A New Cylindrical Capacitance Sensor for Measurement of Water Cut in a Low-production Horizontal Well

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Abstract. In a horizontal well with low flow rate, oil-water two-phase flow is stratified due to gravity. For measuring water cut accurately in a low-production horizontal well, a novel cylindrical capacitance sensor is proposed in this paper. The structure of the sensor is cylindrical and hollow with multi-layer structure which is consisted of inside insulation layer, electrode layer, outside insulation layer and metal casing from inside to outside. And the measurement principle is analyzed in this paper. The mathematical model is established, which shows that theoretically, there is a good relationship between the sensor response and water holdup. The response curve is monotone and the sensor has a good resolution and a high sensitivity in the whole range of water holdup. The electric field of cylindrical capacitance sensor was simulated respectively by using ANSYS software when the sensor is filled with pure water, pure oil and oil-water mixture. The results of the simulation are consistent with the mathematical model. Static experiments with the sensor filled with oil-water mixture were conducted finally. The results have verified the theoretical analysis and show that the proposed sensor is a viable solution to measuring water cut in a low-production horizontal well. Cylindrical capacitance sensor provides a good reference for the water cut in low-production horizontal well and has a good application prospect.

1. INTRODUCTION
In the development of oilfield, production logging (PL) can not be stressed enough. The purpose of production profile logging, which is a branch of PL, is mainly to find out the production rate and water cut of each production layer in an oil well. But how to measure water cut accurately in horizontal wells is still a challenge in oilfield development. In PL area the term “water cut” is defined as water flow rate divided by total flow rate through the cross section of the casing of the production well, while the water holdup is defined as the water content ratio in a measurement volume filled up with fluid. Owing to the slippage between oil and water, water cut is not equal to water holdup which can be usually detected by a hold up sensor directly, and the water cut can be determined from the measured water holdup and flow rate by using the calibration chart or theoretical models. Also, the
cylindrical capacitance sensor is only sensitive to water holdup, here called "sensor for measuring water cut" is a traditional name. Some new tools widely used for measuring water cut, like CAT (Gary Frisch et al., 2002), are generally based on the full-bore measurement method in which the array sensors sense the water holdup of entire wellbore. This method is suitable for measuring the oil wells of high flow rate. But in Daqing oilfield, due to the long time development, the production rates of most wells are usually under 50m3/day which is too slow to be measured accurately by using this way. Instead of the full-bore measurement method, the packing method is usually used to measure the flow rate and water cut of a low-production well. The traditional capacitance sensor which is composed of a cylindrical metal electrode coated with insulating layer and a outside shield housing is effectively used to measure water cut in vertical wells, but in low-production horizontal wells, it fails to work due to the stratified flow and high water cut (over 50%). By contrast, the impedance sensor (Liu Xingbin et al., 2006) which depends on the continuous water phase is more suitable for high water cut and stratified flow, but so far, no successful data has been reported by using the impedance sensor. Recently, with the increasing of the horizontal wells in China oilfields, the logging tools with high-precision and high-reliability are being expected. Much of research work on horizontal wells is being carried out. This research has provided a viable solution to measuring water cut in low-production horizontal wells, aiming at satisfying the requirements for practical measurements.

2. The STRUCTURE AND MEASUREMENT PRICIPLE of the SENSOR

In a horizontal well with low flow rate, oil-water two-phase flow is stratified (G. Oddie et al., 2003, M.Vielma et al., 2002, P. Abduvayt et al., 2004) due to gravity. For stratified flow, the level of the interface between oil and Water crossing the sensor reflects the water holdup. The present sensor can provide a real-time detection of the water level, and then accomplish the continuous measurement of water cut.

