MEASUREMENT OF THE SINGLE AND TWO PHASE FLOW USING A NEWLY DEVELOPED AVERAGE BIDIRECTIONAL FLOW TUBE

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A new instrument, an average BDFT (Birectional Flow Tube), was proposed to measure the flow rate in single and two phase flows. Its working principle is similar to that of the Pitot tube, wherein the dynamic pressure is measured. In an average BDFT, the pressure measured at the front of the flow tube is equal to the total pressure, while that measured at the rear tube is slightly less than the static pressure of the flow field due to the suction effect downstream. The proposed instrument was tested in air/water vertical and horizontal test sections with an inner diameter of 0.08m. The tests were performed primarily in single phase water and air flow conditions to obtain the amplification factor(k) of the flow tube in the vertical and horizontal test sections. Tests were also performed in air/water vertical two phase flow conditions in which the flow regimes were bubbly, slug, and churn turbulent flows. In order to calculate the phasic mass flow rates from the measured differential pressure, the Chexal drift-flux correlation and a momentum exchange factor between the two phases were introduced. The test results show that the proposed instrument with a combination of the measured void fraction, Chexal drift-flux correlation, and Bosio & Malnes' momentum exchange model could predict the phasic mass flow rates within a 15% error. A new momentum exchange model was also proposed from the present data and its implementation provides a 5% improvement to the measured mass flow rate when compared to that with the Bosio & Malnes' model.

KEYWORDS : Bidirectional Flow Tube, Pitot Tube, Momentum Exchange Factor, Two Phase Flow, Mass Flow Rate

1. INTRODUCTION

Measurement of single and two phase flow rates is essential in a flow system such as that in the chemical, oil, and nuclear industries. Recently, measurement of the flow rate in a single fluid flow has been made easily thanks to the many kinds of available instrument. However, measurement of the two phase flow rate remains difficult and somewhat complex. Many previous investigators have attempted to measure this flow rate by employing the instrument used for measurement of the single phase mass flow rate. Some examples include single or combination of pressure drop devices, a turbine meter, a drag body, and the Pitot tube together with the measured void fraction. These kinds of instrument have frequently been applied to integral or separate effect test facilities simulating a nuclear power plant system.

However, single pressure drop devices such as a venturi or an orifice meter may cause a severe blockage in the horizontal pipe of the integral effect test facility and excessive permanent pressure loss even though the instruments are mechanically strong. A turbine meter requires a special ball bearing made by a sapphire to prevent damage from thermal shock. Meanwhile, a drag body requires a sophisticated calibration procedure to guarantee an acceptable measurement uncertainty whereas a Pitot tube can not be used in a depressurization system without a cooling system for the pressure impulse tubes that are inserted in the pipe. Thus, each flow meter has its own characteristics, applicable range, and advantages and weakness.

In the present paper, the authors propose a new type of instrument, an average BDFT (Bidirectional Flow Tube), for the measurement of single and two phase mass flow rates in the primary pipes of an integral effect test facility ATLAS (Advanced Thermal-hydraulic Test Loop for Accident Simulation). This test facility is currently being constructed at KAERI[1]. The instrument was developed on the basis of a local bidirectional flow tube (BDFT)

The local bidirectional flow tube was first introduced by Heskestad et al.[2] for measurement of the flame velocity

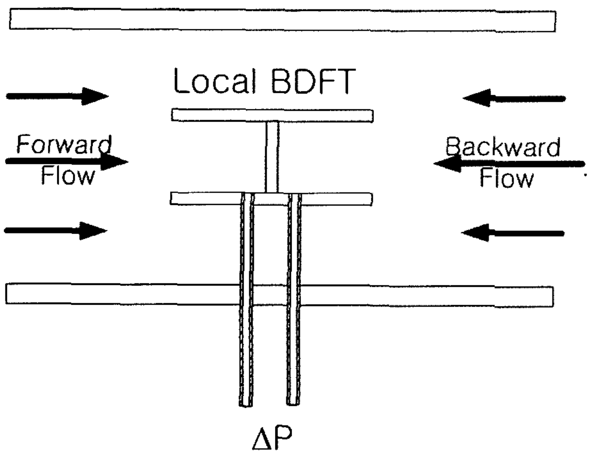


Fig. 1. Schematic Diagram of the Local Bidirectional Flow Tube

in a fire system. Fig. 1 shows a schematic diagram of the local bidirectional flow tube. Mccaffery et al.[3] applied it to an air flowing system. They found that the flow tube during calibration was independent of the flow tube size in a range from 12.7mm to 25.4mm in diameter. They measured the bidirectional flow with slight sensitivity to the fluid attack angle, that is, about ±50°, to a BDFT. Liu et al.[4] attempted to develop a miniature local bidirectional flow tube with a diameter ranging from 4.7mm to 8.8mm for application to the measurement of a low velocity air flow. They also found that the calibration factor, which relates the flow velocity and the pressure difference across the BDFT, was almost independent of the Reynolds numbers. Recently, Kang et al.[5] estimated the applicability of the local bidirectional flow tube in a single phase water and air flow system using the FLUENT 5.4 code. They showed that the calibration curve of the flow tube could be fitted to the Re number of a flow tube regardless of the changes of the fluids, the fluid temperature, and the system pressure. Summarizing the literature, the local bidirectional flow tube has good applicability for a single phase low flow condition. Furthermore, it can be used to measure a bidirectional flow, and it is relatively insensitive to the fluid attack angle on it.

