Oil-water two-phase flow velocity measurement with Continuous wave ultrasonic Doppler

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Abstract. Oil-water two-phase flow exists widely in many industries. Accurate measurement of flow velocity is of significance for quantify the volume or mass flow rate as well as monitor the operation safety. A non-intrusive one-side Continuous Wave Ultrasonic Doppler (CWUD) sensor is presented for measuring the overall superficial velocity of oil-water two-phase flow. The one-side CWUD sensor consists of two-chip transducer with resonant frequency of 1MHz, both of which are installed at the bottom of test pipe, and the sample volume cover the whole radial direction of pipe cross-section. The Doppler shift signal collected by ultrasonic sensor is directly related to the average velocity of dispersed phase within the sample volume of CWUD. The overall superficial flow velocity is derived by a linear correction of measured average velocity, based on the analysis of average Doppler shift properties in different flow conditions, i.e. water continuous flow and oil continuous flow. Dynamic experiments were conducted at a horizontal oil-water two-phase flow loop. It can be found that the average Doppler shift within the sample volume increases with overall superficial flow velocity, however, varies with different continuous phases at the same overall superficial flow velocity. The results show that the mean relative error of overall superficial flow velocity is 3.45%.

1. Introduction
Oil-water two-phase flow is common in many industries, for example, the extraction, transportation and storage of petroleum industry, energy industry, and chemical industry. The significant differences of density and kinematic viscosity between oil and water and the change of phase velocity, phase fraction can affect the flow condition [1]. The complex flow structure and slip between two phases make it difficult to accurately measurement flow velocity. Many methods have been applied to measure flow velocity, such as differential pressure method, cross-correlation method, ultrasonic method, et al.

With the development of ultrasonic technique, ultrasonic Doppler method has been gradually used in two-phase flow velocity measurement based on Doppler Effect and the advantage of simple structure, low cost and non-invasion. Luebbert verified experimentally that it is a useful method for measuring local bubble velocities in bubble column reactors, demonstrating the applicability in real two-phase flow. The ultrasound velocity profile (UVP) monitor was firstly developed based on pulse wave [2], which has an ability of measuring velocity profile along a measuring line. It was applied to measure vertical low velocity oil-water flow in big-diameter pipe [3], and found that the change of phase fraction may bring measuring error. Nguyen measured the bubbly two-phase flow in vertical pipe using multi-wave UVP. Murai extend ultrasonic pulses method for movement detection of gas-liquid interfaces in two-phase flow [4]. Kouame applied Continuous-Wave Ultrasonic Doppler...
(CWUD) method to measure the flow velocity in low void fraction gas-water flow [5]. Abbagoni used CWUD based on two-chip transducer in gas-water two-phase flow to classify the flow patterns [6]. Since the strong reflection effect between gas and water, most researchers investigate the velocity profile or flow structure of low fraction gas-water two-phase flow in vertical pipe by ultrasonic Doppler sensor, and paid less attention on horizontal oil-water two-phase flow measurement. Dong applied the two-side CWUD method to measure the horizontal oil-water two-phase flow based on drift-flux model [7]. By using the traditional two-side CWUD sensor, only the average velocity of dispersed phase within the fixed local sample volume (located at pipe centre) can be estimated. Hence, the sample volume was then designed to cover the whole radial direction of pipe cross-section by one-side two-chip transducer [8], and the measured Doppler shift is related to average velocity of all bubbles in the sample volume.

This work focuses on applying one-side CWUD to measure overall superficial velocity of oil-water two-phase flow. The dynamic experiments were conducted at horizontal oil-water flow test loop. The average Doppler shift properties within the whole radial direction of pipe cross-section are analysed for different flow conditions and overall superficial flow velocity is then derived by a linear correction of the measured average Doppler velocity. The results show that measured results are good in line with the reference flow velocity.

2. Principle of CWUD

The structure of the one-side CWUD sensor [8] is shown in Figure 1 (a). A two-chip piezoelectric transducer with resonant frequency of 1MHz and diameter of 9mm was installed at the bottom of a horizontal pipe, transmitting and receiving the continuous ultrasound waves at the same time. Each chip adheres on a piece of acoustic coupling material (ACM), and a piece of acoustic insulation material was placed between the two chips for avoiding interference of ultrasound waves. The acoustic coupling material was cut with an inclined angle to make sure the Doppler angle between the ultrasound beam and the flow direction is 60°. Considering the near-field distance and the spread angle of ultrasound beam, the structure of sample volume of this sensor is shown in Figure 1 (b) when pipe filled with water.

