Flow Measurement and Instrumentation 31 (2013) 96–101

Contents lists available at SciVerse ScienceDirect

Flow Measurement and Instrumentation

journal homepage: www.elsevier.com/locate/flowmeasinst

Experimental validation of the calculation of phase holdup for an oil–water two-phase vertical flow based on the measurement of pressure drops

Jian Zhang, Jing-yu Xu*, Ying-xiang Wu, Dong-hui Li, Hua Li

Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China

ARTICLE INFO

Available online 23 October 2012

Keywords:
Holdup
Oil–water vertical flows
Pressure drop

ABSTRACT

The performance of metering the phase holdup of an oil–water two-phase vertical flow has been investigated based on the measurement of the gravity and frictional pressure drops. A U-tube, in which the same flow patterns can be obtained in downward and upward vertical flows, is designed to measure both gravity and fractional pressure drops. During the experiments, the mixture velocities of the oil and water are in the range of 0.28–4.65 m/s and the oil volume fraction from 0 to 1.0. The results show that the oil holdups calculated are satisfactory with the absolute error of $\pm 10\%$. The method presented in this work can be used to verify the results of tomography due to its simplicity and therefore is sufficient enough to be applied in industry.

1. Introduction

Accurate measurement of an oil–water two phase flow is of great importance in a variety of industry process, such as petroleum industry, nuclear industry and so on [1]. A considerable body of work has been reported on the measurement methods of an oil–water two-phase flow including both mixture measurement and separated measurement [2]. For the mixture measurement, the radiation methods are used frequently with the advantages of being non-intrusive, highly accurate and reliable. Radiation methods include α-ray attenuation, x-ray attenuation, multi-beam γ-ray attenuation and dual-energy γ-ray tomography and so on [3,4]. Most of these methods have their drawbacks, such as the radioactivity. Moreover, the microwave methods are also applied for metering the holdup based on the different permittivities between oil and water phases. Recently, the electrical impedance measurements have been developed quickly. The results show that the electrical resistance tomography, the electrical capacitance tomography and the capacitance wire-mesh sensor can satisfy the distinguishing flow patterns in the certain regions [5–8]. Furthermore, other metering methods also include ultrasonic techniques, optical fiber probes, venturi and some algorithms [9,10]. For the separated measurements, most research focuses on the separation through gravity settling. Thus, it needs a long time to present the metering message although it has a great accuracy of $\pm 0.5\%$.

In this work, the method based on the measurement of pressure drops is put forward to obtain the oil holdup. A new metering structure, in which the same flow patterns can be obtained in downward and upward vertical flows, is designed to measure both gravity and fractional pressure drops. A series of experimental runs have been carried out to verify its feasibility.

2. Measurement principle

The method of metering the holdup is based on the difference between oil and water densities. The equal frictional pressure drops in the U-tube are assumed because of the same flow patterns. The total pressure drop comprising frictional, gravity and acceleration pressure drops can be calculated as follows:

$$dp/dx = (dp/dx)_f + (dp/dx)_g + (dp/dx)_a \tag{1}$$

Provided a fully developed flow, the accelerated pressure drop can be neglected

$$dp/dx = (dp/dx)_f + (dp/dx)_g \tag{2}$$

here, the pressure drops are said in the flowing orientation, thus the pressure drops in the downward and upward flows can be obtained, respectively, as

$$(dp/dx)_d = (dp/dx)_{d,f} - (dp/dx)_{d,g} \tag{3}$$

$$(dp/dx)_u = (dp/dx)_{u,f} + (dp/dx)_{u,g} \tag{4}$$

The gravity pressure drop can be obtained from Eqs. (3) and (4)

$$(dp/dx)_g = 0.5[(dp/dx)_{d,g} + (dp/dx)_{u,g}] \tag{5}$$

here,

$$(dp/dx)_g = \rho_m gh \tag{6}$$

* Corresponding author. Tel.: +86 10 8254 4179; fax: +86 10 6256 1284.
E-mail address: xujingyu@imech.ac.cn (J.-y. Xu).