In the present paper, an average BDFT expected to have similar characteristics as the local BDFT is proposed for the measurement of average single and two phase flow rate in an air/water system[6]. Fig. 2 illustrates the proposed conceptual design of the average BDFT, which is installed in a flowing pipe. The width, the height, and the depth of the probe are 6mm x 80mm x 20mm, respectively. This instrument does not require any additional special cooling system, in contrast to the pressure impulse line of the Pitot tube, which is required in the depressurization condition.

The proposed average bidirectional flow tube was tested in air/water vertical and horizontal test sections having an inner diameter of 0.08m. The tests were performed primarily in single phase water and air flow conditions to obtain the amplification factor, *k*, of the flow tube in the vertical and horizontal pipes. Tests were also performed in an air/water vertical two phase flow condition and bubbly, slug, and churn turbulent flows were covered. In order to calculate the phasic or total mass flow rate from the measured differential pressure, the Chexal drift-flux correlation and the

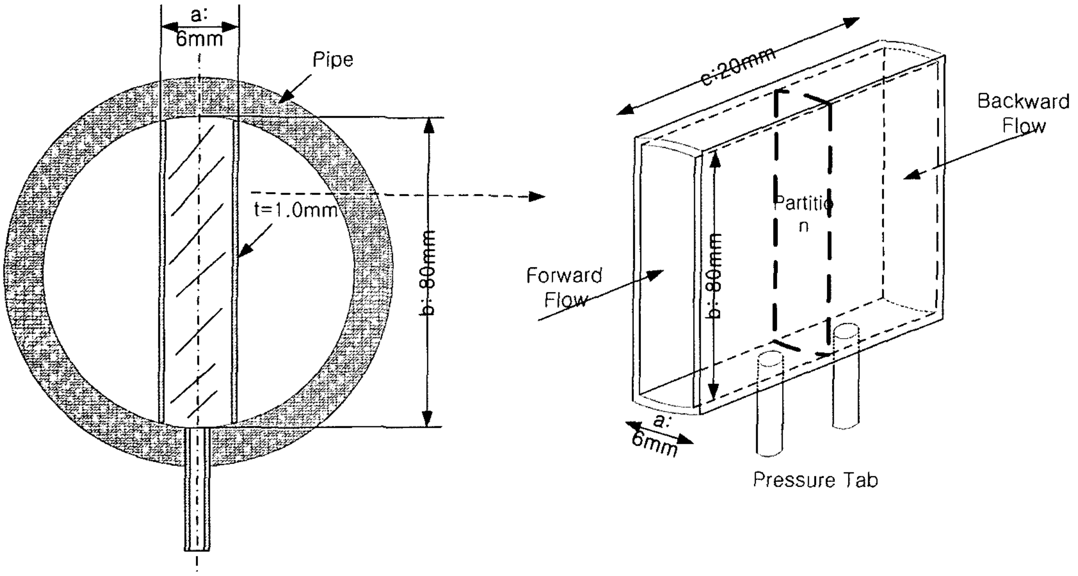


Fig. 2. Design of the Average Bidirectional Flow Tube

momentum exchange factor between the two phases were used. For improvement of the mass flow calculation, a new model for the phasic momentum exchange factor is proposed.

2. WORKING PRINCIPLE OF THE AVERAGE BIDIRECTIONAL FLOW TUBE

While the working principle of the bidirectional flow tube is similar to that of the Pitot tube, there are critical differences. The pressure measured at the front of the flow tube is equal to the total pressure, while that measured at the rear tube, called the base pressure, is slightly less than the static pressure of the flow field. This lower base pressure is due to a suction effect induced by the flowing fluid downstream[4]. Thus, the differential pressure measured by the flow tube is amplified compared to the dynamic pressure of the fluid, and its magnitude is changed by the flow velocity. The square root of the ratio of the differential pressure to the dynamic pressure is defined as the amplification factor, k, as follows:

$$k = \frac{\sqrt{2\Delta p / \rho}}{V} \tag{1}$$

As shown in Equation (1), if the amplification factor k is known, the flow velocity can be inversely obtained by measuring the differential pressure across the flow tube. Thus, k can be regarded as the calibration constant. In order to obtain the amplification factor k, single phase tests should be preformed in air or water flow conditions. The calibration constant k obtained from the tests is used in the measurement of both the single and two phase mass flow rates.

3. EXPERIMENTAL FACILITY

The tests were performed in vertical and horizontal test loops. The former is for measurement of single air and water flows in the low flow condition and the latter is for a high convective air flow condition. Although a two phase flow is possible in the horizontal test loop, the two phase flow test is carried out only in the vertical test section, because the flow regime of the present work is limited to a dispersed two phase flow, which is easily made in the vertical test section.

