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Quality Measurement of Two Phase Flow with Plug Flow

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ABSTRACT

In refrigeration cycles especially at an injection line of injection cycles, quality measurement of two-phase refrigerant flow is required to check or control the cycle. Although sectional void fraction of the two-phase flow at a certain position of the pipe can be detected, the quality of the two-phase flow is not obtained from the sectional void fraction since velocities of liquid and gas phase in the pipe are different from each other. In this study, the new quality measuring method was developed based on a concept that the velocities of liquid and gas become almost the same in a narrow tube with flow pattern of plug flow, where the quality of the two-phase flow can be derived from the void fraction of the plug flow. The feasibility of the quality measurement based on the void fraction measurement in the narrow tube with plug flow is shown. The quality range of the measurement can be extended with installing a gas bypass tube. The accuracy of the quality measurement within ±10% error is achieved in the plug flow region.

1. INTRODUCTION

In refrigeration cycles, quality measurement or quality control of two-phase refrigerant is sometimes required especially at an injection line of injection cycles (JSRAE, 2018)(Hagiwara *et al.*, 2011) and at a suction inlet of compressor with wet compression. As a method which identifies the two-phase flow condition, many techniques have been proposed for a sectional void fraction measurement. Jaworek *et al.*(2004) and Kerpel *et al.* (2013) proposed a capacitance sensor. Revellin *et al.*(2006) and Ruixi *et al.*(2013) developed an optical sensor, and also visualization and image processing techniques were applied by Puli *et al.*(2012), Charnay *et al.* (2013) and Li *et al.*(2017). An electrical resistance tomography sensor was used by Meng *et al.*(2010). In recent years, the measurement by using a broad beam gamma ray attenuation technique was utilized with Artificial Neutral Networks (ANNs) (Cong *et al.*, 2013) to predict the void fraction (Nazemi *et al.*, 2016). Despite of these measurement techniques for the void fraction measurement, the quality measurement of two-phase flow is quite difficult since the quality of the two-phase flow is not obtained from the sectional void fraction when there is velocity difference between the liquid phase and the gas phase.

In this study, the new quality measuring method is developed based on a concept that the velocities of liquid and gas becomes almost the same in case of a horizontal two-phase flow through a narrow tube with flow pattern of plug flow. The void fraction of the two-phase flow through the narrow tube is measured by lengths of the liquid plug and the gas plug, and the quality of the two-phase flow is derived from the void fraction of the plug flow. Authors examined the quality measurement based on the void fraction of air-water two-phase flow in the narrow tube with the plug flow (Shinohara *et al.*, 2015) and the feasibility of the quality measurement in refrigeration cycle is discussed in this paper.

2. EXPERIMENTAL APPARATUS

2.1 Principle

When gas-liquid two-phase flow flows through a horizontal tube having small diameter, the flow pattern tends to be plug flow. Velocities of the gas phase and the liquid phase of the plug flow are thought to be almost the same and slip ratio becomes one. In such plug flow, the void fraction, f_g, becomes the ratio of length of the gas plug to that of the liquid and gas plugs as shown in Figure 1 and it is expressed by Equation (1).

$$f_g = \frac{V_g}{V_g + V_l} = \frac{L_g}{L_g + L_l} \tag{1}$$

where V_g and V_l are volume flow rates of gas and liquid flow, and L_g and L_l mean length of gas and liquid plug. It can be measured by detecting a boundary between the gas phase and the liquid phase. If the flow condition is steady state, i.e. there is no velocity change against time, the void fraction is equal to the time proportion of the gas phase passing at a certain section. On the other hand, when the flow is not steady state, both the length and velocity of each plug should be measured to obtain the mean void fraction. Once the void fraction without slip is measured, the quality is calculated by Equation (2) based on the void fraction and densities of both phases.

$$x = \frac{1}{1 + \left(\frac{1}{f_g} - 1\right)\frac{\rho_l}{\rho_g}} \tag{2}$$

