line of injection cycle (Hagiwara *et al*., 2011) and at a suction inlet line to a compressor with wet compression to control the refrigeration cycle more precisely. In the measurement of two-phase flow, sectional void fraction can be detected in many ways, such as by a capacitance sensor (Jaworek *et al*., 2004), an electrical resistance tomography sensor (Meng *et al*., 2004), an image processing through a glass tube (Puli *et al*., 2012), a multi-wire capacitance probe (He *et al*.,

2018) and so on. However, it is difficult to obtain the quality from the sectional or spatial void fraction since velocities of gas phase and liquid phase are generally different.

In previous researches, a quality measurement was proposed based on a concept that the velocities of liquid and gas become almost the same in a horizontal two-phase flow through a narrow tube with flow pattern of plug flow (Fukuta *et al*., 2018). In order to enlarge the applicable quality range, a quality measurement by installing multiple narrow tubes in the test section was examined (Iyoda *et al*., 2020 and Fukuta *et al*., 2021). Figure 1 shows the test section with 33 narrow passages. By applying the multiple narrow passages arranged vertically and separating the two-phase flow into the gas phase and liquid phase in an upstream header connected to the passages, the liquid phase flows through the passage located bottom, the gas phase flows upper passages and the two-phase flows through the passage at the gas-liquid interface in the header. The quality could be obtained from the number of passages through which the liquid phase or the gas phase flows with taking account of the void fraction of the two-phase flow through the passages at the interface. Figure 2 shows the flow pattern at the test section under different quality condition of the two-phase flow. As shown in Figure 2, the liquid level at the test section decreased and the position of two-phase flowing tube changed downward with increasing the quality of the two-phase flow. The number of passages through which the liquid phase flowed was detected by image processing, and the flow rates of the liquid phase and the gas phase were calculated based on the number of passages for each phase and the pressure difference across the passage. The quality of two-phase flow was calculated based on the flow rates of both phases with taking account of the flow rate of the two-phase flow through the passages at the interface. It was confirmed that quality measurement with an error of about ±5% was achieved in the quality range from 0.1 to 0.9. However, the experiment was performed with small refrigerant flow rate compared with that in actual refrigeration cycles. Therefore, it was necessary to improve the test section in order to apply the quality measurement to the larger flow rate.

In this study, 96 small holes were adapted at the test section instead of the narrow passages for an application to the larger flow rate and simplicity. When many holes are applied and the each liquid phase and gas phase is separately supplied to the many holes in the upstream header, the two-phase flow flows through the holes at the gas and liquid interface. The number of holes through which two-phase flow flows is a few among the many holes and the flow rate of the two-phase flow through those holes is negligible compared to the liquid-phase flow rate through lower holes and the gas-phase flow rate through upper holes. Therefore, only the number of holes through which the gas phase or liquid phase flows and pressure difference across the holes are needed to obtain the flow rates of both phases and consequently the quality of whole two-phase flow. In the experimental setup, detection of liquid level in the upstream header was done to obtain the number of holes for the liquid-phase flow. The quality measurement of air-water two-phase flow was examined by measuring the liquid level in the header and the pressure difference across the hole.