As can be seen from Fig.1, the capacitance sensor is cylindrical and hollow with multi-layer structure which is consisted of inside insulation layer, electrode layer, outside insulation layer and metal casing from inside to outside. The inside insulation layer and electrode layer are very thin, just about 1 millimeter. The excitation voltage is applied to the electrode layer, and the metal casing is grounded. When the fluid flows through the sensor, the heavier phase water at the bottom of the sensor will contact with the casing at the ends of the sensor. The water in the bottom can be considered as grounded electrode, because the tap water and the formation water are good electric conductor in low frequency range (Liu Xingbin et al., 1998). Usually formation water and tap water contain numbers of conductive particles. According to electromagnetic theory, if the material satisfies:

![Fig.1 Cross section of the proposed capacitance sensor](image-url)
\[ \frac{\sigma}{\omega \varepsilon_0} = G >> 1 \]  

(1)

It can be considered as a conductor. At the low frequency 10 KHZ calculating \( G \) value according to typical data can get table 1, which shows that both formation water and tap water can be regarded as good conductors at a low frequency.

| testing water     | temperature (°C) | salinity (mg/kg) | \( \sigma \) (S/m) | \( \varepsilon \) | \( G \)       |
|-------------------|------------------|------------------|-------------------|----------------|-------------|
| tap water         | 20               | 400              | 0.08              | 78             | 1.75×10^3   |
| formation water   | 60               | 1000–20000       | 0.38–5.88         | 60             | 1.13×10^4–1.76×10^6 |

As the formation water is conductive at low frequency, the outer surface of water in the sensor is thought to be equipotential. The surface can be divided into two parts: \( S_1 \) is contacted with the inside wall of the sensor and \( S_2 \) is the oil-water interface.

The value of the capacitance formed by electrode layer, outside insulation layer and metal casing is constant and can be computed by:

\[ C_0 = \frac{2\pi \varepsilon_0 \varepsilon_0 L}{\ln \left( R_3/R_2 \right)} \]  

(2)

The value of the capacitance formed by electrode layer, inside insulation layer and \( S_1 \) is variable with water hold up within the sensor, it will become larger with the increase of angle \( \alpha \), and namely, with the increase of water holdup \( H_w \), the value can be computed by:

\[ C_1 = \frac{\alpha \varepsilon_0 \varepsilon_0 L}{\ln \left( R_1/R_0 \right)} \]  

(3)

The value \( C_2 \) of the capacitance formed by electrode layer, oil, inside insulation layer and \( S_2 \) is relatively small and changes slightly and contributes little to the response of the sensor, to simplify the analysis, it can be neglected.

So the whole response \( C \) of a cylindrical capacitance sensor is the sum of \( C_0 \) and \( C_1 \).

\[ C = \frac{2\pi \varepsilon_0 \varepsilon_0 L}{\ln \left( R_3/R_1 \right)} + \frac{\alpha \varepsilon_0 \varepsilon_0 L}{\ln \left( R_1/R_0 \right)} \]  

(4)

By geometric method, we have

\[ H_w = \frac{\alpha - \sin \alpha}{2\pi} \]  

(5)
H is a function of $\alpha$, so is C. The approximate-linear curve is obtained from (4) and (5), where $R_0$ 12.5mm, $R_1$ 13.5mm, $R_2$ 14.5mm, $R_3$ 20.5mm, $L$ 80mm, and relative permittivity for oil and inside/outer insulation layer 3.5 (parameters of the actual sensor applied in static experiments). Fig.3 shows that the response curve is monotone and the sensor has a good resolution and a high sensitivity in the whole range of water holdup.

3. ANSYS SIMULATIONS

In order to understand the electric field distribution of the sensor with different water holdups and verify the theoretical analysis, the electric field of the sensor is simulated by using ANSYS software. Set the equivalent relative dielectric constants (permittivity) 1000 for water, metal casing and electrode layer, +10V for excitation voltage. Remaining parameters agree with that of the actual sensor applied in static experiments.

