XVIII IMEKO WORLD CONGRESS
Metrology for a Sustainable Development
September, 17 – 22, 2006, Rio de Janeiro, Brazil

A MULTI-LOOP SENSOR FOR THE FLOWRATE MEASUREMENT OF GAS-LIQUID TWO-PHASE FLOW

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Abstract: A multi-loop flowmeter is designed for the flowrate measurement of the gas-liquid two-phase flow. The differential pressure signals can be collected from the multi-loop sensor at different positions. The total flowrate measurement model is established according to the average differential pressure value obtained from the optimal position. The time serial of the signals is obtained by using the high speed data capture device. A non-dimensional characteristic value related to the root-mean-square of the dynamical differential pressure signals is obtained. The relationship between this value and the volume void fraction is established. The online measurement of the volumetric void fraction of gas-liquid two-phase is realized and the flowrate of the gas phase and the liquid phase are measured. The experiments showed that the results were satisfactory.

Keywords: flowrate, measurement, multi-loop flowmeter.

1. INTRODUCTION

Gas-liquid two-phase flow widely exists in the industries, such as the petroleum, chemical engineering, metallurgy, energy and environment protection. The improvement of the flowrate measurement technology for two-phase flow will bring significant benefits to the industry, particularly, to the oil and gas production [1,2]. However, the two-phase is complex and the flowrate measurement is a big challenge for the metrological engineering.

The conventional measurement method for gas-liquid two-phase flow is phase separation. This method separates the two-phase mixture into single-phase flows. Then the liquid flowrate and the gas flowrate are measured respectively, which leads to expensive facilities and logistics [2]. Measuring the two-phase mixture directly is a more convenient method that is often using single-phase flow measurement devices, such as the orifice, turbine meter and venturi meter, or employing the cross-correlation technique to analyse the signals from the sensors [3-7]. Generally, this method needs the combination of the voidage or mass quality measurement instruments including process tomography system [8], radiological devices [9], et al. Compared with the conventional separation method, the meters measuring the two-phase fluid directly has the advantage of light-weigh, compact structure, simplicity and low cost. It will improve operational logistics and safety [10].

The purpose of this paper is to design a flowmeter for the gas-liquid two-phase flow based on the loop flowmeter. A multi-loop flowmeter is developed to obtain four differential pressure values at the different positions on the loop. The models for the flowrate measurement of two-phase mixture, liquid phase and gas phase are established. Experimental results on the horizontal multiphase flow loop show that the measurement accuracy was satisfactory.

2. DESIGN OF THE MULTI-LOOP SENSOR

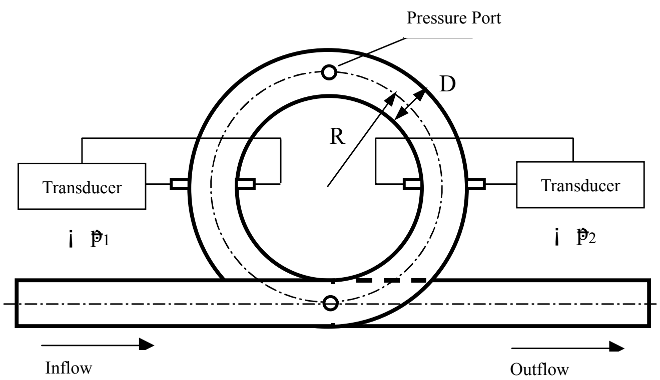

Fig. 1. Diagram of pressure ports at the horizontal diameter.

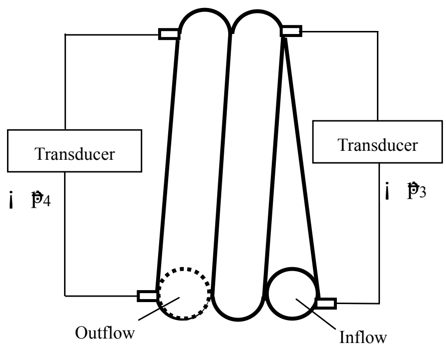

Fig. 2. Diagram of pressure ports at the vertical diameter.