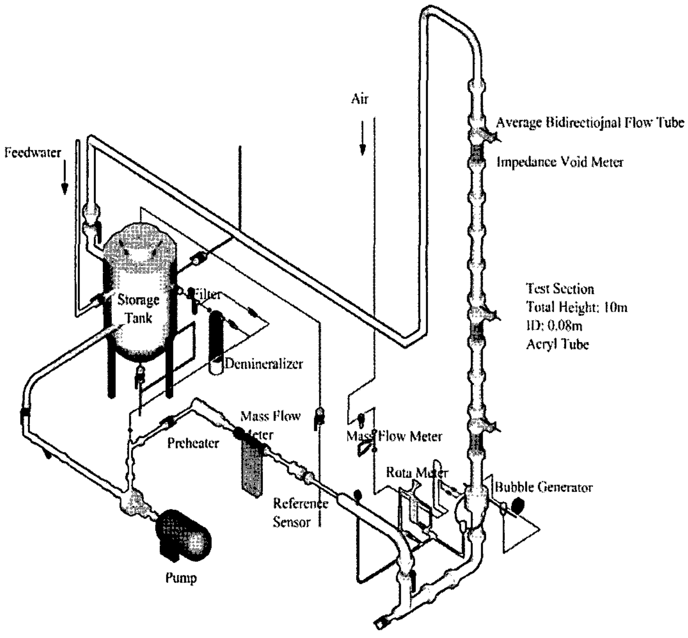
3.1 Vertical Test Loop

The vertical air/water loop consists of a test section, a bubble generator, a water supply system, an air supply system, a pre-heater, and a data acquisition system. Fig. 3(a) shows a bird's eye view of the test section. The test section is composed of a transparent acryl pipe having a diameter of 0.08m and a height of 10m. The bubble generator, which can control the injected bubble size, is equipped at the entrance of the test section. The circulating two phase mixture is separated in the storage tank, and the air is subsequently vented to the atmosphere. The system's pressure is controlled by the air ventilating flow rate. The pre-heater and cooling systems for the circulating water are installed at the entrance pipe and storage tank, respectively, to minimize change of the temperature and the conductivity of the working fluid.

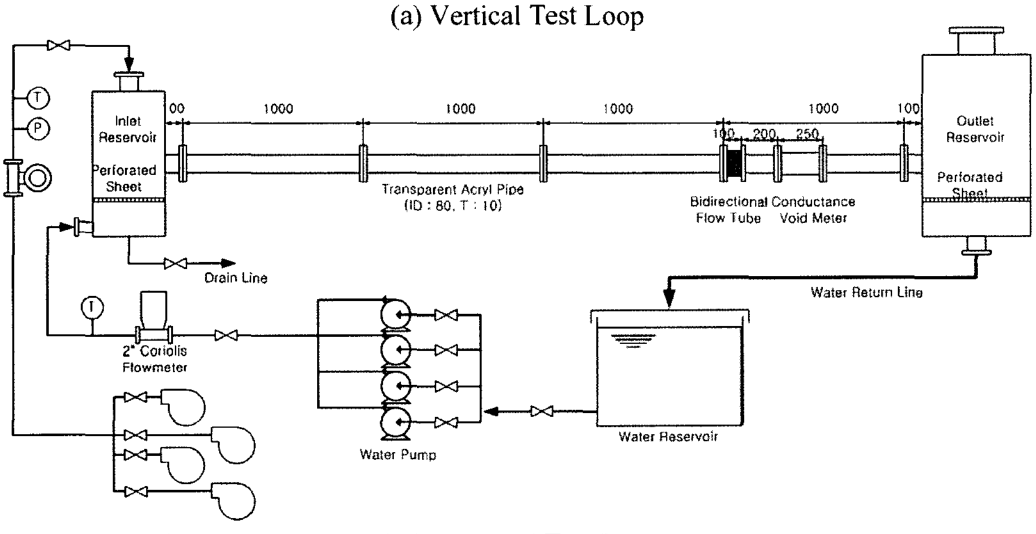
In the test facility, several instruments are equipped for precise measurement of the single and two phase flow parameters. IVMs (Impedance Void Meters) are installed at L/D =10, 40, and 100 from the entrance of the test section. A pair of electrodes to consider the water conductivity change for the IVM is installed at the pipe inlet, and thus they can be used to obtain the conductivity of the single phase water. The uncertainty of the average void fraction measured by the IVM is estimated to be less than ±2% for a reading in the range of a void fraction greater than 2.5%. An average bidirectional flow tube is installed at 120 L/D from the entrance, and it is downstream of the highest positioned IVM. The pressure difference across the flow tube is measured by a Rosemount SMART type 3051CD differential pressure transmitter. A static pressure transmitter (Rosemount SMART type 3051C) is also installed between them. The uncertainty of the measured pressure and differential pressure transmitters is ±0.11% of the span. In the test, the span of the differential pressure transmitter is changed according to the measurement range so as to minimize the measurement error. Two Rosemount Coriolis mass flow meters are installed at the inlet of the test section to measure the water and air injection flow rates. The measurement errors of the water and air flow rate in the present test are estimated as ±0.6% and ±0.4% of the reading, respectively. A RTD with a PT-100Ω is installed at the inlet of the test section to measure the fluid temperature. The estimated uncertainty of the temperature measurement is ±0.5K.

3.2 Horizontal Test Loop

The horizontal air/water loop consists of a test section, an inlet reservoir, an outlet reservoir, a water supply system, an air supply system, a water storage tank, and a data acquisition system. Fig. 3(b) shows the schematics of the test loop. The test section is composed of a transparent acryl pipe whose diameter is also 0.08m; its length is 4.2m. The inlet reservoir is located at an entrance of the test section for inflow of a single or air/water two phase flow. The outlet reservoir is installed mainly for phase separation of the two phase mixture flowing out from the test section. The separated air is vented to the atmosphere and the water is drained into the water storage tank. The system pressure is not controlled but determined naturally. The water supply system consists of four parallel installed pumps and a flow control valve. The maximum water flow rate is 12 kg/s. The air flow system consists of four Roots type blowers



(a) Vertical Test Loop



(b) Horizontal Test Loop

Fig. 3. Schematics of the Vertical and Horizontal Test Loops

and the maximum air flow rate is 1.6 kg/s at atmospheric pressure. In order to reduce pressure and flow oscillation, a damper tank is installed at each exit of the blowers.