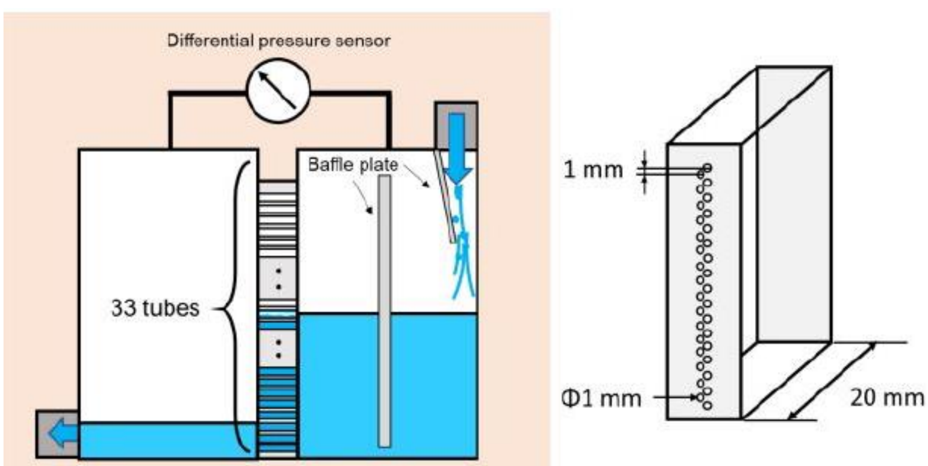


Figure 1: Test section with 33 passages

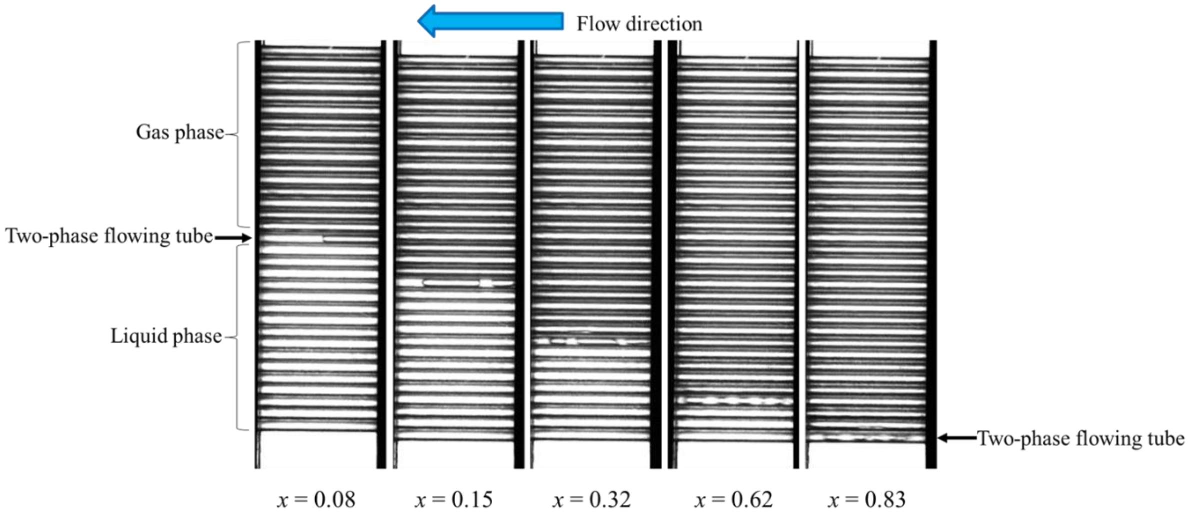


Figure 2: Flow pattern with 33 passages

2. EXPERIMENT

2.1 Experimental apparatus

Figure 3 shows a schematic diagram of an experimental apparatus. The experimental apparatus consisted of an air compressor, a thermal flowmeter, a magnet pump, a liquid tank, a Coriolis flowmeter and the test section. Air and water were used in this experiment. Air supplied from air compressor was mixed with water supplied by the pump, and air-water two-phase flow was fed to the test section. Air flow rate was measured by the thermal flowmeter and water flow rate was measured by the Coriolis flowmeter. The quality of two-phase flow was set based on each flow rate. The experiment was carried out under the condition that the volumetric flow rates of gas phase and liquid phase changed from 0 to 140 L/min, and to 2 L/min respectively so that apparent flow velocities of gas-liquid two-phase flow was the same as that of an actual system using refrigerant.

