Measurement of water content in high water-cut oil-wells based on rayleigh scattering

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Abstract. According to the lack of traditional method measuring high water-cut production level effectively, this paper discusses the measurement of high water content by Rayleigh scattering. When launching high-frequency electromagnetic waves downward along the axial, the diameter of the oil-in-water emulsion can range from millimeter to centimeter in an oil-water two-phase case. Because the Electromagnetic Wave can be scattered by oil droplets and is related to their quantities and size, we can measure the water content using suitable electromagnetic wave with the right wavelength. Then, the measuring accuracy of Water Content in High Water-cut Oil-wells can be improved and the confluent-liquid umbrella can also be canceled.

1 Introduction
Most of the oil fields in our country have came into middle-later developed period and water-cut of oil reservoir is in a high level. In the production, measuring water content of the produced fluid accurately has important significance for the production of oil-wells. At present, measuring production fluid with high water-cut using the traditional method is of bad accuracy and even unable to distinguish. Therefore, the technology measuring the water content of the oil-well production layer accurately is needed when extracting oil at the frontline[1].

Traditionally, we measure water content follow three steps. Putting a metal capacitor into the production layer of production wells firstly. Then, making the oil-water fluid in oil-wells go into the container. Finally, calculating the capacitance. The capacitance is related to the dielectric constant of
the mixture, and the dielectric constant of water and oil vary greatly (dielectric constant of water is about 80 while the value of pure oil ranges from 2 to 3). So, we can calculate the water content of oil-water mixture from the capacitance[2]. However, when adopted in an oil-well with high water content, the measurement cannot figure out the available capacitance because the conductive water can lead to the short circuit of two electrodes in the capacitor. Furthermore, the effective capacitance cannot be measured and we can only get the inaccurate data in high water-cut oil-wells. At the same time, the method mentioned is carried out by the closed measurement, which means the measured water content only includes the part entering the container rather than the average water content of the production layer[3]. In order to measure the average water content, an open measurement should be developed.

In this paper, we propose an open measurement based on Rayleigh scattering. Then we can accurately measure the water content with the cancellation of confluent-liquid umbrella in a high water-cut condition.

2 Theory of measuring the water content with Rayleigh scattering

When traveling in the air, the acoustic wave and electromagnetic wave can be scattered by some water vapor condensation such as clouds, rain and hail. These scattering bodies can be equivalent to a medium sphere. When the sphere radius \( a \) is much smaller than the wavelength \( \lambda \), the scattering of sound waves or electromagnetic waves is called Rayleigh scattering. Similarly, in high water-cut oil-wells, the water is used as a continuous phase and the oil droplets play the role of the scattering body.

Generally, the scattering wave is generated because particulate matters in the liquid oscillate and then become the second wave source under the driving of the incident wave. In a homogeneous medium, the wave superposition makes the wave travel in the direction of wave refraction and is offset in other directions because of the interference. While in an inhomogeneous media, the coherence of second wave is destroyed due to the presence of inhomogeneous particles leading to the occurrence of scattering wave. Oil droplets can be considered inhomogeneous medium in high water-cut condition. Hence, the oil content (also the water content) can be obtained by measuring scattering wave. The theory of measuring the oil content with scattering wave and wave characteristics is shown in Figure 1[4].

As shown in the left of Figure 1, \( I_\lambda \), \( I_o \) and \( I_0 \) represent the intensity of incident wave transmission wave and scattered wave respectively and \( C \) means the oil content. According to Figure 1, we can obtain that the scattering intensity is approximately linear with oil content in a certain range. The intensity of the scattered wave decreases when oil content increases to a certain extent because the increase of oil droplets particles with the increase of oil content prevents the scattering of the wave. So, the method above can be applied to the water-cut measurement in a high water-cut condition.

3 Mathematical model of measuring water content with Rayleigh scattering

In oil-water two-phase wells, when there are higher water content, the oil exists in the oil-in-water form[5]. Therefore, if water is viewed as the continuous medium, the oil droplets can be viewed as scattering bodies and the quantity of oil content (i.e. water content) can be measured by calculating the strength of Rayleigh scattering.

For an accurate result, the chosen wavelength of the ultrasonic wave or electromagnetic wave
should be larger than the diameter of oil droplets. For example, in order to measure oil droplets in millimeter range, the wavelength must be greater than or equal to 10mm. Moreover, assuming that the sound velocity of oil-water two-phase flow is 1000 m/s in a wellbore, oil droplets in millimeter range can be measured with ultrasonic wave, whose frequency should be 100KHz. By the same way, the maximum frequency of the electromagnetic wave is 30GHz[6].