In the test facility, several instruments are installed for measurement of the single phase flow parameters. An average bidirectional flow tube is installed at L/D=37 from the entrance. The pressure difference across the flow tube is measured by two Rosemount SMART type 3051CD differential pressure transmitters. A static pressure transmitter (Rosemount SMART type 3051C) is also installed between them. The uncertainty of the measured pressure and differential pressure transmitters are the same as those of the vertical test loop. A Coriolis mass flow meter (Rosemount CMF 200) is installed at the inlet of the test section to measure the water flow rate. The measurement errors of the water and air flow rate in the present test are estimated as ±0.6%. The air flow rate is measured by a combination of a vortex meter, a pressure transmitter, and a TC (Thermo-couple), which are installed at the inlet pipe of the test section. The uncertainty of the measured air flow rate is estimated as ±1.1% of the reading. A TC is also installed to measure the water temperature at the inlet pipe. The estimated uncertainty of the measured temperature is ±2.2K.

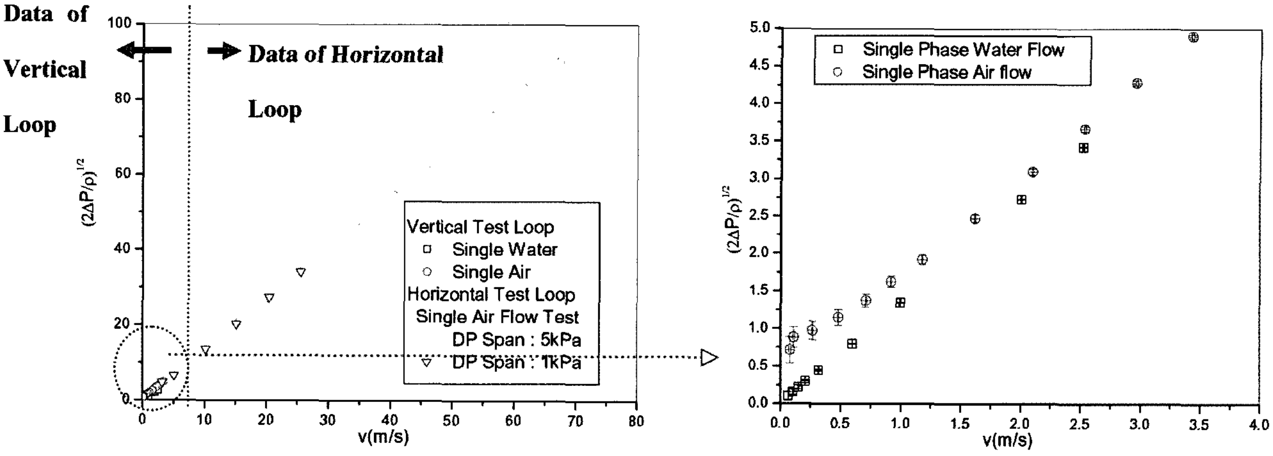


Fig. 4. $\sqrt{2\Delta p/\rho}$ Against the Average Velocity

4. EXPERIMENTAL RESULTS

The average bidirectional flow tube was primarily tested in single phase water and air flow conditions to obtain the amplification factor, k, of the flow tube. The test was also performed in a vertical air/water two phase flow condition and the covered flow regimes were bubbly, slug, and churn turbulent flows.

4.1 Single Phase Flow Test

In order to obtain the amplification factor k, a calibration test was performed in the vertical and horizontal water and air single phase flow conditions. In the vertical test loop, the velocity ranged from 0.06 m/s to 2.5 m/s and from 0.07 m/s to 3.4 m/s for the water and air flows, respectively. A convective air flow higher than 3m/s was tested in the horizontal test loop. The velocity range in the horizontal test loop was from 3m/sec to 70 m/s. A plot of $\sqrt{2\Delta p/\rho}$ against V is shown in Fig. 4. It illustrates the linear relationship between the two parameters in the whole range of the velocity. The plots show that a constant k value can be assumed in the high flow condition. However, in the low flow condition, i.e., less than 3.5m/s, the k values of air and water are different for a given velocity. Furthermore, the inclinations of each fluid are also slightly different. This is natural because the Re number of the average BDFT is small in this flow condition. For general and extensive applicability, the k factor should be expressed to a single function reflecting the flow velocity and properties of fluids regardless of fluid type. Fig. 5 shows a plot of the k value against the Reynolds number of a flow tube. Here, the Reynolds number

$$\mathrm{Re}_{BDFT} = \frac{\rho D_h V}{\mu} \qquad (2)$$

is defined for the flow tube as follows,

The value is fitted by the Re of the flow tube in Fig. 5. The figure indicates that the k value in the viscous regime increases drastically as the flow velocity decreases and it could be fitted by a single function of the Reynolds number regardless of the fluid type. However, the k value can be assumed to be constant in a turbulent region where the Reynolds number is larger than 2,000. In the present study, the k value was obtained by a piecewise least square fitting method using a polynomial equation for its application both to the single and two phase flow conditions.

