Journal of Zhejiang University SCIENCE
ISSN 1009-3095
http://www.zju.edu.cn/jzus
E-mail: jzus@zju.edu.cn

Investigation of oil-air two-phase mass flow rate measurement using Venturi and void fraction sensor*

ZHANG Hong-jian (张宏建)†, YUE Wei-ting (岳伟挺), HUANG Zhi-yao (黄志尧)

(*Institute of Automation Instrumentation, Department of Control Science and Engineering, Zhejiang University, Hangzhou 310027, China*)

†E-mail: hjzhang@iipc.zju.edu.cn

Received Feb. 10, 2004; revision accepted June 19, 2004

Abstract: Oil-air two-phase flow measurement was investigated with a Venturi and void fraction meters in this work. This paper proposes a new flow rate measurement correlation in which the effect of the velocity ratio between gas and liquid was considered. With the pressure drop across the Venturi and the void fraction that was measured by electrical capacitance tomography apparatus, both mixture flow rate and oil flow rate could be obtained by the correlation. Experiments included bubble-, slug-, wave and annular flow with the void fraction ranging from 15% to 83%, the oil flow rate ranging from 0.97 kg/s to 1.78 kg/s, the gas flow rate ranging up to 0.018 kg/s and quality ranging nearly up to 2.0%. The root-mean-square errors of mixture mass flow rate and that of oil mass flow rate were less than 5%. Furthermore, coefficients of the correlation were modified based on flow regimes, with the results showing reduced root-mean-square errors.

Key words: Oil-air two-phase flow rate, Venturi, Void fraction, Flow regime, Electrical capacitance tomography
doi:10.1631/jzus.2005.A0601 **Document code:** A **CLC number:** TP216

INTRODUCTION

Accurate measurement of multiphase fluids flow rates in the petroleum industry is of great importance. The most reliable measurement technique for multiphase flow is separating the mixture and using conventional devices for measuring single-phase flow. However, in many cases the separation is not practical from both technical and economical points of view. An alternative solution is the multiphase flow metering system, usually consisting of a combination of devices for phase fraction measurement and velocity measurement.

The relationship between differential pressure, quality, void fraction and mixture flow rate must be known for measuring the flow rate by means of differential pressure devices. In the last decades, many investigations focused on air-water or steam-water two-phase flow measurement using orifices. Numerous orifice equations for gas-liquid mixtures have been developed and some typical equations were proposed by Murdock (1962), James (1965), Chisholm (1974), Lin (1982). Compared with other kinds of differential pressure devices, Venturi has little influence on flow regimes (Lin, 1987), the smallest pressure loss, and the shortest straight pipe upstream and downstream. Considering the great technical importance as well as pure scientific interest, two-phase flow through Venturi has been widely studied both experimentally and theoretically by Xu and Xu (2003), Steven (2002) and Moura and Marvillet (1997).

It is well known that measurement models based on experiments are closely dependent on experiment conditions such as pressure, temperature, medium, devices, etc. Due to lacking of valid oil-gas Venturi correlations, the oil industry has to choose between existing general air-water or steam-water two-phase flow orifice correlations so that measurement errors

---

* Project (No. 2001AA413210) supported by the Hi-Tech Research and Development Program (863) of China

are inevitable. It is necessary to develop the measurement model of oil-gas two-phase flow using Venturi.

The mass flow rates measurement methods proposed by Murdock, James, Chisholm and Lin were based on quality measurement. However, measuring quality on-line is rather difficult at present so that measurement of mass flow based on quality is not practical in gas-liquid two-phase flow system. Alternative solutions have been researched. Air-water mass flow rates were measured with orifice and void fraction by Zhang *et al.*(1992), refrigerant R-134a liquid-vapor mass flow rates were measured with Venturi and void fraction meters by Moura and Marvillet (1997).

