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Study on the sensitivity of electromagnetic wave to water content of oil-water mixture

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Abstract: With the deepening of oilfield development and the increasing shortage of water resources, the accurate measurement of water content in oil-water mixture has become a key issue in oilfield development and production. This paper analyzes the sensitivity of electromagnetic waves to water content in water-oil mixture. By assuming that there is a linear relationship between the dielectric properties and water content, a water content detection model of crude oil is established. Full-wave simulation is made with COMSOL. The feasibility of water content detection with electromagnetic wave is studied by analyzing the receiving electric field and its frequency dependence. The research is instructive for non-destructive measurement of water content based on electromagnetic waves.

1. Introduction

Crude oil water content is an important parameter in the petrochemical industry, and accurate detection of crude oil water content plays a very important role in the extraction and utilization of oil[1]. Most of the domestic oilfields have entered the late stage of oil extraction, and the water content of crude oil has increased significantly, which poses a new challenge to the measurement of water content.

At present, the existing crude oil water content detection consists of artificial measurement methods and dynamic measurement methods, including distillation method, Karl Fischer method, capacitance method, conductivity method, electromagnetic wave method, magnetoacoustic coupling method, process chromatography imaging technology, multi-sensor information fusion technology and so on[2]. Traditional measurement methods have strong uncertainties and the methods of capacitance, conductivity, and gamma-ray have limitations in monitoring the water content of crude oil[3]. The capacitance method is strongly affected by temperature and weather. The conductivity method is susceptible to oil-water distribution, and the γ-ray method has high maintenance costs[4]. Compared with the above methods, the microwave-based method adopts a non-contact structure and uses the amplitude and phase changes when the microwave passes through the measured oil to determine the oil-water content[5], which has a high detection accuracy. It is less affected by the temperature as well as the mineralization of the water, and can be a good solution to the effects of unfavorable factors such as the presence of scale and wax, and the changes in temperature and pressure and it is a potential method of detection in oilfields.

Microwave non-invasive detection has been widely used in various applications. In the medical field, the inherent scattering properties of microwaves propagating in inhomogeneous media are often used for disease detection. For example, the liquid in the lungs is detected by microwave to determine the possibility of pulmonary edema[6]; to detect whether there is bleeding in the gray matter of the brain for the initial diagnosis of stroke patients[7]; the effective dielectric constant and effective conductivity measured by microwave technology are used to detect breast cancer[8], and non-invasive blood glucose measurement by microwave detection dielectric spectroscopy[9]. In industry, real-time monitoring of concrete status[10], crack detection of railway tracks[11], monitoring of changes in the composition of polyols and isocyanates used in the polyurethane industry[12], and detection of industrial pollutants[13]. In agriculture, real-time monitoring of grain moisture content using microwaves to ensure the quality of agricultural products[14], leaf humidity detection to prevent pests and diseases[15], single-site fat depth measurement of beef carcasses[16], and fruit maturity detection[17].

In this paper, the feasibility of microwave water content in oil detection is studied based on full-wave simulation[18]. Linear assumptions are made between the dielectric properties of the water-oil mixture and corresponding water content, and the pipeline is modeled using COMSOL to detect the electric field amplitude in the receiving field, which is frequency-dependent. The results show that the range of frequency variation expands as the water content increases. At the same time when the frequency is higher, it is less sensitive to the water content.

The paper is organized as follows. The simulation model is given in Section II. Numerical results are discussed in Section III. Conclusions are drawn in Section IV.

2. Fundamental principle

2.1 Simulation model

The working principle of microwave method to detect the moisture content of oil-water mixture is: when microwave passes through a material, its amplitude, phase and propagation speed will change accordingly. The specific change depends on the composite dielectric constant of the passing material. The composite dielectric constant of the oil-water mixed solution is mainly determined by the water content of the mixed solution.

Two identical microwave antennas are arranged in parallel on the wall of the oil pipe, one is the transmitting antenna, which transmits the microwave signal outward so that it passes through the oil pipe and the oil-water mixing solution; the other is the receiving antenna, which receives the transmitting microwave signal, and finds out the water content of the mixing solution through the amplitude of attenuation[2].

