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Research on Ultra Short Wave Method to Measure Water Content of Crude Oil

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Abstract

The full measuring range and real-time on-line measurement are new requirements for measuring the water content of the crude oil in oil pipeline with the application of the water flooding technique. The ultra short wave method made best use of the relationship between the ultra short wave transmission property in the crude oil medium including the amplitude attenuation and phase difference and the crude oil physical parameters including the electrical conductivity and permittivity to measure the water content of the crude oil. This method can measure the high and low water content of the crude oil in oil pipeline. The parallel conductor sensor was chosen according to the real workstation and the relationship of the amplitude attenuation, phase difference and the water content. The experimental results prove the ultra short method is feasible. The method has the advantages of the wide measurement range, simple sensor structure and easy installation.

1. Introduction

The water content ratio of the crude oil in the oil tank, oil well and oil pipeline is a vital measurement parameter in order to accurately measure the crude oil production. The measurement range should be up to 100% because the usage of water flooding technique at present. Too many factors which include the time variant mixture state of the crude oil and water, the complex ingredients, the multi-flow pattern and the poor oil field environment etc. lead to the difficulty to measure accurately the water content of the crude oil for a long time. A lot of the classical methods have some limitations for the full range measurement. The capacitance method is more suitable for measuring the low water content. The electrical conductance method is more suitable for measuring the high water content. The ray method can measure the low and high water content at present, but its shortcomings are very complex and expensive [1,2]. The paper discusses a new method to measure the full measurement range of the water content of the crude oil in oil pipeline with the ultra short wave.

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2. Measurement basis

2.1 The analysis of crude oil physical character

The crude oil contains the carbon, hydrogen, sulfur, nitrogen, oxygen, nickel, vanadium, iron elements and so on whose main elements are carbon, hydrogen, sulfur, nitrogen and oxygen. Hydrocarbon is the main ingredient of the crude oil, about 95-99%, therefore, the crude oil is dielectric and non-magnetic, and its permittivity is about 2.5, relative magnetic conductivity is about 1.0.

The water contains hydrogen and oxygen elements. The pure water is non-conductive and non-magnetic, its permittivity is about 80 at 20℃, relative magnetic conductivity is about 1.0. The magnetic conductivity effect of the crude oil and water can be ignored, as they are non-magnetic matter.

The water in crude oil mainly comes from the underground water containing lots of mineral, and the crude oil will contain some conductive ions under certain condition, which will make the crude oil and water mixture has certain conductive ability. The higher the water content is, the more conductive ability is. So, the crude oil and water mixture has the dielectric and electrical conductive properties.

From the physical mechanism analysis, in alternating electromagnetic field, the electrical character of the fluid medium depends on the amount and conductive ability of the conductive ion. Its dielectric properties will depend on the induced polarization and permanent dipole moment of the fluid molecule. Induced polarization is caused by the deformation of the electronic structure, when the frequency is less than 10^{15} Hz, the induced polarization and electrical field are simultaneous so that it has a very small impact on the overall polarization of the material. The permanent dipole moment is formed by the molecular structure, and much larger than the induced dipole moment generally. Thus, the differences between the polar and nonpolar molecular are very obvious. The ingredient of the crude oil is the hydrocarbon, which is made of the micro-polar molecules, its electrical conductivity is less than 10^{-9}~10^{-16} S/m, the relative permittivity is about 2.5-1.0. The water is the hydrogen and oxygen compound which is made of the polar molecules and often contains some salt ions, its electrical conductivity is generally 10~0.1S/m, the relative permittivity is about 80 when the frequency of electromagnetic field is lower than 10^{10} Hz [3-5].

The great differences of the permittivity and electrical conductivity between the crude oil and the water are the measurement basis of the ultra short wave method.

2.2 The transmission property of electromagnetic wave

According to the transmission line theory, the transmission property of the electromagnetic wave in the parallel conductor has close relation to the distribution resistance, distribution conductivity, distribution inductor and distribution capacitance, the value of distribution parameters depends on the size and material of the parallel conductor, and the medium around the conductors[5,6]. Based on the relationship between the distribution parameters and the medium, the paper chooses the parallel conductor as the sensor to measure the water content of the crude oil. Figure 1 shows the section of the parallel conductor sensor in the oil pipeline, the r is the radius of conductor; D is the distance of two conductors.

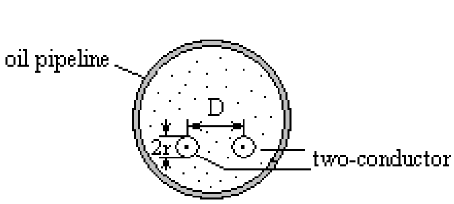

Figure 1. Section of the parallel conductor sensor

The equivalent circuit is shown in Figure 2, where *dz* is the micro length of the transmission line, *Rdz, Gdz, Ldz* and *Cdz* represent the distribution resistance, distribution conductivity, distribution inductor, distribution capacitor in *dz*. The value calculation formula is (1).