0955-5986/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.flowmeasinst.2012.08.002

Nomenclature

dp/dx	pressure gradient, (Pa/m)
g	acceleration of gravity, (m/s^2)
h	distance of two points, (m)
V	velocity, (m/s)
S	velocity ratio, (dimensionless)

Greek symbols

α	oil holdup, in-situ oil volume fraction
β	inlet volume fraction, (%)
μ	viscosity, (mPa s)
ρ	density, (kg/m^3)

Subscripts

a	acceleration
d	downward flow
f	frictional
g	gravity
m, mix	mixture
o	oil
sw	apparent velocity of water
u	upward flow
w	water

The gravity pressure drop of single phase flow is given as

$$(dp/dx)_{g,o} = \rho_o g h \tag{7}$$

$$(dp/dx)_{g,w} = \rho_w g h \tag{8}$$

here, the mixture density is expressed by using the oil holdup (α_o)

$$\rho_m = \rho_o \alpha_o + \rho_w (1 - \alpha_o) \tag{9}$$

Thus, the oil holdup can be solved analytically by substituting Eqs. (2), (5–8) to Eq. (9) as

$$\alpha_o = [(dp/dx)_{g,w} - (dp/dx)_g]/[(dp/dx)_{g,w} - (dp/dx)_{g,o}] \tag{10}$$

3. Experimental set-up and procedure

A schematic diagram of the experimental system is shown in Fig. 1. It has 0.6 m length between two metering points. The straight region in the U-tube is 1.2 m. All experiments are conducted by using white oil and tap water at room-temperature and atmospheric outlet pressure. The physical properties of liquid phases are listed in Table 1. A nozzle with the inner diameter from 50 mm to 25 mm is used to connect the main pipes with the U-tube. The inner diameter of the U-tube is 25 mm. All Perspex pipes are used to observe the mixture flows of fluids, including flow patterns and slip phenomenon between two phases. White oil and tap water are pumped from their respective storage tanks, metered, and introduced into pipes through a Y-junction, which ensures a minimum mixing. There is 3 m length between Y-junction and the test section, which provides enough distance to stabilize the mixture flows [11].

The data are collected by four absolute pressure sensors and two differential pressure sensors. The sampling frequency is 1000 Hz and a total of 10,000 samples were used, which correspond to 10 s by using 16-bit Data Acquisition Card. The absolute pressure sensors are used to calculate the gravity pressure drop, while the differential pressure sensors are used to meter the frictional pressure drop. All these sensors are made by Honeywell of 40PC and DC series. The accuracies of absolute pressure sensors and differential pressure sensors are 0.15% and 0.25%, respectively. The values and standard deviations of the absolute pressure sensors are displayed in Fig. 2 under four different flow conditions, respectively.

The oil phase is measured by the quick closing valve (QCV) system [12], which is used to check the accuracy of the in-situ oil volume fraction calculated. For this system of QCV, two valves are installed on the two ends of U-tube. The volumes of the liquid phases can be noted after gravity separation and then the oil holdups are calculated. A total of 464 data points have been obtained under the following conditions: the mixture velocities vary from 0.28 m/s to 4.65 m/s and the inlet oil volume fractions in the range of 0–1.0. Experiments are carried out by keeping the superficial water velocity constant and increasing the superficial oil velocity.

4. Experimental results and discussions

4.1. Frictional pressure drop

In the present study, the superficial water velocities are fixed at 0.28 m/s, 0.43 m/s, 0.57 m/s, 0.71 m/s, 0.85 m/s, 0.99 m/s, 1.13 m/s,

Table 1
Physical properties of liquid phases measured at 27 °C and 0.101 MPa.

Properties	Tap water	White oil
Density, ρ (kg/m^3)	998	840
Viscosity, μ (mpa s)	1	60

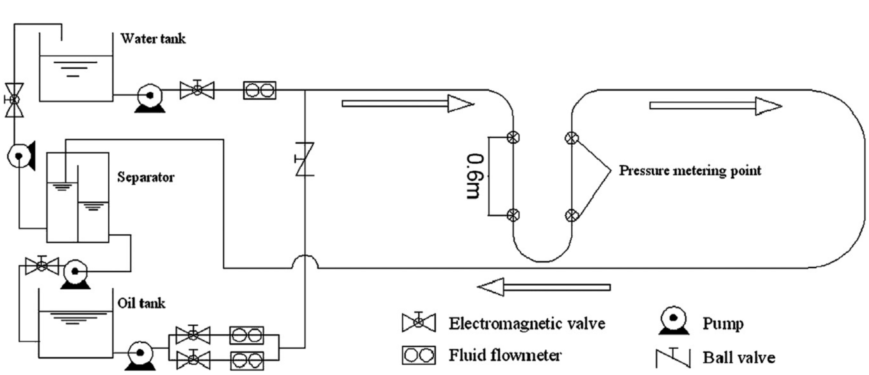

Fig. 1. Schematic view of the flow loop.