The oil pipeline with a radius of 1.2m is modeled as Figure 1. At 0.2m from the boundary of the circular pipe take (1,0), $(\frac{\sqrt{2}}{2},\frac{\sqrt{2}}{2})$, (0,1), $(-\frac{\sqrt{2}}{2},\frac{\sqrt{2}}{2})$, (-1,0), $(-\frac{\sqrt{2}}{2},-\frac{\sqrt{2}}{2})$, (0, -1), $(\frac{\sqrt{2}}{2},-\frac{\sqrt{2}}{2})$ eight points as antennas.

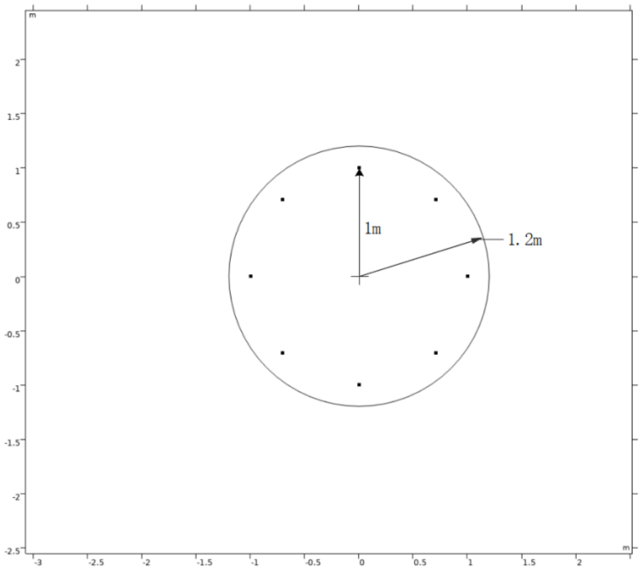

Figure 1: Piping model diagram

2.2 Calculation of dielectric constant

The dielectric constant of an oil-water mixture is related to the water content, and assuming a linear relationship between the effective dielectric constant and the water content[3], the effective relative permittivity and conductivity are expressed as follows:

$$\varepsilon_r = 2V + 79(1 - V) \tag{1}$$

$$\sigma = 0.2(1 - V) \tag{2}$$

where ε is the relative dielectric constant, V is the water content, σ is the conductivity. At room temperature, the dielectric constant and conductivity of oil are 2 and 0 S/m, respectively, while those of water are 79 and 0.2 S/m, respectively.

3. Results

Due to the symmetry of the circular pipe, the electric field distribution of all the receiving antennas can be obtained by simulating the receiving electric field at the four positions $(\frac{\sqrt{2}}{2},\frac{\sqrt{2}}{2})$, (0,1), $(-\frac{\sqrt{2}}{2},\frac{\sqrt{2}}{2})$, (-1,0). The electric field generated by the receiving antenna at the point $(\frac{\sqrt{2}}{2},\frac{\sqrt{2}}{2})$ is called a receiving electric field, and the remaining three antennas in the counterclockwise direction are called the b, c, d receiving electric fields, as shown in Figure 2.

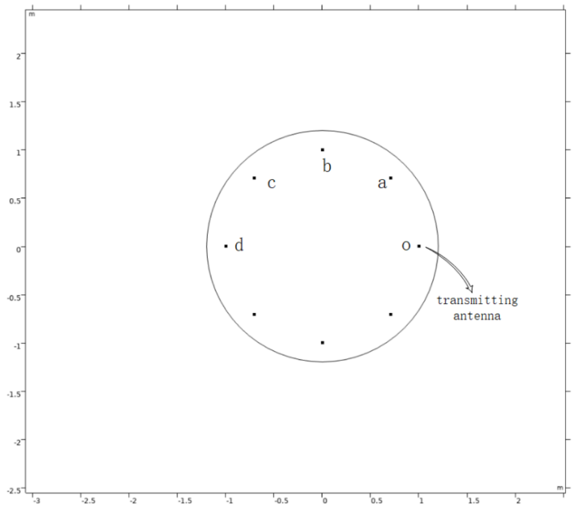

Figure 2: Receiving electric field diagram

Setting the pipe as a perfect electric conductor boundary condition, the transmitting antenna line current (out-of-plane) is 1 A. The water content is varied in the range of 0% to 30%, and the frequency of the electromagnetic wave is varied in the range of 300 to 700 MHz in steps of 10 MHz, and the change in the magnitude of the field magnitude of the received electric field of each receiving antenna is observed[19].