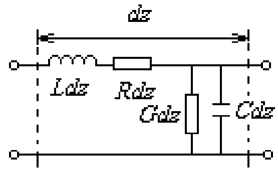

Figure 2. Equivalent circuit of transmission line

$$\left.\begin{aligned} C &= \frac{\varepsilon}{V_0 V_0^*}\int E\cdot E^* ds \qquad L = \frac{\mu}{I_0 I_0^*}\int H\cdot H^* ds \\ G &= \frac{\sigma}{V_0 V_0^*}\int E\cdot E^* ds \qquad R = \frac{R_m}{I_0 I_0^*}\int H\cdot H^* ds \end{aligned}\right\} \quad (1)$$

The ε, μ, σ and R_m are respectively the equivalent permittivity, magnetic conductivity, electrical conductivity and resistivity[3], the I_0 and V_0 are current and potential difference, the *H* and *E* are the magnetic field and electrical field, the sign * expresses the conjugate. Formula (1) shows that the transmission property of the electromagnetic wave has close relation with the equivalent magnetic conductivity, permittivity, electrical conductivity and resistivity which are decided by the conductors and the crude oil and water mixture. The equivalent parameters vary with the water content ratio, as the parameter of conductors is constant. Note that the crude oil and water belong to non-magnetic material, the impact of the magnetic conductivity can be ignored. Therefore, the transmission property of the electromagnetic wave in the crude oil and water mixture mainly depends on the permittivity and electrical conductive of mixture.

The transmission of the electromagnetic wave conforms to the Maxwell equation group and Helmholtz equation group [3]. The following is the Maxwell equation group:

$$\left.\begin{aligned} &\nabla\times H = \sigma E + j\omega\varepsilon E = j\omega(\varepsilon - j\frac{\sigma}{\omega})E \\ &\nabla\times E = -j\omega\mu H \\ &\nabla\cdot H = 0 \\ &\nabla\cdot E = \rho_v / \varepsilon \end{aligned}\right\} \quad (2)$$

where $\varepsilon - j\frac{\sigma}{\omega}$ is the equivalent complex permittivity of the conductive medium, the σ is electrical conductivity, the ρ_v is the volume density of charge, the ω is the angular frequency of the electromagnetic wave.

Introducing the equivalent permittivity, Helmholtz equation group becomes:

$$\left.\begin{aligned}\nabla^2 E + [\omega\sqrt{\mu(\varepsilon - j\frac{\sigma}{\omega})}]^2 E = 0 \\ \nabla^2 H + [\omega\sqrt{\mu(\varepsilon - j\frac{\sigma}{\omega})}]^2 H = 0\end{aligned}\right\} \quad (3)$$

where $\omega\sqrt{\mu(\varepsilon - j\frac{\sigma}{\omega})}$ is the propagation constant, it can be expressed by:

$$\omega\sqrt{\mu(\varepsilon - j\frac{\sigma}{\omega})} = k' - jk'' \quad (4)$$

where

$$k'' = \omega\sqrt{\frac{\mu\varepsilon}{2}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2} - 1\right]} \quad (5)$$

$$k' = \omega\sqrt{\frac{\mu\varepsilon}{2}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2} + 1\right]} \quad (6)$$

The k'' and k' express the amplitude attenuation and phase difference in 1 meter distance, units are Np/m and rad/m[3], the amplitude attenuation ΔA and phase difference $\Delta\Phi$ in L distance are:

$$\Delta A = k'' \cdot L / 0.115 \quad (7)$$

$$\Delta\Phi = k' \cdot L \quad (8)$$

Formula (2)-(8) show that the amplitude attenuation and phase difference of the electromagnetic wave propagating in the crude oil and water mixture depend on the electrical conductivity and permittivity of mixture [3,7]. That is, the electrical conductivity and permittivity of the crude oil and water mixture can be achieved by measuring the amplitude attenuation ΔA and phase difference $\Delta\Phi$.

2.3 Mathematical model of water content measurement

The crude oil and water mixture can be regarded as the pure crude oil and water mixture, thus, the effective permittivity of mixture obeys the two materials mixture law based on the H-B formula, the equivalent permittivity of the crude oil and water mixture ε_m is:

$$\sqrt{\varepsilon_m} = \sqrt{\varepsilon_o}(1 - W) + W\sqrt{\varepsilon_W} \quad (9)$$

The ε_o and ε_W are respectively the permittivity of crude oil and water, W is the water content ratio.

According to Maxwell resistance approximation theory, the equivalent electrical conductivity of the crude oil and water mixture σ_m is:

$$\sigma_m = \frac{2W\sigma_w}{3 - W} \quad (10)$$

The σ_w is the conductivity of water, it is correlative with the fluid distributing configuration and pattern [7].

