ESTIMATION OF TWO-PHASE FLOW QUALITY WITH PRESSURE DIFFERENCE OSCILLATION

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ABSTRACT

The oscillation of differential pressure *dp* in two-phase flow is very important not only for the design of two-phase components such as heat exchangers or steam generators but also for the estimation of flow behavior by detecting vibration or noise transferred from the components. The skilled engineers sometimes can determine the two-phase behavior with vibration or noise from the components. To understand the oscillation behavior and possibility to estimate the flow behavior, the air-water two-phase flow experiments were conducted with small vertical tubes of 1 to 10mm in inner diameter. The differential pressure was measured at the long observation span more than fifty times of diameter to avoid the static pressure oscillation due the fluctuation of void fraction. The time-averaged value of *dp* was well predicted with the conventional correlations for pressure loss and void fraction. The FFT analysis on the oscillatory *dp* was conducted and the spectrum peak shifts due to the change of flow behavior were observed. The root mean square (RMS) value of *dp* was well correlated with Lockhart-Martinelli parameter. It was also demonstrated that the two-phase quality could be estimated with the proposed correlation for RMS values when the liquid flow rate and RMS value were known.

INTRODUCTION

The oscillation of differential pressure *dp* in two-phase flow is very important not only for the design of two-phase components such as steam generators, boilers or heat exchangers but also for the estimation of flow behavior by detecting vibration or noise transferred from the components. The skilled engineers sometimes can determine the two-phase behavior with the vibration or noise from the components. They usually use an acoustic rod to pick up the vibration or noise. The vibration at the various frequencies can be amplified, transformed and transferred with the rod. How to translate the obtained information is depending on the experience of engineers.

The differential pressure oscillation was also used to characterize various flow patterns in two-phase flows by Matsui et al.[1]. Their experimental results showed two-phase flows in an inclined pipe of 20mm in inner diameter exhibited peculiar features of statistical properties such as probability density function and power spectrum, and the flow patterns could be classified by the statistical characteristics of differential pressure oscillation. The differential pressure was measured both at short observation span equal to the pipe diameter and long observation span equal to ten times of the diameter. They pointed out that the short span measurement was preferable for the proper judgment of flow pattern.

To understand the vibration behavior and possibility to estimate the flow behavior independently on individual experiences, air-water two-phase flow experiments were conducted with small vertical tubes of 1 to 10mm in diameter. These sizes of small tubes are expected to use in compact heat exchanger [2]. The experiments were conducted at bubble, slug and churn flow patterns. The differential pressure was measured at the long observation span more than fifty times of diameter to avoid the static pressure oscillation due the fluctuation of void fraction. The time-averaged (mean) value of *dp* was compared with conventional correlations for two-phase pressure loss and void fraction. For the comprehensive understanding of oscillatory behavior, FFT analysis was conducted and spectrum peaks were obtained. Furthermore root mean square (RMS) value of *dp* was considered to be an important parameter to describe the two-phase characteristics and was studied carefully in this study.

EXPERMIMENTAL APPARATUS AND METHOD

Shown in Fig.1 is a schematic of experimental apparatus. Air and water were supplied into the lower plenum and flow through test tubes of 1, 2, 4, 6 and 10mm in inner diameter. The test tubes were made of cupper or transparent glass and the tolerance of the inner diameter was ±50μm. The measurement by a microscope showed that their accuracies were all in the range of the tolerance. By using the same tubes, the pressure losses of single-phase water flow were measured and good agreements with the conventional correlations were reported [3]. The two-phase flow from the test tubes entered to the upper plenum where the water level was kept with water drain tubes. The air was separated in the upper plenum and released to the atmosphere. The flow rates of air and water were measured with several sets of rotameters before entering the lower plenum. The differential pressures between 500mm vertical span were measured at sampling rate of 5 Hz during 60 s with a reluctance-type differential pressure cell. The measurement error was within ±0.13% and the time constant was 0.0025s.