1) Analysis of the relationship between received electric field magnitude and electromagnetic wave frequency

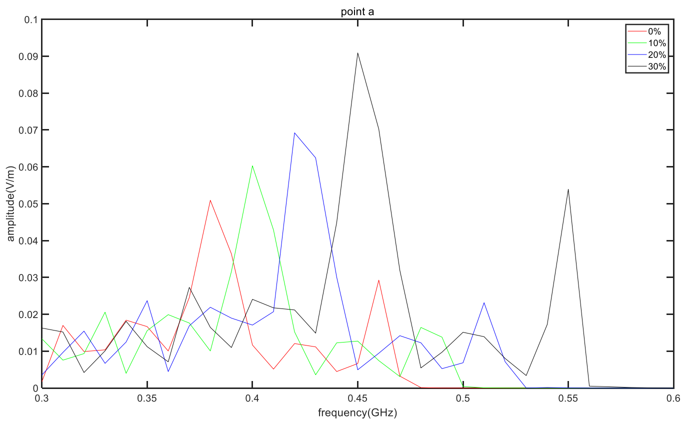

Figure 3: Simulation results at point a.

Figure 3 shows the relationship between frequency and the electric field magnitude at point a when the water content is 0%, 10%, 20%, and 30%, respectively[20]. It can be seen that the electric field magnitude with the increase of frequency first fluctuates to rise, then fluctuates to fall. With the increase in water content, the electromagnetic wave frequency corresponding to the peak point also increases, and at the same time, the dynamic range increases.

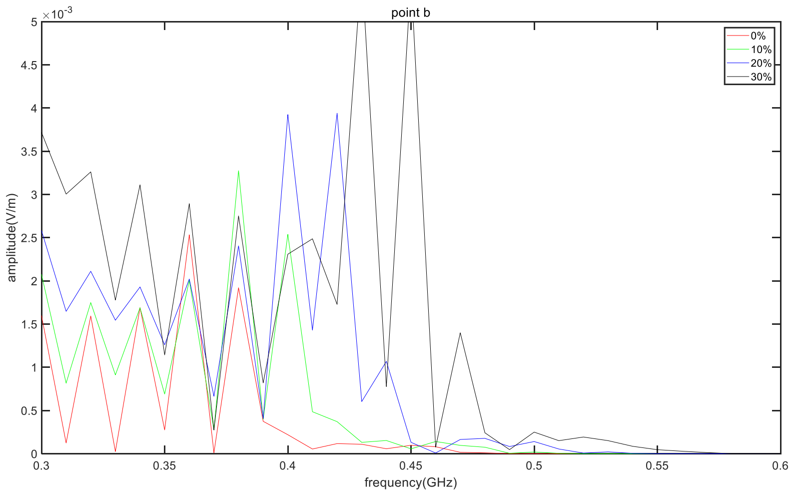

Figure 4: Simulation results at point b.

Figure 4 shows that the electric field magnitude at point b shows periodic sawtooth changes with the increase of frequency, and then fluctuates and rises to appear peaks, and finally, the field magnitude tends to 0. With the increase of water content, the frequency of the electromagnetic wave that appears peaks also increases.

