Flow measurement of oil-in-water flows in vertical low flow rate and high water-cut flow conditions

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Abstract. This paper reports on the flow measurement of oil-in-water flows with low flow rate and high water-cut in vertical 20mm inner diameter pipe. By using arc type conductivity sensor (ATCS) and cross-correlation flow meter (CCFM) based on conductance method, water holdup and mixture velocity are obtained. Afterward, oil-in-water flows drift-flux model is established to predict individual phase superficial velocity. The research results show that ATCS has high resolution on water holdup and CCFM performs well in mixture velocity measurement. Based on drift-flux model, individual phase superficial velocity can be predicted with high accuracy.

1. Introduction

Oil-in-water flows with low flow rate and high water-cut are commonly encountered in the processes of crude oil exploitation. Due to the severe slippage effect and non-uniform distribution of phases in vertical pipe flows, it is a great challenge for flow measurement in oil wells. Owing to the highly sensitive and homogenous detection field, arc type conductance sensors with guard electrodes can achieve better performance in phase volume fraction measurement [1-4]. In the aspect of mixture velocity measurement, cross-correlation methods are widely utilized in multiphase flow systems [5-7]. However, because of the complex flow patterns and slippage effect between phases, the relationship between cross-correlation velocity and mixture velocity is difficult to obtain. Based on the equivalence of the measured cross-correlation velocity and the kinematic wave velocity [1], mixture velocity can be acquired reasonably from the kinematic wave model [8-10]. In the present study, arc type conductivity sensor (ATCS) are utilized to measure water holdup in oil-in-water flows. Additionally, cross-correlation flow meter (CCFM) with two ring-shape conductance sensors embedded on the centre body can simplify the relationship between the cross-correlation velocity and mixture velocity, then the drift-flux model is established to measure the individual phase velocity.

2. Measurement system and experimental facility

Measurement system is shown in figure 1. ATCS and CCFM with centre body are installed in the test pipe to obtain water holdup and cross-correlation velocity respectively. The pipe diameter is 20mm. The experimental facility is presented in figure 2. Tap water and white oil are respectively pumped into test pipe by industrial peristaltic pumps. The velocity of mixture $U_\infty$ ranges from 0.0184m/s to 0.2578m/s and water-cut $K_w$ is set from 80% to 98%, which are precisely controlled by the pumps. The whole experiment consists of 80 flow conditions and three typical flow patterns, namely dispersed oil-

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in-water slug flow (D OS/W), dispersed oil-in-water flow (D O/W) and very fine dispersed oil-in-water flow (VFD O/W) are observed and recorded by high-speed camera. Quick closing valves (QCV) are applied to obtain actual water holdup and signals of ATCS and CCFM are collected by PXI-4472 synchronous acquisition card of NI company.

Figure 1. Schematic diagram of measurement system.

3. Measurement results and analysis

3.1. Water holdup measurement

For the purpose of quantitatively describing the measurement characteristic on water holdup using ATCS, we introduce an index designed as generalized conductance $Ge^*$, which can be given by:

$$Ge^* = \frac{\sigma_m}{\sigma_w} = \frac{V_{ref}^w}{V_{ref}^m} = \frac{V_m^w}{V_m^m}$$

(1)

where $\sigma_m$ and $\sigma_w$ are the conductivity of mixture fluid and water respectively. $V_{ref}$ and $V_m$ represent the voltage on reference resistance and ATCS under the circumstance of oil-in-water flows. $V_{ref}^w$ and $V_m^w$ denote the voltage on reference resistance and ATCS in water. As dispersed oil bubbles scatteringly distribute in continuous phase, water holdup $Y_w$ can be calculated using Maxwell assumption [11]:

$$Y_w = \frac{3Ge^*}{2 + Ge^*}$$

(2)

Figure 3. Generalized conductance calculated from ATCS.