From the formula (9) and (10), the permittivity and electrical conductivity of mixture depend on the mixture ratio of crude oil and water, so the water content of the mixture can be achieved by measuring the amplitude attenuation and phase difference.

3. Parameters calculation and selection

The relative permittivity will reduce when the frequency of electrical magnetic wave is more than10^{10}Hz. The permittivity of crude oil, water and mixture are almost constant when the frequency range of electromagnetic wave is in 10^7~10^9H[5]. In order to keep the max difference of permittivity between the crude oil and water, the ultra short wave is chosen, its frequency is from 30 MHz to 300 MHz and its wavelength range is from 1 to 10 meters. On the basis of the transmission line theory, the length of the parallel conductor sensor should be more than or equal to the wavelength of the ultra short wave [3,4].

When the water content varies from 0 to 100%, the equivalent permittivity range of the crude oil and water mixture is from ε_o to ε_W, the equivalent electrical conductivity of the mixture is from 0 to σ_W.

4. Experimental results

4.1 Experimental equipment and process

At room temperature circumstance, the experiment chooses the copper wires as the sensor, and chooses an integrated oscillator MAX2606 as the ultra short wave generator. The output frequency of MAX2606 is 75-150MHz, the 90MHz frequency is chosen in the experiment. The mixture is made of the water and machine oil. The water content ratio of mixture includes 0%, 25%, 50%, 75% and 100%. A digital oscilloscope TDS2012B with the dual-channel and 100 MHz bandwidth is used to measure the amplitude attenuation ΔA and phase difference $\Delta\Phi$.

4.2 Insulation experiment of sensor

The contrastive experiments of the insulated sensor and uninsulated sensor are done to judge the impact of salinity. The Table 1 shows the data with the uninsulated sensor, the V_{INA} and V_{INB} express the input and output signal amplitude, the units are mv. The amplitude is stable when the sensor is in the pure water, but when put 10 grams salt into the pure water, the output signal is rapidly reduced, specially, when put 20 grams salt into the pure water, the V_{INB} has no any signal output, which shows the signal attenuation is too large to measure. The Table 2 shows the measurement data with the insulated sensor, the output signal V_{INB} is stable with 10 grams salt and 20 grams salt, so it is necessary to insulate the sensor.

Table 1. Measurement data with of uninsulated sensor

Pure water		With 10g salt	
V_{INA}	V_{INB}	V_{INA}	V_{INB}
57.6	18.4	31.2	7.6
56.4	17.2	32.0	6.4
57.6	17.6	29.6	5.6
58.0	17.2	30.4	7.2
56.8	16.8	31.2	7.6
58.0	18.0	30.4	6.8
57.2	17.2	30.0	5.6
58.4	17.6	30.4	6.4
58.0	18.0	31.2	6.8
56.8	17.2	30.0	6.4

Table 2. Measurement data with of insulated sensor

Pure water		With 10g salt		With 20g salt	
V_{INA}	V_{INB}	V_{INA}	V_{INB}	V_{INA}	V_{INB}
26.4	18.4	30.4	14.4	30.0	15.2
24.8	18.8	29.6	14.4	30.4	14.0
26.4	19.2	30.4	14.8	30.4	14.4
25.2	18.8	30.4	15.6	30.4	13.2
26.4	18.4	29.6	15.2	31.2	15.2
25.2	18.4	30.4	15.2	30.0	14.4
25.6	17.2	30.4	15.2	30.8	14.0
26.0	18.4	30.8	14.4	30.4	14.8
26.4	18.4	31.2	14.4	31.6	14.0
26.4	17.2	30.8	14.4	30.4	15.2

4.3 Experimental data of water content

With the different water content and the insulated sensor, the amplitude attenuation ΔA and phase difference $\Delta\Phi$ are measured, let $\Delta A = \log(V_{INA}/V_{INB})$. The Table 3 shows the result. When the water content ratio is from 0% to 100%, the amplitude attenuation ΔA varies from 0.076 to 0.145, and the phase difference $\Delta\Phi$ varies from 48° to 128°, the two groups data are monotonous variation.

The experiment proves the ultra short wave method with the parallel conductor can realize the water content measurement. According to the measurement value of the amplitude attenuation ΔA and phase difference $\Delta\Phi$, the equivalent permittivity and the electrical conductivity of mixture can be obtained. Therefore, on the basis of the formula (9) and (10), the low water content can be obtained with the permittivity, and the high water content can be obtained with the electrical conductivity.

Table 3. Measurement data of water content

Water Content	Amplitude attention	Phase difference
0%	0.076	48°
25%	0.109	90°
50%	0.112	96°
75%	0.127	120°
100%	0.145	128°

5. Conclusions

The feasibility of the ultra short wave method to measure the water content of the crude oil based on the parallel line sensor has been proved. The fusion measurement of the permittivity and electrical conductivity, the simple sensor structure and the full measurement range are its prominent features which make the field installation easy. The method adapts to the oil field circumstance.

6. Acknowledgements

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