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2013 Meas. Sci. Technol. 24 125304

(http://iopscience.iop.org/0957-0233/24/12/125304)

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Meas. Sci. Technol. **24** (2013) 125304 (5pp) doi:10.1088/0957-0233/24/12/125304

Online measurement of water concentration of oil–water mixtures in the flow of pipeline by using eddy current method

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Received 7 July 2013, in final form 27 September 2013
Published 12 November 2013
Online at stacks.iop.org/MST/24/125304

Abstract
Measurement of water concentration of oil–water mixtures in a pipeline is important in the oil industry. Capacitance, γ-ray and ultrasonic techniques have been developed for the purpose of water-cut measurement for years. In this paper, we demonstrate a new non-contact method, which uses an eddy current sensor to monitor the flow in a pipeline based on the relationship between the water-cut of the flow and the inductance of the sensor. A simulation model and a simple experiment setup are presented. The experimental results have shown that the measurement error for water-cut over the range of 0–100% is less than 4.5%.

Keywords: eddy current, oil–water mixture, measurement

(Some figures may appear in colour only in the online journal)

Introduction

In the oil industry, it is important to measure online the oil fraction of the fluid being produced from oil wells for the evaluation of well life and oil production optimization. Crude oil usually contains oil, gas and water components, and it is difficult to accurately measure the fraction of each component in flows. For this reason, a number of multiphase flow-meters have been developed based on different strategies and principles [1–6]. During the early years, crude oil was first separated into individual components, and then the flow quantity of each component was measured with a single-phase flow meter. With the development of multiphase flow measurement technology, the pre-separation of the flow is not needed in the latest three-phase flow meter such as the Roxar MPFM 2600 [7]. However, the fully two-phase separation system that separates fluids into liquid and gas phases before measurement is still in wide use, such as the Weatherford Red Eye multiphase metering systems (REMMS) [7].

In a pre-separation system, the phase fraction in liquid is measured with a two-phase flow meter and the gas fraction is passed through a gas flow meter. The gas and liquid streams are recombined together after passing the fluid and gas meters. The advantages of the fully two-phase separation system are the high accuracy and the suitability for all types of flow. In order to measure the phase fractions in oil–water flow, two methods, γ-ray method and electric impedance, are commonly used in industry. The γ-ray method has a stable performance, but the safety problem limits its application. The electric impedance technique relies on the electrical impedance across two capacitance plates, which is a function of the ratio of the two phases. The limitation of the capacitance method is that a short circuit will occur when water concentration in fluid is high, because of the high electrical conductivity of water. In order to overcome the problem of the limited water-cut range, some new methods, including infrared absorption and microwave attenuation, have been developed.

In this paper, a new online measurement method based on the principle of eddy current for water-cut meter in oil–water flows is investigated. The eddy current method is usually used in industry for applications such as displacement

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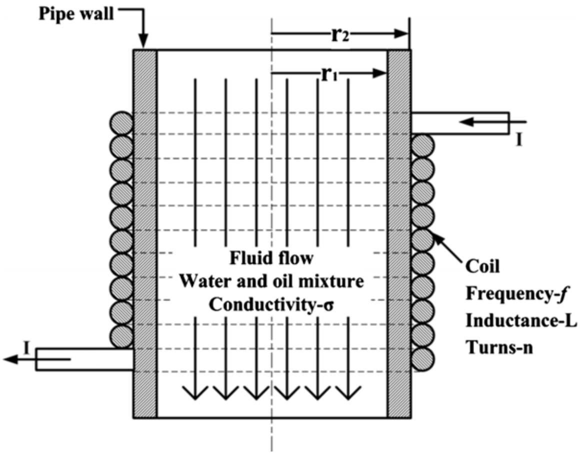

Figure 1. Eddy current sensor on pipeline for water-cut measurement.

