Study on the Response of the Full-bore Conductance Sensor for Water Cut Measurement

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Abstract. This paper has proposed a new structure of full-bore conductance sensor, which is designed for measuring water cut of the oil-water two-phase flow. The structure of the full-bore conductance sensor and the measurement principle are introduced in the paper. The mental ring-shaped electrode is mounted on the outside wall of the cylindrical insulation body. When the electrode is provided with constant current, according to the electrical theory, the electrode generates a voltage, the value of which is inversely proportional to the conductivity of fluid flowing between the sensor and the casing.

The electrostatic field simulations of the sensor are accomplished by using ANSYS software. The results of the potential distribution simulation show that the potential decays quickly from the electrode along r direction (radial) and z direction (axial) to both sides, and the potential only distributes in a very narrow area near the electrode.

A series of static experiments on the sensor are carried out in laboratory. The experiment results agree with the simulation results. In radial direction, the closer the rod is to the sensor, the more sensitive the sensor becomes and the greater the relative response becomes. In axial direction, the electrode only responds in a certain region on both sides of the electrode and decays rapidly from the electrode to both sides.

And the salinity experiment is conducted in salt solution (3000 ppm), which shows that within the allowable range of experiment error, there is no effect of salinity on the sensor response.

1. INTRODUCTION
As an important part of production logging, production profile logging mainly monitors production rate and measures water content of each production layer in an oil well to estimate the exploitation effects of various types of oil layers, so as to provide a reliable basis for water plugging and readjustment of injection-production strategy. In China, most oilfields are developed with multilayered...
exploitation technique and zonal injection method. Therefore, it is important to learn about the flow rate and water cut of each layer with logging tools (Wang Peilie et al., 2001, Liu Xingpu et al., 1999). In China, two-parameter logging tools have been developed for production profile logging, in which a spinner sensor is used for measuring flow rate and a capacitance sensor for water cut. To overcome the shortcoming of the capacitance sensor which will lose resolution with high water cut, Daqing Logging & Testing Services Company has produced a kind of conductance water cut meter, based on packing method, which appears more preferable with high water cut and has widely used in low-production wells. A packer can mix the two phases more sufficiently, so as to decrease the effects of two-phase slippage and the uneven spatial distribution of dispersed phase. But, this method may change the flow regime and is not adaptive for high-production wells, can not complete the continuous measurement. The full-bore measurement method can overcome above shortcomings and fulfill the continuous measurement of water cut in high-production wells with less impact on the flow state.

2. MEASUREMENT PRINCIPLE OF FULL-BORE CONDUCTANCE SENSOR

The conductivity of the two-phase fluid composed of continuous conductive phase and dispersed non-conductive phase mainly depends on the conductivity of the continuous phase and the volume content (holdup) of the continuous phase, also it is influenced by the spatial distribution of the dispersed phase. Maxwell proposed an analytical model in 1881: When small solid non-conductive particles, small gas-bubbles or small oil-bubbles are distributed uniformly in continuous conductive phase of which the conductivity is \( \sigma_c \) and the holdup is \( \beta \), the relationship between the mixture phase conductivity \( \sigma_m \), \( \beta \) and \( \sigma_c \) is:

\[
\sigma_m / \sigma_c = 2 \beta / (3 - \beta)
\]

Maxwell model is applicable to finely bubbly flow. In ideal annular flow, the relationship between the mixture phase conductivity and the holdup of continuous phase was put forward by Begovich & Watson in 1978 (Begovich J.M. et al., 1978):

\[
\sigma_m / \sigma_c = \beta
\]

When water is continuous, for oil-water two-phase upward flowing fluid, the flow regime usually is bubbly flow, so Maxwell model can be applied. But even in bubbly flow, it is possible that the mixed state of oil and water should be very different. With higher velocity, the oil-water two-phase flow which is mixed uniformly can be regarded as finely bubbly flow, while with very low velocity, the uneven distribution of water and oil make the relationship between the conductivity of the mixture and water holdup different from that of uniformly mixed state. Therefore in practice, the analytical model can not be used directly, and it is necessary to calibrate the water cut meter at different flow rates to get a calibration chart.

The structure of the full-bore conductance sensor is shown in Fig.1. The mental ring-shaped electrode is mounted on the outside wall of the cylindrical insulation body. When the electrode is provided with constant current, according to the electrical theory, the electrode generates a voltage, the value of which is inversely proportional to the conductivity of fluid crossing the sensor:

\[
u_w / u_m = \sigma_m / \sigma_w
\]

Where \( u_w \) is the voltage when the casing is full of water, \( u_m \) is the voltage when the casing is filled with oil-water two-phase fluid, water holdup \( \beta \) can be obtained by \( u_w / u_m \).
3. ELECTRIC FIELD SIMULATIONS OF FULL-BORE CONDUCTANCE SENSOR

As shown in Fig.1, suppose that the fluid flowing between the sensor and the casing is uniform, linear and isotropic with conductivity $\sigma$. When the excitation electrode is provided with constant current $I$, a surface potential is generated on the interface where the electrode contacts with the fluid, that is, a sensitive electric field is generated in the area through which the fluid flows. According to the electromagnetic theory, the potential $u$ of the field meets the Laplace equation. In cylindrical coordinate system, taking the axial symmetry of the model into account, the Laplace equation becomes:

$$
\nabla^2 u(r, z) = \frac{\partial^2 u(r, z)}{\partial r^2} + \frac{1}{r} \frac{\partial u(r, z)}{\partial r} + \frac{\partial^2 u(r, z)}{\partial z^2} = 0
$$