Supposing that a droplet radius is a, the dielectric constant is $\varepsilon$ and the dielectric constant of water is $\varepsilon_0$. Then the calculating model can be established shown in Figure 2 and the formula of Rayleigh scattering can be represented as

$$H_\phi = -\frac{E_0(\varepsilon - \varepsilon_0)k^2a^3}{\eta_0(\varepsilon + 2\varepsilon_0)r} \sin \theta e^{-jkr}$$

(1)

The meanings of related parameters in the formula are shown below:

$\eta_0$: Scattering coefficient related to the properties of the medium.

$H_\phi$: Scattering intensity, Mw/m.

$E_0$: Wave intensity, Mw/m.

$r$: The distance between the oil droplets and wave source, m.

$k$: Coefficient, also a constant.

From the above formula, we can obtain that the Rayleigh scattering is proportional to the three times of the oil droplet diameter and is proportional to the dielectric constant difference between oil and water. For a number of oil droplets, measured results is the superposition of all Rayleigh scattering. So, we can obtain the volume of all oil droplets in the casing pipe statistically. Thus, it is sure that the electromagnetic wave can cover the liquid in cylindrical shaft when launching downward and the water content can be measured accurately without a confluent-liquid device.

4 Theoretical experiment and result analysis

4.1 Experimental device

As shown in Figure 3, the test instrument and wave source are placed on central axis of the casing and ultrasonic or electromagnetic waves are launched downward, making oil droplets move along the opposite direction of propagation of the wave. It means that we can get the maximum Rayleigh scattering when the parameter $\theta$ in formula 1 is set as 90 degree. At the same time, quantities and size of oil droplets can be measured, which correspond to the oil content and water content.
To verify the feasibility of the program quickly, the scalar network analyzer (8756A) produced by HP/Agilent Company in the United States is used to set up a water test instrument with electromagnetic wave. The functional block diagram is shown in Figure 4.

Directional coupler is a kind of microwave device used for signal isolation and separation. The electromagnetic probe is used for the conversion between electromagnetic wave and electrical signal.

4.2 Experimental method
With the crude oil water content testing instrument, the theoretical experiment was carried out on the three phase flow experiment device belonging to Institute of oil production engineering in Huabei oilfield. During the experiment, the Electromagnetic probe was stuck into the internal casing and the rest of the device was placed on the ground. The electromagnetic probe was connected with the directional coupler through a coaxial cable. Considering that coaxial cable would attenuate the high-frequency signals, the frequency of electromagnetic waves were set between 250 and 259 MHz ultimately. The three phase flow experiment device was used to allocate different proportions of oil and water mixture, which was sent into the casing. After a lot of experiments, we have got satisfying results.

4.3 Experimental data analysis
The Experimental results generated by Matlab are shown as Figure 5.

According to the figure, the Rayleigh scattering intensity is linearly distributed under the irradiation of 250-259MHz electromagnetic wave when the water content is from 80% to 100%. Taking 253MHz wave as an example, the empirical formula describing the connection of scattering intensity and water content can be obtained.

\[
Y_{\text{water}} = -0.0344H + 0.0138
\]

(2)

\(Y_{\text{water}}\) means the water content (%) and \(H\) means the scattering intensity (dB).
It can be seen that curves in the situation where the water content is 60% or 70% do not meet the formula. This is because the increase of liquid droplet in numbers with the increase of oil content can result in the fuzzy boundaries between oil and water. In addition, the scattering effect is unpredictable without a scattering body. So, Rayleigh scattering measurement is suitable for the condition where water content is more than 80%. Similarly, the water used as a scattering body can be adopted to measure the water content with Rayleigh scattering when water content is less than 30%.

5 Conclusion

In the oil-water two-phase case where water and oil droplet are viewed as the body and scatterer respectively, water content can be measured through Rayleigh scattering intensity. Thus, theoretical and experimental data show that the method proposed is applicable to oil-wells where the water content is more than 80%.

The method can be used to detect a certain area below the electromagnetic probe. So, the confluent-liquid umbrella can be canceled, which is suitable for high water-cut horizontal wells.

The miniaturization and practicality of the instrument should be achieved as quickly as possible.

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