![Figure 1. CWUD sensor structure and sample volume](image)

In oil-water two-phase flow, the scatters are dispersed droplets, and the frequency difference between the transmitting and receiving wave used to calculate the velocity of the scatters, which is called Doppler shift. Following the Doppler theory and refraction law, the average velocity of droplets $U_{dop}$ in the sample volume can be expressed as:

$$U_{dop} = \frac{C_0 \Sigma f_0}{2 \cos \theta_0 f_0}$$

$$\overline{f_d} = \frac{\int f_0 S_d(f_0) df_0}{\int S_d(f_0) df_0}$$

where $C_0$ and $\theta_0$ demonstrates the sound velocity of ACM and Doppler angel in acoustic coupling material; $f_0$ is the frequency of ultrasound emitted; $\overline{f_d}$ is the average Doppler shift generated by multiple droplets in the sample volume according to Brody’s theory, $S_d(f_0)$ is the power spectrum of Doppler shift, $f_0$ is the frequency shift component.
3. Experiments
The oil-water two-phase flow experiments were conducted at horizontal oil-water flow test loop of Multiphase Flow Laboratory. The transport pipeline is manufactured of steel tubing with an inner diameter of 50mm. The observed flow patterns include ST&MI, o/w, w/o flow, Dw/o&Do/w and Do/w&w. The range of overall superficial velocity is from 0.15 to 3.17 m/s and the water holdup changed from 4% to 96%. Besides, a set of quick shutting valves (QSV) was used to calibrate water holdup exactly. All the experiment points are marked in Figure 2, plotted against Trallero’s flow map. In each experiment point, the Doppler shift signal is collected for 10 seconds and the sampling frequency is set as 50 kHz to ensure the sampling precision and resolution.

![Figure 2. Experiment Points.](image)

![Figure 3. Average Doppler shift distribution.](image)

4. Average Doppler shift analysis and Results

4.1. Average Doppler shift analysis
The Doppler shift signal of each experiment point was processed by using frequency spectrum analysis (fast Fourier transform, FFT), and average Doppler shift \( f_d \) was calculated through the weighted average power spectrum. Then, the average velocity of droplets within the sample volume can be obtained. Figure 3 shows the relationship of average Doppler shift \( f_d \), overall superficial flow velocity \( J \) and water holdup. The average Doppler shift increases with \( J \) and varies with different flow patterns in two major linear relationships (line-A and line-B). Combined with the holdup information, it can be found that the water holdups of experiment points gather around line-A are almost lower than 30%, in contrary, higher than 30% around line-B. Based on experimental investigations, phase inversion occurred when water holdup changes from 15% to 30% in oil-water two-phase flow [1]. When water holdup is less than 30%, usually oil dominates and forms oil-continuous flow, otherwise, water-continuous flow. Hence, these two major linear relationships in Figure 3 represent the oil-continuous flow and the water-continuous flow respectively, and the corresponding results of average velocity of droplets \( U_{dop} \) are shown in Figure 4. When \( J \) is the same, the \( f_d \) or \( U_{dop} \) in the oil-continuous flow is faster than that in water-continuous flow.

Previous study concluded that the Doppler shift was produced by the accumulation of each moving scatter in the sample volume and it is a synthetic frequency response of these droplets movement, so the structure of sample volume directly related to the measured Doppler shift. Besides, the velocity profiles of water oil-continuous flow and oil-continuous flow are different [7] and their actual velocity profiles will deform with the changes of Re number, phase fraction, flow velocity and flow pattern [9], which leads to a non-axisymmetric velocity profile in most cases. As a result, although the sample volume of one-side CWUD covers the whole radial direction of pipe cross-section, the phenomenon in Figure 3 still exist, i.e. the average velocity or average Doppler shift in this sample volume in the oil-continuous flow is faster than that in water-continuous flow when the overall superficial velocity is the same.
4.2. Results

As shown in Figure 4, using linear fitting, the linear correlations between average velocity $U_{dop}$ and overall superficial velocity $J$ in water-continuous flow is $J=1.18U_{dop_{wc}}+0.18$ and in oil-continuous flow is $J=1.15U_{dop_{oc}}$. Therefore, the overall superficial flow velocity $J$ can be derived by a linear correction of measured average velocity of droplets $U_{dop}$. The result of overall flow velocity measurement and relative error distribution of oil-water two-phase flow are shown in Figure 5. The root mean squared error (RMSE) of $J$ is 0.02m/s. The mean relative error for all experiments is 3.45% and the confidence probability of relative error in 5% is 72.31%.

5. Conclusion

A non-intrusive one-side Continuous Wave Ultrasonic Doppler (CWUD) sensor is used for the overall superficial velocity measurement of oil-water two-phase flow. The sensor consists of two-chip transducer and the sample volume cover the whole radial direction of pipe cross-section. The average velocity of dispersed phase within the sample volume can be directly calculated from the collected Doppler shift signal. The overall superficial flow velocity is derived by a linear correction of the average velocity based on the analysis of average Doppler shift properties in water continuous flow and oil continuous flow. Dynamic experiments were carried out at horizontal oil-water two-phase flow loop. The results show that the RMSE of overall superficial velocity is 0.02m/s, mean relative error is 3.45% and the confidence probability of relative error in 5% is 72.31%.

6. References

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