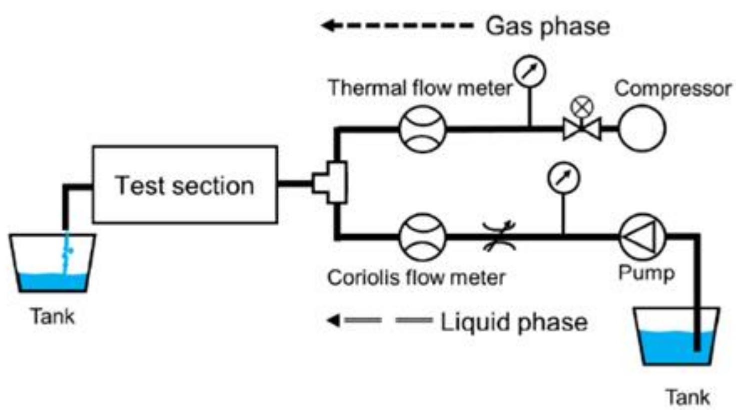


Figure 3: Experimental apparatus

2.2 Test section

Figure 4 shows the test section in this research. The test section was divided into a separator section and a header with many holes where the liquid level and the pressure difference across the holes were measured to obtain the quality of the two-phase flow. Since it is important to make an interface of liquid and gas phase in the header stable, a cyclone separator was adopted outside the header and the separated gas phase and liquid phase were separately fed to the header. The liquid line had a trap with minimum head of 60mm to prevent gas flow through the liquid line under high quality condition. In the header, gas phase and liquid phase flowed from the outside to the inside of a cylinder with the multiple small holes. The gas phase flowed through the upper holes, liquid phase through the lower holes and the two-phase flow through a few holes at the interface. The number of the holes through which the liquid phase flows (hereinafter, they are called liquid flowing holes) decreases with increasing the quality. The small hole was 1 mm in diameter and 96 holes were arranged on the cylinder. In addition, there were four gas bypass holes of 5mm in inner diameter above the small holes to enlarge the applicable quality range. The liquid level is measured by two methods, a capacitance level meter whose accuracy was within ±1mm and a visualization sight tube. A baffle plate was inserted around the cylinder with holes to stabilize the gas-liquid interface. The pressure difference across the holes was measured by a differential pressure sensor. The accuracy of the pressure sensor was within 0.25% of full scale, the accuracy of the flow meter was 0.2% of reading scale. In this measurement, no image processing and no detection of the two-phase flow were needed and the quality measurement, therefore, became simplified.

