Water holdup measurement of oil–water two-phase flow using dual-mode microwave method

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Abstract

Water cut is one of the key parameters in the process of oil and gas production. In the present study, we propose a microwave resonant cavity sensor(MRCS) which can work in both TM_{010} and TM_{110} modes, and established a water cut measurement of vertical upward oil–water two-phase flow in the range of 0-100%. The response characteristics of the two resonant modes to water cut are analyzed by the coupling simulation of flow field and electromagnetic field using COMSOL finite element simulation software. A flow experiment is conducted with the designed MRCS measurement system. The sensitivity of the two modes resonant frequency in different water holdup range is compared. The results show that 95% of the experimental points' relative errors is less than ± 5%.It is indicated that the model can predict water hold with high accuracy, which may provide a solution for wellhead water cut measurement of oil field.

1. Introduction

Oil-water two-phase flow is a common flow pattern which widely exists in oilfield production, storage and transportation. The accurate measurement of water cut is of great significance for ensuring production safety, improving the production, and planning oilfield development. The traditional phase separation method for water cur measurement not only has problems such as large area of separation equipment, high cost, and the complexity of measurement system increases with the increase of the number of oil wells, And the whole process often takes several hours to complete, which means the data is unable to get in time. The online and accurate measurement of water cut of wellhead plays an important role in energy saving, consumption reduction, production cost reduction and intelligent management of oil field. With the development of oilfield exploitation, the water cut range of produced fluid may cover 0-100%. In addition, there is slip effect between oil and water, which increases the complexity of the flow pattern, and then brings difficulties to the detection of two-phase flow parameters. At present, the common on-line monitoring methods of phase holdup of oil-water two-phase flow include gamma-ray method [1], conductivity method and capacitance method [2]. Gamma-ray method has potential hidden danger caused by ionizing radiation; Conductivity method and capacitance method have limitations in the measurement range of water cut, and the measurement results are greatly affected by salinity. How to provide a simple, long-term and reliable online real-time monitoring of water cut measurement has been a problem for many years.

In recent years, microwave technology has attracted much researchers' attention in this field in the past few decades because of its sensitivity to water, and compared with other electrical measurement methods, it increases the frequency of electromagnetic waves and weakens the influence of salinity. In 1974, Castle first proposed an online crude oil water cut sensor based on the microwave principle, and summarized the sensing principle into wave transmission, reflection and vibration according to the different transmission modes of microwave signals [3]; Al kizwini et al. proposed a non-invasive microwave resonator sensor for annular flow and stratified flow. By comparing the HFSS simulation with the static experimental results of 0-100% water cut, they demonstrated the feasibility of using the shift of resonance frequency to predict the ratio of gas to water and gas to oil in the pipeline [4]; Yuan established a prediction model with a water cut range of 0-20%, and proved that the static experimental results of the resonant sensor are in good agreement with the dynamic data[5]; Yang obtains the dielectric constant of oil-water mixture through the accurate field solution of the resonant cavity theory, and then the water cut can be get through the solution of Hanai-Bruggeman model, realizing the prediction of 30-100% water cut [6].

In this paper, MRCS which can work in TM_{010} and TM_{110} dual-mode is proposed to overcome the problems of traditional on-line water cut measurement technology. Firstly, the size structure of the sensor is designed through COMSOL finite element simulation. Then, the measurement system of MRCS is built, and the vertical upward oil-water two-phase flow experiment is carried out. Finally, based on the experimental results and the simulation results, the influence of water cut on the amplitude frequency characteristics of sensors TM_{010} and TM_{110} is analyzed, and the high-precision prediction of water cut of 0-100% is realized.

2. Sensor principle & simulation

2.1 Sensor principle

Microwave cavity is a basic microwave component, which is a metal cavity composed of closed conductors. In the process of microwave transmission in the resonant cavity, the reflection will occur when encountering the metal wall. For the specific frequency, the incident wave and the reflected wave will be superimposed to form a standing wave, which will produce resonance. The microwave frequency that can produce resonance is called resonance frequency. Figure 1 is an ideal cylindrical resonator, with a radius of R and a height of L. It can be regarded as a circular waveguide with short circuit at both ends. For an ideal conductor, the tangential component of the surface electric field and the normal component of the magnetic field are 0. There are two propagation modes (TM_{mnp} and TE_{mnp}) in the circular waveguide, which is no magnetic field component (Hz=0) in the propagation direction of TM_{mnp} mode, no electric field component (Ez=0) in the propagation direction of TE_{mnp}. By introducing the boundary conditions into the solution of circular waveguide, the electromagnetic field distribution of TM_{mnp} and TE_{mnp} modes in cylindrical cavity can be obtained.