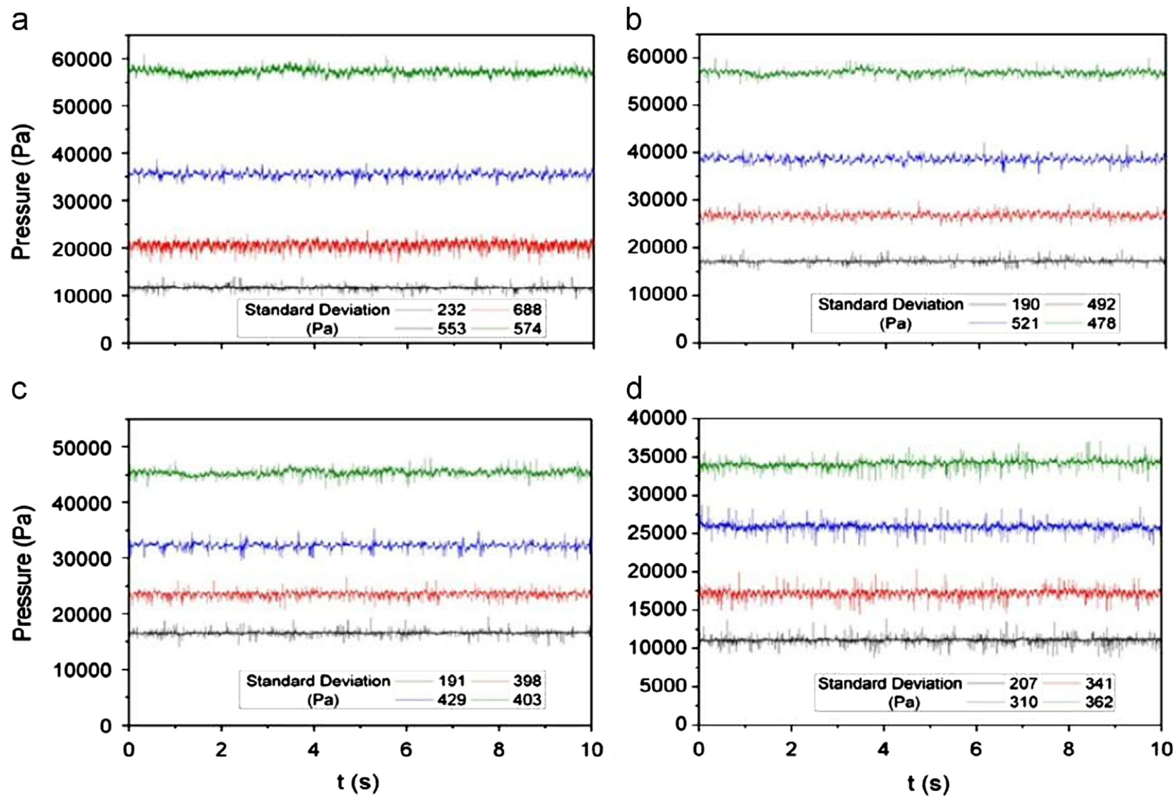

Fig. 2. Standard deviation of four pressure sensors in the collecting 10,000 points.

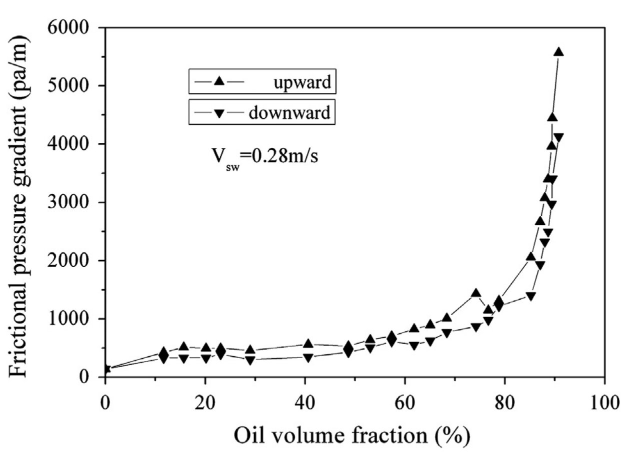

Fig. 3. Frictional pressure gradients against oil volume fractions at V_{sw}=0.28 m/s.