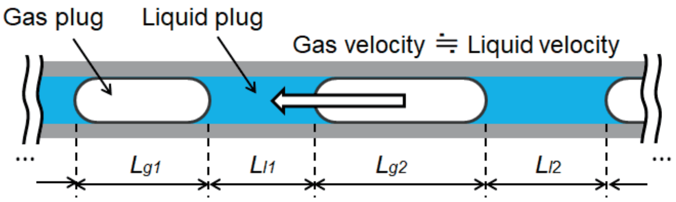

Figure 1: Principle of the quality calculation

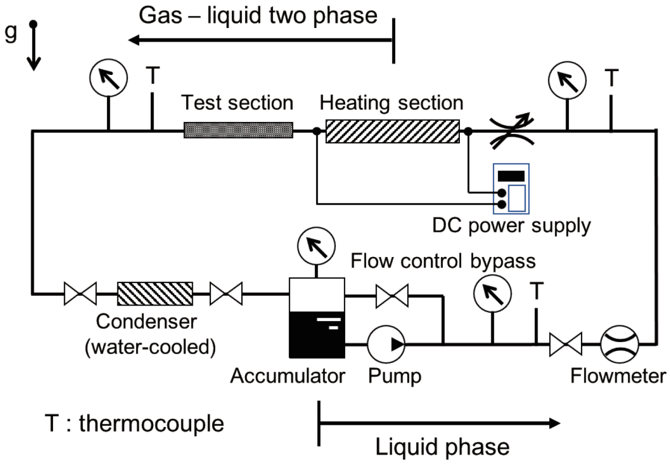

Figure 2: Experimental circuit

where x is quality, and ρ_g and ρ_l are gas density and liquid density respectively.

2.2 Experimental circuit

Figure 2 shows a schematic diagram of an experimental circuit. The experimental circuit consists of a liquid accumulator, a gear pump, a Coriolis flowmeter, a heating section, a test section and a condenser. Refrigerant is R134a. Polytetrafluoroethylene (PTFE) tube of 1 mm in diameter is used as the test section. Since PTFE has repellency and is transparent, the plug flow is formed easily and visualized. The length of the PTFE tube is determined to be 200 mm to make the flow pattern steady based on a research by Sekoguchi *et al.* (1968) as reference. The liquid refrigerant in the accumulator is supplied to the heater section by the gear pump through the Coriolis flowmeter to measure mass flow rate. Then, the liquid refrigerant is heated by an electrical heating method in the heating section made of stainless steel tube. The refrigerant flow becomes gas-liquid two-phase flow and enters the test section. After leaving the test section, the two-phase refrigerant flow is condensed back into liquid condition in the condenser and returns to the accumulator. The quality of refrigerant in the test section is set by adjusting an electric current applied to the heater. The test quality set by the heater is obtained based on enthalpy of refrigerant, which is calculated from the refrigerant enthalpy before heating, the heating power and the mass flow rate. The heating power is estimated by the electric power supplied to the heater and thermal efficiency of the heater. The thermal efficiency of the heater is found to be 95% by a preliminary test done under liquid condition. The relative error of the quality by errors of the heating power and the flow rate is about 4 %.

2.3 Detection of plug

An optical sensor shown in Figure 3 is used to detect the gas and liquid plugs in the PTFE tube. The sensor is composed of a green laser, a cylindrical lens and a photo transistor. The laser and the lens are arranged so that the laser light converges at the center of cross section of the tube. The photo transistor detects intensity of laser light which passes through the tube. Since refractive index of the liquid refrigerant is close to that of PTFE while the refractive index of the gas refrigerant is much smaller than PTFE's, when the gas plug exists at the detection point, the intensity of the transmitted light becomes small due to refraction and scattering at an internal surface of the pipe. The existence of the plug is detected at two points with distance of 30 mm between them. The velocity of plug flow can be determined by a time gap between two output waveforms and the distance. The volumetric flow rate ratio of gas and liquid phase, i.e. the void fraction, can be measured by the flow velocity and occupied time for each phase. The outputs of the photo transistors are connected to a data logger. Sampling frequency of the sensor output is 10 kHz and data is acquired for 10 seconds.