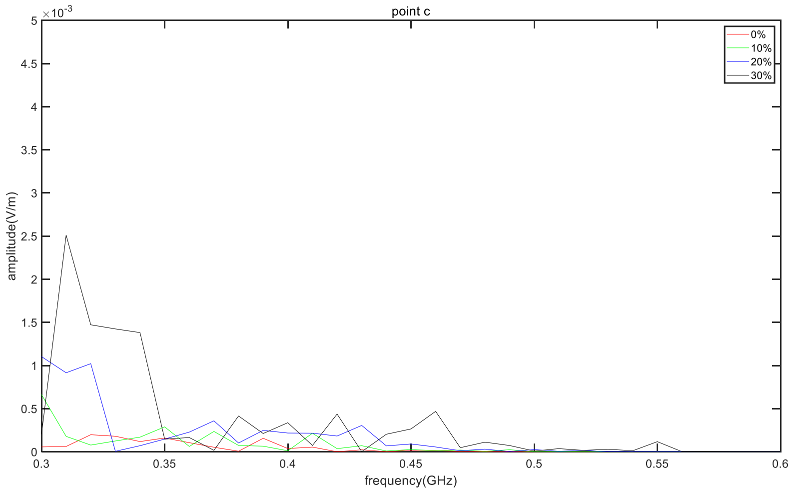

Figure 5: Simulation results at point c.

Figure 5 shows that the electric field magnitude at point c fluctuates widely only in the range less than 350 MHz, and does not vary much above this range. The attenuation increases when the frequency becomes larger, which leads to an unobvious fluctuation.

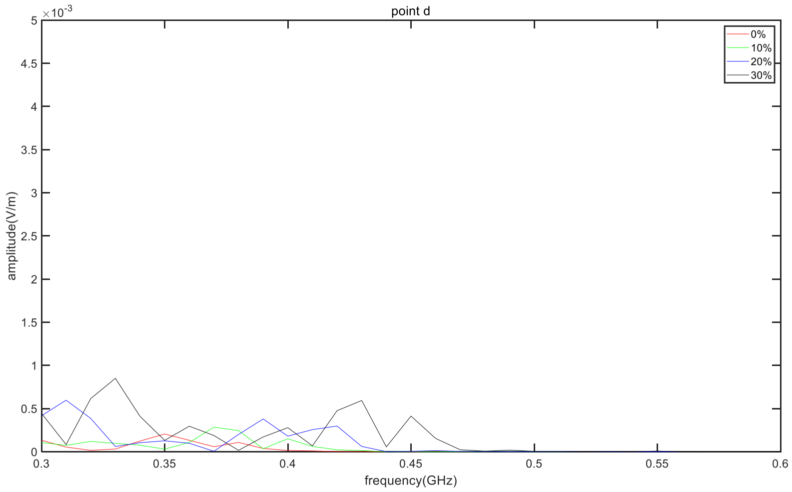

Figure 6: Simulation results at point d.

Figure 6 shows that the overall change in the electric field magnitude at point d with increasing frequency is not significant. This is due to a large attenuation between the transmitter point and the receiving point.

2) Analysis of the relationship between received electric field magnitude and water content