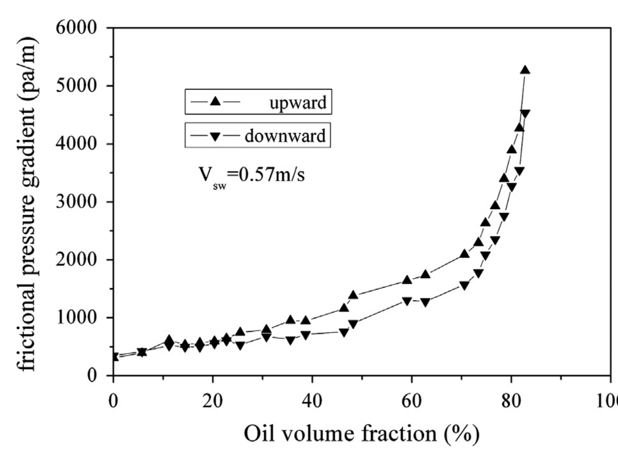

Fig. 4. Frictional pressure gradients against oil volume fractions at V_{sw}=0.57 m/s.

1.27 m/s, 1.42 m/s and 1.70 m/s. Figs. 3 and 4 give the frictional pressure gradients at two superficial water velocities (0.28 m/s and 0.57 m/s, respectively). Here, the frictional pressure gradients are reported as the function of the inlet oil volume fractions. As can be observed, in general, the frictional pressure drops increase with increasing inlet oil volume fractions. However, the differences of pressure drop between downward and upward flows are small and negligible. These findings support our hypothesis, namely that the equal fractional pressure drops in the U-tube can be obtained approximately by this installation.

4.2. Phase holdup

In this section, firstly the oil holdups measured by the quick closing valve system against the inlet oil volume fractions are displayed. Hereafter, the oil volume fractions calculated by Eq. (10) are compared with those measured by the quick closing valve system.

4.2.1. Slip phenomenon in the U-tube

In the present study, a nozzle with the inner diameter from 50 mm to 25 mm is used to obtain the same annular flow patterns [13], in which the oil phase always flows in the core of the pipe and the water phase contacts the wall of pipe. The flow patterns in the U-tube are displayed in Figs. 5–7 at the superficial water velocities of 0.28 m/s, 0.56 m/s and 0.84 m/s respectively. Here, all the flow patterns are recorded by the Quick Camera. It can be seen that there are similar flow patterns (i.e. annular flow) in the U-tube. Although the oil phase becomes more dispersed by increasing the superficial water velocity, it still stays at the core

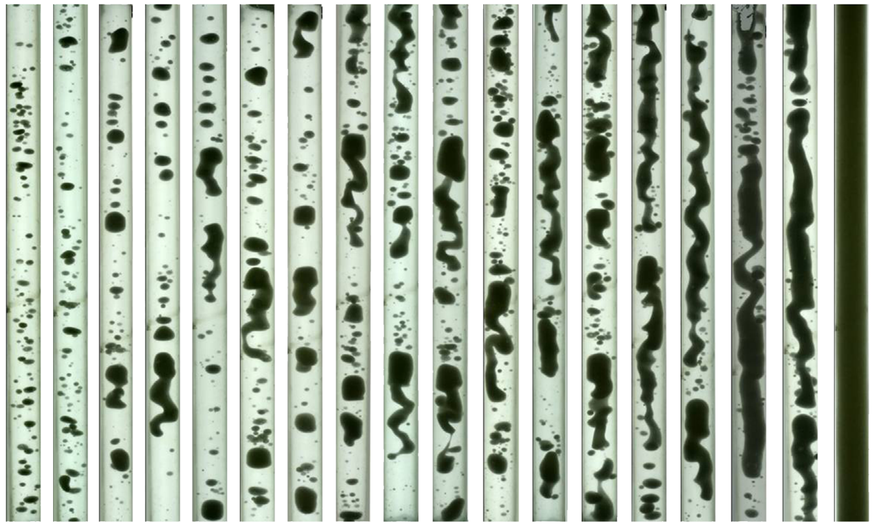

Fig. 5. Flow patterns in the U-tube at V_{sw}=0.28 m/s (inlet oil volume fraction from left to right: 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%, 55%, 60%, 65%, 70%, 75%, 80%, 85%, 100%).