Figure 4 shows an example of the output signal of the optical sensor. The signal having higher voltage shows the flow of liquid plug and lower shows the gas plug or bubble. To binarize the waveform corresponding to the gas and liquid phase, a threshold is determined as follows. A histogram of the sensor output is made against the output voltage as shown in Figure 5 with referring Rahim *et al.* (2011). The histogram shows two peaks; one peak with the lower voltage corresponds to the gas phase and the other with higher voltage indicates the liquid phase. As one can see in Figure 4 that when small bubble passes at the sensor the sensor output decreases but the output voltage has relatively higher value than that for complete gas phase, while the output is stable with higher output voltage for the liquid phase. To detect the interface or boundary between the liquid phase and the gas phase sharply, therefore, the

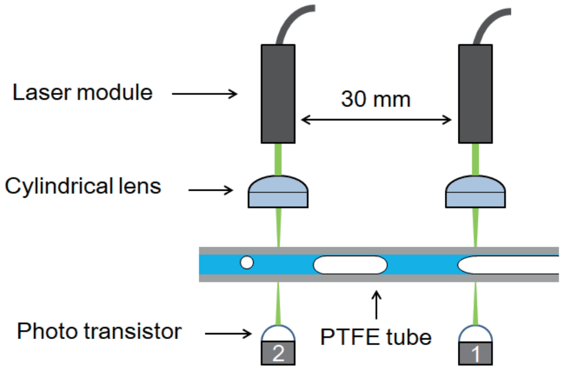

Figure 3: Optical sensor

threshold is determined close to the output level for the liquid phase. In this experiment, the threshold is set at 90% of a difference between the two peaks as shown in Figure 5. According to the threshold, the output signal of each sensor is binarized and the binarized signals are shown in Figure 6. Since the sensor #1 is mounted at upper-stream in the test section, the output signal for each plug appears first at the sensor #1 and a corresponding signal for each plug appears at the sensor #2 with a certain time delay. By comparing two binarized signals, the time difference between two signals is derived by taking the maximum correlation factor. The average velocity of the plug flow at the test section for the recording period (10 seconds) is calculated from the time difference of signals and the distance between the two sensors. In the case shown in Figure 6, the velocity is 1.5 m/s.