$$\begin{Bmatrix} E \\ H \end{Bmatrix} = A_{mn} J_m(k_c r)_{\sin m\varphi}^{\cos m\varphi} \{C_1 \cos(\beta z) + C_2 \sin(\beta z)\} \quad (1)$$

Where, E and H are the modulus values of electric field and magnetic field intensity respectively, J_m is the Bessel function, and n, m, and p are the half-standing wavelength numbers of the cylindrical resonant cavity in three spatial directions respectively.. Therefore, when the microwave signal wavelength meets the above conditions, resonance can be generated. Set the resonant frequency band type (1):

$$f_r = \frac{1}{2\pi\sqrt{\mu\varepsilon}} \sqrt{\left(\frac{\mu_{mn}}{R}\right)^2 + \left(\frac{p\pi}{l}\right)^2} \quad (2)$$

Where, f_r is the resonant frequency, μ and ε is the permeability and dielectric constant of the cavity material, and μ_{mn} is the nth root of the m-order Bessel function. Through theoretical analysis, we can obtain that the higher the dielectric constant of the measured medium in the resonant cavity and the higher the stored energy, the lower the resonant frequency. Water is a polar material with a high dielectric constant of about 80, while oil is a non-polar material with a dielectric constant much smaller than that of water, about 2.2-2.5. Therefore, the dielectric constant of oil-water mixture is mainly determined by the water cut. According to the above, the sensor based on the principle of resonant cavity can be designed to detect the water cut of oil-water two-phase flow.

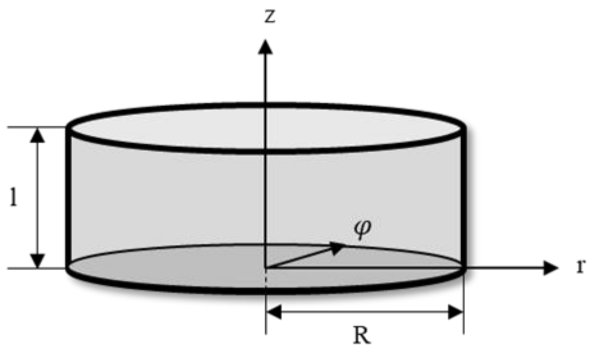


Figure 1: Cylindrical Microwave Cavity

Figure 2 is the diagram of MRCS, which is composed of a stainless steel cavity, a waveguide and a coupling antenna. The oil-water two-phase fluid will pass through the sensor from the pipe in the center. The medium in the cavity is air. The pipe in the cavity is a polycarbonate guided wave tube. The waveguide is connected with the external pipe, and the inner diameter D of the pipe is 50mm. The ring antenna is used to transmit and receive microwave signals. The inner and outer conductors of the antenna are made of copper, and the intermediate insulating layer is made of PTFE polytetrafluoroethylene. Among them, the cavity size of the sensor will have an important impact on the performance of water cut measurement. When designing the size of resonator sensor, the choice of working mode should be considered first. The working mode should avoid the interference of other modes. This paper studies TM_{010} and TM_{110} modes. In addition, due to the openings at both ends of the resonant cavity, in order to reduce the leakage of electromagnetic field energy of the resonant cavity and avoid the resonance of microwave in the pipeline, the resonant frequency of the resonant cavity should be lower than the minimum cut-off frequency of the pipeline when designing the size of the sensor. To sum up, the inner diameter D and thickness l of the cavity are finally determined to be 200mm and 20mm respectively.