Void fraction could be measured by many methods such as quick-close valve, γ rays, X rays, microwave, etc. Electrical Capacitance Tomography (ECT) technology is prospectively useful because it is accurate, economical, non-intrusive, safe and fast. Electrical capacitance tomography technology is a kind of tomography process technology and provides a new way to solve the problems of void fraction measurement (Li, 2001). Different phase component of two-phase flow has different dielectric constant. The change of the value of the two-phase void fraction and its distribution will result in the variation of the measured capacitance. ECT sensor was applied successfully to measure the void fraction and identify the flow regime of gas-solid multi-phase flow by Huang and Ji (2002). The aim of this investigation is to combine the ECT sensor with a Venturi meter to measure the total combined oil-gas two-phase flow rate, and then to develop a new measurement model from which individual phase mass flow rates and the flow quality can be obtained simultaneously.

THEORETICAL MODELS

In single-phase flow that is in thermal equilibrium, the mass flow rate is related to the pressure drop across a differential pressure device by the following equation:

$$G = \frac{CYA_O}{\sqrt{1-\beta^4}}\sqrt{2\Delta P\rho} \tag{1}$$

where G is the mass flow rate; C is the Venturi discharge coefficient; A_O is the area of the Venturi throat; β is the throat-to-pipe diameter ratio; Y is the compressibility coefficient of the fluid, the air-oil fluid is considered incompressible at low pressure and Y is considered to be unity; ΔP is the pressure drop across the device (differential pressure between the upstream pressure and the throat pressure); and ρ is the upstream density of the flowing fluid.

In two-phase flow, the two-phase mass flow rate and the two-phase pressure drop can be expressed in the form of Eq.(1) if an appropriate two-phase fluid density is used in place of the single-phase fluid density. The homogeneous flow model treats the two-phase flow as if it were a single-phase flow. Using the homogeneous equilibrium model, which assumes that the gas and the liquid have the same velocity and are in thermal equilibrium, the two-phase fluid density is given by:

$$\rho_m = \left(\frac{\chi}{\rho_\mathrm{G}} + \frac{1-\chi}{\rho_\mathrm{L}}\right)^{-1} \tag{2}$$

where χ is the quality of the two-phase flow, i.e. the ratio of the gas to total mass flow rate; ρ_m is the homogeneous density and subscripts ‘L’ and ‘G’ are for liquid and gas, respectively. Therefore substituting this homogeneous density into Eq.(1) and replacing ΔP with the mixture fluid pressure drop ΔP_TP, the two-phase mass flow rate is given by:

$$G = \frac{CA_O}{\sqrt{1-\beta^4}}K_\mathrm{L}\sqrt{2\Delta P_\mathrm{TP}\rho_\mathrm{L}} \tag{3}$$

For the homogeneous flow model, the theoretical equation for the liquid phase coefficient K_L is as follows:

$$K_\mathrm{L} = \frac{1}{\sqrt{1+\left(\frac{\rho_\mathrm{L}}{\rho_\mathrm{G}}-1\right)\chi^n}} \tag{4}$$

where n is coefficients and dependent on the test condition.

The relationship of mixture flow rates, liquid flow rates and gas flow rates can be described as:

$$G = G_L + G_G \tag{5}$$

$$G_L = G(1-\chi) \tag{6}$$

The velocity ratio of gas and liquid is called slip ratio. In homogeneous flow the velocity of gas is identical to that of liquid so that the slip ratio is equal to unity. Homogeneous model does not take the slip ratio into account. In many investigation reports, the velocities usually are not identical, which is one of main reasons why homogeneous model caused measurement error. This paper modified the model.

It was found by Chisholm (1974) and Lin (1982) that the slip ratio is mainly affected by the ratio of densities of gas and liquid. Slip ratio can be described simply as the follows:

$$s = c'\left(\frac{\rho_L}{\rho_G}\right)^h \tag{7}$$

where c' and h are coefficients which depend on the fluid conditions such as pressure and quality.

Void fraction data can be converted to quality values according to the standard formula:

$$\chi = \frac{1}{1+\dfrac{\rho_L}{\rho_G}\dfrac{1}{s}\dfrac{1-\varphi}{\varphi}} \tag{8}$$

where φ is the void fraction.

