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Water holdup measurement of oil-water two-phase flow with low velocity using a coaxial capacitance sensor

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ABSTRACT

This paper is devoted to measuring water holdup of oil-water two-phase flow with low velocity using a coaxial capacitance sensor. We first investigated the distribution characteristics of the coaxial capacitance sensor via the finite element method (FEM) and optimized its geometry size. Afterward, we carried out a vertical upward oil-water two-phase flow experiment in a pipe with a 20-mm inner diameter (ID) to obtain the responses of four flow patterns: transition flow (TF), dispersed oil-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). The sensor outputs were normalized to equivalent water holdup and compared with the set values from a quick closing valve (QCV) method. Finally, we studied the time-frequency dynamic characteristics of different flow patterns based on the Adaptive Optimal Kernel Time-Frequency Representation (AOK-TFR) algorithm to further analyze the evolution of oil-water two-phase flow with low velocity. The results show that the coaxial capacitance sensor can be effectively applied in the measurement of water holdup under moderate and low water-cuts as well as uncovering discrepancies regarding different flow patterns.

1. Introduction

Oil reservoirs with low permeability and low fluid productivity are commonly encountered in China, most of which are characterized by low velocity due to long-term water flooding. Considering the inhomogeneous local concentration and velocity profile of a dispersed phase, especially the severe slippage effect between water and oil phase with low velocity, it is difficult to measure water holdup in oil-water two-phase flow. Realizing water holdup measurement is of great significance to comprehensively understand the production characteristics of oil-water flows with low velocity and optimize the production profile well logging technology.

Capacitance sensors are seldom affected by conductivity and also possess a high measurement sensitivity. This presents a unique advantage in measuring the water holdup in oil-water two-phase flow. Generally, capacitance sensors can be classified as either non-invasive or invasive. The measurement principle of non-invasive capacitance sensors was a research focus of early studies [1–3] and has been proved beneficial for designing capacitance sensors. Besides, some scholars investigated the effect of the geometric structure of non-invasive capacitance sensors on their measurement characteristics [4–10]. Recently, 3D capacitance tomography systems have been widely utilized to visualize and uncover the flow regime and concentration distribution of multiphase flows [11,12]. With the progress of electrical engineering, the measurement circuits for capacitance sensors are also constantly developing and improving [13–15].

In contrast to non-invasive capacitance sensors, invasive sensors can improve sensitivity and response speed due to the direct contact with fluid. With regard to higher flow velocities (0.3686–2.2116 m/s), Liu et al. [16] investigated the correlation between the responses of coaxial capacitance sensor and water-cut. The results demonstrated that the areas with high sensitivity mainly distribute near the inner electrode. Ye et al. [17] designed a capacitance sensor consisting of inner and outer rings. The sensitivity and uniformity error were selected as the criteria in the optimization process. Currently, capacitance wire-mesh sensors have been proved effective in visualizing phase distribution and widely applied in the investigation of multiphase flows [18,19]. Additionally, some researchers measured the liquid holdup in horizontal oil-water two-phase stratified flow using a capacitance wire sensor [20–22]. However, there is limited literature reporting the distribution characteristics of sensitivity field and geometry parameter optimization regarding coaxial capacitance sensors. Research focusing on the responses of coaxial capacitance sensors under low mixture velocity is also deficient.

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Based upon the advantages that a finite element method presents in guiding the optimal design of sensors [23,24], we first investigated the electrical sensitivity distribution of a coaxial capacitance sensor and the effect of oil bubble size on the response characteristics to optimize its geometry parameters. By performing a vertical upward oil-water two-phase flow experiment in a pipe with a 20-mm inner diameter, the responses of the coaxial capacitance sensor under various flow patterns were obtained. The outputs were then normalized to equivalent water holdup and compared with the set values from a quick closing valve (QCV) method. Finally, the time-frequency characteristics of different flow patterns were explored using an AOK-TFR algorithm. The results show that the coaxial capacitance sensor presents a satisfactory resolution of water holdup measurement under moderate and low water-cuts and can be effectively applied in the investigation of discrepancies regarding different flow patterns.

2. Measurement principle

2.1. Structure of coaxial capacitance sensor

The structure diagram of the coaxial capacitance sensor is shown in Fig. 1(a). It consists of two parts: an inner electrode and an outer electrode. The surface of the inner electrode located at the pipe center-line is coated with an insulation layer (Teflon), and the outer electrode encircles the inner surface of the pipe. The structure parameters to be optimized are presented in Fig. 1(b), including electrode length (l), thickness of the insulation layer (t), diameter of the inner electrode (d) and inner diameter of the outer electrode (D). Detailed geometry optimization of the coaxial capacitance sensor will be present in the following sections.