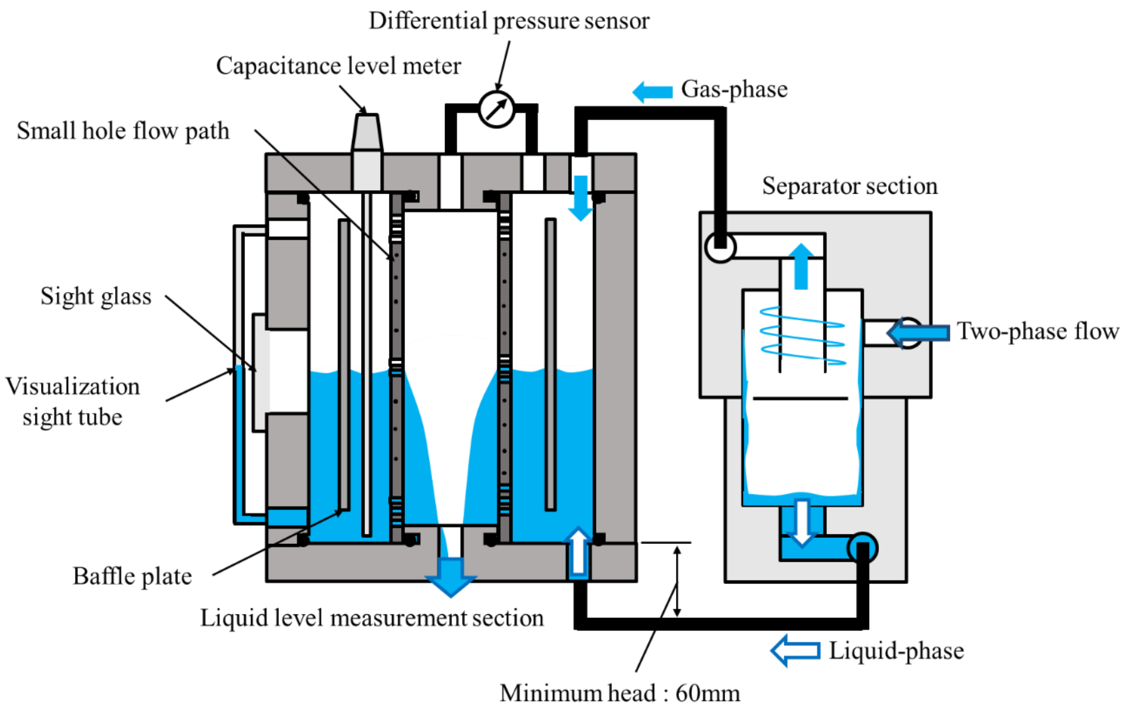


Figure 4: Test section

2.3 Calculation of the quality and mass flow rate

Quality is obtained as the ratio of gas-phase flow rate to total flow rate. The flow rate of each phase can be calculated based on the numbers of the gas and the liquid flowing holes. Since the holes with two-phase flow were a few among the 96 holes, the flow rate of the two-phase flow was negligible. The liquid level in the header was detected to obtain the number of holes for the liquid-phase flow in this experiment.

The pressure difference is so small that the gas flow can be treated as an incompressible one. The gas-phase flow rate, G_g, is calculated by the following equation.

$$G_g = \alpha_g A n_g \sqrt{2\Delta p \rho_g} \tag{1}$$

where α_g is a flow coefficient for gas phase, A is sectional area of the small hole, n_g is the number of the gas flowing holes, Δp is the pressure difference across the holes, and ρ_g is the density of gas phase in the test section. The gas flow rate flows through the gas bypass holes, G_{by}, is calculated also by Equation (1) with using the sectional area and flow coefficient of the bypass holes. In the same manner but with taking account of liquid head in the upstream header, the liquid-phase flow rate, G_l, is obtained by the following equation.

$$G_l = \sum_{k=1}^{n_l} \alpha_l A \sqrt{2\{\Delta p + \rho_l g(h_l - h_k)\}\rho_l} \tag{2}$$

where α_l is a flow coefficient for liquid phase, n_l is the number of the liquid flowing holes, ρ_l is the density of liquid phase, h_l is liquid level in the upstream header and h_k is height of the k^{th} small holes from bottom.

The quality is shown as follows.

$$x = \frac{G_g + G_{by}}{G_g + G_{by} + G_l} \tag{3}$$

3. RESULTS AND DISCUSSION

3.1 Arrangement of the small holes

96 small holes were arranged on the cylinder. Figure 5 shows distribution of holes in vertical direction on the cylinder. Horizontal axis in Figure 5 is hole number from bottom and vertical axis is the height of each hole. When an interval of the holes was equally arranged, the height of holes was proportional to the hole number. Meanwhile, Figure 6 shows the distribution of holes so that the interval of holes become smaller with higher position of holes, *i.e.* there is a higher density of holes at the upper part.