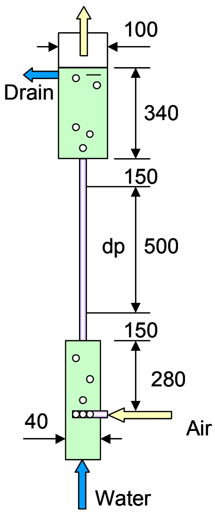

Fig. 1 Experimental apparatus

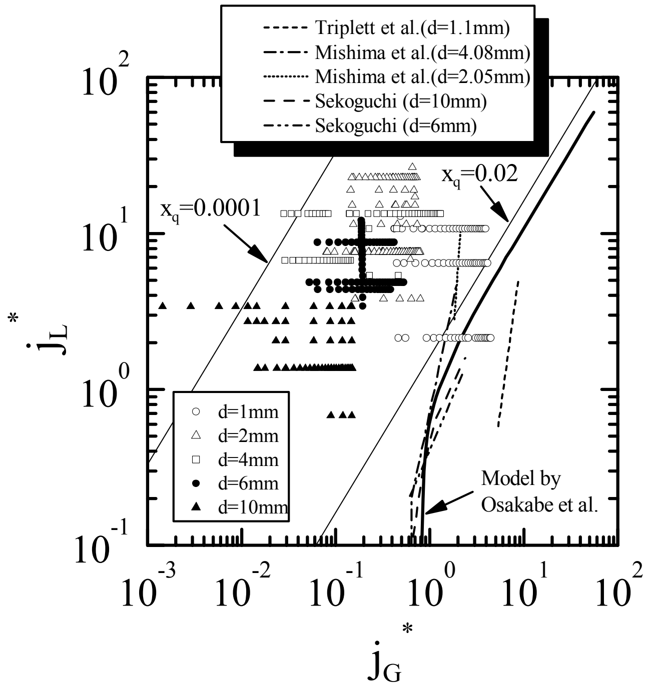

Fig. 2 Experimental condition on flow pattern map

Table 1 Superficial velocity of air and water

d (mm)	j_G (m/s)	j_L (m/s)
1	1.07~11.7	0.21~1.27
2	0.31~3.06	0.53~3.71
4	0.15~6.64	1.06~2.65
6	0.36~3.65	0.83~2.95
10	0.01~1.37	0.21~1.06

Osakabe et al.[4] proposed the following annular transition model in the vertical pipes of various shapes and sizes. The model gave good prediction for channels whose hydraulic diameters were between 4 and 20mm both in earth gravity and micro gravity conditions [5].

$$j_G^* = 0.412\left[4\frac{g}{g_0} + 5(j_L^*)^2\right]^{1/2} \tag{1}$$

where g is acceleration due to gravity and a suffix 0 indicates earth gravity condition. The transition gas velocity is expressed with the gravitational and shear stress terms. The non-dimensional superficial velocity is defined as,

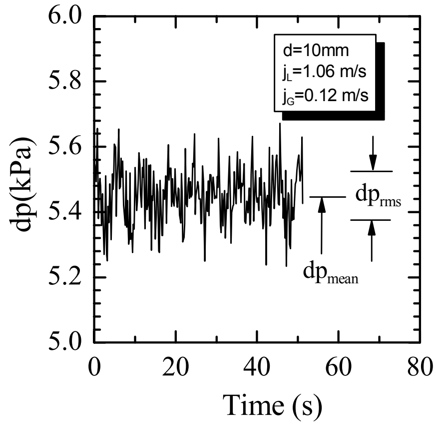

Fig. 3 Typical oscillation of pressure difference

$$j_i^* = \frac{\rho_i^{1/2} j_i}{\left[g_0 d(\rho_L - \rho_G)\right]^{1/2}} \quad (i = L \ or \ G) \tag{2}$$

where ρ is density, j is superficial velocity, d is tube inner diameter, suffix L and G indicate water and air, respectively.

Shown in Fig.2 is the experimental condition comparing with the annular transition model and experimental annular transition boundaries of air/water two-phase flow. Mishima et al. [6] and Sekoguchi[7] conducted experiments at atmospheric pressure using small vertical tubes of 2.05, 4.08, 6 and 10 mm in inner diameter. Triplett et al.[8] used a small horizontal tube of 1.1 mm in inner diameter at atmospheric pressure. It should be noted that the annular transition boundary obtained in the small tube experiments are well predicted with the model without the surface tension. The present experiments were conducted at non-annular flow region jugging from the previous experimental observations and the transition model.

