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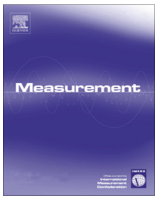

Liquid holdup measurement in horizontal oil–water two-phase flow by using concave capacitance sensor

Zhao An, Jin Ningde *, Zhai Lusheng, Gao Zhongke

School of Electrical Engineering and Automation, Tianjin University, Tianjin 300072, China

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ABSTRACT

Due to the complex flow structures of horizontal oil–water flows, the liquid holdup measurement is still a challenging problem. In this paper, we using the finite element analysis build a two-dimensional model of the concave capacitance sensor and investigate the effect of sensor geometry on the distribution of the sensitivity field. Through calculating the sensor static response for different horizontal oil–water flow patterns, we figure out the optimum geometry of the concave capacitance sensor. In addition, we conduct experiment to obtain the measured response of the concave capacitance sensor and achieve the oil-holdup by using quick closing valve. The results indicate that the optimized concave capacitance sensor shows good performance for liquid holdup measurement of horizontal oil–water two-phase flow.

1. Introduction

Horizontal oil–water two-phase flow widely exists in petroleum industry. The measurements of flow parameters are of great importance for the optimization of industrial production process. The electrical methods are widely used in two-phase flow measurement due to its simple operation and fast response. Taking advantages of the different permittivity values of fluids, the capacitance method is of great significance in the phase volume fraction measurement of two-phase flows.

In early studies, much work has been systematically carried out in phase volume fraction measurement of two-phase flow by using capacitance sensor. It was found that concave capacitance sensor had a higher sensitivity for void fraction measurement in two-phase flow [1–3]. Especially, Xie et al. [4] comprehensively investigated the sensitivity distribution of concave capacitance sensor by using two-dimensional finite element model, and indicated that the pipe wall thickness is one of the predominant factors that great influence the sensitivity variation. Kok et al. [5] designed a capacitance sensor in a rod-bundle geometry for void fraction measurement by using a new design criterion. Tollefsen and Hammer [6] investigated the effect of electrode helical angle on the response of capacitance sensor in terms of the linearity in void fraction measurement.

More recently, Caniere et al. [7,8] identified different flow patterns in time and frequency domain by using concave capacitance sensor. Guo et al. [9] using their designed software investigated the model of production profile interpretation for horizontal wells and obtained good results. Ye et al. [10,11] used the finite element analysis to optimize the structure of double helix capacitance sensor, and pointed out that the helical capacitance sensor demonstrates a good linearity and adaptability for the void fraction measurement of gas–liquid two-phase flow in a small diameter pipe. Foletti et al. [12] experimentally investigated the pressure drop and the elongated bubble dynamics in horizontal very-viscous-oil/air flow by using the capacitance probes. De Kerpel et al. [13] proposed a calibration method for void fraction measurement by using concave capacitance sensor in liquid–vapor flow. Teniou and Meribout [14] presented a novel signal-processing algorithm for capacitance sensor.

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* Corresponding author. Tel.: +86 22 27407641.
E-mail address: ndjin@tju.edu.cn (J. Ningde).

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Additionally, some researchers focused their research on the effect of the conductive water on the response characteristics of capacitance sensor. Demori et al. [15] designed a sensor system to measure the oil holdup for horizontal oil–water two-phase flow. The designed system decreases the coupling between conductive water and outside of the measurement region. For different flow patterns, the measured oil holdup well agrees with the quick closing valve. Strazza et al. [16] proposed a modelization to solve the problems induced by the tap water conductivity and presented a concave electrode sensor system for holdup measurement in oil/conductive-water flow. Based on the works mentioned above, we stress that Ye et al. [11] optimized the geometry of the double helix capacitance based on the FEM and obtained better sensor response in flow regions of conductive water contacting with the pipe, but the principal factor causing the high sensitivity is the large range of the edge guarding electrodes that can reduce current losses rather than the other optimized sensor parameters. Besides, Golnabi and Sharifian [17] using a capacitance sensor of novel geometry investigated the electrical properties of different types of water with the change of driving frequency.