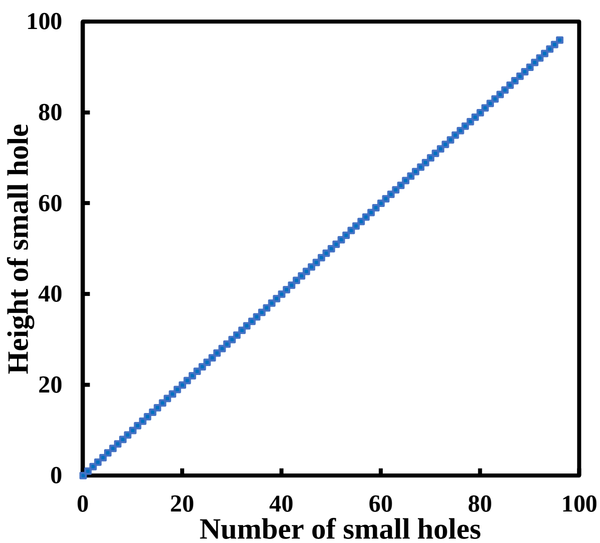


Figure 5: Arrangement of the small holes (Linear)

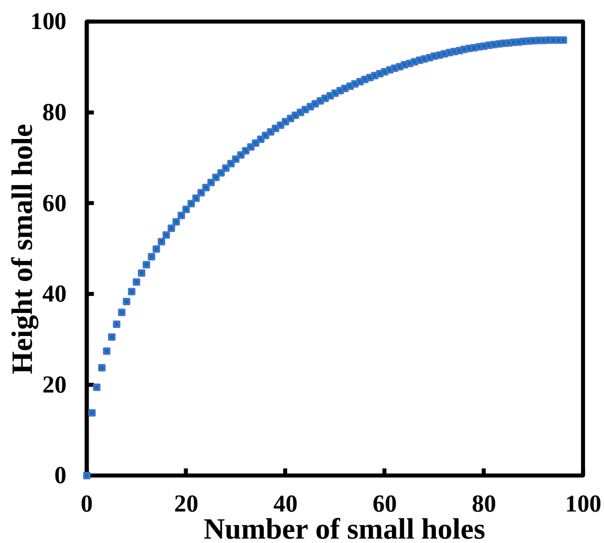
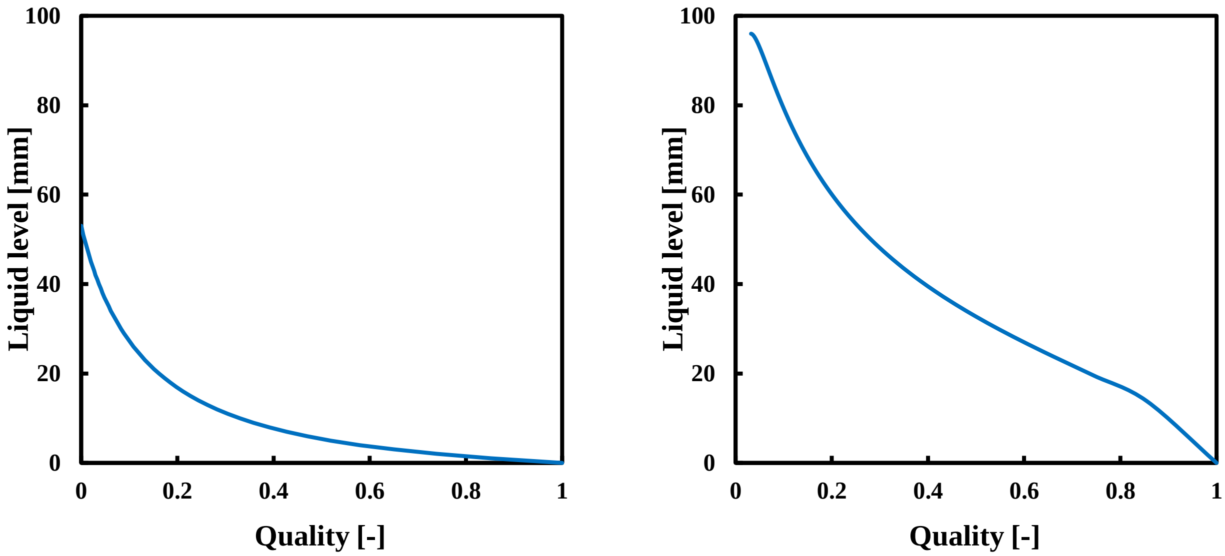