When the flow quality x_q is constant, the relation between the non-dimensional superficial gas and liquid velocities is given by

$$j_G^* = \frac{x_q}{1 - x_q}\sqrt{\frac{\rho_L}{\rho_G}}\, j_L^* \tag{3}$$

The solid lines in Fig.2 are the relation at x_q =0.0001 and 0.02 using the densities of air and water at atmospheric pressure. It can be confirmed that the almost data in the present experiment exist between the quality of 0.0001 and 0.02. The range of superficial velocity are shown in Table 1.

MEAN DIFFERENTIAL PRESSURE

Shown in Fig.3 is a typical transient differential pressure measured in a pipe of 10 mm in diameter. The superficial water and air velocities were 1.06 and 0.12 m/s, respectively. From the differential pressure oscillation, important information such as the time-averaged (mean) value and the root mean square (RMS) value can be obtained. In the conventional two-phase flow system, the mean value of the differential pressure has been used to control the water mass content in tubes. The RMS value is considered to be a representative parameter to express the oscillation behavior.

It is not difficult to predict the time-averaged differential pressure dp_{mean} from the previous studies. The extensive studies have been conducted for the mean value and the prediction methods for two-phase pressure loss and void fraction were proposed by many researches. The mean differential pressure can be described as,

$$dp_{mean} = 4c_L \frac{h}{d} \Phi_L^2 \frac{\rho_L}{2} j_L{}^2 + \rho_m g h \tag{4}$$

where g is acceleration due to gravity, h is vertical length of pipe. The first term in the right hand side of Eq.(4) is the frictional pressure loss and the second term is the static pressure. The frictional pressure loss coefficient is c_L is expressed as,

$$c_L = 16/Re \quad \text{(laminar)} \tag{5}$$

$$c_L = 0.079\, Re^{-0.25} \quad \text{(turbulent)} \tag{6}$$

Φ_L is the two-phase multiplier by Lockhart-Martinelli [9] described as,

$$\Phi_L = \left(1 + \frac{C}{X} + \frac{1}{X^2}\right)^{1/2} \tag{7}$$

where C is Chisholm[10] parameter defined as Table 2. The parameter X can be defined as,

$$X = \sqrt{\frac{dp_L}{dp_G}} \tag{8}$$

where dp_L and dp_G is the single-phase frictional pressure loss evaluated with superficial liquid and gas velocities, respectively. Chisholm originally defined Re number for turbulent and laminar transitions as 2000 and 1000, respectively. In the present calculation, the transition Re number of 1500 was used for the both. On the other hand, Mishima et al.[6] proposed the following correlation for C value from their small tubes experiments of 1.05 to 4.08 mm in inner diameter.

$$C = 21\left(1 - e^{-0.333d}\right) \tag{9}$$

The modified Chisholm parameter by Mishima et al. depends only on the tube diameter.

Table 2 Chisholm parameter

Re_L	Re_G	C
>1500	>1500	20
<1500	>1500	12
>1500	<1500	10
<1500	<1500	5

The average density of two-phase ρ_m is,

$$\rho_m = \alpha\rho_G + (1-\alpha)\rho_L \tag{10}$$

The void fraction α can be estimated with the following drift flux model by Zuber-Findlay[11], which is applicable to the wide range of gas volume fraction in pipes.

$$\alpha = \frac{j_G}{1.13(j_L + j_G) + 1.18\left[\frac{\sigma(\rho_L - \rho_G)g}{\rho_L{}^2}\right]^{1/4}} \tag{11}$$

On the other hand, Mishima et al.[6] proposed the following modified drift flux model from their small tubes experiments of 1.09 to 3.9 mm in inner diameter.

$$\alpha = \frac{j_G}{\left(1.2 + 0.51e^{-0.691d}\right)(j_L + j_G)} \tag{12}$$

Shown in Fig.4 is the comparison between measurements and predictions using Chisholm parameter and Zuber-Findlay drift model for mean differential pressure. Generally the predictions agree well with the experimental results. Considering that the Re number becomes lower in the smaller tubes, the two-phase multiplier by Lockhart-Martinelli and Chisholm parameter works very well in such a laminar flow region. Figure 5 shows the comparison between measurements and predictions using the modified parameter by Mishima et al. and Zuber-Findlay drift model for mean differential pressure. The good agreement is also obtained in the comparison. The modified Chisholm parameter by Mishima et al. depending only on the tube diameter successfully represents the flow condition in small tubes. However, when the Re number is significantly increased, the discrepancy with the original Chisholm parameter may appear. Shown in Fig.6 is the comparison between measurements and predictions using Chisholm parameter and modified drift flux model by Mishima et al.. The good agreement is also obtained in the comparison.