The density of gas is far smaller than that of oil at low-pressure oil-gas two-phase flow, so it's assumed that $\rho_L/\rho_G-1\approx\rho_L/\rho_G$ in Eq.(4). In addition, it's assumed that $1/x-1\approx 1/x$ at low quality two-phase flow. Then the following equation can be derived from Eqs.(4), (7) and (8):

$$K_L = \frac{1}{\sqrt{c\left(\dfrac{\varphi}{1-\varphi}\right)^n\left(\dfrac{\rho_L}{\rho_G}\right)^m+1}} \tag{9}$$

where $c=c'^n$, $m=1-Hn$. c and m are derivative coefficients and dependent on the test condition.

From Eqs.(7) and (8), the following equation can be derived:

$$\chi = c'\left(\frac{\varphi}{1-\varphi}\right)\left(\frac{\rho_G}{\rho_L}\right)^H \tag{10}$$

where $H=1-h$, c' and H are dependent on the test condition.

Quality and mixture mass flow rate could be calculated from Eqs.(3), (9) and (10) if void fraction and differential pressure could be measured at the same time. In this investigation, Venturi was used to measure differential pressure and ECT sensor was used to measure void fraction at real time on-line.

EXPERIMENTAL FACILITIES

Experiments were carried out in an oil-gas two-phase flow loop, as shown in Fig.1. Air and diesel fuel were used as the gas and liquid phase respectively. Before they were mixed, the pressures of air and diesel fuel were stabilized with air-tank and diesel fuel tank, and then the flow rates were measured respectively. Gear meter was used to measure the volume flow of diesel fuel that ranged from 4.5 to 6.3 m^3/h. The density of fuel ρ_L=840 kg/m^3, from which the actual mass flow of diesel fuel can be calculated. Vortex meter was used to measure the volume flow of air that ranged from 0 to 14 m^3/h. The actual mass flow of air can be calculated from the measured pressure and temperature of air. The quality ranged up to 1.98% during the test. The Venturi used for the tests was mounted on a horizontal pipe. The diameter of the Venturi was 50 mm with β=0.55. If ΔP_{TP} is

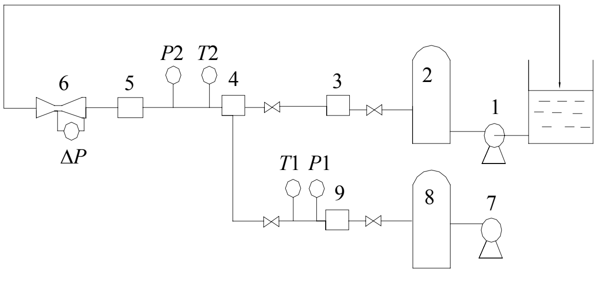

Fig.1 Schematic diagram of experimental apparatus
1: Oil pump; 2: Oil-tank; 3: Gear meter; 4: Mixing arrangement; 5: 12-electrode ECT system; 6: Venturi; 7: Compressor; 8: Air-tank; 9: Vortex flow meter

measured by a differential pressure transmitter connected to the Venturi, K_L can be calculated from Eq.(3). The test pressure of the oil-tank ranged from 0.2~0.4 MPa; the pressure of the air-tank was kept at 0.4 MPa. An ECT sensor was used to measure the void fraction on-line showing that it ranged from 15% to 83%. It was difficult for the vortex meter to measure accurately the mass flow rate when it is very small. During the test, although the vortex meter indicated zero when the volume flow of air was less than 5 Nm^3/h, the quality was so small at that time that it had almost no effect on the measurement accuracy.

Electrical capacitance tomography technique was applied to develop void fraction and flow regime visual sensor shown in Fig.2. In the experiment the ECT sensor was mounted near the Venturi on the horizontal pipe.

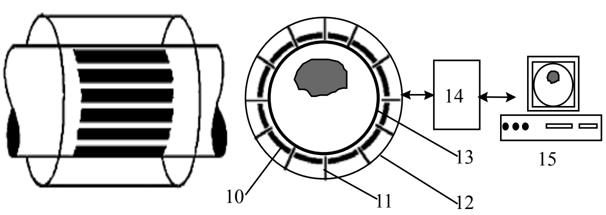

Fig.2 12-electrode ECT system
10: Electrode; 11: Radial electrode; 12: Screen; 13: Transducer; 14: Data acquisition; 15: Image reconstruction computer

Many measurement capacitance values can be obtained by using a 12-electrode capacitance sensor. Then the void fraction distribution of two-phase flow can be determined by image reconstruction algorithm. Regularized pseudo-inverse algorithm and algebraic reconstruction technique algorithm were combined to obtain improved reconstructed image. The grey level distribution of the reconstructed image can be applied to calculate the void fraction value and identify the flow regime. During the test the speed of image reconstruction, which closely depended on the performance of the computer, was over 4 frames per-second.