Figure 6: Arrangement of the small holes (Non-linear)

The relationship between the quality and the liquid level in the header was calculated. Firstly, the liquid level was assumed and the number of small holes through which the gas or liquid phase flows were obtained. Secondly, the pressure difference was determined so that the total flow rate became given value, *e.g.* 100kg/h. The gas-phase flow rate was given by Equation (1), the liquid-phase flow rate was given by Equation (2), and the total flow rate was the sum of them. Flow coefficient of 0.9 was used in this calculation for both liquid and gas phase. Finally, the quality was obtained by Equation (3).

Figure 7(a) shows the relationship between the liquid level and the quality when the hole arrangement has linear distribution shown in Figure 5. The liquid level decreases steeply with the quality at low quality region, while the change of liquid level becomes small at high quality region. Therefore, it is difficult to measure the quality accurately in the high quality region. Figure 7(b) show the relationship in case of the hole distribution shown in Figure 6. It was confirmed that the change of the liquid level against the quality becomes linear in wide quality range. The hole distribution shown in Figure 6 was desirable for the air-water two-phase flow. Figure 8 shows an appearance of the cylinder with holes used in this study. The holes on the cylinder distributed in the manner shown in Figure 6. There were 96 small holes of 1mm in inner diameter. Four gas bypass holes of 5mm in inner diameter were arranged at the top to enlarge the applicable quality range.



(a) Holes with linear arrangement

(b) Holes with non-linear arrangement

Figure 7: Relationship between liquid level and quality

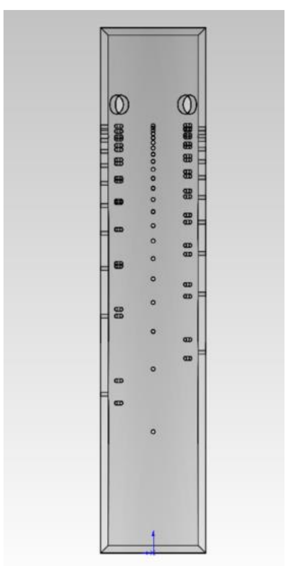


Figure 8: Appearance of cylinder with holes

3.2 Quality measurement based on liquid level

The quality measurement of the air-water two-phase flow was carried out with measuring the liquid level in the header and the pressure difference across the holes. The experimental condition was determined based on the volume flow rate so that the apparent flow velocity of each phase became the equal to that when the mass flow rate of HFO1234yf is 50 kg/h. The flow rate of gas phase changed from 0 to 140 L/min, and flow rate of liquid phase changed from 0 to 2 L/min.

Figure 9 shows a result of flow rate measurement. The horizontal axis is the setting quality, and the vertical axis is the ratio of the flow rate calculated from the pressure difference, Gm, to the flow rate measured by the flowmeter, Gs. Liquid level in the upstream header was measured by the capacitance level sensor. As shown in Figure 9, the flow rate was measured by this equipment with an error of about 30% in low quality range, and the error increased when the quality was more than 0.8. Gas-phase flow rate became high in high quality region, and it affected the measurement of pressure difference.

The accuracy of the quality measurement is shown in Figure 10. The horizontal axis is the setting quality, and the vertical axis is the quality measured by this equipment. As shown in Figure 10, the quality measurement with an error of about ±3% was achieved in the quality range from 0.2 to 0.9.

When the pressure difference across the holes is larger enough than the liquid head in the header, Equation (2) is reduced into the following equation.

$$G_l = \alpha_l A n_l \sqrt{2\Delta p \rho_l} \tag{4}$$

In this case, the quality can be obtained simply by the following equation without using the pressure difference across the holes.

$$x = \frac{\alpha_g n_g \sqrt{\rho_g}}{\alpha_g n_g \sqrt{\rho_g} + \alpha_l n_l \sqrt{\rho_l}} \tag{5}$$

In a refrigeration cycle, the pressure difference becomes large compared with the air-water two-phase flow since the density of gas-phase refrigerant is much larger than the atmospheric air. The quality in the refrigeration cycle is expected to be measured only by detecting the liquid level in the header although the flow rate of the two-phase flow is not derived.