Despite many attempts to measure the two-phase flow parameters by using capacitance method, it has still been a challenging topic in the liquid holdup measurement of horizontal oil-water two-phase flows with respect to the very complicated flow patterns encountered. Trallero et al. [18] classified the flow patterns into segregated flow and dispersed flow, in which the segregated flow includes stratified flow (ST) and stratified flow with mixing at interface (ST&MI), the dispersed flow includes dispersion of oil in water and water flow (D O/W&W), dispersion of water in oil and oil in water flow (D W/O&D O/W), dispersion of oil in water flow (D O/W) and dispersion of water in oil flow (D W/O). Up to now, investigations on the measurement of void fraction in horizontal oil–water two-phase flow by using concave capacitance sensor are quite limited except for the works of [3,15,16]. Furthermore, in early study, the flow patterns encountered in horizontal oil–water two-phase flow pipe are oversimplified, and the response of concave capacitance sensor has never been systematically investigated for all six flow patterns proposed by Trallero et al. [18].

In this study, the mini-conductance array probes have been used to indentify the flow patterns occurred in the flow loop test for horizontal oil–water flows. Meanwhile, the response of concave capacitance sensor is obtained for each flow condition, and the actual liquid holdup is achieved by using the quick closing valve technology. The measured results show that the concave capacitance sensor has good sensitivity and resolution in the liquid holdup measurement of dispersion of water in oil flow (D W/O) and partial dispersion of water in oil and oil in water flow (D W/O&D O/W), whereas the sensor shows its limitations in the liquid holdup measurement of dispersion of oil in water flow (D O/W) and dispersion of oil in water and water flow (D O/W&W) in terms of low sensitivity. Note that the poor response of concave capacitance has also been certified by Strazza et al. [16] when the conductive water is the only one phase in contact with the pipe wall.

2. Two-dimensional sensitivity field of concave capacitance sensor

2.1. Characteristic parameter of sensitivity field

The concave capacitance sensor consists of exciting electrode, measuring electrode, guard electrode and the screen. The structure of sensor is shown in Fig. 1, in which θ is the angle of measuring and guard electrode, L is the length of exciting and measuring electrode, L_g is the length of guard electrode, L_c is the distance between guard electrode and measuring electrode, L_{cs} is the length of the screen, R_1 and R_2 are respectively the inner and outer pipe radius, and R_3 is the radius of outer screen. The electric field is formed between exciting and measuring electrode where an AC excitation voltage is adopted. The above parameters and the pipe wall permittivity ε_{pw} and the screen permittivity ε can affect the sensitivity distribution of the electric field. Because of the complicated nature, it is rather difficult to establish a function to describe the relationship between the sensor output and sensor parameters. Thus, we apply the finite element analysis to optimize the geometry of concave capacitance sensor. In the finite element calculation, we first investigate the affection of electrode angle on the sensitivity distribution, and then calculate the sensor responses under different flow patterns in horizontal oil–water two-phase flow.

For a given dielectric distribution, electrodes configuration, and boundary conditions, the potential inside the screen can be calculated by solving Poisson's equation:

$$\nabla^2 \varphi = -\frac{\rho}{\varepsilon} \tag{1}$$

In the two-dimensional electric field:

$$\frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} = -\frac{\rho(x,y)}{\varepsilon(x,y)} \qquad \varphi = \varphi(x,y) \tag{2}$$

In the three-dimensional electric field:

$$\frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} + \frac{\partial^2 \varphi}{\partial z^2} = -\frac{\rho(x,y,z)}{\varepsilon(x,y,z)} \qquad \varphi = \varphi(x,y,z) \tag{3}$$

where φ represents the space potential distribution function, ρ is the space charge density, ε denotes the space permittivity distribution function. If there is no free charge in the measurement field ($\rho = 0$), the Eq. (1) can be given as:

$$\nabla^2 \varphi = 0 \tag{4}$$

Thus, based on the Gauss law, we can obtain the capacitance value by using the finite element method.

Since permittivity change in any subdomain of the measurement field will cause a change of the capacitance value between the electrodes, we can employ the element sensitivity to describe the changing degree of the capacitance value resulting from the permittivity change of the subdomain [4]. Accordingly, for the whole measurement field, the distribution of element sensitivity forms a sensitivity field. To access the sensor sensitivity distribution, we mesh the measurement field of the sensor into several small elements by using the finite element method (FEM), in which the sensitivity of element k can be expressed as: