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Design of a Conductance and Capacitance Combination Sensor for water holdup measurement in oil–water two-phase flow

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ABSTRACT

Oil–water two-phase flow widely exists in the process of petroleum industry. The liquid holdup measurement in horizontal pipeline is very important and difficult. In this work, a Conductance and Capacitance Combination Sensor (CCCS) system with four conductance rings and two concave capacitance plates is designed and validated for its measurement performance of in situ water holdup through dynamic experiments. A set of fast electronic switches controls the conductance rings and the capacitance plates alternatively set up each own sensing field in the same sensing volume. This configuration ensures the water holdup estimation in the range from 0% to 100% regardless of flow direction. A set of quick closing valves was used to acquire the in situ holdup for the on-line calibration of the CCCS system. The theoretical correlations of conductance sensor and capacitance sensor were established to make the real-time measurement convenient. A real-time measurement method by CCCS system is provided based on the fusion of the conductance and the capacitance measurement without flow pattern recognition. This method delivers an average error of 1.06% for the CCCS system measuring the water holdup of oil–water two-phase flow, with a standard deviation of 0.038 and a relative error less than ±5%.

1. Introduction

Oil–water two-phase flow widely exists in nature and industry process, such as production wells and transportation in petroleum industry and chemical industry. For petroleum industry, the real-time phase fraction is important to ensure oil production safety and exploration economy. Therefore, the measurement of phase fraction plays an important role in such cases. Because of the difference of viscosity and density of the oil and the water, the mixture fluid exhibits several flow patterns during the flow process in a horizontal pipe. The flow patterns change with many factors including the flow rate of each individual phase, the phase fraction and pipe diameter [1,2]. Accurate water holdup measurement is therefore affected by the complex flow patterns. Many methods have been developed to measure the liquid holdup, such as quick closing valves [1], radiation sensors [3], microwave sensors [4], wire-mesh sensors, ultrasonic sensors [5,6] and electrical sensors [7].

Quick closing valve (QCV) is a widely-applied technique in multi-phase flow study [1,8], which provides a reliable online calibration of in situ phase fraction. However, it is limited by the non-continuous measurement thus not applicable to measure the instantaneous changes of phase fraction.

The electrical method is widely used in flow parameters measurement due to its simple structure and fast response. The electrical method can be divided into conductance method, capacitance method, impedance method and electromagnetic method based on their sensing principle and different electrical properties of each phase. The conductance method and the capacitance method are the most commonly used for the two-phase flow measurement.

There are many structures of electrical sensors, wire-mesh sensors, as a particular structure of electrical sensors, can obtain phase fraction and phase distribution through capacitance or conductance measurement [9]. Since the wire-mesh sensor is an intrusive sensor, small deformation of the mesh induced by the fluid superficial velocity changes will lead to erroneous results. There are some other sensor structures for recognizing the flow patterns and measuring the water holdup, such as parallel-wire conductivity probes [10], arc-shaped conductance method with the guard electrodes [11,12], conductance probes array [13] and so on.

Many studies have been carried out for the two-phase flow volume fraction measurement by the electrical methods. For conductance method, continuous phase is electrically conductive, and non-continuous phase has a different conductivity from the continuous phase. The phase fraction is obtained by measuring the mixture's conductivity between two sensing electrodes. Fossa

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designed a conductance probe for measuring the liquid fraction in gas–liquid two-phase flows and evaluated its performance. The device consisting of two pairs of electrodes (two ring electrodes and two plate electrodes) was placed on the internal wall of a cylindrical duct and flushed to the pipe surface [14]. Then, Devia and Fossa designed and optimized an impedance probe for void fraction measurement for different gas–liquid flow patterns [15]. Lucas and Mishra proposed a local four-sensor probe to measure the swirl influence for bubble flow in vertical pipe, and analyzed the impedance and time sequence of electronic measurement system [16]. Xu et al. measured the water hold-up of stratified oil–water flow by a conductance array consisting of 24 needle-like electrodes that mounted on 12 supporting arms arising from the central shaft [17]. Zhai et al. numerically designed and optimized the geometry of a ring conductance probe for measuring the conductance of oil–water mixtures in horizontal pipes [18]. Dang et al. used the conductance sensor to measure the flow rate of oil–gas–water three-phase flow [19].

