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

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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:

$$dp/dx = (dp/dx)_f + (dp/dx)_g + (dp/dx)_a \quad (1)$$

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

$$dp/dx = (dp/dx)_f + (dp/dx)_g \quad (2)$$

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

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

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

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

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

here,

$$(dp/dx)_g = \rho_m g h \quad (6)$$

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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

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

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

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

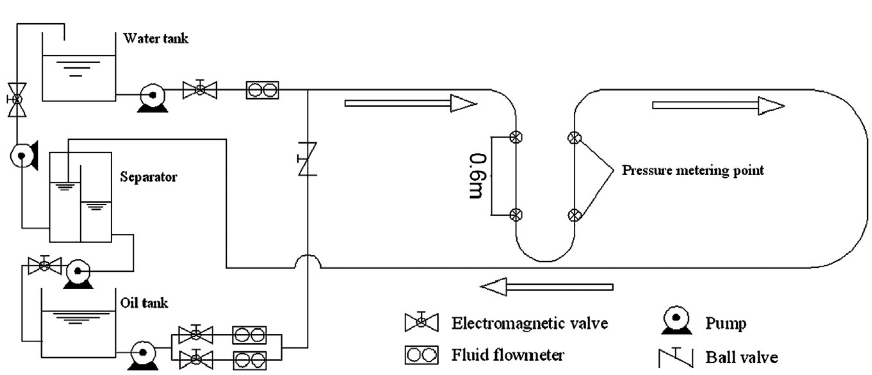

Fig. 1. Schematic view of the flow loop.