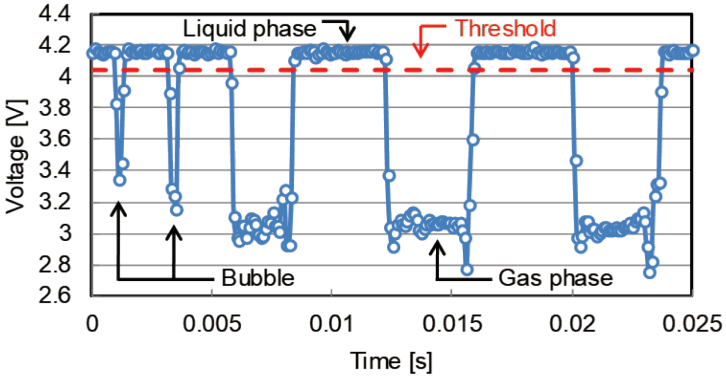

Figure 4: Output signal

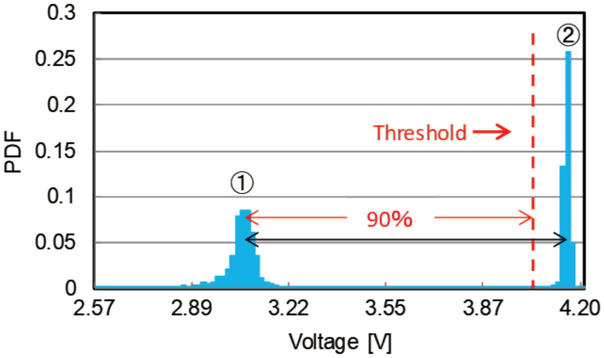

Figure 5: Decision of threshold

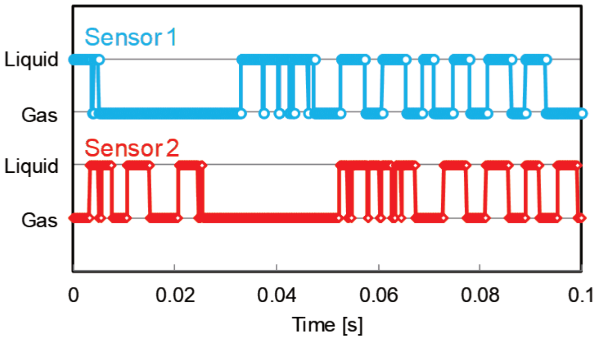

Figure 6: Binarized signal of two sensors

3. RESULTS

3.1 Single Tube

Firstly, accuracy of the quality measurement is examined in a single PTFE tube. Experiment is carried out under the condition that the refrigerant mass flow rate ranges from 1.8 to 3 kg/h and absolute pressure is from 0.6 to 0.7 MPa. The flow pattern in the experiment is either bubble or plug flow. The accuracy of the measurement is evaluated by comparing the mass flow rate, G_o, calculated from the volumetric flow rate measured by the optical sensor with the mass flow rate measured by the Coriolis flowmeter, G_m, because the mass flow rate through the narrow tube is needed when a bypass tube is introduced to the test section as described in next section. The average velocity of the plug flow during 10 seconds is used to calculate the volumetric flow rate. Densities of gas and liquid refrigerant needed to calculate the mass flow rate based on the volumetric flow rate are obtained by REFPROP (Lemmon *et al.*,

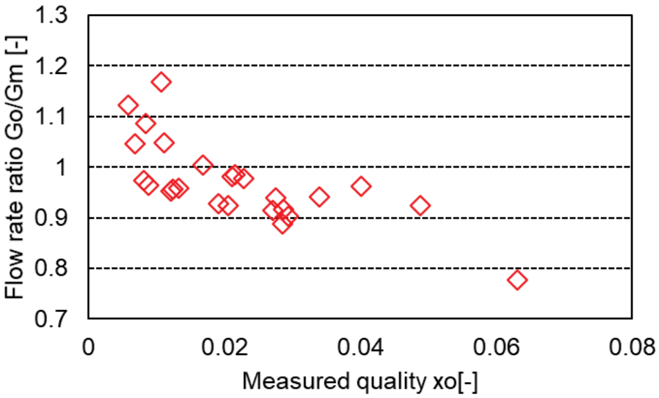

Figure 7: Flow rate ratio

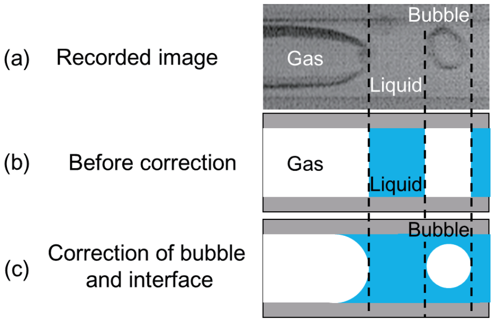

Figure 8: Improvement of signal processing

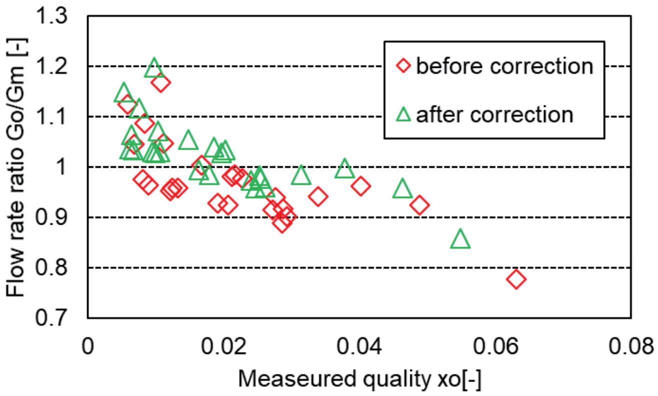

Figure 9: Flow rate ratio with correction

2013). The ratio of the flow rates, G_o/G_m, is plotted against the measured quality, x_o, in Figure 7. As shown in Figure 7, it is confirmed that the flow rate measurement and consequently the quality measurement in the narrow tube with the plug flow is feasible. The ratio of the flow rate, G_o/G_m, decreases with increasing the quality. The accuracy of the measurement is ±20% in the comparison of mass flow rates.

