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Cross-correlation velocity measurement of horizontal oil–water two-phase flow by using parallel–wire capacitance probe

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ABSTRACT

Horizontal oil–water two-phase flow widely exists in petroleum industry. The flow measurement in oil well, which is one of key production logging technologies, is becoming more and more important for horizontal well production management. The complicated flow structures happened in horizontal oil–water two-phase flow bring a great challenge to flow measurement. We employ a parallel–wire capacitance probe (PWCP) to compose the cross-correlation velocity measurement. Firstly, we investigate the distribution of sensitivity field of PWCP by using finite element method (FEM). Then, we carry out the flow loop test to figure out the cross-correlation velocity from the voltage fluctuation signals measured from upstream and downstream probes. The results indicate that the cross-correlation characteristic of PWCPs depends on the oil–water flow structures. Finally, we use the kinematic wave model to predict the homogeneous velocity for six different horizontal oil–water two-phase flow patterns.

1. Introduction

The flow measurement in horizontal oil–water oil well is of great importance for optimizing oil reservoir performance. As reported by Trallero et al. [1,2], there primarily exist six different flow patterns including stratified flow (ST), stratified flow with mixing at interface (ST&MI), dispersion of oil in water and water flow (DO/W&W), dispersion of water in oil and oil in water flow (DW/O&DO/W), dispersion of oil in water flow (DO/W) and dispersion of water in oil flow (DW/O). However, the complex phase distribution and slip phenomenon between oil and water phases [3–7], as often happen in such complex flows bring a great challenge on the flow rate measurement of horizontal oil–water two-phase flows.

In early studies, the Venturi meter and orifice plates have proven to be an effective flow measurement where a significant pressure drop can be detected [8–14]. However, the interpretation of the pressure drops is ambiguous when the velocity slip occurs at the throat of Venturi tube [10]. Moreover, the turbine flowmeter has often been used in multiphase flow measurement [15–17], but the calibration operation of turbine flowmeter should be repeatedly executed with respect to the blade internal friction.

The cross-correlation technique is frequently used for velocity measurement of multiphase flows. By using the probe to measure fluctuations at two points in mixture flow, which are axially separated by a short distance, the total velocity can be determined by using cross-correlation [18]. Yang and Beck [19] designed a direct cross-correlator used for pipeline flow velocity measurement. Xu et al. [20] developed the pulsed ultrasonic cross -correlation flowmeter and pointed out its advantages in measuring the dynamic flow characteristics of two component gas–liquid mixtures. Worch [21] combined the correlation techniques and ultrasonic clamp-on techniques to measure the average velocity of the dispersed phase in two-phase flow, and confirmed the systematic errors arise from flow profiles and slip appearance between particles and carrier fluid. Some researchers also presented their achievement about the cross-correlation flow meter based on the ultrasonic technology [22–24]. Gurau et al. [25] used the cross-correlation of signals from a double sensor hot-film probe to measure the velocities of air–water two-phase flow. Takashima et al. [26] presented the principle and experimental results of a cross-correlation flowmeter using fiber Bragg grating sensors, and shown the better linear characteristic of the flowmeter at velocity range from 0 to 1 m/s.

Meanwhile, the electrical methods have also been widely used in measurement of cross-correlation velocity due to its simple operation and fast response. Baker Atlas Corporation proposed Multi-Capacitance Flowmeter (MCFM) which uses capacitance array to calculate cross-correlation velocity and measure individual phase volume fraction according to the different dielectric constant of oil and water [27]. Ohira et al. [28] placed capacitance-type densimeters at two locations along the piped flow to measure the density and the flow velocity of two-phase solid–liquid cryogenic fluid, simultaneously. Lucas et al. [29] optimized a local six-electrode conductivity probe which can be used in solids–water pipe

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flows to measure the local solid volume fraction and the local solids axial velocity.

Some researchers attempt to use the wire-type sensor to measure the flow characteristics in two-phase flows [30–33]. To our knowledge, the wire-type electrode based on the electrical method is seldom used in cross-correlation flow measurement except for the application of the wire-mesh sensor used by Manera et al. [34] and Kanai et al. [35]. Generally, the wire-type capacitance probe probably has the advantages in capturing the local flow characteristics owing to their directly immersing into the fluid. In considering of complex flow structure in horizontal oil–water two-phase flows [36], we propose a novel parallel–wire capacitance probe (PWCP), which consists of a pair of metal wire electrodes coated with Teflon layer, to compose the cross-correlation flowmeter. Using finite element method (FEM), we first investigate the sensitivity field of the PWCP. Then, we carry out the flow loop test in horizontal small diameter pipe, and present the cross -correlation characteristics, i.e., the relationship between cross-correlation velocity and homogeneous velocity of the mixture, of PWCP under six flow patterns. Finally, we employed the kinematic wave model to predict the total flow rate of oil–water two-phase flow. The results show its advantages in flow measurement of complex fluid flows.

2. Sensitivity field of the PWCP

The PWCP consists of a pair of metal parallel–wire coated with Teflon layer, and is inserted into the flow pipe along the radial section direction. The sketch of PWCP is shown in Fig. 1, in which E_1 and E_2 represent the electrodes, l is the separation between two electrodes, d is the diameter of the metal parallel–wire, and t is the thickness of the Teflon layer.