RESULTS AND ANALYSIS

Lin (1982; 1987) compared many methods for measuring two-phase two-medium flow rate based on quality, and found that the root-mean-square (RMS) error of mass flow of most of the methods was higher than 10% and that the smallest RMS error was 7.4%. In Moura and Marvillet (1997)'s investigation in which Venturi and void fraction meters were used, it was expected that the liquid-vapor mass flow rate and quality could be measured with an accuracy of better than 20% over the entire range of flow conditions.

The actual value of K_L can be calculated from Eq.(3) according to the measured ΔP_{TP} and G. Taking no account of the influence of two-phase flow regimes on the measured flow rate, the coefficients of Eq.(9) were calculated by the method of least squares based on the measured φ and the actual value of K_L, and c=1, n=12, m=0.07 were obtained as a result. Then the mixture mass flow can be calculated with Eq.(9).

The actual value of quality χ can be calculated according to the measured mass flow G_L and G_G. The coefficients c'=1, H=0.85 of Eq.(10) were calculated by the method of least squares based on the measured void fraction φ and the actual value of χ. After the void fraction is measured on-line by ECT sensor, the quality can be calculated using Eq.(10) with the result being shown in Fig.3. The maximum difference between calculated value and actual value was 0.8%.

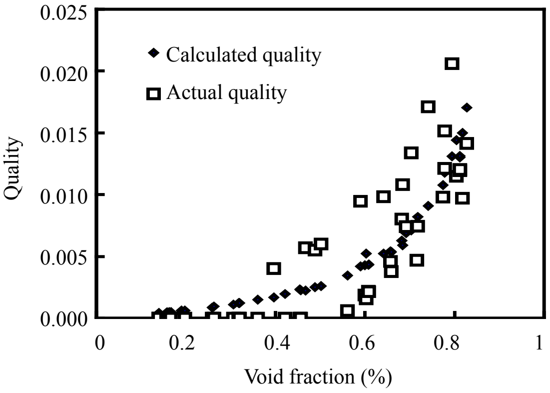

Fig.3 Comparison between experimental and calculated quality

Eq.(9) was used to calculate the mixture mass flow rate. Comparison of the experimental and calculated mixture mass flow rate without the effect of flow regime is shown in Fig.4. Comparison of the experimental and calculated liquid mass flow rate is shown in Fig.5. In the test setup, the RMS error of mixture mass flow was 4.18%, and that of liquid mass flow was 4.47%. As shown in Fig.4 and Fig.5, the measurement error is comparatively small because the slip ratio influence was considered in the theoretical model of this paper.

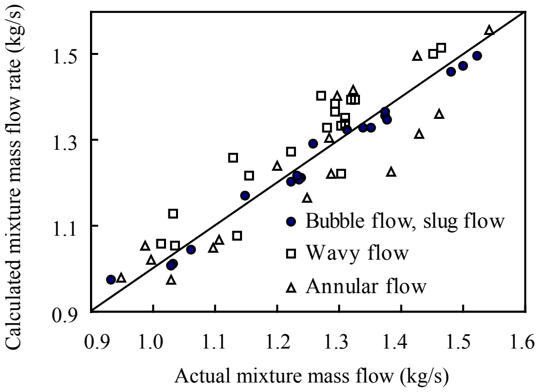

Fig.4 Comparison between experimental and calculated mixture mass flow rate without the effect of flow regime