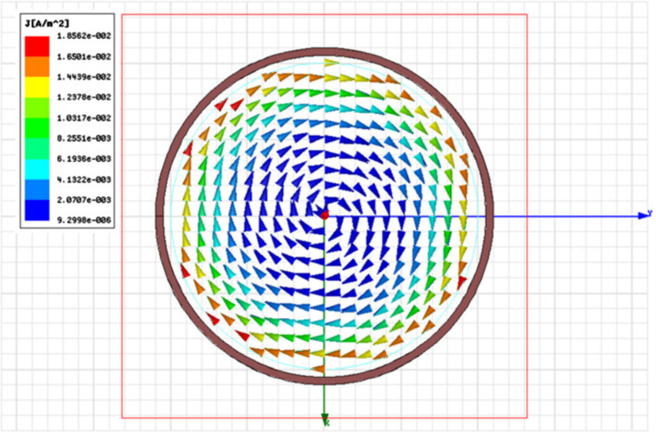

Figure 2. The eddy current distribution in a two-phase flow.

measurement, flaw detection and metal film thickness measurement [8–10]. In the offshore oil industry, Yin *et al* [11] have used an eddy current sensor to determine the water level and the conductivity of process water. The eddy current method is both nondestructive and non-contact. As shown in the experiment below, the water-cut can be measured over the full range of 0–100% with the eddy current sensor, wider than that of the capacitance method. It should be noted that the eddy current sensor, like electrical impedance methods, also requires a stable flow regime in measurement region.

This paper is structured as follows: in the theory section, the principle of the eddy current sensor for water-cut measurement is introduced and a simulation model is established. In the next section, an experimental installation including the sensor, fluid supply system and data acquisition system is described. In the final section, two-phase flows with different water-cuts are prepared and measured. The test results demonstrate the potential applicability of the new method.

Theory

The eddy current method is based on the magnetic field created by a coil sensor. The magnetic field will induce eddy currents in a conductive sample, which can change the inductance of the sensor. In the work to be described here, we consider that oil–water two-phase fluid flows through a pipe, an eddy current sensor is wound on the outside of the pipe to induce a magnetic field and detect the eddy current in the fluid, as shown in figure 1. The inner and outer radii of the pipe are denoted r_1 and r_2 respectively. The work frequency and inductance of the coil are assumed to be f and L, respectively. The number of turns of the coil is denoted by n. σ is the conductivity of the fluid flowing through the pipe.

ANSOFT MAXWELL, powerful electromagnetic analysis software, was used to study the relationship between the sensor parameters and the measurement sensitivity. A simulation model was set up as illustrated in figure 2. The principle of the analysis is to solve the field equation (1), which is derived from the general Maxwell's equations by assuming the relationships $B = \nabla \times A$ and $E = -\nabla\phi - \mathrm{j}\omega A$, where B is the density of magnetic flux, A the magnetic vector and φ electric scalar potential, in the domain of the fluid region with the finite element method:

$$\nabla \times \frac{1}{\mu}(\nabla \times A) = (\sigma + \mathrm{j}\omega\varepsilon)(-\nabla\varphi - \mathrm{j}\omega A). \tag{1}$$

After getting the distributions of A and φ by numerical simulation, the magnetizing field H and magnetic field B can be calculated from A and φ. Finally, the inductance L of the coil can be obtained from the following equation:

$$W = \frac{1}{2}LI^2 = \frac{\varepsilon}{2}\int_\Omega B \cdot H \,\mathrm{d}\Omega. \tag{2}$$

Here Ω denotes the magnetic field region of the sensor. In the simulation model, we assume that the inner and outer radii of the pipe are 48 mm and 50 mm respectively, the material of the pipeline is Teflon, the number of coil turns is 20. The fluid in the pipeline is assumed to be homogeneous with the conductivity ranging from 3.5 to 1.0 S m^{-1} due to different water-cuts. The assumed conductivity is much larger than the real values of crude oils, which will be discussed later in the experiment set up section. The higher conductivity assumption was used because the ANSOFT MAXWELL software is not able to deal with medium whose conductivity is lower than 1 S m^{-1}. Although this will probably lead to simulation results different in magnitude from the real situation, it can predict the tendency of the influence of water-cut. The work frequency of the coil sensor ranges from 1 to 10 MHz and the amplitude of the applied voltage on the coil is 1.5 V.

Figure 2 shows the calculated eddy current distribution on a cross section in the two-phase flow. It can be observed that the eddy current is distributed across the section of the mixture in the pipeline. The inductance of the coil sensor will be changed through the mutual inductance with the eddy current generated in the mixture. The simulation results indicate that the inductance of the sensor will decrease with the increase in the conductivity of the flow, which can be used to detect the water-cut in the fluid. When the work frequency is 10 MHz, the largest sensitivity of the sensor is reached as 0.032 μH per S m^{-1}.