4.2 Air/Water Two Phase Flow Test

4.2.1 Calculation Model of the Two Phase Mass Flow Rate

The average bidirectional flow tube was applied to a vertical air/water two phase flow system. In the test, the void fraction was changed from 2.8% to 42%, and the

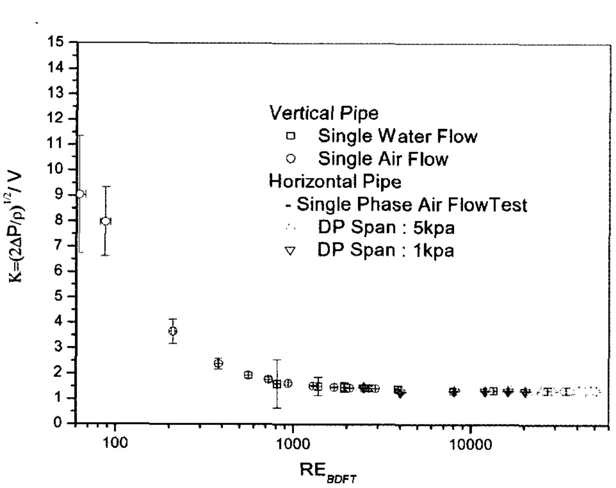


Fig. 5. Amplification Factor k Against the Reynolds Number

maximum phasic superficial velocities were 2.5m/sec and 1.5m/sec for the water and air flows, respectively. The covered flow regimes were found to be bubbly, slug, and churn turbulent flows.

In order to calculate the two phase mass flow rate from the measured differential pressure of the flow tube, physical modeling is required. It is reasonable to develop the model on the basis of the calculation model of the Pitot tube, because the measuring principle of the flow tube is similar to that of the Pitot tube. The generalized pressure difference across the flow tube in the dispersed two phase flow is expressed as follows,

$$k^2 = \frac{2\Delta p}{G^2 / \rho_e} \tag{3}$$

where the mass flux and apparent density are

$$G = \rho_e V_{tp} = (1-\alpha)\rho_f V_f + \alpha\rho_g V_g \tag{4}$$

$$\frac{1}{\rho_e} = \frac{x^2}{\alpha\rho_g} + \frac{(1-x)^2}{(1-\alpha)\rho_f} \tag{5}$$

The average velocity of the two phase flow is obtained from Equation (4) as follows,

$$V_{tp} = \frac{(1-\alpha)\rho_f V_f + \alpha\rho_g V_g}{\rho_e} \tag{6}$$

Here, it is assumed the amplification factor k in Equation (3) is replaced by k_f and k_g for the water and gas flows, respectively. A momentum exchange factor J is introduced to consider the momentum exchange between the water and gas phases on the front of the flow tube. Finally, Equation (3) becomes

$$\Delta p = \frac{k^2 \rho_e V_{tp}{}^2}{2} = \frac{1}{2\rho_e}\left[k_f \sqrt{J}(1-\alpha)\rho_f V_f + k_g \alpha\rho_g V_g\right]^2 \tag{7}$$

The available momentum exchange factor, J, of the Pitot tube is summarized in Table 1 [7]. In the table, the applicable range is also summarized. From Equation (7), the relation of the two phasic velocities V_g and V_f can be obtained if the average void fraction, the pressure difference across the flow tube, and phasic fluid densities are known. In the present test, the average void fraction is obtained by the IVM, and each phasic density is calculated from the measured static pressure and fluid temperature. Here, the Chexal-Lellouche [8] drift-flux correlation is introduced to obtain each phasic velocity from the velocity relation. It is chosen from among the many available drift-flux correlations because it eliminates the need to know the flow regime. It is validated for the full range of pressures, flows, and void fractions for the co-current or counter current vertical and horizontal conditions against an extensive experimental data base. From the correlation, we can obtain the drift-flux parameters C_o and V_{gj}, which provide information about the distributions of the gas phase and the velocity difference in the pipe, and thus the phasic superficial velocities can be calculated using them as follows;

$$j_f = (1-\alpha)V_f = \frac{(1-\alpha C_o)\left[\frac{W}{A} - \frac{\alpha\rho_g V_{gj}}{1-\alpha C_o}\right]}{\rho_f\left[1-\alpha C_o\left(1-\frac{\rho_g}{\rho_f}\right)\right]} \tag{8}$$

$$j_g = \alpha V_g = \frac{\alpha(C_o j_f + V_{gj})}{1-\alpha C_o} \tag{9}$$

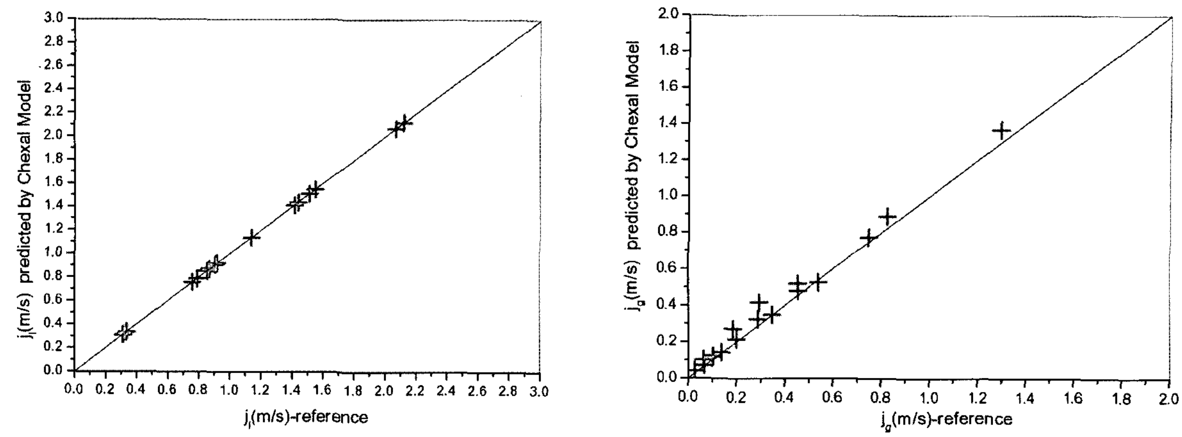
However, some iterative calculations are needed to obtain each phasic parameter, using Equations (7) to (9). In the present test, the calculations were repeated until the phasic superficial velocity reached a constant value.