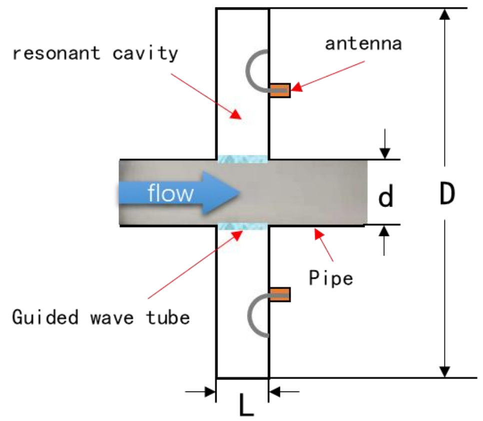


Figure 2: Microwave Resonant Cavity Sensor

2.2 TM_{010}&TM_{110} simulation

From equation (2), it can be calculated that the resonant frequencies of the ideal microwave cavity sensors TM_{010} and TM_{110} are 1.15Ghz and 1.83GHz respectively. At this frequency, the change of the dielectric constants of water and oil with frequency can be ignored. Therefore, the corresponding dielectric constants of water and oil can be set directly in the simulation. The boundary condition of the model is set as perfect electrical conductor. Figure 3 shows the radial distribution of electric field intensity obtained by simulation. It can be seen that the electric field of TM_{010} mode is the strongest in the center of the cavity, and the closer it is to the cavity wall, the weaker the electric field is; TM_{110} has two strongest electric fields in the circumferential direction of the cavity, which increases first and then decreases along the radial direction. With the increase of water cut, the electric field intensity inside the pipeline increases with the change of dielectric constant of oil-water mixture, while the electric field intensity outside the pipeline gradually decreases with the increase of water cut. For TM_{010} mode, because the center is the strongest position of the electric field, the electric field distribution is less affected by the change of water cut; On the contrary, the strongest electric field in TM_{110} mode gradually approaches the center of the cavity with the increase of water cut. Theoretically, the strongest excitation can be obtained when the coupling antenna is arranged at the place with the strongest electric field. In order to achieve the better measurement effect of TM_{010} and TM_{110} dual-mode at the water cut of 0-100%, it is finally determined that the distance from the antenna to the center of the sensor is 70mm.

3. Experimental device & method

The experiment was carried out on the oil-water two-phase flow test device of Tianjin University. Experimental test system is shown as Figure 4. Tap water and 15# white oil were selected as the experimental medium. First, the oil and water were sent to the circulating pipeline by the pump and the flow rate was controlled. A standard electromagnetic flowmeter was installed on the pipeline for verification and calibration. The oil and water were mixed into two-phase flow through the Y-shaped pipeline and then fully developed to the experimental pipeline. The inner diameter of the pipeline in the experimental pipe was 50mm. Finally, The two-phase mixed fluid flows into the separation tank and continues to be recycled after separation.

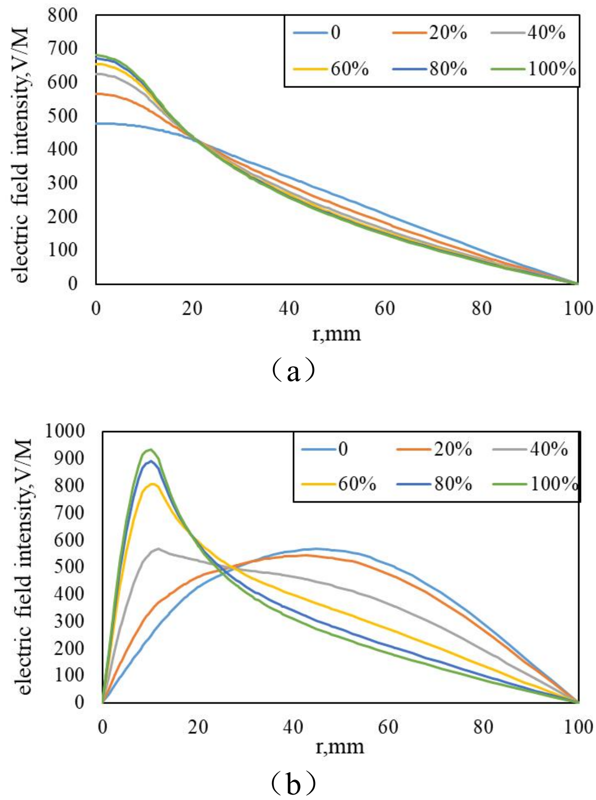


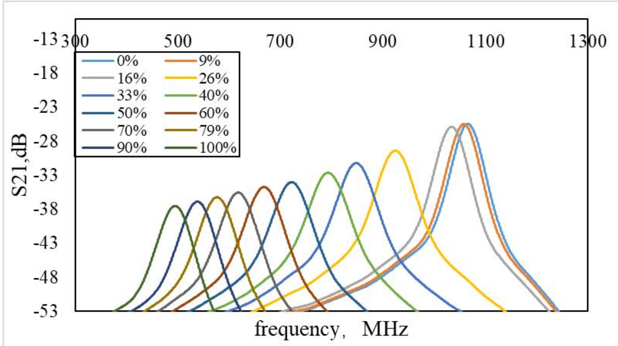
Figure 3: the Distribution of Electric Field Intensity(a) TM_{010} (b) TM_{110}.