The loop flowmeter with new structure is designed for the complexity of the gas-liquid two-phase (as shown in Fig. 1

and Fig. 2). The sensor has two loops, on which four groups of pressure ports are settled to achieve the differential pressure. Two groups at the horizontal diameter are set to measure the differential pressure on the wall of the inner circle and the outer circle (as shown in Fig. 1). The other two groups at the vertical diameter are set to measure the differential pressure between the top and the bottom of the loop (as shown in Fig. 2). The new loop flowmeter can provide more information for the liquid and the gas flowrate measurement of the two-phase flow.

3. MEASUREMENT PRINCIPLE

The loop flowmeter is one of the centrifugal meters. The flowrate measurement principle of the loop flowmeter is similar to that of the conventional elbow flowmeter. According to the forced swirl flow theory, forced swirl flow occurs when the fluid goes through the annuli because of the bend of the pipe. The angular acceleration of the fluid results in the centrifugal force, which brings the differential pressure between the wall of the inner circle and outer circle of the pipe. The differential pressure values are proportion to the average velocities of the fluid. So the flowrate can be measured if the geometrical structure of the loop flowmeter is determined

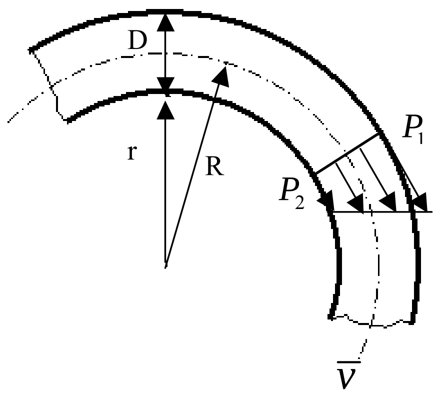

Fig. 3. Diagram of measurement principle

Fig. 3 shows the measurement principle of the loop flowmeter. According to the theory of forced swirl flow, the fluid velocity at the center of the pipe $\overline{v}$ can be given by:

$$\overline{v} = \sqrt{\frac{\Delta PR}{\rho D}} \tag{1}$$

where R denotes the radius of curvature of the annulus tube, D is diameter of the pipe, ΔP is the value of differential pressure calculated as $P_1 - P_2$ and ρ is the density of the fluid.

Then the flowrate can be calculated as

$$q_v = \sqrt{\frac{R}{2D}} \cdot \frac{\pi D^2}{4} \cdot \sqrt{2 \cdot \Delta P / \rho} \tag{2}$$

where $\sqrt{R/(2D)}$ can be regard as the flow coefficient.

In the applications, the flow coefficient $\sqrt{R/(2D)}$ should be modified because of the different distribution between the practical flow field and the theoretical flow field. The modified measurement model can be given by:

$$q_v = \alpha\sqrt{\frac{R}{2D}} \cdot \frac{\pi D^2}{4} \cdot \sqrt{2 \cdot \Delta P / \rho} \tag{3}$$

where α is the correction factor, which is generally determined by the position of the pressure port and can be obtained by experiments [11].

For the gas-liquid two-phase flow, the flowrate measurement is a multi-parameters measurement problem because it is related to the mass quality (or the voidage) and the density of the mixture except for the differential pressure values. In this work, a loop flowmeter with new structure is developed. The measurement models are established by experiments.

4. EXPERIMENTS AND RESULTS

4.1. Experimental Condition

The tests of flowrate measurement were carried out in a horizontal multiphase flow loop at China Jiliang University. The diameter of the pipeline was 50mm. The diameter of the pipeline was 50mm. The radius of the loop was 250mm. The ratio of the elbow was $R/D = 5$. The measurement range of the sensor is 50 m^3/h. The experimental materials were water and air. During the experiments, the water flowrate was in the range of 4m^3/h to 45 m^3/h under the pressure of 0.2 Mpa and the air flowrate was in the range of 0.21 m^3/h to 2.2 m^3/h under the pressure of 0.7Mpa. A high speed sampling card was used to collect the time serials of the differential pressure values. The sampling frequency was 1kHz. 8000 values were collected for each measurement point.