Supposing that when the electrode is enough narrow, the current density on the electrode surface is uniformly distributed. The surface potential $u$ of the excitation electrode meets:

$$
\left. \frac{\partial u(r, z)}{\partial r} \right|_{r=R_1} = -\frac{I}{2\pi\sigma R_1 S} \quad \left( \frac{S}{2} \leq z < \frac{S}{2} \right)
$$

Where $S$ is the width of the excitation electrode, $R_1$ is the radius of the electrode and $R_2$ is the radius of the well bore. The structure of the sensor is symmetrical to the roz plane and the excitation electrode is just in the center of the plane, there is:

$$
\left. \frac{\partial u(r, z)}{\partial z} \right|_{z=0} = 0
$$

Metal casing is grounded, there is:
Using ANSYS software, in accordance with above boundary conditions, the electrostatic field of the sensor is simulated. As the axial symmetry of the experiment model, three-dimensional model can be simplified for two-dimensional axial symmetric plane to complete ANSYS simulation. Set inside radius of the casing 75mm, height 800mm. Taking the contamination of the electrode, the divergence of current field and the grounded casing into account, set radius of the full-bore conductance sensor 14mm, height 725mm, and width of the electrode 5mm. The excitation electrode is also the measurement electrode, which connects to a constant current resource. Fig.2 is the ANSYS model of the full-bore conductance sensor. Fig.3 (a) is the potential distribution of the sensor showing that the potential decays quickly from the electrode along r direction (radial) to both sides. Fig.3 (b) shows the potential decays quickly from the electrode along z direction (axial) to both sides, and the potential only distributes in a very narrow area near the electrode.

4. STATIC EXPERIMENTS

The purpose of static experiments is to find out the response characteristics of full-bore conductance sensor and verify the results of simulation qualitatively. Locate the sensor just at the center of a cylindrical metal container vertically, which is full of tap water (the salinity is about several hundreds ppm), ground the cylinder, and supply a constant alternating current to the excitation electrode. Use long cylindrical dielectric rods (slightly higher than the cylinder with diameter 20mm) to simulate non-conductive phase oil. Different number of rods inserted into the cylinder will result in different water holdup which can be calculated easily. When there is no rod in, the voltage of the electrode is named full-water value, and when several rods were inserted, the voltage of the electrode is named mixture value. The mixture value dividing by the full-water value is the relative response.

(1) Insert one rod into the container vertically on a circumference with radius 65mm and the same center as the sensor, record the voltage of the electrode and calculate the volume fraction of water. Then, insert the rods one by one at different position of the circumference, until 5, record the voltage of the electrode and calculate the volume fraction of water at each increment of rod. Change the radius of the circumference (55mm, 45mm, 35mm, and 25mm) and repeat above steps. Fig.4 is the dependence of relative response on water fraction with different radial distances and shows that the
relative response is proportional to water holdup and, the sensitivities and the intensities of electric fields are the same with the same distance between the rods and the sensor.

(2) Remove one rod from 65mm to 25mm from the sensor gradually, record the voltage of the electrode at different positions. Then, increase the number of the rods and repeat the above steps. Fig.5 is the dependence of relative response on radial distance from the sensor with different water fractions and shows that the closer the rod is removed to the sensor, the more sensitive the sensor becomes and the greater the relative response changes, that is, the electric field is much stronger near the sensor, which is identical to the simulation in Fig.3 (a).

(3) Put a piece of rod downwards into the container at 65mm from the sensor, record the electrode voltage at each decline of 1cm until the voltage is constant. Then change the point and repeat above steps. Fig.6 is the dependence of relative response on axial distance from the sensor with different radial distance from the sensor. It is obvious that the electric field is stronger only in a certain area near the electrode, and the electrode is sensitive to the change of impedance in this area. On the contrary, there is little response outside this area, and the potential decays rapidly from the electrode to both sides, which is identical to the simulation in Fig.3 (b).

(4) In order to know the effect of salinity on the relative response, the 4th experiment is conducted in salt solution (3000 ppm), in a manner similar to the 1st experiment. Fig.7 shows the relative response.
in tap water and that of salt solution is very small. Within the allowable range of experiment error, there is no effect of salinity on relative response (Hu Jinhai et al., 1999).

5. CONCLUSIONS
This paper has proposed a full-bore conductance sensor and carried out simulation and experimental researches on it. Simulation results and experiments results are presented by which the response characteristics of the full-bore conductance sensor are known, the conclusions are listed as follows:
(1) It is learned from the simulation results that the potential decays rapidly from the electrode along r direction (radial direction) to the casing wall, along z direction (axial direction) to both sides, and the potential only distributes in a very narrow area near the electrode.
(2) It is learned from the static experiments that the relative response is proportional to water holdup and, the sensitivities and the intensities of electric fields are the same with the same distance between the rods and the sensor. In radial direction, the closer the rod is removed to the sensor, the more sensitive the sensor becomes and the greater the relative response changes. In axial direction, the electrode only responds in a certain region on both sides of the electrode and decays rapidly from the electrode to both sides. Within the allowable range of experiment error, there is no effect of salinity on relative response.
(3) The experiment results agree with the simulation results. The electrostatic field simulations and the static experiments show that full-bore conductance sensor proposed in the paper is affected by inhomogeneous distribution of fluid. When the water cut is same, with different spatial distribution of the oil phase, the response of the sensor is different. Under this circumstance, this sensor can not be applied directly to measure water cut in boring casing. Whereas when the measured fluid is distributed uniformly, the sensor can be used to measure water cut. Based on the characteristics of the sensor, it can be applied to study the flow regime. In actual flow fields, when the oil-water fluid is distributed uniformly with high flowrate, the sensor can be used to measure water cut directly.

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