To achieve the quality measurement with satisfactory accuracy, factors that cause the error should be considered. In the present signal processing, the output signal of the sensor is binarized by the threshold as described in section 2.3. The flow shown in Figure 8(a) is recognized as the pattern shown in Figure 8(b) although the actual gas plug has an interface with a curvature. A compensation is, therefore, introduced to correct the difference between (a) and (b) in Figure 8 so that shape of both ends of the gas plug becomes hemisphere having the same radius as the tube as shown in Figure 8(c). In addition, when the plug whose length is smaller than the diameter of test section (1 mm) is detected, it means that a small bubble having smaller diameter than the tube diameter exists as shown in the right side of Figure 8. In such case, the volume of gas plug is corrected to be the same as the volume of sphere with the diameter of the detected length (< 1 mm). Figure 9 shows an effect of the treatment considering the volume correction for boundary shape and small bubble on the accuracy of G_o/G_m. Diamond (◇) shows the result before the volume correction and triangle (△) shows the result after the correction. Since the volume correction increases the volume of liquid portion and decreases the gas portion, the mass flow rate calculated from the output signal of the sensor increases and the measured quality decreases with the correction. Compared to the result before correction, the accuracy of measurement is improved in a high quality region (x_o > 0.02). On the other hand, the error slightly becomes larger in a low quality region ($x_o \approx$ 0.01).