Figure 4. Water holdup calculated from ATCS versus from QCV.
The results of $Ge^*$ measured by ATCS are shown in figure 3. As to an identical $K_w$, $Ge^*$ presents a decreasing trend with the increasing $U_m$, and decreases slower when $U_m$ is larger. Additionally, under different $U_m$, the difference of $Ge^*$ is larger when $K_w$ is lower. Those results can be attributed to the fact that when the $U_m$ and $K_w$ are lower, the slippage effect is more severe and it reduces with increasing $U_m$ and $K_w$. The value of $Ge^*$ increases with increasing $K_w$ if $U_m$ is hold constant, and the difference of $Ge^*$ between adjacent water-cut is obvious even under low $U_m$, which manifests the good measurement resolution for water holdup in oil-in-water flows using ATCS. Figure 4 illustrates that the calculated water holdup from ATCS presents a good agreement with actual water holdup from QCV, and a satisfied accuracy is obtained with absolute average deviation (AAD) equalling to 0.00712 m/s and absolute average percentage deviation (AAPD) equalling to 0.761%.

3.2. Mixture velocity measurement

Figure 5 presents the upstream and downstream signals of CCFM under three typical flow patterns and their cross-correlation functions. The upstream signals and downstream signals are similar with each other and the cross-correlation functions have obvious peaks. As shown in figure 6, the calculated $U_{cc}$ indicates better increasing tendency with the increasing $U_m$, and the results are almost not affected by $K_w$, which can be ascribed to the fact that the centre body makes the flow structures stable in the annular space and enhances the correlation of upstream and downstream signals. Additionally, the slippage effect between phases is reduced by accelerating fluid velocity in annular space and enhances the correlation of mixture velocity achieved by CCFM.

![Figure 5](image1)

**Figure 5.** Cross-correlation functions of three typical flow patterns.

3.3. Drift-flux model for oil-in-water flows

Considering the severe slippage effect in oil-in-water flows, drift-flux model [12] is established to measure the individual phase velocities. The expression for drift-flux model is given as follows:

$$ U_{so} \over Y_o = C_0 \cdot U_m + U_* \cdot (1 - Y_o)^n $$

(3)

where $U_{so}$ denote oil phase superficial velocity and $Y_o$ is oil holdup obtained by ATCS. $U_m$ is mixture velocity achieved by CCFM. $C_0$ and $n$ represent distribution parameter and droplet size exponent. $U_*$ is defined as the terminal rise velocity of a single oil droplet in the infinitely still water. Through setting different values of $n$ in equation (3), we investigate the distribution of data points of $U_m/(1-Y_o)^n$ and $U_{so}/Y_o \cdot (1-Y_o)^n$ in a 2D plane. For D OS/W, when $n$ is determined as 1.3, data points disperse along a better straight line. Using linear fitting method, the values of $C_0$ and $U_*$ are determined as 1.23333 and 0.08651 m/s. For D O/W and VFD O/W, $n$ is determined as 3.6 and the
values of $C_0$ and $U_{\text{so}}$ are calculated as 0.84734 and 0.13144 m/s. The ultimate expression for drift-flux model in oil-in-water flows is expressed as:

$$\begin{align*}
\frac{U_{\text{so}}}{Y_{\text{m}}} &= 1.23333 \cdot U_{\text{m}} + 0.08651 \cdot (1 - Y_{\text{m}})^{1.3} \quad (\text{D OS/W}) \\
\frac{U_{\text{so}}}{Y_{\text{m}}} &= 0.84734 \cdot U_{\text{m}} + 0.13144 \cdot (1 - Y_{\text{m}})^{3.6} \quad (\text{D O/W and VFD O/W})
\end{align*}$$

(4)

The predicted results of individual superficial velocities are shown in figure 7 and figure 8. As seen, satisfied accuracies are acquired with AAPD smaller than 11.1% and AAD smaller than 0.0047 m/s. It is noteworthy that large predicted deviations mainly distribute at flow conditions with low individual phase superficial velocities which can be associated with the severe slippage effect at low velocities.

**Figure 7.** Prediction on water phase superficial velocity.

**Figure 8.** Prediction on oil phase superficial velocity.

4. Conclusions

Considering severe slippage effect and non-uniform distribution of phases in oil-in-water flows in vertical pipe, ATCS combined with CCFM are utilized for flow measurement. ATCS has high resolution on water holdup and it is not sensitive to non-uniform distribution of phases. CCFM with centre body can enhances the correlation of upstream and downstream signals and reduces the slippage effect, which acquires a better linear relationship between the cross-correlation velocity and mixture velocity. As the drift-flux model takes the phase distribution and slippage velocity into account, high prediction accuracy of individual phase superficial velocity are achieved.

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