The MRCS test system is composed of microwave resonator sensor, vector network analyser(VNA) and computer. The model of VNA is ceyear 4957d, the frequency range is 30kHz-18GHz, and the dynamic range is ⩾ 85dB. During the experiment, the resonant cavity is vertically installed on the experimental pipe. VNA is connected with the resonant cavity through coaxial cable, and is controlled by the upper computer software on the computer to excite and receive microwave signals to the resonant cavity. The experimental water cut range is 0-100%, the frequency range of VNA sweep measurement is 0.3-2GHz, and the step interval is 1MHz. For each experimental point, the sweep measurement time is about 1s, and the sweep measurement is repeated for 90 times.

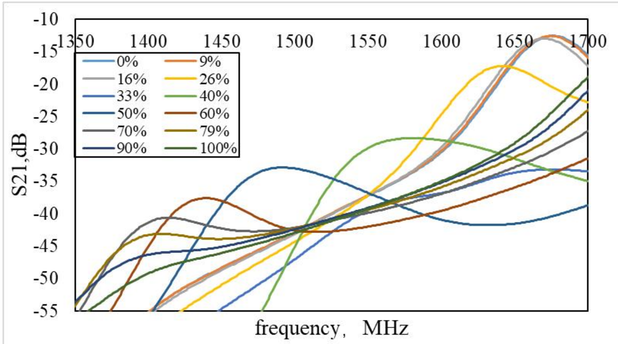
Figure 4: Experimental Test System.

4. Results & discussion

On account of the radio frequency noise in the space may interfere with the microwave signal collected by the measurement system, first, the experimental data are filtered by low-pass filter, and the average value of 90s experimental data is obtained as the experimental result under the current working condition to eliminate the influence of noise. Figure 5 shows the response of TM_{010} and TM_{110} to the change of water cut respectively. It can be seen that the resonant peaks of TM_{010} and TM_{110} modes shift to the left with the increase of water cut, and the attenuation of microwave signal during resonance also increases with the increase of water cut, which is consistent with the theoretical and simulation results. When the water cut is less than 20%, the continuous phase is oil, and the mixed dielectric constant changes slightly with the increase of water cut. On the contrary, when the water cut is greater than 20%, the continuous phase is water, and the mixed dielectric constant changes greatly with the increase of water cut.



(a)



(b)

Figure 5: TM_{010} and TM_{110} mode response to water cut(a) TM_{010} (b) TM_{110}..

In addition, we can also find that compared with TM_{010} mode, the attenuation of TM_{110} mode changes more. Combined with the simulation results of electric field distribution of the two modes under different water cut given in Figure 3, we can draw the following conclusion: the larger the dielectric constant is, the greater the stored electromagnetic field energy is. Therefore, when the water cut of two-phase flow in the pipe at the center of the cavity increases, the strongest position of the electromagnetic field will gradually move to the center. For TM_{010} mode, because its electric field is originally the strongest in the center, the electromagnetic field distortion caused by the change of water cut is small; In TM_{110} mode, the strongest electric field gradually moves to the center, and the electric field intensity in the center is the weakest, and the electromagnetic field distortion is large, so the measured S21 amplitude attenuation changes more.

According to relevant theories in Section 2, the relationship between water cut k_w and relative frequency shift η can be established as follows:

$$k_w = a \cdot \eta^b + (1-a)\eta^c \qquad (3)$$

Fig. 6 shows the relationship between the predicted water cut and the experimental water cut. It is showed that the absolute error predicted by the water cut model is less than 2.71% in the full range of water cut from0 to 100%

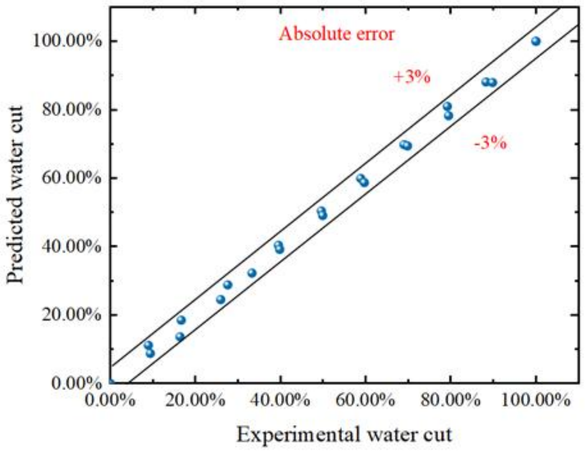


Figure 6: Predicted water cut VS experimental water cut.

5. Conclusion

This paper designs MRCS that can work in both TM_{010} and TM_{110} modes. Based on COMSOL finite element simulation, the structure of the sensor is designed, and the performance of the sensor is tested through experiments. The experimental results show that the resonant frequencies of both TM_{010} and TM_{110} modes decrease with the increase of water cut, which can well predict the water cut.

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