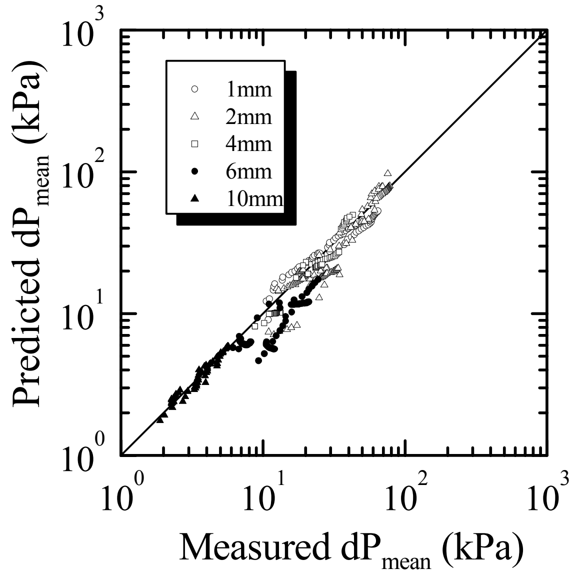

Fig. 4 Comparison between measurements and predictions with Chisholm parameter and Zuber-Findlay drift flux model for mean differential pressure

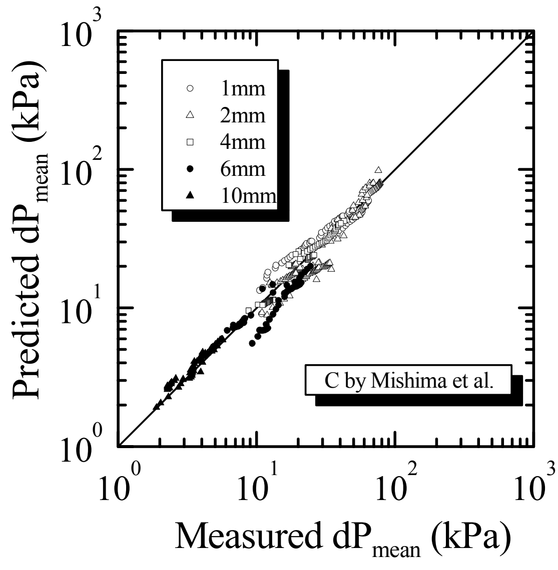

Fig. 5 Comparison between measurements and predictions with modified parameter by Mishima et al. and Zuber-Findlay drift flux model for mean differential pressure

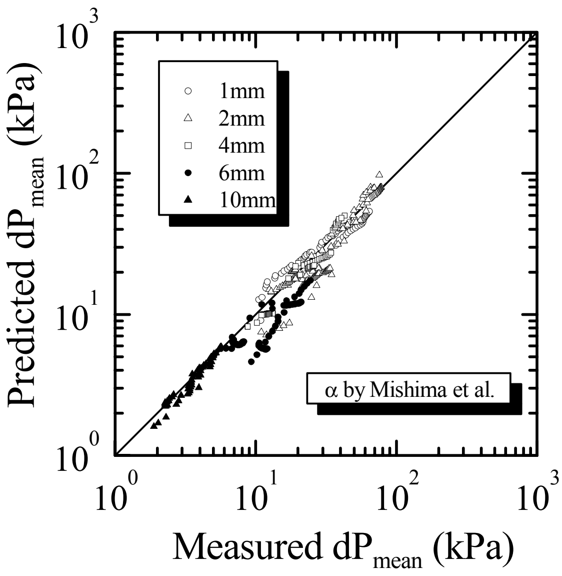

Fig. 6 Comparison between measurements and predictions with Chisholm parameter and modified drift flux model by Mishima et al. for mean differential pressure