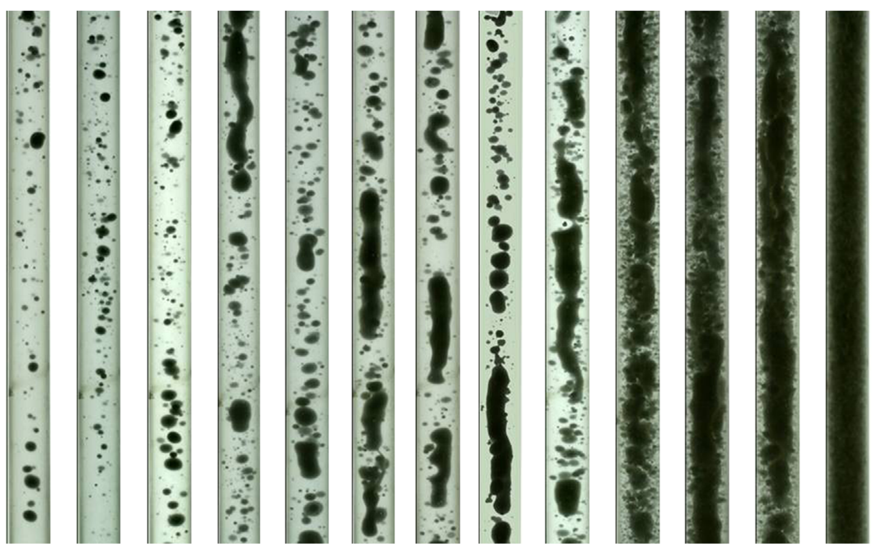

Fig. 6. Flow patterns in the U-tube at V_{sw}=0.57 m/s (inlet oil volume fraction from left to right: 5%, 8%, 15%, 25%, 30%, 40%, 45%, 50%, 55%, 65%, 70%, 80%, 95%).

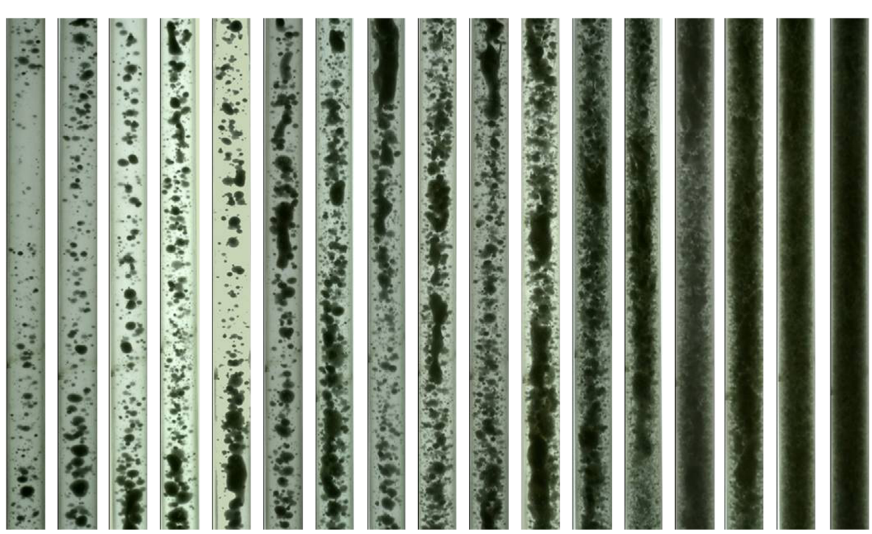

Fig. 7. Flow patterns in the U-tube at V_{sw}=0.84 m/s (Inlet oil volume fraction from left to right: 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%, 55%, 60%, 65%, 70%, 80%, 90%, 100%).

of pipe. These patterns make sure of the minimum difference of frictional pressure drops in the U-tube [14].

It is well-known that there is a slip velocity between two phases due to the different densities of the two fluids. It can be found in Figs. 5–7 that the oil phase moves faster than the water phase. To express the slip phenomenon, a ratio between the average in situ velocities of the two fluids is suggested [11]. The velocity ratio, S, is defined as

$$S = \frac{\beta_O/\beta_W}{\alpha_O/\alpha_W} \tag{11}$$

Here, β_o and β_w are the inlet volume fractions of oil and water respectively, and α_o and α_w are the in situ volume fractions of oil and water, respectively, averaged over the pipe cross section. Consequently, S is greater than 1 when the velocity of oil phase is bigger than water, and conversely S is less than 1 when the velocity of water phase is bigger than oil.