When the sensor is filled with oil-water mixture (Fig.4), the complete electric field of the sensor is divided into three parts: the one between electrode layer and metal casing is invariable, the one between electrode layer and $S_1$ can be regarded as a field of an incomplete cylindrical capacitor, and the one between metal layer and $S_2$, with very small intensity, could hardly impact on anything. Therefore, the three parts can be simplified for two parts: the constant part (outer) and the variable part (inside), which is consistent with the mathematical model, and the variable part is more important. When the sensor is full of oil, the variable part disappears, there only exists the outer electric field (Fig.5). The output of the sensor is the minimum at this moment.
When the sensor is full of water, because of the axial symmetry, the profile simulation only shows a part of the electric field distribution. Two evenly radial parts with opposite directions can be seen from Fig.6 and Fig.7. At this moment, the area of the variable part is the maximum, and so is the capacitance of the sensor.

4. STATIC EXPERIMENT
The static experiment was carried out with oil and water to confirm the theory. Water (tap water) and oil (kerosene) were put into a transparent container to simulate the stratified flow, and then, the cylindrical capacitance sensor was set in the container. The water was injected into the container to increase the level of the interface between the water and the oil gradually, and the capacitance was recorded by a programmable RCL, the relative level of oil-water interface was recorded by a ruler which was fixed on the sensor, which was repeated three times. The experiment result was shown in Fig.8. Similarly, the water was extracted from the container to decrease the interface level, and the capacitance of the capacitor was measured, which was repeated three times. The experiment result was shown in Fig.9. The two figures indicate that the sensor has good water holdup sensitivity and reasonable repeatability.

Convert the interface level into the holdup, average the three curves of up-travel and the three of down-travel respectively, then put the two curves and the theoretical curve into Fig.10 to comprise together. As can be seen, actual responses of the sensor are well consistent with the theoretical
response, but there is a slight difference between the response of up-travel and down-travel, which belongs to "lost motion error ".

In fact, there exists a slight friction between the liquid in the sensor and the inside wall of the sensor, it makes the state of oil-water interface in up-travel (convex) different from that of down-travel (concave), which leads to the lost motion. But in dynamic case, this error will disappear due to the flow of fluid.

5. FURTHER WORKS
Dynamic experiments will be conducted in DLTS (Daqing Logging & Testing Services Company) multiphase flow loop facility. The proposed prototype for dynamic experiments is composed of 4 parts: circuits, cylindrical capacitance sensor, basket packer and motor driver as shown in Fig.11. A packer can trap the fluid into a narrow passage to increase the velocity for measuring the flow rate accurately.

But there is no measurement devices of flow rate installed on the prototype, the purpose to fix the packer is to get the characteristics of the sensor response in packing conditions. The circuits can convert the capacitance value into a frequency signal and supply power to the prototype. The motor controls the mode of the packer.

6. CONCLUSIONS
Theoretically, the cylindrical capacitance sensor with multi-layer structure has a good response to water holdup in the whole range of measurement. The electric simulations have verified the mathematical model and the static experiment results with good repeatability are also well consistent with the mathematical model, which shows that the cylindrical capacitance sensor could better answer the question of water cut measurement in a low-production horizontal well and has a good application prospect. Next, dynamic experiments will be conducted to study the response characteristics of the sensor in dynamic case and the chart of sensor response plotted against water cut will be calibrated.
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NOMENCLATURE

$R_0$  inside radius of inside insulation layer  [mm]
$R_1$  outside radius of inside insulation layer (inside radius of electrode layer)  [mm]
$R_2$  outside radius of electrode layer (inside radius of outside insulation layer)  [mm]
$R_3$  outside radius of outside insulation layer (inside radius of metal casing)  [mm]
$L$ length of the electrode layer of the sensor  [mm]
$H_w$ water holdup

Greek letters

$\sigma$ conductivity of material  [S/m]
$\omega$ work frequency  [rad/s]
$\alpha$ central angle of semi-cylindrical surface  [rad]
$\varepsilon$ permittivity of vacuum, $8.85 \times 10^{-12}$  [F/m]
$\varepsilon_0$ relative permittivity of material
$\varepsilon_1$ relative permittivity of the outside-insulation-layer material
$\varepsilon_2$ relative permittivity of the inside-insulation-layer material

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