For the capacitance method, the non-continuous phase should have a different relative permittivity compared with the continuous phase [20]. Sami et al. found that a concave-plate capacitance sensor has a higher sensitivity for void fraction measurement in two-phase flow [21]. Huang et al. discussed the conductivity effects on capacitance measurements, and concluded that the conductance effects can be reduced by using semiconductor switches [22]. Xie et al. used finite element model to prove that the pipe wall is an important factor to the sensitivity distribution of the concave capacitance sensor [23]. Jaworek and Krupa increased the excitation frequency up to 80 MHz to solve the capacitance measurement problem when the continuous phase is conductive [24]. Strazza and Demoria obtained the relationship between the accurate phase fraction and the axis length of the capacitance plate for the core-annular oil–water two-phase flow [25]. Ye and Peng suggested an optimal structure of helical capacitance sensor by simulation and experiments for gas–liquid two-phase flow in small diameter tubes [26,27]. Kerpel used the capacitance sensors to evaluate the gas–water two-phase flow behaviors in up and downstream of a sharp return bend [28]. Dos Reis et al. compared the advantages and disadvantages of different capacitance sensors, such as helical electrodes sensor, concave electrodes sensor and double ring sensor [29].

However, in the oil–water two-phase flow, phase inversion happens when water holdup ranges from 0% to 100%. When water holdup is large, water is continuous phase, and oil disperses in the water, and vice versa. Capacitance method can deal with full range holdup measurement with careful configuration of the sensing circuit, but the sensitivity is relatively low for the water continuous flow, especially for high water holdup situation. Conductance method can deal with the high water holdup situation with relatively high sensitivity, but it is incapable to deal with the low water holdup situation. Since capacitance sensor and conductance sensor are sensitive to phase inversion condition, it is necessary to design an electrical method to realize water holdup measurement for full range of oil–water two-phase flow with high sensitivity. Thus a new Conductance and Capacitance Combination Sensor (CCCS) system is presented based on the different sensitivity ranges of capacitance and conductance method. It takes the advantages of the conductance sensor and capacitance sensor in different flow conditions, and measures the water holdup from 0% to 100% with high sensitivity. The measurement complementary information deals with phase inversion, and redundant information and data fusion improve the accuracy of water holdup measurement.

The configurations of both the conductance sensor and the capacitance sensor of the CCCS system have been optimized. The measurement system and control software were designed to realize the fast and accurate acquisition of the conductance and the capacitance data. Theoretical correlations of the conductance sensor and the capacitance sensor have been improved to make the real-time measurement convenient. The CCCS system can measure the full range of in situ water holdup without flow pattern recognition. The installation method and the measurement results are not influenced by the flow direction based on its symmetrical structure. The non-intrusive water holdup measurement method can reduce pressure loss and processing difficulty. Therefore, the CCCS system has application prospect in petroleum industry.

2. Sensor structure

The test section of CCCS is shown in Fig. 1, which consists of four stainless alloy ring-electrodes (conductance sensor) and a pair of copper plates (capacitance sensor). All the electrodes are placed on a Plexiglas pipe of 50 mm inner diameter. The conductance rings and the capacitance plates of the CCCS set up each own sensing field in the same sensing volume alternatively. The switch time is short enough to make sure the fluid condition remains almost the same in the sensing volume during the switches between conductance and capacitance. This structure is non-intrusive and can deal with the incoming flow at either direction.

2.1. Conductance sensor

The four probes conductance sensor is designed to measure the water holdup in water continuous oil–water two-phase flow. The detail of conductance sensor is shown in Fig. 2(a). The ring electrodes are embedded in the inner wall of a Plexiglas pipe, where E1 and E2 are the exciting electrodes; S1 and S2 are the measuring electrodes. In a pipe of 50 mm inner diameter, the distance between E1 and E2 is 200 mm, the distance between S1 and S2 is 60 mm, the distance between E1 and S1, E2 and S2 is 70 mm, the width of E1 and E2 is 5 mm, and the width of S1 and S2 is 3 mm. This configuration has been numerically optimized and experimentally tested in previous work [30].

The measured electrical impedance across an electrode pair immersed in a conducting liquid is resistive when the frequency of the alternating current (AC) exciting signal is high enough (for tap water, 10–100 kHz) [14]. In this system, the conductance electrodes E1 and E2 are connected to a constant electric current signal source that generates a 20 kHz square wave of 2 mA peak-to-peak amplitude (Fig. 2(b)). The electric potential drop increases with the overall resistance between E1 and E2 under the constant exciting current. Therefore, the voltage collected between S1 and S2 (Sensor A) is directly related to the water holdup.

2.2. Concave capacitance sensor

A pair of capacitance electrode is designed to measure water

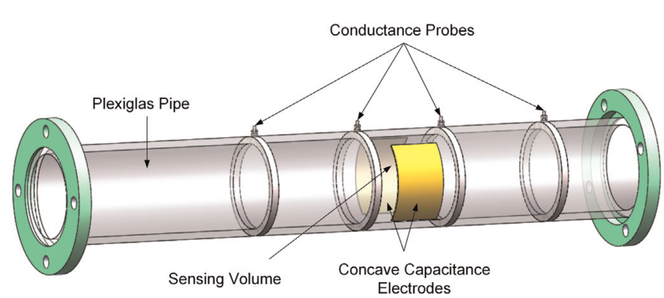

Fig. 1. Structure of Conductance and Capacitance Combination Sensor (CCCS).

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