4.2.2 Evaluation of the Chexal Drift-flux Model and the Calculation of the Two Phase Mass Flow Rate

The phasic mass flow rate is highly dependent on the Chexal drift-flux parameter [8], and thus it should be evaluated against the present measured data. For this purpose, the phasic superficial velocities obtained by the Chexal model are compared with those of the Coriolis meter. The comparison is shown in Fig. 6. The input parameters of the Chexal model are W, α, and the phasic densities. The

Table 1. Model of the Momentum Exchange Factor J for the Vertical Flow[7]

Authors	J	Applicable Range
Adomi(1961)	$1+\alpha$	Argon-water, annular flow
Neal & Bankoff(1965)	2.0	Mercury-nitrogen, bubbly, slug flow
Malnes(1966)	1.0	Air/water, bubbly flow
Bosio & Malnes(1968)	$(1\text{-}0.5\alpha^2)(1\text{-}\alpha)$	Air/water
Walmet & Staub(1969)	$1+\alpha/2$	Steam/Water,bubbly flow



(a) Liquid Superficial Velocity

(b) Air Superficial Velocity

Fig. 6. Comparison of the Measured and Predicted Phasic Superficial Velocity

present test was performed near the atmospheric pressure, and thus the differences of the phasic velocities resulting from the difference of the phasic densities are the largest. Fig. 6 implies that the Chexal drift-flux correlation could predict the present experimental data accurately. It also confirms the successful applicability of the Chexal drift-flux correlation to the present low pressure condition.

Fig.7 shows a comparison of the measured two phase flow parameters with reference values, which were obtained according to the choice of *J*. As in Table 1, the correlations are constant or a simple function of a void fraction. The measured mass flow rates of the flow tube are also highly dependent on the momentum exchange factor *J*. As shown in Fig.7, Adoni's model estimates well the air mass flow rate; however, the water flow rate, total mass flow rates, and flow quality are not predicted as well. Neal & Bankoff's model underestimates the phasic mass flow rates, and shows a somewhat wide scattering of the flow quality. Malnes' model overestimates the phasic mass flow rates, and then underestimates the flow quality. Walmet & Staub's model can predict the air mass flow rate fairly well; however, it overestimates the water and total mass flow rates.

Among the models, Bosio & Malnes' model shows the best prediction capability. It predicts the present data to within a 15% error, as shown in Fig. 7. The *J* values calculated from Bosio & Malnes' model are between 1.0 and 1.5 for the present calculation. However, it should be noted that the *J* value of Bosio & Malnes' model increases rapidly as the void fraction reaches unity. This indicates that the model is only applicable to the lower void fraction region with a mixed flow regime as in the present flow condition, and thus it should be noted that some experimental verification is needed before applying it to a higher void fraction region. All of the comparisons show that Bosio & Malnes' model is the best choice for the prediction of the present data.

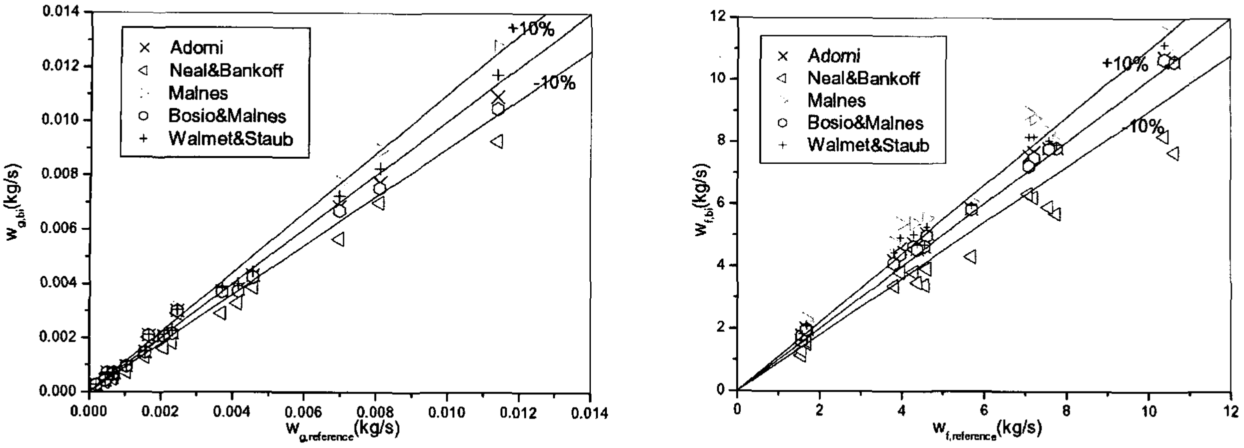
4.2.3 Proposal of a New Momentum Exchange Factor