4.2. Measurement of Volume Void Fraction

The process of the gas-liquid two-phase flow is a complex phenomena. The flowing of the fluid is always at the fluctuation state, which is one of the intrinsic characteristics of the two-phase flow. The feather of the differential pressure signals is related to the parameters of the two-phase such as flow patterns and the void fraction. The characteristic values extracted from the time serial signals of the differential pressure are applied in this work to measure the volume void fraction through the statistical method. The root-mean-square of the signals is defined as:

$$\delta = [\frac{1}{n}\sum_{i=1}^{n}(\Delta P_i)^2 - \Delta P^2]^{1/2} \tag{4}$$

where n is the sampling number, ΔP_i is the instantaneous values of the differential pressure, and ΔP is the average value of the serial.

A non-dimensional variable is selected as the characteristic value of the fluctuated signals, which is given by:

$$I = \frac{\delta}{\Delta P} \tag{5}$$

Fig. 4. shows the relationship between the volume void fraction β and $1/I$.

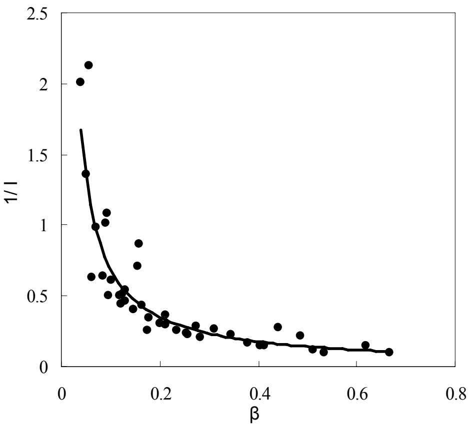

Fig. 4. Relationship between β and $1/I$

Because of the variation of the gas density during the experiments, the variable I is calibrated according to the gas density. The calibration model can be expressed as:

$$I' = I(\rho_g / \rho_l)^{\xi} \tag{6}$$

where ρ_l , ρ_g is the density of the liquid phase and gas phase respectively, and ξ is the coefficient adjustable to the experimental condition.

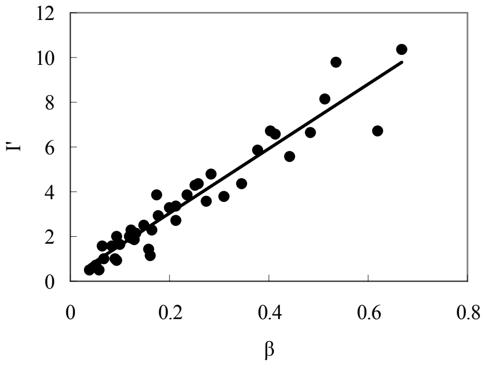

Fig. 5. Relationship between β and I'

The relationship between I' and β can be determined after ξ is selected. Fig. 5 shows the relationship of I' - β when $\xi = -1$, which is satisfied the linear relationship and can be given by:

$$I' = K\beta + B \tag{7}$$

where $K = 14.465, B = 0.1182$, that are calculated by least square regression.

4.3 Measurement of Flowrate

The measured differential pressure values mainly depend on the fluid velocity and the position of the pressure ports. The total flowrate measurement models can be established by using the differential pressure values. For the new mulit-loop sensor, the differential pressure signals, as shown in Fig. 1 and Fig. 2, can be collected from four places. These values have the different characteristics when they are used to measure the total flowrate of the two-phase flow. In order to obtain the optimal model, the relationship between the volume flowrate q_v and the average value of the differential pressure signals in the four different positions is analyzed. The comparison of the experimental results is shown in Fig.6.

To evaluate the performance of the measurement models, the root-mean-square (RMS) fractional deviation σ is calculated as:

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{q_{i(\text{model})} - q_{i(actual)}}{q_{i(actual)}}\right)^2} \tag{8}$$

where $i(i = 1, 2, 3, 4)$ denotes the sampling position, n is the number of tests, $q_{i(actual)}$ is the actual flowrate and $q_{i(\text{model})}$ is calculated flowrate.