Figs. 8 and 9 give the in situ oil volume fractions against the inlet oil volume fractions at two different water superficial velocities and two mixture velocities, respectively. All the in situ oil volume fractions are less than the corresponding inlet oil volume fractions. These results are similar with the findings of previous literature [14]. Furthermore, the slip velocity becomes small when the water superficial velocity is increased. However, there are a few differences under the conditions of the fixed mixture velocity, as shown in Fig. 9.

The in-situ oil volume fractions metered by quick closing valve system are displayed in Figs. 10 and 11. It can be observed that most of the velocity ratios are greater than one unit. The main reason may be that the oil phase flows in the core and water phase close to the pipe wall, as shown in Figs. 5–7. Thus, the oil phase velocity is always bigger than the water phase velocity in these flow patterns.

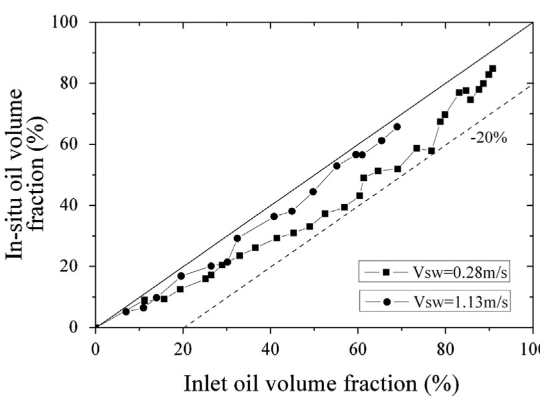

Fig. 8. In-situ oil volume fractions metered by quick closing valves against inlet oil volume fractions at V_{sw}=0.28 m/s and 1.13 m/s.

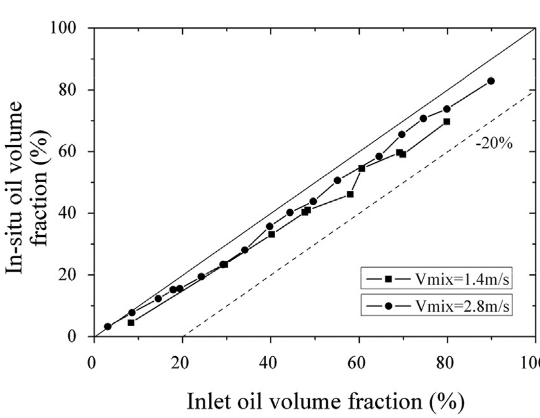

Fig. 9. In-situ oil volume fractions metered by quick closing valves against inlet oil volume fractions at V_{mix}=1.4 m/s and 2.8 m/s.

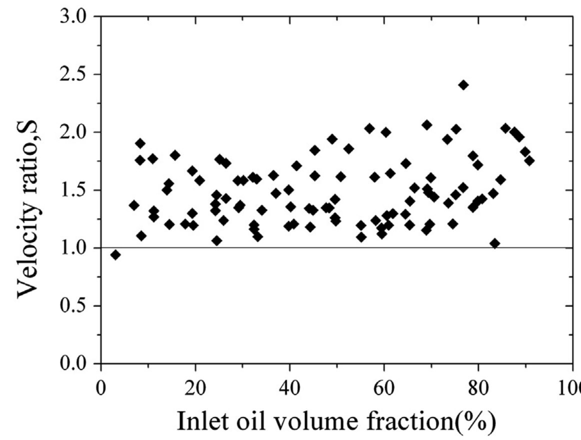

Fig. 10. Phase velocity slip phenomenon in the U-tube.

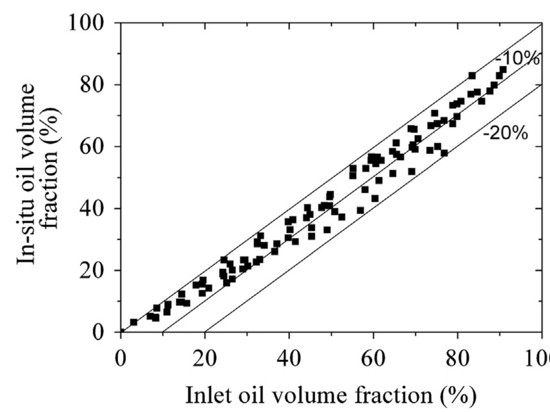

Fig. 11. Inlet oil volume fractions against in-situ oil volume fractions in the U-tube.