In order to convert the weak change of the inductance of the sensor to a voltage for reading, a conversion circuit based on

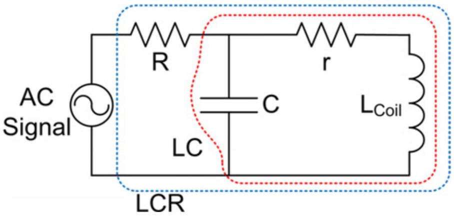

Figure 3. Diagram of the measurement circuit.

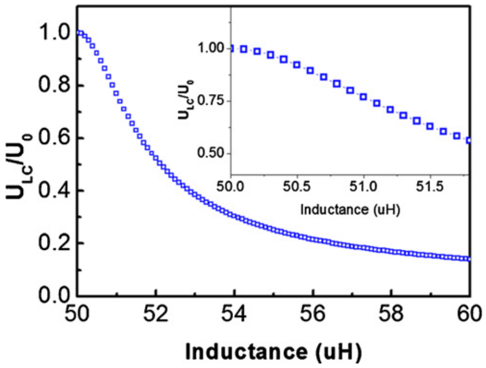

Figure 4. The voltages of LC loop versus inductance of the sensor.

LC oscillation principle is adopted. The schematic of the circuit is shown in figure 3. In this circuit, L_{coil} is the inductance of the coil sensor, r is sensor resistance, capacitance C is parallel with the sensor, R is the divider resistance. U_{LC} represents the voltage of the LC circuit.

The working principle of the circuit is as follows: at the beginning, the LC circuit is in the resonant state under a certain work frequency when only oil phase is in the pipeline. When the oil–water mixture flows in, the conductivity of the flow increases; as a result, the inductance L_{coil} is changed and the LC circuit is detunes. The change in the voltage U_{LC} is amplified to reflect the change of water-cut in the mixture.

The analytical solution for the voltage U_{LC} of the circuit is given as follows:

$$U_{\text{LC}} = U_0 \frac{Z_{\text{LC}}}{Z_{\text{LCR}}}, \tag{3}$$

where the excitation signal U_0 is defined by (4)

$$U_0 = A \sin(\omega t), \tag{4}$$

where A is the amplitude of signal U_0 and ω is the work frequency. The impedance of the LC circuit, Z_{LC}, can be written as

$$Z_{\text{LC}} = \frac{Z_L Z_C}{Z_L + Z_C} = \frac{-\mathrm{j}\frac{1}{\omega C}(r + \mathrm{j}\omega L_{\text{coil}})}{r + \mathrm{j}\omega L_{\text{coil}} - \mathrm{j}\frac{1}{\omega C}}, \tag{5}$$

where C is the parallel capacitance, r the resistance of the coil sensor and L the inductance of the sensor. The impedance of LCR circuit, Z_{LCR}, indicated by the large blue broken line in figure 3 is defined by (6)

$$Z_{\text{LCR}} = R + \frac{Z_L Z_C}{Z_L + Z_C}. \tag{6}$$

In equation (3), U_0 and R are constant, the work frequency is 750 kHz. When the inductance L is 50 μH, the LC circuit is in the resonant state and the voltage of the LC circuit is equal to U_0. The change of the ratio between U_{LC} and U_0 with the bias of the inductance L off the resonant state is shown in figure 4. It is clear that the circuit converts a slight change of inductance to a significant voltage output.

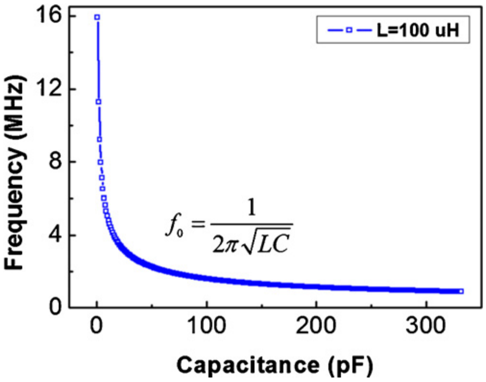

Figure 5. The resonant frequency of the sensor versus different parallel capacitance.