As mentioned before, the accuracy of the air and water mass flow rates is highly dependent on the momentum exchange factor *J*. Even though Bosio & Malnes's model predicts the present data to within a 15% error, an improved model of the momentum exchange factor is desirable for a more precise prediction of the air and water mass flow rates. The velocity of the air and water flow can be obtained by using the air and water injection flow rates measured by the Coriolis flow meters at the entrance of the test section. The momentum exchange factor can then be calculated reversely by using Equation (7). Fig. 8 shows a comparison of the momentum exchange factor obtained using the present data with the conventional momentum exchange factors summarized in Table 1. In the low void fraction region below 0.4, where the present test was actually performed, the conventional momentum exchange factors induce underestimations of the current data, as shown in Fig. 8. Since the present momentum exchange factor is insensitive to flow variation and only a unique function of the void fraction, α, then it is correlated as follows;

$$J(\alpha) = 2 - \frac{1.25}{1 + e^{(\alpha - 0.22)/0.15}} \tag{10}$$

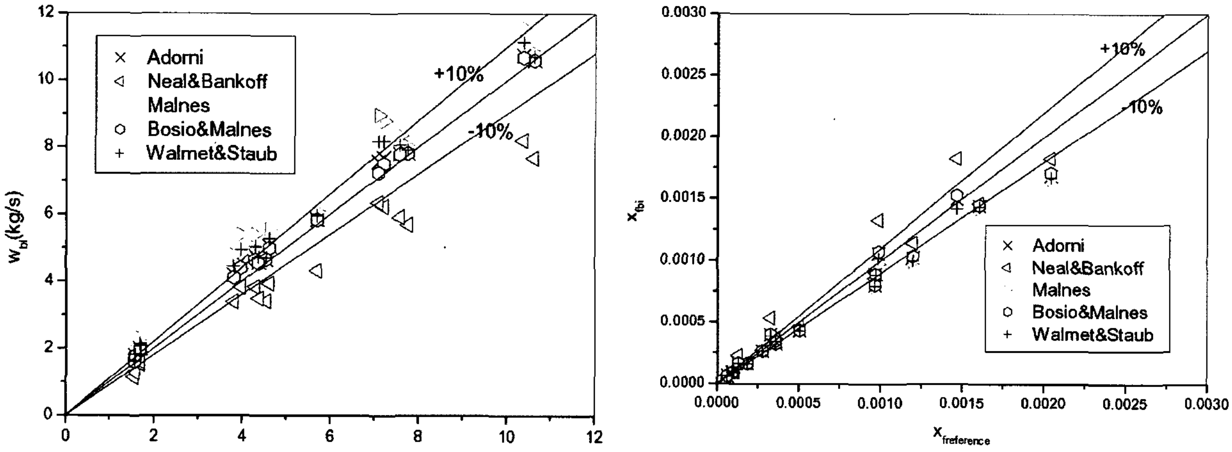
According to Fig. 8, the new correlation in Equation (10) can predict the present data of the momentum exchange factor to within a 10% error.

Fig. 9 shows a comparison of the measured two phase flow parameters with reference values using the proposed momentum exchange model. The new momentum exchange model can predict the phasic mass flow rates to within a 10% error for the present data, which indicates that it



(a) Gas Mass Flow Rate

(b) Water Mass Flow Rate



(c) Total Mass Flow Rate

(d) Flow Quality

Fig. 7. Comparison of the Measured Two Phase Flow Parameters with Reference Values According to the J

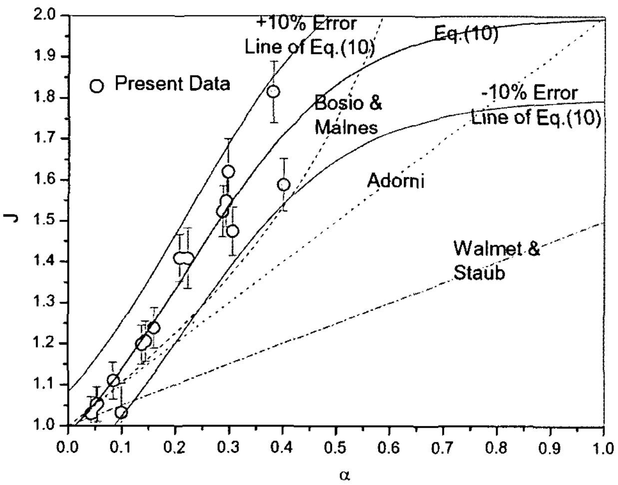
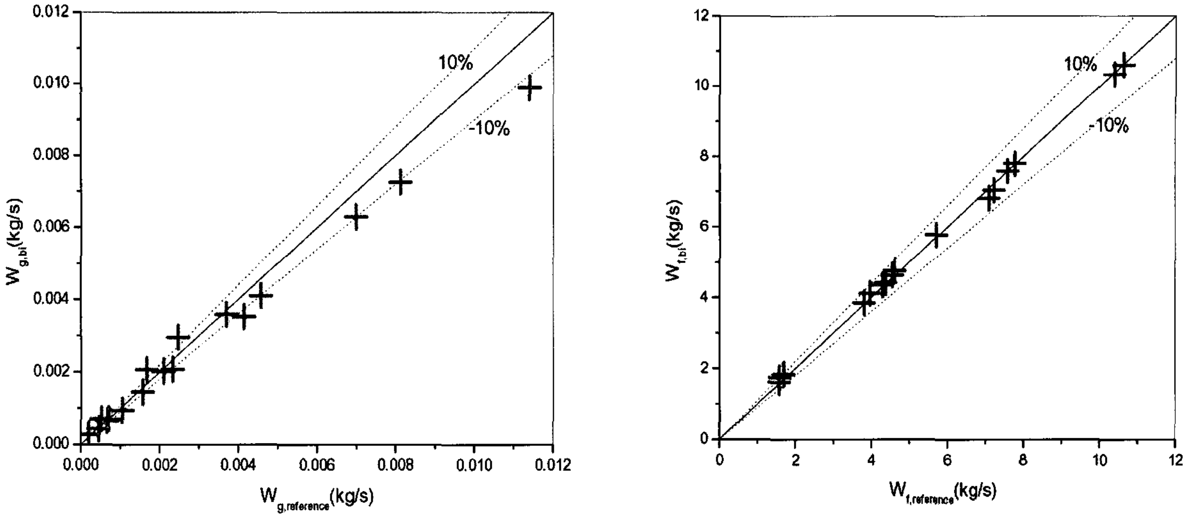