4.2.2. Accuracy analysis

The oil volume fractions calculated by Eq. (10) against the oil holdups measured by the quick closing valve system, at two water superficial velocities and two mixture velocities, are displayed in Figs. 12 and 13, respectively. Most of the errors are less than $\pm 10\%$. Thus, the method suggested in this study is steady and acceptable although it has no regular tendency.

Fig. 14 shows the absolute deviation of the in-situ oil volume fractions calculated. Most of the data points are also in the range of $\pm 10\%$. Fig. 15 gives the relative errors of the in-situ oil holdups calculated by this method. Here, the oil holdup metered by quick closing valves is assumed as the real one. It can be observed that most of the data points are good and included in the relative errors of $\pm 20\%$.

5. Conclusion

A U-tube has been applied to obtain the oil holdup based on both gravity and frictional pressure drops measured. The same flow patterns in the U-tube can be observed by using a nozzle so that the errors will be reduced. The quick closing valve system is used to check the accuracy of this method. The results show that the oil holdups are less than the corresponding inlet ones because of the slip velocity of two phases in the U-tube. The frictional

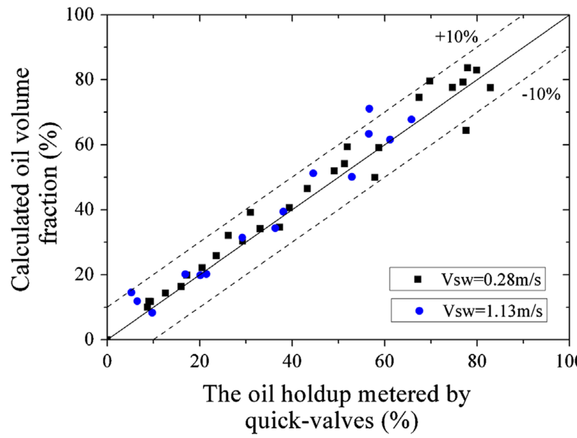

Fig. 12. Comparison of the calculated oil volume fractions with those measured at V_{sw}=0.28 m/s and 1.13 m/s.

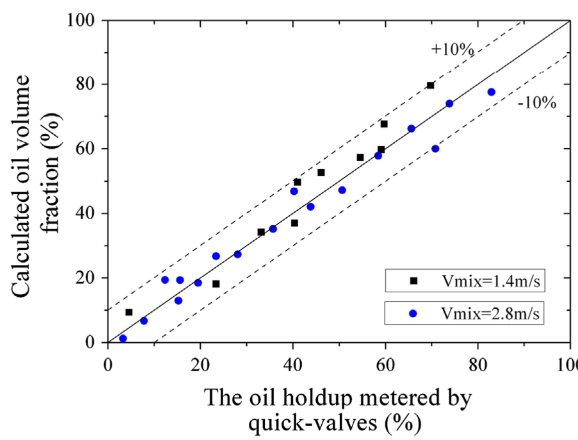

Fig. 13. Comparison of the calculated oil volume fractions with those measured at V_{mix}=1.4 m/s and 2.8 m/s.

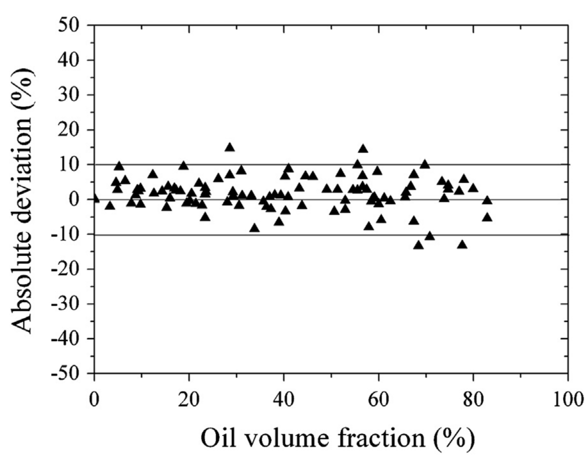

Fig. 14. Absolute deviation of the in-situ oil volume fractions calculated.

pressure gradients between downward and upward flows show few differences so that most of the oil holdups predicted are well with the error of ±10% in the range of the inlet oil volume fractions of 0–0.8.