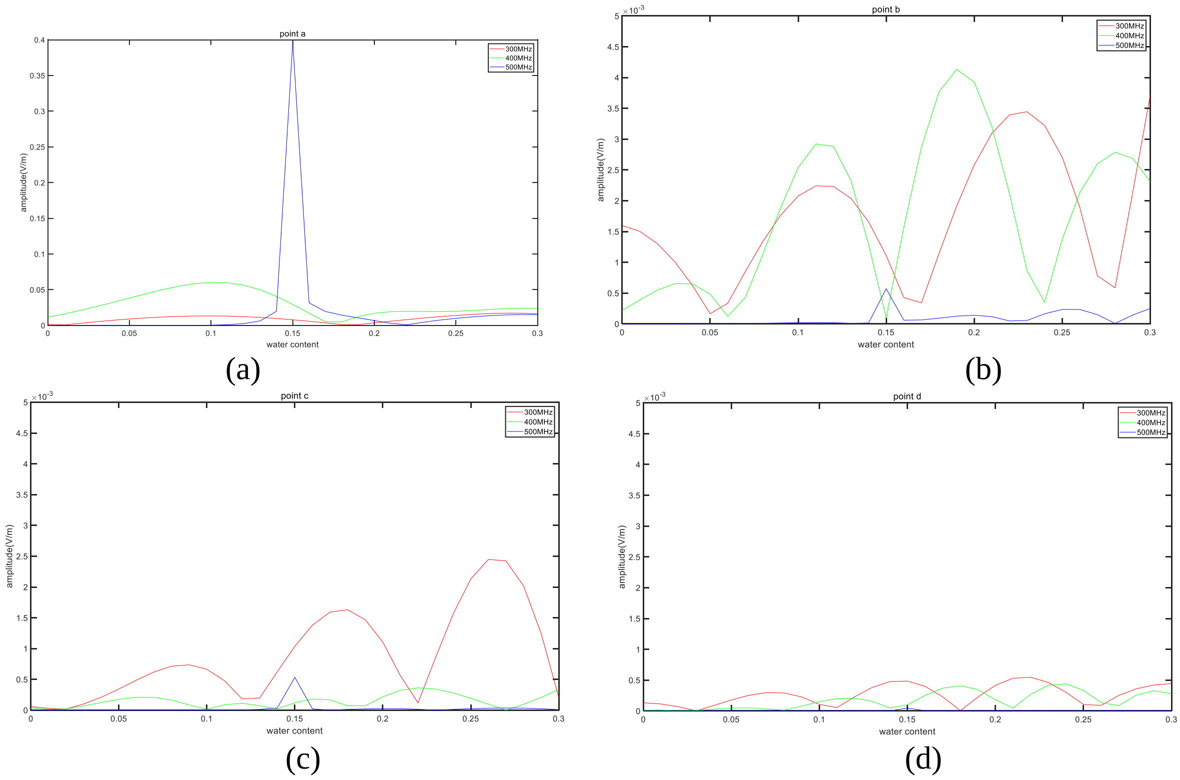

Figure 7: Comparison between water content and electric field magnitude.

Figure 7 shows the relationship between water content and electric field strength when the electromagnetic wave frequencies are 300MHz, 400MHz, and 500MHz respectively. The field magnitude of the received electric field at 300MHz and 400MHz varies periodically with the increase of water content with a slight increase in amplitude, which is due to the wave property of electromagnetic waves. At 500MHz the electric field magnitude varies significantly only near 15%

water content. From the four received fields a,b,c and d, the range of the electric field amplitude decreases from a to d with the increase of water content, and the field is the most sensitive to the change of water content.

3) Analysis of the relationship between electromagnetic wave frequency and water content