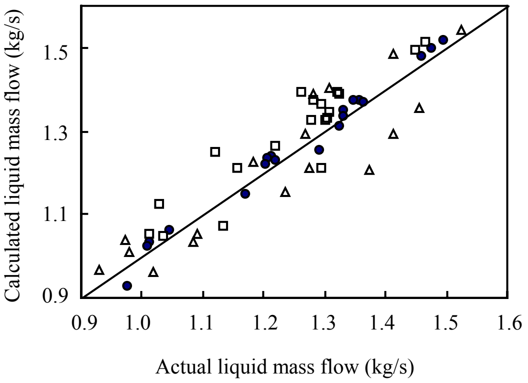

Fig.5 Comparison between experimental and calculated liquid mass flow rate without the effect of flow regime

With increasing void fraction, the two-phase flow regime transformed from bubbly flow and slug flow to wavy flow and annular flow, and the measurement accuracy decreased also, as shown in Fig.4 and Fig.5.

In order to study the influence of flow regime on measurement of mass flow rate, the coefficients of Eq.(9) and Eq.(10) were modified based on different flow regime by the method of least squares. And then the mass flow rates were calculated when the flow regimes were identified and specified. For bubbly and slug flow, c=0.5, n=0.95, m=0.02, c'=0.51, H=0.65. For wavy flow, c=1.3, n=1.15, m=0.08, c'=1.25, H=0.70. For annular flow, c=1.2, n=0.95, m=0.05, c'=1.21, H=0.95. The measurement accuracy was increased after the modification. RMS error of mixture flow was 3.83% and that of liquid flow was 4.05%. Comparison of the experimental and calculated mixture mass flow rate and that of liquid mass flow rate are shown in Fig.6 and Fig.7, respectively. The mass flow rates calculated by the modified equations agreed better with the actual mass flow rates, especially for wavy flow and annular flow when the void fraction was bigger than 40%.

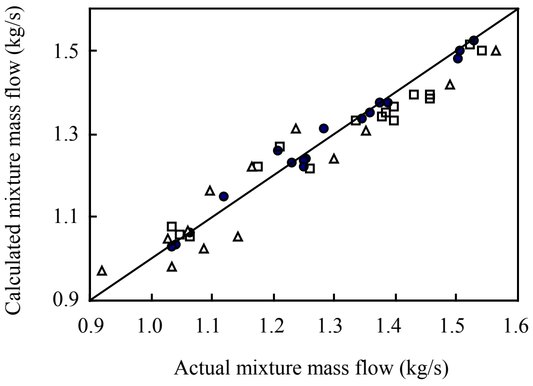

Fig.6 Comparison between experimental and calculated mixture mass flow rate with the effect of flow regime

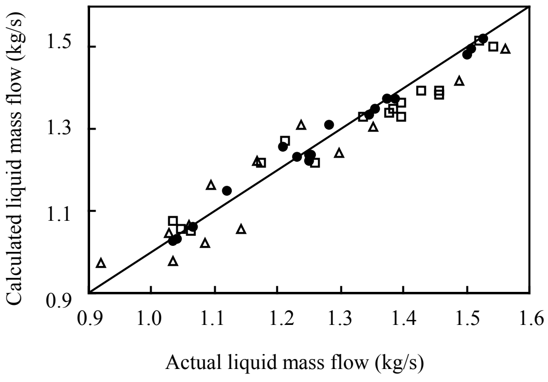

Fig.7 Comparison between experimental and calculated liquid mass flow rate with the effect of flow regime

The flow regimes can be identified by the ECT sensor along the transverse cross-section and longitudinal cross-section of the flow pipe, respectively, and the visual results are shown in Fig.8.