Although more accurate methods for the calculation of the oil holdup can be applied, we consider the method presented in this work as advantageous to other methods due to its simplicity and

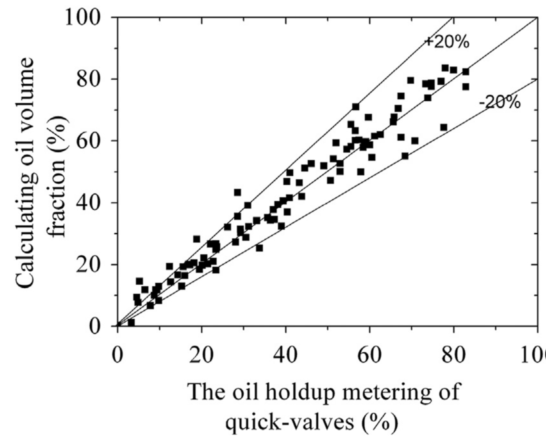

Fig. 15. Relative errors of the metering oil volume fractions.

therefore is sufficient enough to be applied in the verification of the tomography results.

Acknowledgments

The authors gratefully acknowledge that the work described here is financially supported by the Special Development of National Key Scientific Instruments in China (2011YQ120048-02) and the Outstanding Young Talent Incubation Program at Institute of Mechanics, Chinese Academy of Sciences.

References

[1] Zhang FS, Dong F, Tan C. High GVF and low pressure gas–liquid two phase flow measurement based on dual-cone flowmeter. Flow Measurement and Instrumentation 2010;21:410–417.

[2] Skea AF, Hall AWR. Effects of water in oil and oil in water on single phase flowmeter. Flow Measurement and Instrumentation 1999;10:151–157.

[3] Yin FH, Afacan A, Nandakumar K, Chuang KT. Liquid holdup distribution in packed columns: gamma ray tomography and CFD simulation. Chemical Engineering and Processing 2002;41:473–483.

[4] Bruvik EM, Hjertaker BT, Hallanger A. Gamma-ray tomography applied to hydro-carbon multiphase sampling and slip measurements. Flow Measurement and Instrumentation 2010;21:240–248.

[5] Vlaev D, Wang M, Dyakowski T, Mann R, Grieve BD. Detecting filter-cake pathologies in solid–liquid filtration: semi-tech scale demonstrations using electrical resistance tomography. The First World Congress on Industrial Process Tomography; 1999.

[6] Jaworski AJ, Dyakowski T. Measurements of oil–water separation dynamics in primary separation systems using distributed capacitance sensors. Flow Measurement and Instrumentation 2005;16:113–127.

[7] Ismail I, Gamio JC, Bukhari SFA, Yang WQ. Tomography for multiphase flow measurement in oil industry. Flow Measurement and Instrumentation 2005;16:145–155.

[8] Da Silva MJ, dos Santos EN, Hampel U, Rodriguez IH, Rodriguez OMH. Phase fraction distribution measurement of oil–water flow using a capacitance wire-mesh sensor. Measurement Science and Technology 2011;22:P129901.

[9] Falcone G, Hewitt GF, Allmontl C, Harrison B. Multiphase flow metering: current trends and future developments. Society of Petroleum Engineering 2002;54:77–84.

[10] Li X, Huang ZY, Meng ZZ, Wang BL, Li HQ. Oil–water two phase flow measurement using a venture meter and an oval gear flow meter. Chemical Engineering Communications 2010;197:223–231.

[11] Xu JY, Wu YX, Feng FF, Chang Y, Li DH. Experimental investigation on the slip between oil and water in horizontal pipes. Experimental Thermal and Fluid Science 2008;33:178–183.

[12] Xu JY, Li DH, Guo J, Wu YX. Investigations of phase inversion and frictional pressure gradients in upward and downward oil–water flow in vertical pipes. International Journal of Multiphase Flow 2010;36:930–939.

[13] Ghosh S, Mandal TK, Das G, Das PK. Review of oil water core annular flow. Renewable and Sustainable Energy Reviews 2009;13:1957–1965.

[14] Rodriguze OMH, Bannwart AC. Experimental study on interfacial waves in vertical core flow. Journal of Petroleum Science and Engineering 2006;54:140–148.