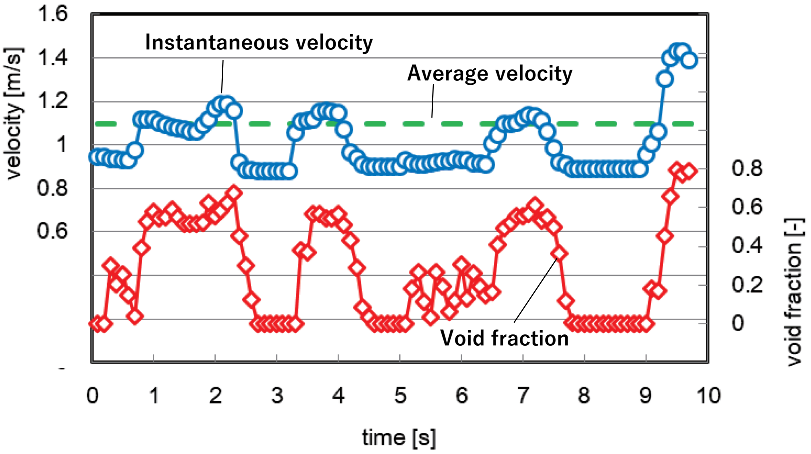

Figure 10: Fluctuation of void fraction and velocity

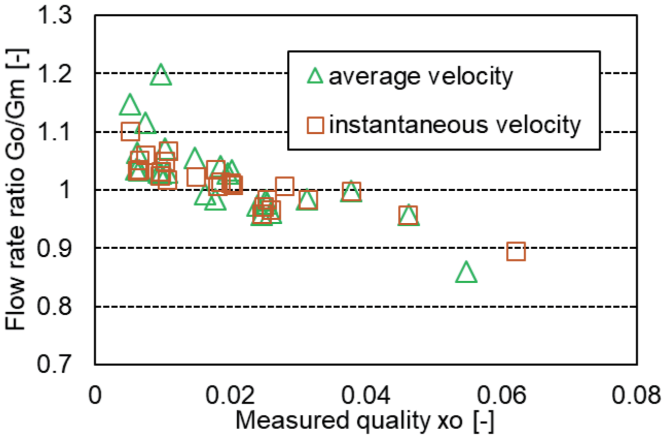

Figure 11: Correction with velocity fluctuation

Another factor of the error is velocity fluctuation. Figure 10 shows time variations of the void fraction and instantaneous velocity as well as the average velocity. This data corresponds to the quality of 0.01 showing the maximum flow rate ratio in Figure 9. The instantaneous void fraction and velocity are acquired every 0.1 seconds. Although the average velocity is used to calculate the volume flow rate in Figure 9, it is found that the instantaneous velocity has large fluctuation corresponding to the void fraction, i.e. the velocity becomes higher with the void fraction. The average velocity does not coincide with an average of the instantaneous velocity and is close to the velocity when the void fraction is large. Since the quality is small in this case and the sensor output signal tends to be characterized by the low-frequent signal caused by the gas plug, the average velocity obtained by the correlation of two sensor signals for 10 seconds is significantly influenced by the signal of gas plug. Figure 11 shows the influence of the velocity fluctuation on the flow rate ratio. Triangle (△) shows the same result shown in Figure 9, while square (□) shows the result with using the instantaneous velocity to calculate the flow rate. Figure 11 indicates that considering the velocity fluctuation improves the accuracy of measurement. As a result, the measurement with the error within ±10% of flow rate ratio is attained. Nevertheless, the flow rate ratio shows small value than 1.0 when the quality is large. It is supposed due to thin liquid film existing on the inner wall of the tube at the gas plug. In contrast, the flow rate ratio becomes larger than 1.0 at low quality region. Although the velocity of the plug flow with lower quality must be slower, it is impossible to detect the velocity if the liquid plug flows solely for a long time, i.e. without the signal of gas plug. In this study, when there is no signal of gas plug at a focused period, the velocity is given to be the same as the velocity right before. The velocity of such long liquid plug may be smaller than the velocity determined by this process. Using a differential pressure to calculate the velocity of the long liquid plug is recommended to eliminate this problem.

3.2 Single Tube with Bypass

As shown in the previous section, the error of the measurement of mass flow rate of refrigerant gas-liquid two-phase flow is approximately within ±10% in the narrow tube with the optical sensors under the condition of plug flow. However, the range of the quality at which the flow pattern in the narrow tube becomes the plug flow is very small as shown in Figure 11. When the quality becomes higher than 0.1, the flow pattern becomes annular flow and the proposed technique cannot be applied. In order to enlarge the range of the quality measurement, the new test section with a gas bypass tube is examined (Shinohara et al., 2015). Figure 12 shows a schematic view of the test section with the bypass tube. The bypass tube is a glass tube of 2 mm in diameter. A baffle plate is installed in a upstream header to prevent a liquid spray flowing with the gas flow so that only gas phase flows into the bypass tube. Most of gas phase flows through the bypass tube. Flow rate of the gas phase through the bypass tube is calculated from pressure difference measured by a differential pressure transducer and by using well-known correlations of pipe friction coefficient, i.e. 64/Re for laminar flow and Blasius formula for turbulent flow. The liquid phase and the rest gas phase flowing through a lower narrow tube forms the plug flow. The flow rate of the plug flow through the lower narrow tube is measured by the same way as is done to the plug flow through the single narrow tube.

Comparison between the given quality and the measured quality is shown in Figure 13. The given quality is calculated from the heater input and the flow rate measured by the Coriolis flowmeter. The flow rate in the experiment ranges from 3 to 6 kg/h, and the given quality is changed from 0.5 to 0.7. The result is shown by different symbol for each flow rate. Hatched symbol means bubble flow or bubble-plug flow, filled symbol