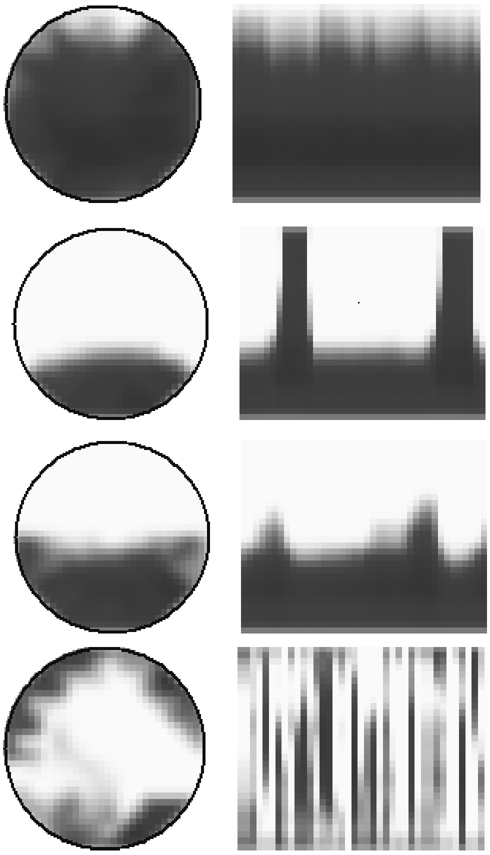

Fig.8 Flow regime identified by the ECT sensor along the cross-section and longitudinal cross-section respectively of the flow pipe
(a) Bubbly flow; (b) Slug flow; (c) Wavy flow; (d) Annular flow

CONCLUSION

Oil-air two-phase flow measurement was investigated with a Venturi and void fraction meters in this work, unlike previous investigation that commonly used orifice and quality meters. Void fraction was measured at relatively high accuracy by means of ECT sensor. Venturi was adopted because of its simple design, low cost and the lowest pressure loss, especially.

This paper proposed a based on homogeneous model new correlation for mass flow rate measurement wherein the influence of slip ratio on mass flow rates was considered. With the given void fraction and pressure drop across a Venturi, both mixture flow rate and oil flow rate can be calculated.

Even for the unknown flow regimes, the RMS error of total mass flow rate and that of oil mass flow rate are both less than 5%.

ECT sensor can be used to identify the flow regime, whose influence on mass flow rates was also considered. The study results showed that RMS error was lowered.

The above conclusions were derived from experiment results with oil-air two-phase flow. Oil-gas two-phase flow rate can be measured on-line with the equations derived in this study. To prove their general validity, additional experiments with different two-phase mixtures, pipe diameters, fluid densities and fluid pressure are required. This work may be instructive in further study of oil-gas mixture measurement using Venturi and void fraction sensor.

References

Chisholm, D., 1974. Pressure drop during steam/water flows through orifices. *J Mech Engine Sci*, **16**(5):353-355.

Huang, Z.Y., Ji, H.F., 2002. Study on voidage measurement of gas-solid fluidized bed by using electrical capacitance tomography. *Journal of Chemical Engineering of Chinese Universities*, **16**(5):490-495 (in Chinese).

James, R., 1965. Metering of steam-water two-phase flow by sharp-edged orifices. *Proc. Inst Mech. Engrs*, **180**:549-566.

Li, H.Q., 2001. Applications of electrical capacitance tomography technique to flow pattern display and voidage measurement of two-phase flow. *Journal of Chemical Industry and Engineering*, **52**(11):1035-1038 (in Chinese).

Lin, Z.H., 1982. Measurements of vapor quality and flow rate in Herschel Venturi. *Journal of Xi'an Jiaotong University*, **16**(3):25-33 (in Chinese).

Lin, Z.H., 1987. Gas-liquid Two-phase Flow and Boiling Heat Transfer. Xi'an Jiaotong University Press, Xi'an, China (in Chinese).

Moura, L.F.M., Marvillet, C., 1997. Measurement of Two-phase Mass Flow Rate and Quality Using Venturi and Void Fraction Meters. Proceedings of the 1997 ASME International Mechanical Engineering Congress and Exposition, Dallas, TX, USA (special issue), Fluids Engineering Division, FED 244, p.363-368.

Murdock, J.W., 1962. Two-phase flow measurements with orifices. *J. Bas. Engine.*, **84**:419-433.

Steven, R.N., 2002. Wet gas metering with a horizontally mounted Venturi meter. *Journal of Flow Measurement and Instrumentation*, **12**:361-372.

Xu, L.J., Xu, J., 2003. On fluctuation of the dynamic differential pressure signal of Venturi meter for wet gas metering. *Flow Measurement and Instrumentation*, **14**:211-217

Zhang, H.J., Lu, S.J., Yu, G.Z., 1992. An investigation of two-phase flow measurement with orifices for low-quality mixtures. *Int. J. Multiphase Flow*, **18**(1):149-155.