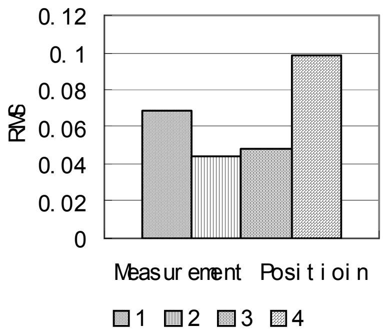

Fig. 6. RMS of measurement models

The comparison results in Fig. 6. indicate that better results can be given by $\sqrt{\Delta P_2}$ so that it is selected to establish the measurement model for total flowrate. The measurement model is expressed as equation (9) and illustrated in Fig. 7.

$$q_v = k\sqrt{\Delta P_2} + b \tag{9}$$

where $k = 0.6033, b = 6.8949$, that are calculated through least square regression.

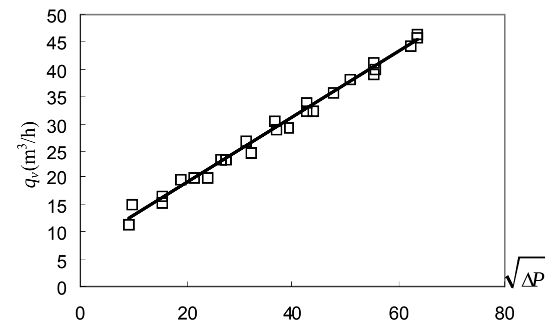

Fig. 7. The relationship between q_v and $\sqrt{\Delta P_2}$

Then the flowrate of the liquid and the gas can be obtained respectively by:

$$q_l = q_v(1-\beta) \tag{10}$$

$$q_g = q_v \beta \tag{11}$$

where β is the volume void fraction.

The tests results of the measurement for the gas flowrate and the liquid flowrate were illustrated in Fig. 8 and Fig. 9. The results show that the fiducial errors of water flowrate can be limited in 6% and that of the gas flowrate can be limited in 10% in the experimental range.

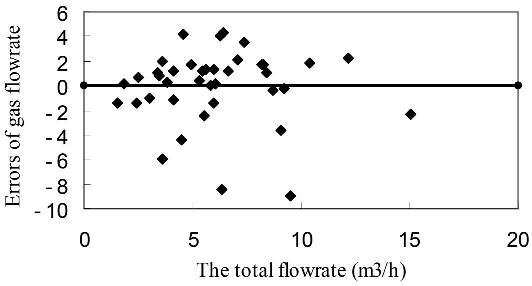

Fig. 8. The fiducial errors of gas flowrate

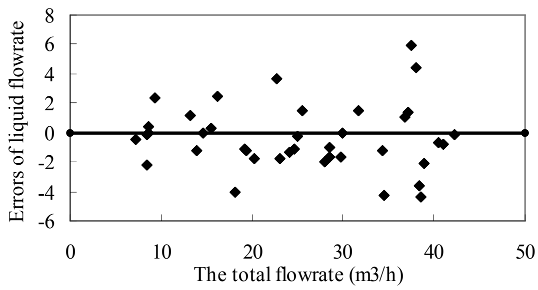

Fig. 9. The fiducial errors of liquid flowrate

3. CONCLUSION

A new sensor for the flowrate measurement of gas-liquid two-phase flow is proposed based on the conventional loop flowmeter. This multi-loop flowmeter has two loops. The differential pressure values are obtained from four different places located at the horizontal diameter and the vertical diameter of the multi-loop sensor. The studies indicate that the total volume flowrate has good linear relationship with the average of the differential pressure values obtained from the position 2. A non-dimensional characteristic value related to the root-mean-square of the dynamical differential pressure signals is extracted from the time serials of the signals. The relationship between this value and the volume void fraction is achieved. The measurement of the liquid flowrate and the gas flowrate is realized associated with the volume fraction.

ACKNOWLEDGMENTS

This work is supported by Science and Technique Department of Zhejiang Province Grant #2004C31104 and China Jiliang University Grant #XZ0514.

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