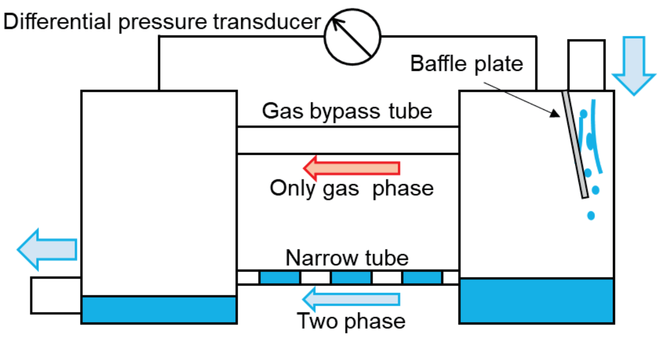

Figure 12: Test section with gas bypass

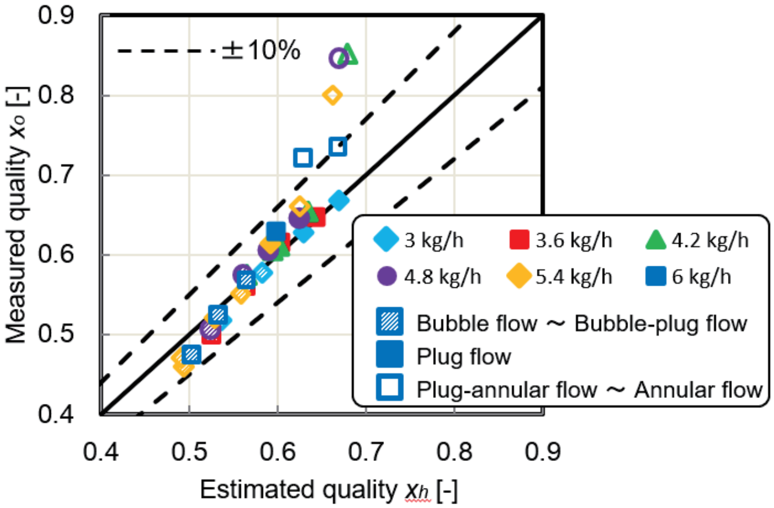

Figure 13: Accuracy of quality measurement with gas bypass

expresses plug flow and open symbol shows plug-annular flow or annular flow. As shown in Figure 13, when the flow through the lower narrow tube is bubble or plug flow, the measurement error of the quality is less than ±10% in the quality range from 0.5 to 0.7. When the quality increases and the flow pattern becomes the plug-annular or the annular flow, the measurement accuracy is insufficient and this method cannot be applied for the quality measurement. The criteria for the plug flow regime through the PTFE tube of 1 mm in diameter is that superficial velocity of gas (j_G) is less than 1 m/s (Shinohara, *et al.*, 2015). Almost the same flow regime of the plug flow was reported in previous studies, e.g. Chen *et al.* (2006) for R-134a two-phase flow through a vertical tube of 1.1 mm in diameter, Yang and Shieh (2001) for R-134a through a horizontal tube having a diameter of 2.0mm and Enoki *et al.* (2013) for R-410A through a horizontal tube of 1.03 mm ID. In order to apply this method, the flow in the narrow tube should be the plug flow. The test section having multi narrow tubes with the bypass tube is examined to apply this method to wide range of quality condition for practical use. The result by the new test section with the multi tubes will be reported in another work.

4. CONCLUSIONS

In this study, quality measurement in a plug flow regime in a narrow tube is proposed. Since the velocities of gas phase and liquid phase become almost the same in the plug flow in the narrow tube, the quality is obtained from the void fraction. The void fraction is obtained by optical sensors and the velocity is determined by time delay between two sensor output signals. The accuracy of measurement at single narrow tube is confirmed by comparison of mass flow rate. By applying volume corrections to compensate an influence of round shape boundary between the gas and liquid phases and small bubbles, the accuracy is improved in a quality range from 0.02 to 0.06. The velocity fluctuation corresponding to the void fraction has large influence on the accuracy and the error can be reduced to less than ±10% by using an instantaneous velocity. Existence of a thin liquid film in the gas plug and inaccurate instantaneous velocity of the liquid plug at extremely low quality are dominant factors reducing the accuracy.

Although the quality range where the flow pattern in the narrow tube becomes the plug flow is limited to very small quality region, measurement range of quality can be extended by installing a gas bypass tube to the test section. When the flow through a lower narrow tube is bubble or plug flow, the measurement error of the quality is less than ±10% in the range of quality from 0.5 to 0.7. The test section having multi narrow tubes with the bypass tube is examined to apply this method to wide range of the quality condition for practical use. The result by the new test section with the multi tubes will be reported in another work.

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