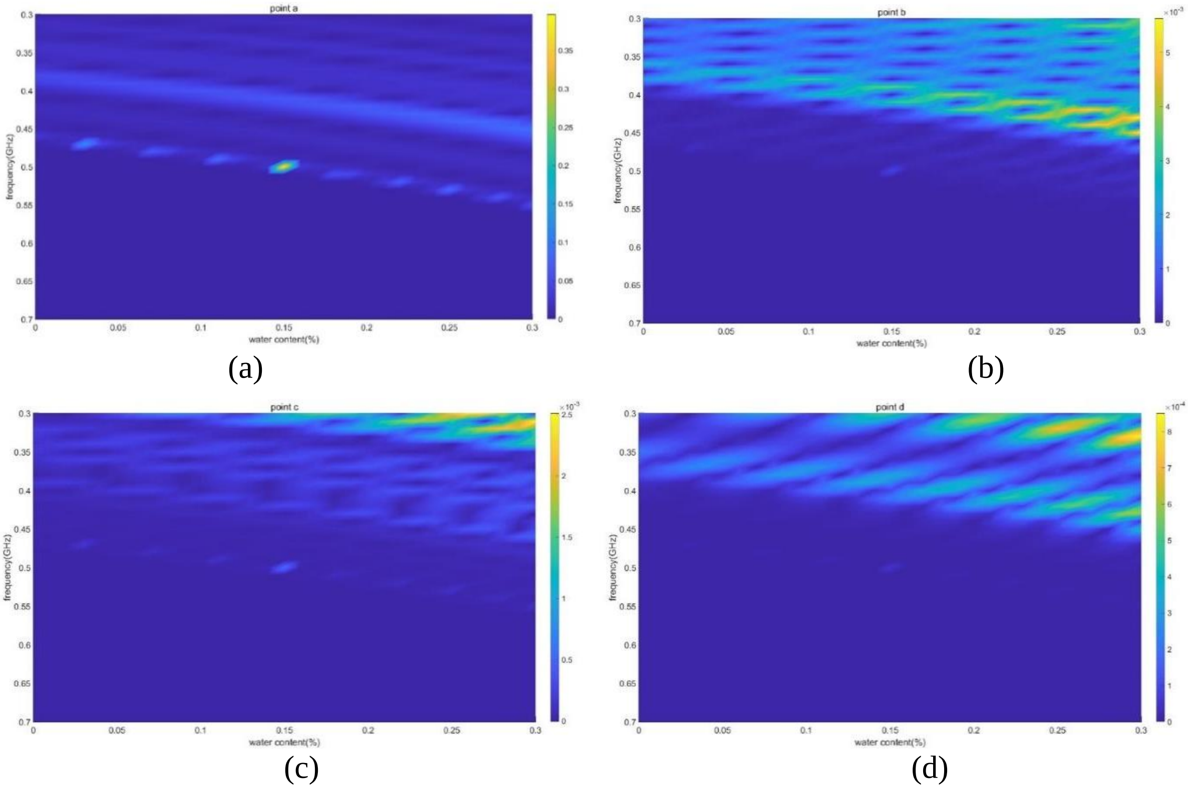

Figure 8: Overview of the simulation results.

It can be observed from Fig. 8 that when the frequency is larger than 500 MHz, the receiving field encounters a large attenuation which will bring difficulties to the sensitivity of measurement devices. The selection of a proper frequency is also affected by the size of the pipe. As the water-oil mixture can be recognized as a homogeneous medium, an optimal receiver position is necessary as well.

The average values of the electric field of the four receiving fields a, b, c, and d are listed below.

Table 1: Average value of electric field

	Water content				Frequency		
	0%	10%	20%	30%	300MHz	400MHz	500MHz
a	5.99	8.10	10.65	15.25	11.85	16.18	6.11
b	0.30	0.56	0.92	1.55	2.15	1.20	0.08
c	0.04	0.08	0.20	0.41	1.10	0.10	0.01
d	0.03	0.04	0.11	0.19	0.33	0.13	0.001

Table 1 shows the average value of the electric field magnitude of each receiving electric field as it changes with frequency and water content. It can be seen that the average value decreases from a to d, and there is not much difference between b, c, and d. When the water content increases from 0% to 30%, the field magnitude gain of every 10% of the receiving field is about 3V/m, the b receiving field is about 0.41V/m, the c receiving field is about 0.12V/m, and the d receiving field is approximately 0.16V/m, indicating that the receiving field at point a is the most sensitive to changes in water content.

Oil is a dielectric whose relative permittivity and conductivity are low, which means the attenuation during microwave propagation is lower compared with water[21]. When the water content is larger, more water in the mixture will lead to more attenuations. In order to keep a proper signal to noise ratio, the antennas should be placed in a relatively near distance. On the other hand, it is also an important issue to ensure a stable radiation property of the antennas as there will be interference when they are placed nearby. In future research, the feasibility of electromagnetic wave water content detection should be studied with a more realistic model consisting of more hardware, which will make the results more convincing.

4. Conclusion

In this paper, the influence of electromagnetic wave frequency and water content on oil-water mixtures in oil transport pipelines detected by microwave method is investigated, experimental simulation observation is carried out by COMSOL, and the frequency range in which electromagnetic waves are sensitive to water content is obtained from the above simulation results, as well as the antenna position which is the most sensitive to the change of water content after fixing the transmitting antenna.

Moreover, various external factors such as temperature and pressure can interfere with the accuracy of electromagnetic wave detection of water content in oil-water mixtures. Future research can focus on developing more realistic calculation methods, simulation models, and incorporating acoustic and optical technologies to enhance detection comprehensiveness. Additionally, exploring the application of artificial intelligence, big data, and other advanced technologies in electromagnetic wave detection can lead to more intelligent and efficient detection methods.

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