4. CONCLUSIONS

In this research, quality measurement applying multiple small holes into the test section was examined and the following conclusions were obtained.

- By using multiple small holes, the applicable range of flow rate for quality measurement could be enlarged and the quality measurement was simplified.

- The quality measurement of air-water two-phase flow was carried out. The quality could be measured by detecting liquid level in a header and pressure difference across the holes. With arranging the holes on a cylinder so that a vertical interval of holes become smaller with higher position of holes, the liquid level changes linearly against the quality. The quality measurement with an error of about ±3% was achieved in the quality range from 0.2 to 0.9 for the air-water two-phase flow.

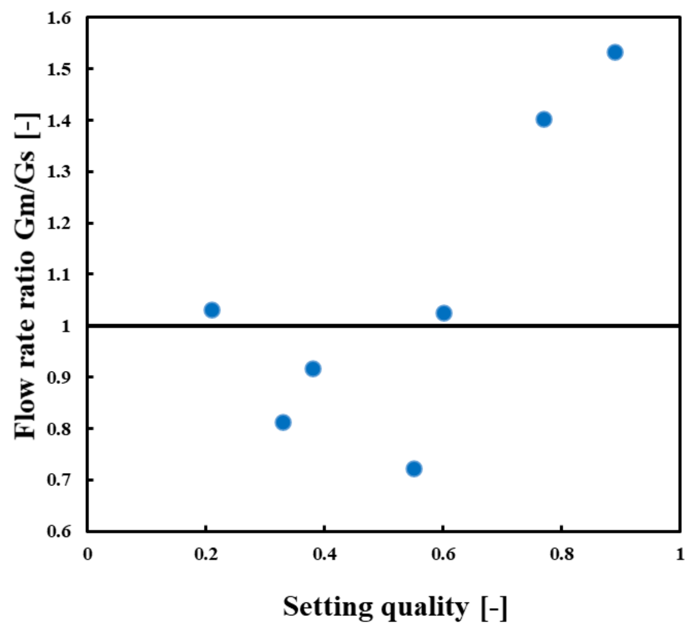


Figure 9: Flow rate measurement

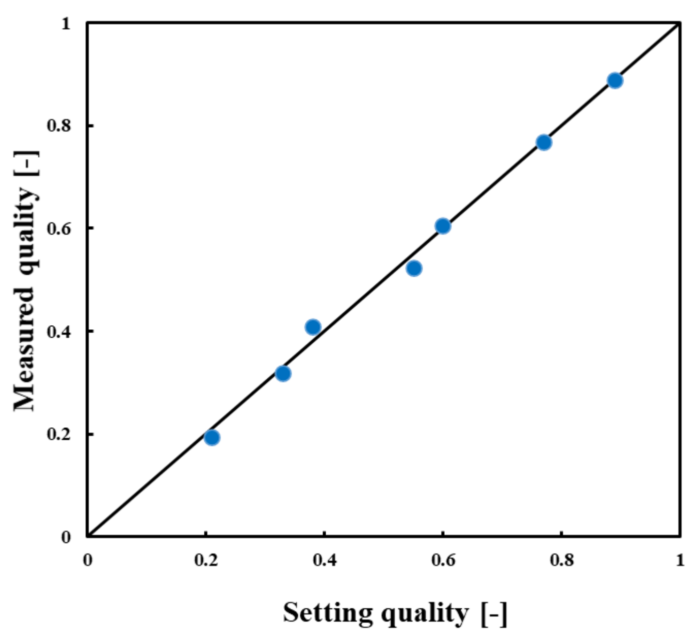


Figure 10: Quality measurement

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