Fig. 8. Plot of the Momentum Exchange Factor

provides up to a 5% improvement of the measured mass flow rate when compared to that with Bosio & Malnes's momentum exchange model.

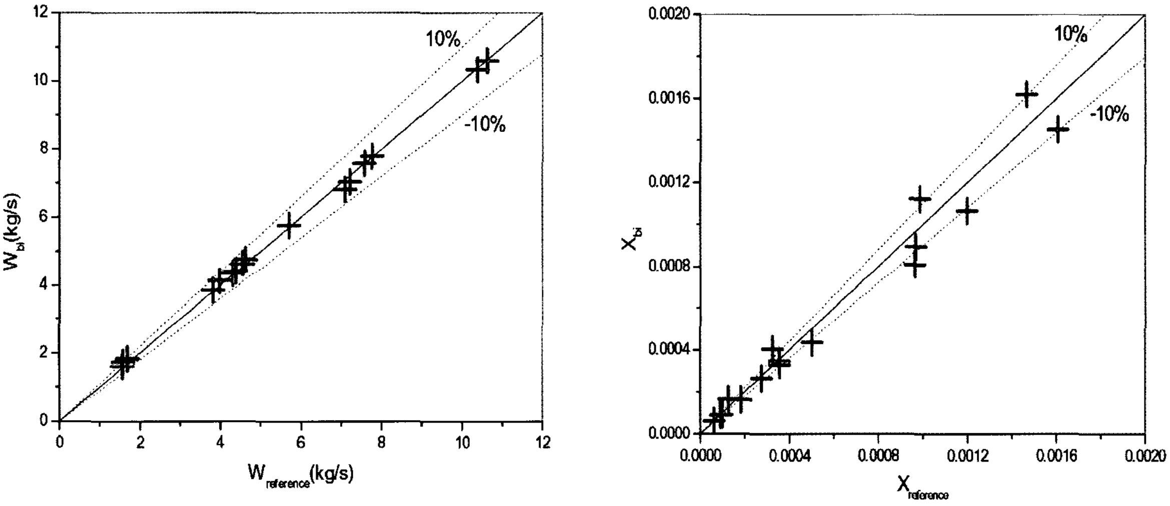
5. CONCLUSIONS

An average bidirectional flow tube was proposed for measurement of the mass flow rate in single and two phase flow conditions. It was shown that the flow tube could be applicable to the low flow condition, and that it has the capability of measuring a bidirectional flow in a flow system. In the flow tube, the base pressure of the flow tube is lower than the static pressure of the flow stream due to the suction effect of the flow downstream. In order to correlate the pressure difference and average velocity, tests for a single phase air and a water flow were performed separately in vertical and horizontal test loops. The test results show



(a) Gas Mass Flow Rate

(b) Water Mass Flow Rate



(c) Total Mass Flow Rate

(d) Flow Quality

Fig. 9. Calculated Two Phase Flow Parameters Using the Present Momentum Exchange Model

that the calibration factor *k* can be fitted by a function of the Reynolds number regardless of the fluid type, even in an extremely low Re region.

The proposed flow tube was also applied to the two phase flow condition, and a physical modeling to calculate the two phase mass flow rate from the pressure difference across the flow tube was developed. From a comparison with the experimental data, it was found that among the various conventional momentum exchange models, Bosio & Malnes' momentum exchange model was the most appropriate for the present data. In this study, for a more precise prediction of the air and water mass flow rates, a new momentum exchange model was proposed based on the present data.

The new momentum exchange model provides up to a 5% improvement of the measured mass flow rate when compared to that with Bosio & Malnes's momentum exchange model.

In further studies, the present instrument and the measurement method should be confirmed in the steam/water flow. In addition, the applicability of the average bidirectional flow tube to a stratified two phase flow in a horizontal pipe will be investigated.

Nomenclatures

A area of a flow channel (m^2)
a width of the BDFT (m)
b height of the BDFT (m)
$C_o(\equiv \frac{<\alpha_{lc} j_{lc}>}{<\alpha_{lc}><j_{lc}>})$ distribution parameter

$D_h (\equiv \frac{2ab}{a+b})$ hydraulic diameter of the BDFT (m)

J momentum exchange factor

$j (\equiv j_f + j_g)$ superficial velocity (m/s)

V velocity of fluid (m/s)

$V_{gj} (\equiv \frac{< (V_{g,lc} - j_{local}) \alpha_{lc} >}{< \alpha_{lc} >})$ drift-velocity (m/s)

W total mass flow rate (kg/s)

x flow quality

Greek letters

α average void fraction

Δp differential pressure across flow tube (Pa)

ρ density of fluid (kg/m^3)

μ viscosity of fluid (N-s/m^2)

Subscripts

f liquid phase

g gas phase

lc local value

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