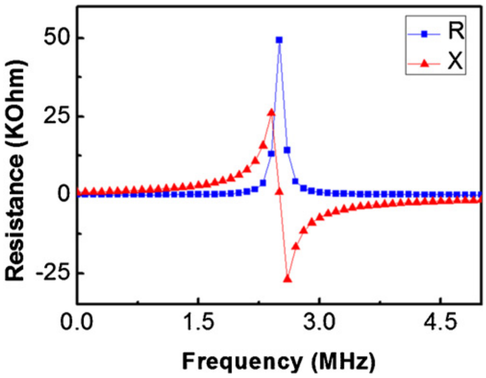

Figure 6. The self-resonance of the sensor.

A higher work frequency is beneficial for increasing the sensitivity of the sensor. However, the work frequency in a resonance circuit is limited by the parasitic capacitance existing in the inductive element. The resonance frequency of an LC circuit can be expressed as

$$f_0 = \frac{1}{2\pi\sqrt{LC}}, \tag{7}$$

where capacitance C is the sum of the parallel capacitor and the parasitic capacitance of the sensor. The resonance frequency versus capacitance curve is plotted in figure 5, showing the rapid decrease in the resonance frequency with the increase in capacitance. In order to reduce parasitic capacitance, we adopt a single-row circular sensor with 20 turns. The self-resonance of the sensor is shown in figure 6, which shows that the actual self-resonance frequency of the sensor is 2.5 MHz.

Experiment setup

A simple flow measurement setup was constructed for experimental investigation of oil–water flow in a vertical pipeline, as shown in figure 7. In the experiment, a sensor with 20 turns wound on a plastic tube was used. The diameter of the pipeline is 40 mm and the length is 300 mm. The length of the test section is 25 mm. The experiment facility consists

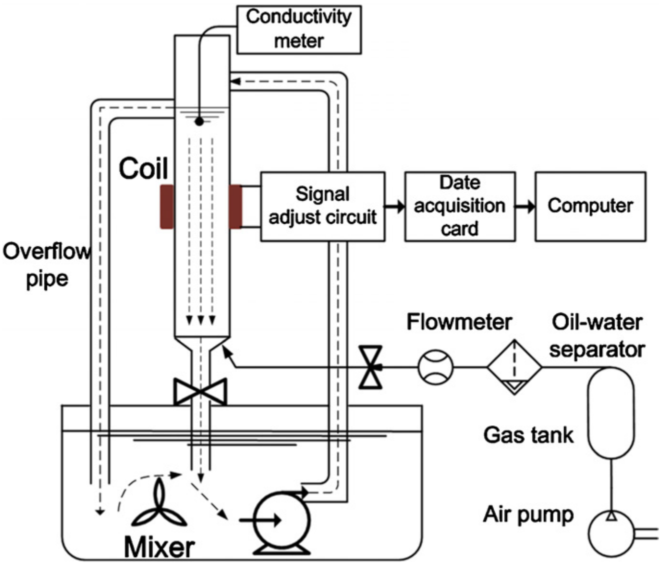

Figure 7. The experimental setup for water-cut measurement.

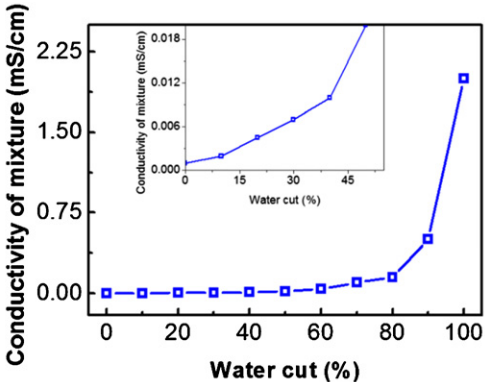

Figure 8. The relationship between the conductivity and water-cut of mixture.

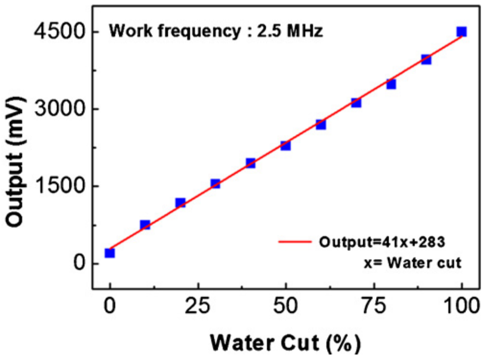

Figure 9. The relationship between water-cut and voltage output.