2.2. Geometry optimization of coaxial capacitance sensor

The three-dimensional finite element model of the coaxial capacitance sensor was established using ANSYS software. The inner diameter and outer diameter of the pipeline were set as 20 mm and 30 mm, respectively. A three-dimensional 10-node tetrahedron element named PLANE123 was selected as the element type with a total number of 131,630. In the simulation process, the relative dielectric constant of water and oil was set as 80 and 2.1. The inner electrode was stimulated by 10 V DC voltage, while the outer electrode was connected to the ground.

As for describing the degree that the capacitance changes, a parameter designated as sensitivity is determined by placing a test sphere with a diameter of 1 mm as water phase in the k-th location of the detection field:

$$S(k) = \frac{C(\varepsilon_k) - C(\varepsilon_o)}{C(\varepsilon_w) - C(\varepsilon_o)} \quad k = 1, 2, 3 \ldots N \tag{1}$$

where $C(\varepsilon_w)$ refers to the capacitance value for pure water and $C(\varepsilon_o)$ denotes the capacitance value for pure oil. When a test sphere representing a water bubble is placed in the k-th location of pure oil, the capacitance value changes to $C(\varepsilon_k)$. N corresponds to the number of testing positions.

The result of the sensitivity field with FEM is shown in Fig. 2, where X, Z and S represent the radial position of the pipe, the axial position of the simulation area and sensitivity, respectively. We can see that the peak value of sensitivity mainly concentrates near the inner electrode, while the sensitivity near the outer electrode is almost equal to zero.

We first studied the effect of electrode length l on the sensitivity distribution with the thickness of the insulation layer, the diameter of the inner electrode and the inner diameter of the outer electrode held constant and the corresponding result is shown in Fig. 3(a), where X and S refer to the radial position of the pipe and sensitivity. It can be seen that the sensitivity at each radial position

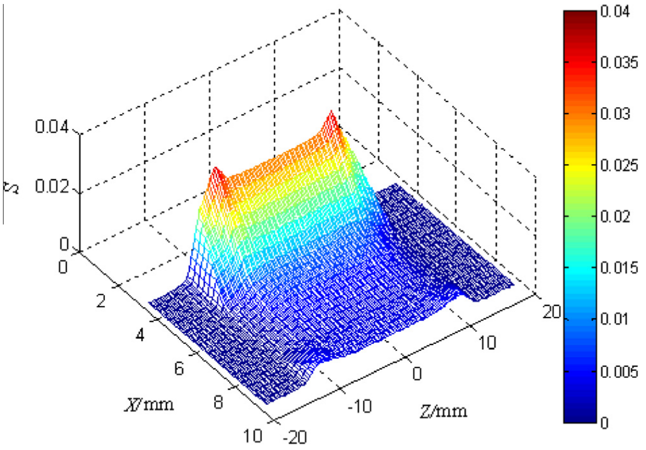
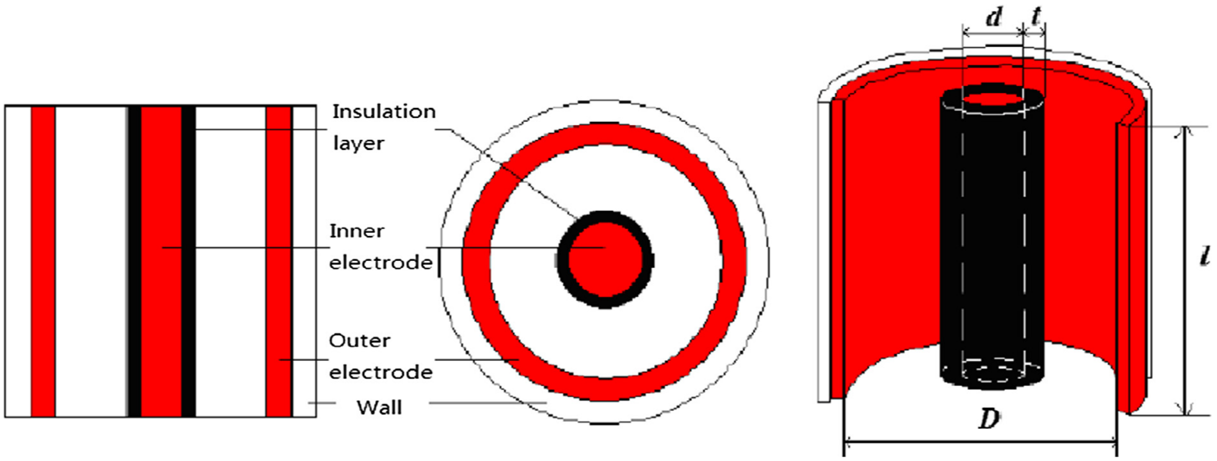


Fig. 2. Sensitivity distribution of the coaxial capacitance sensor (l = 20 mm, t = 0.1 mm, d = 4 mm, D = 20 mm).



(a) Structure

(b) Geometrical dimension

Fig. 1. The structure of the coaxial capacitance sensor.