The above prediction method can give the characteristics of mean differential pressure in tubes when the superficial gas velocity is increased as shown in Fig.7. The calculation was conducted for the tube of 10 mm as an example. When the superficial liquid velocity is low, the differential pressure monotonously decreases with increasing the gas velocity. However when the liquid velocity becomes higher, the differential pressure decreases at the low gas velocity and increases at the high gas velocity. Finally when the liquid velocity is enough high, the differential pressure monotonously increases with increasing the gas velocity. These non-monotonous characteristics make impossible the estimation of gas velocity from the measurement of mean differential pressure even when the liquid velocity is known. To investigate the possibility to determine the gas velocity from the oscillation behavior of differential pressure, the oscillation characteristics were investigated in the following chapter.

POWER SPECTRUM OF DIFERENTIAL PRESSURE

Figure 8 shows power spectrums of oscillating differential pressure in the tube of 10 mm obtained by FFT method. The spectrums at j_G= 0.12 and 0.5 m/s were multiplied by 20 for the comparison in the same figure. When the gas velocity is low, the relatively large spectrum peaks exist at the low frequency range. However when the gas velocity is increased, the spectrum peaks become larger and tend to shift to the higher frequency region. It is possible to notice the gas velocity change if the oscillation behavior can be properly detected but the quantitative estimation is considered to be difficult. The skilled engineer sometimes can determine the two-phase flow behavior in tubes by detecting the noise translated and amplified through an acoustic rod.

Figure 9 shows power spectrums of oscillating differential pressure in tubes of 1 mm. The spectrums at j_G= 1.34, 6.05 and 11.7 m/s were much higher than those in 10mm tube due to the higher two-phase pressure loss. Generally the relatively large spectrum peaks exist at the low frequency range. When the gas velocity is increased, the several spectrum peaks appear at the high frequency region.

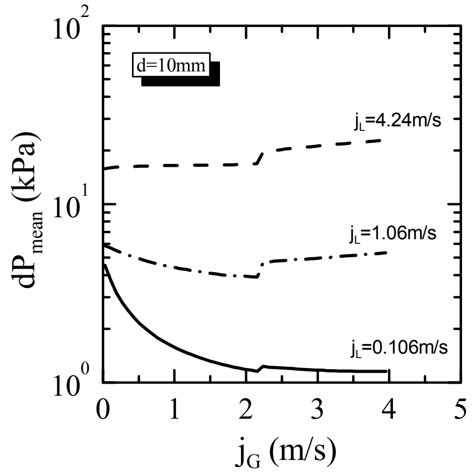

Fig. 7 Predicted mean differential pressure

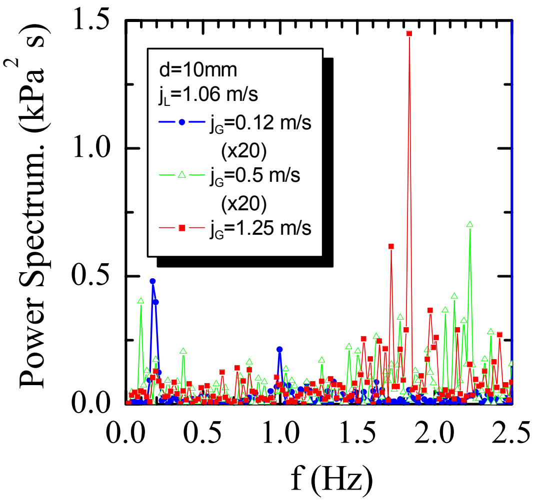

Fig. 8 Power spectrums of oscillating differential pressure in tube of 10 mm in inner diameter

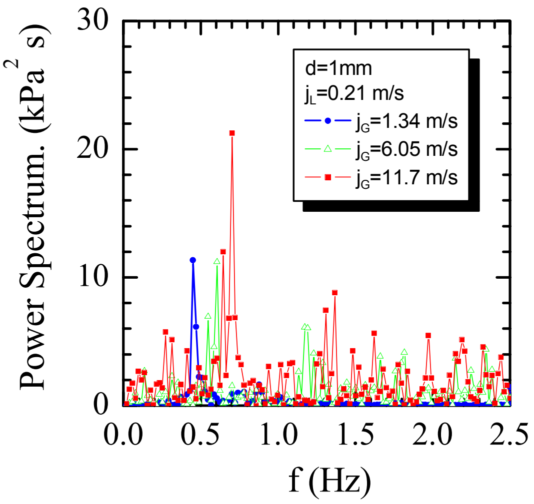

Fig. 9 Power spectrums of oscillating differential pressure in tube of 1 mm in inner diameter

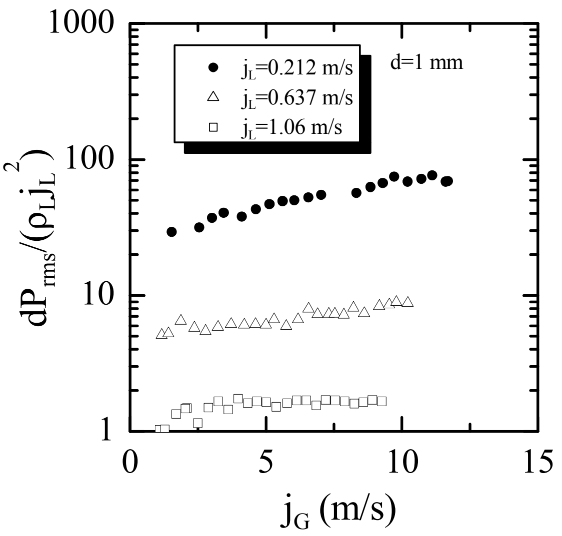

Fig. 10 Relation between RMS value and gas velocity

Though the spectrum behavior is different from that in 10 mm tube, it is also possible to notice the gas velocity change if the oscillation behavior can be properly detected. Figures 8 and 9 shows the integration of spectrum with frequency increases with increasing the gas velocity at a given liquid velocity. These suggest the fluctuation energy is proportional to the amount of gas phase. The integration of spectrum with frequency can be represented by the root mean square (RMS) value of oscillation.

RMS VALUE OF DIFFERENTIAL PRESSURE

As a first attempt to determine the flow behavior from the oscillating differential pressure, the root mean square (RMS) values of oscillation were measured. Shown in Fig.10 are non-dimensional RMS values of differential pressure measured in 1mm tube. Generally the RMS value gradually increases with increasing the gas velocity at a given liquid velocity as also indicated in the power spectrums. This suggests that the gas flow promotes the liquid flow oscillation and wall shear fluctuation. Furthermore, in most cases, the RMS value is significantly suppressed when the liquid velocity becomes enough high as shown in Fig.10. It is considered that the effect of gas phase becomes smaller compared to the higher liquid flow energy.

The oscillation of differential pressure can be attributed to the liquid flow fluctuation affected with the gas phase. It is considered that the fluctuation behavior strongly affected with the non-dimensional tube sizes defined as,

$$d^* = \frac{d}{\sqrt{\dfrac{\sigma}{g(\rho_L - \rho_G)}}} \tag{13}$$

Considering the oscillation of differential pressure is significantly affected with the liquid wall shear and non-dimensional tube size, the following non-dimensional RMS value was proposed.

$$\frac{dp_{rms}}{c_L \rho_L j_L^2 d^*} \tag{14}$$

where c_L is loss coefficient of liquid, ρ_L is liquid density, j_L is superficial liquid velocity, d^* is non-dimensional tube diameter.

Shown in Fig.11 is relation of non-dimensional RMS value and Lockhart-Martinelli parameter X. The non-dimensional RMS value obtained in the vertical tubes can be well correlated with the following correlation.

$$\frac{dp_{rms}}{c_L \rho_L j_L^2 d^*} = \frac{5000}{X^2} \tag{15}$$

By using the Eq.(15), it is possible to estimate the superficial gas velocity j_G or quality x_q from the measured dp_{rms} and the liquid superficial velocity j_L. Shown in Fig.12 is the calculation procedure to obtain the quality x_q. When dp_{rms} and j_L are given, the Lockhart-Martinelli multiplier X can be obtained with Eq.(15). By using X, the superficial gas velocity j_G or quality x_q can be calculated.

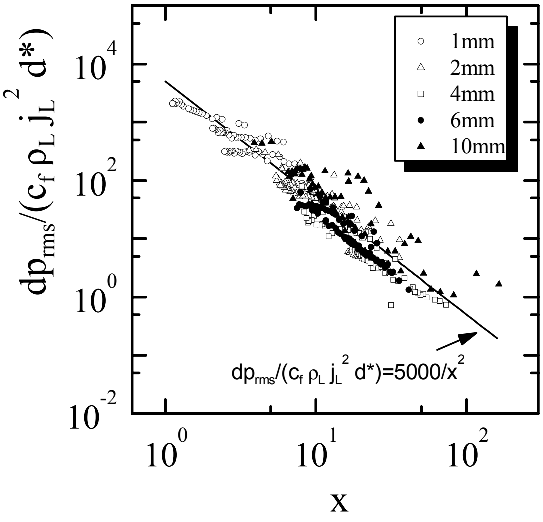

Fig. 11 Measured non-dimensional RMS value

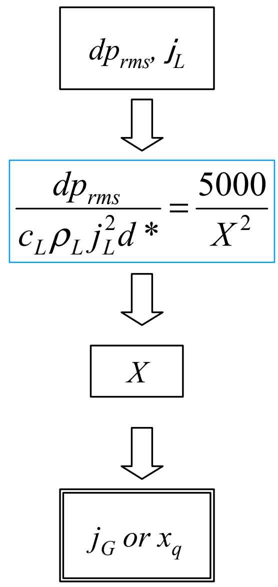

Fig. 12 Calculation procedure for quality

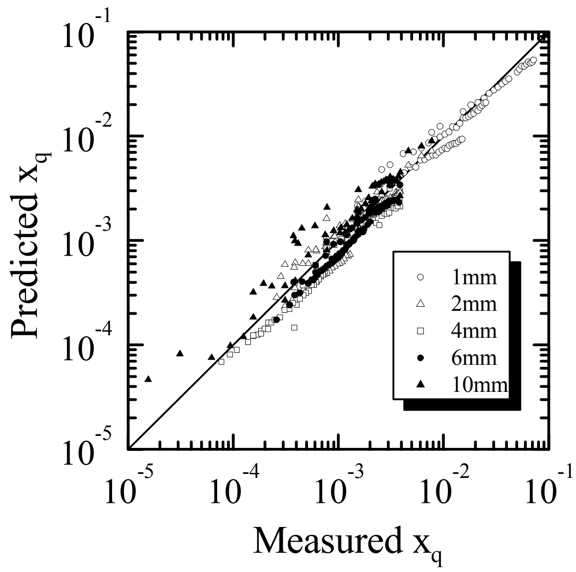

Fig. 13 Measured and predicted quality

Figure 13 shows the comparison of the estimated qualities and the measurements. It was demonstrated that the two-phase quality could be estimated with the proposed correlation for RMS values when the liquid flow rate and RMS value were measured. Generally the time-averaged value of *dp* was considered to be an important parameter and measured in industrial components such as boilers and heat exchangers. The present study showed that the root mean square value of *dp* was also an important and useful parameter to estimate the characteristics of two-phase flow.

CONCLUSION

To understand the oscillation behavior and possibility to estimate the flow behavior, the air-water two-phase flow experiments were conducted with small vertical tubes of 1 to 10mm in inner diameter. The differential pressure was measured at the long observation span more than fifty times of diameter to avoid the static pressure oscillation due the fluctuation of void fraction. The time-averaged value of *dp* was well predicted with the conventional correlations for pressure loss and void fraction. The FFT analysis on the oscillatory *dp* showed the spectrum peak shifts due to the change of flow. The root mean square (RMS) value of differential pressure was well correlated with Lockhart-Martinelli parameter. It was also demonstrated that the two-phase quality could be estimated with the proposed correlation for RMS values when the liquid flow rate and RMS value were measured.

NOMENCLATURE

c: frictional pressure loss coefficient
d: inner diameter of tube
g: acceleration due to gravity
h: length of tube
j: superficial velocity
dp: pressure difference
Re: Reynolds number
X: Lockhart-Martinelli parameter
x_q: quality
α: void fraction
Φ: two-phase multiplier
ρ: density
σ: surface tension

subscript
G: air, L: liquid, 0: earth gravity condition

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