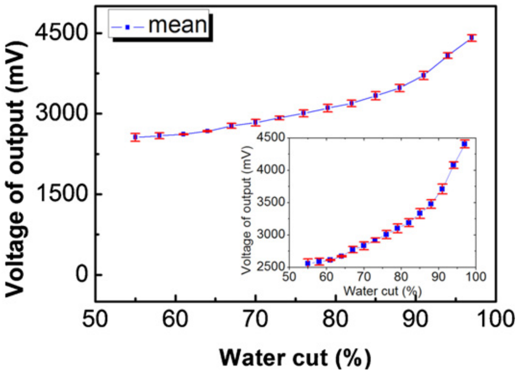

Figure 10. The repeatability error.

of a tank, a fluid support system and a signal process system. This facility can also be equipped with a gas supply unit, but we did not take the influence of gas into consideration in this study. The signal adjust circuit is designed by the authors. The output of the signal circuit is connected to an USB4716 card, which is a 14-bit A/D card from Advantech Company.

As described above, the eddy current method converts the eddy current generated in the fluid to an output voltage. If the conductivity of the fluid is too small, the generated eddy current would be too weak to be detectable. The conductivity of crude oils differs in a wide range with the location and depth of the oil well, mainly depending on the water-cut and the salinity of water in the oil–water mixture. The salinity of crude oils in different oil fields differs from tens of ppm to more than 2.0×10^5 ppm. In our experiment, we added 1000 ppm NaCl into pure water as the model water phase, and mixed with a kind of commercial hydraulic oil (Sinopec [12]). To investigate the dependence of the conductivity of the model oil–water two-phase fluid on the water-cut, we measured the conductivity of the samples with a Con60 conductivity meter (WalkLAB). The results are shown in figure 8. We can see that the conductivity of the sample mixtures increases with the water-cut gradually at first and then sharply when water-cut exceeds 80%.

In experiment, the test samples of oil–water mixtures were put into the tank with specific proportions. After mixing with a high speed mixer, a submersible pump supplied the fluid into the pipeline. The fluid was circulated at a flow rate of 0.5 $m^3 h^{-1}$. The overflow loop on the pipeline determined the level of the fluid; therefore, the flow rate could be stabilized in the test process.

Test results

A series of tests with different water-cuts are performed in the flow loop. The relationship between the voltage output and the water-cut is approximately linear, as shown in figure 9. When the water-cut decreases from 100% to 0%, the voltage changes from 4500 to 0 mV. The sensitivity of the measurement system is about 41 mV per one per cent change in water-cut.

The measurement repeatability results are shown in figure 10, for the water-cut range from 95% to 55%. The test is performed five times for each test condition and the repeatability error is calculated from the differences between the measurements and the average value of the five measurements. The maximum error is less than 4.5%, as shown in figure 10. The discrepancy between figures 9 and 10 is caused by the different mixing time when doing the two experiments.

The stability of this measuring system is shown in figure 11, for the water-cut of 55% as an example. When the fluid is pumped into the pipeline, the output approaches

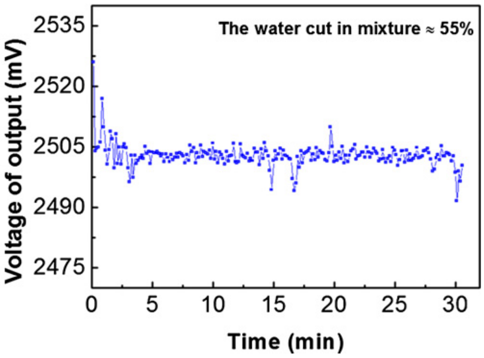

Figure 11. The stability of the measurement system.

a steady value after a short period of decay, and the stability error in the steady stage is less than 0.5%.

Conclusion

In this paper, an eddy current sensor wound on the outside of a plastic pipeline has been designed to measure the water-cut in oil–water mixtures and has been verified by simulations and experiments. The work frequency selected in this facility is 2.5 MHz, which not only satisfies the sensitivity of measurement but also reduces the difficulty of circuit design. An experiment setup has been constructed to verify the design. The measurement results show that the scope of measurement covers the whole range of water-cut in flow and the sensitivity, repeatability and stability of the measurement are reasonable for potential application.

Acknowledgments

This work is supported by the National Basic Research Program of China with the grant no. 2009CB24207 and the National Natural Science Foundation of China (NSFC) with the grant no. 91123033.

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