In the calculation of the two-dimensional PWCP sensitivity field, we employ the element sensitivity to describe the degree of the capacitance change which is brought about by the permittivity change of the subdomain [37]. Accordingly, for the whole measurement field, the distribution of element sensitivity forms the sensitivity field. In order to access to the spatial sensitivity distribution of the capacitance sensor, we can place a test 'particle' into the measurement field and calculate the capacitance change causing by the presence of the test 'particle'. In the calculation, the dielectric of the test 'particle' is set as much different with its surrounding liquid. Through repeating the operation at every specific test position of the measured field, we can obtain the sensor sensitivity field in which the element sensitivity S_k can be defined as

$$S_k = \frac{C_k - C_o}{C_w - C_o} \quad k = 1, 2, \ldots N \tag{1}$$

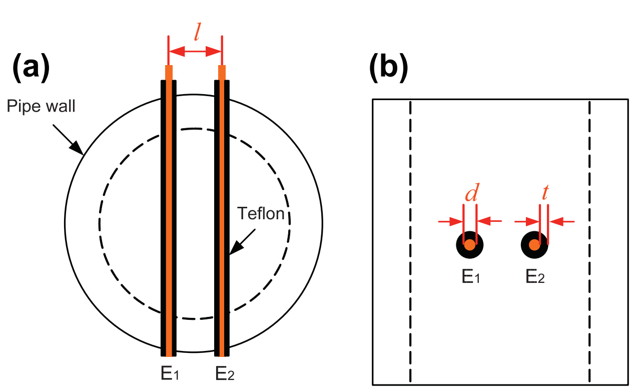

Fig. 1. The sketch of the PWCP: (a) radial section of the pipe and (b) axial section of the pipe.

where C_k is the calculated capacitance with the test 'particle', i.e., spherical water droplet, C_w and C_o are the calculated capacitance for pure water and pure oil, respectively, and N is the total number of the test positions.

In the calculation we set the diameter of the test 'particle' as 0.5 mm. Meanwhile, the relative permittivities of water and oil are respectively set as 80 and 2.1, and the relative permittivities of pipe wall and Teflon are respectively set to be 4.0 and 2.5. It is worth noting that the test 'particles' are located on the two-dimensional radial section and contacted tangentially with each others near the electrodes. The total number of the test positions N is set as 1556.

The following Figs. 2–4 show the effect of the PWCP geometry on its sensitivity field at the axial section of the pipe. In Fig. 2 is obvious that the regions around the electrodes show relatively high sensitivity, while away from the electrodes the sensitivity tends to be quite low. In addition, the maximum of sensitivity is less affected by the distance between the electrode, and with the increase of the distance between the electrodes the sensitivity gradually decreases. In Fig. 3, we can see that around the electrodes the sensitivity greatly reduces down with the metal wire diameter increasing. Conversely, as shown in Fig. 4, the sensitivity near the electrodes shows increase tendency with the thickness of Teflon layer increasing. In general, small distance l can partly increase the sensitivity at the region between the electrodes, and small-diameter metal wire d and large-thickness t of Teflon layer can partly enhance the sensor local sensitivity.

In our experiment we choose the distance l as 5 mm due to the fact that small distance between the exciting and measuring electrodes can increase the area of high sensitivity and make the capacitance value much larger and easy to detect.

However, it should be noted that if the diameter d of metal wire is too small, the compressional deformation of the electrode would happen when the total flow rate is large. Furthermore, the probability of liquid droplet touching the electrode is very low. This case can reduce the degree of the cross-correlation in the sense that the PWCP is used to capturing the local flow structure near by the electrodes. Also, the capacitance value between the electrodes with small diameter will be much smaller which brings about a lot of troubles in the conditioning circuit design and reduces the signal to noise ratio of sensor response. Thus, there should be a compromise in the choice of the diameter of the metal wire. In our manuscript the diameter d is set as 0.8 mm.

In addition, large-thickness t of Teflon layer can make the electrodes contaminated easily, and bring about the unpredictable measurement error. Also, the large-thickness of Teflon layer makes the capacitance value of the sensor much smaller, and brings about troubles in the conditioning circuit design. Thus, the large-thickness of Teflon layer is set as 0.05 mm through balancing the sensitivity and the measurement accuracy.

Generally, for the complex horizontal oil–water two-phase flows, a 'local structure' is time-varying and dependant on the flow conditions. This means that the cross-correlation flowmeter with large scale geometry usually has limitations in capturing the instantaneous 'cross-correlation' structure, especially for the very small scale case. Interestingly, the region near the electrodes of the PWCP proposed in our study has higher sensitivity which can greatly improve the performance of PWCP for capturing the microscopic structure of the fluid. Additionally, the concentrated distribution characteristic of the PWCP can effectively avoid the 'cross-talk' from upstream and downstream. In this regard, the flowmeter composed by the PWCP has potential advantages in the cross-correlation velocity measurement of two-phase flow, especially for the horizontal oil–water two-phase flow with complicated and changeable 'local structure'.