Hindawi Publishing Corporation
Mathematical Problems in Engineering
Volume 2014, Article ID 508571, 9 pages
http://dx.doi.org/10.1155/2014/508571

Research Article

Coupling Analysis of Low-Speed Multiphase Flow and High-Frequency Electromagnetic Field in a Complex Pipeline Structure

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Received 27 September 2013; Revised 17 December 2013; Accepted 18 December 2013; Published 5 January 2014

Academic Editor: Carla Roque

Accurate estimation of water content in an oil-water mixture is a key technology in oil exploration and production. Based on the principles of the microwave transmission line (MTL), the logging probe is an important water content measuring apparatus. However, the effects of mixed fluid flow on the measurement of electromagnetic field parameters are rarely considered. This study presents the coupling model for low-speed multiphase flow and high-frequency electromagnetic field in a complex pipeline structure. We derived the *S*-parameter equations for the stratified oil/water flow model. The corresponding relationship between the *S*-parameters and water holdup is established. Evident coupling effects of the fluid flow and the electromagnetic field are confirmed by comparing the calculated *S*-parameters for both stratified and homogeneous flow patterns. In addition, a multiple-solution problem is analyzed for the inversion of dielectric constant from the *S*-parameters. The most sensitive phase angle range is determined to improve the detection of variation in the dielectric constant. Suggestions are proposed based on the influence of the oil/water layer on measurement sensitivity to optimize the geometric parameters of a device structure. The method proposed elucidates how accuracy and sensitivity can be improved in water holdup measurements under high water content conditions.

1. Introduction

In petroleum extraction, crude oil flows along boreholes and pipelines to the ground. The crude oil fluid contains water because of ground water invasion and water injection in well logging. The proportion of water in oil well development increases over time. Under certain extreme conditions in well production, water constitutes 90% of the oil-water mixture. In the majority of cases, both water and oil fluid are present in the borehole, forming an immiscible two-phase flow. The oil-water mixture exhibits flow patterns different from those of the single phase flow. These patterns result from the heterogeneous distributions of the oil-water phases in space. The flow patterns are largely influenced by various factors, such as water holdup, inlet flow rate, and pipeline structure. When the flow rate or the Reynolds number of the fluid is sufficiently large, one of the phases is dispersed into droplets, thus spreading into the other continuous phase. As the dispersed phase increases, the droplets become closely packed and accumulate to change into a continuous phase at a certain stage. Meanwhile, the continuous phase in the early stage changes into a dispersed phases.

Experimental and theoretical studies reveal that the development of a two-phase flow pattern involves an extremely complex process [1]. Two-phase flow patterns commonly include the stratified flow, dual continuous flow, annular flow, and dispersed flow [2–4]. The stratified flow typically occurs at low flow rates, where water and oil move in a continuous form. Evident interfaces exist between water and oil. As flow rate increases, waveform disturbance is formed at different scales, transporting the droplets of one phase into the other, hence the transition of the mixed fluid to the dual continuous flow state [5]. The relative movement of the oil-water phases results in a vortex motion because of the shear force at the liquid penetration interface [6]. As flow rate increases, the effect of the inertial force becomes more significant. The droplets in one phase become more homogenously distributed in the other phases. In annular flow, one particular phase droplet forms the core annularly surrounded by the other phases. Under high flow rate conditions, the original continuous phase loses its continuity, changes into droplets, and disperses in the other phases.

Water holdup measurement is one of the most difficult problems in multiphase flow detection. Water exhibits properties that completely vary with those of hydrocarbon compounds. For example, the dielectric constant of water is many times higher than those of oil and natural gas. The dielectric property of oil-water mixture is closely related to water content. Consequently, water holdup can be obtained by measuring the dielectric constant of the mixture. However, several other factors influence the measurement. For example, mineral salt ions in the stratum are highly soluble in water. Salinity variation in water results in changes in the dielectric constant. Temperature and pressure also influence the dielectric constant of the oil-water mixture, thus hindering water holdup measurement.

Studies on the dielectric constants of mixed fluids were conducted as early as the 1930s [7]. The study by Little focused on the mechanism of dielectric constant variation for a polar ionic solution [8]. Reynolds and Hough formulated the calculation of the dielectric constant of two-phase mixtures [9]. Harvey and Prausnitz derived the formula for the dielectric constants of mixed fluids at different temperatures and densities [10]. Studies on the dielectric constants of mixtures at microwave frequency are increasing with the development of studies on the dielectric constants of mixed fluid [11–13]. However, the mechanism of dielectric constant variations for a heterogeneously distributed mixture remains unclear, especially with regard to studies considering the coupling effects of low-speed multiphase flow and high-frequency electromagnetic field. The determination of overall effective dielectric constant variations caused by multiphase flow patterns remains an unsolved problem.

Accurate estimation of water holdup performs an important function in well logging, oil storage, and transportation. The microwave transmission line (MTL) method is an important dielectric measurement [7] and water holdup measurement technique. The MTL method mainly uses mixed fluids as transmission media for electromagnetic waves. The dielectric constant is obtained from the measurement of the S-parameter [14, 15]. As a real-time measurement method with small-sized devices, MTL is developing into an accurate, fast, and mature technology. Nevertheless, MTL measurements remain affected by oil/water emulsion phase transition, flow conditions, temperature, pressure, and the coupling of the two-phase flow and the electromagnetic field. However, conventional transmission line methods rarely consider flow-electromagnetic field coupling. A potential model combining the theories of complex fluid flow and transmission line can potentially address this problem.

On the basis of the MTL theory, we formulate S-parameter calculations for the shielded parallel transmission line with short-circuited ends. Oil-water dispersion in the measurement under a low flow rate is considered, and a stratified model, including the fluid flow-electromagnetic coupling, is developed. The relationship between the S-parameter and the relative dielectric constant (RDC) mixture is determined. The multiple-solution problem is then analyzed. The device sensitivity of the S-parameter measurement is analyzed based on the proposed model, and the most sensitive settings are obtained. Finally, we propose a method to improve water holdup measurement. Numerical calculation of the electromagnetic field shows that local oil concentration and stratification under high water holdup conditions can improve measurement sensitivity, which can provide a theoretical foundation for the optimization of microwave water holdup measurement devices.

2. Methods

2.1. Derivation of the S-Parameter for the Mixed Stratified Fluid Model. Oil is composed of nonpolar organics with low RDCs (approximately 2.23) [16]. The RDC of pure water at 20°C is approximately 80. The large difference in the RDC between oil and water allows the derivation of water holdup from the dielectric constant. We adopt the sigmoid function to describe the relationship between the dielectric constant and water holdup [17]:

$$\varepsilon_m = \varepsilon_w - \frac{\varepsilon_w - \varepsilon_{\text{oil}}}{2}\left[(F\cdot\sigma + 1)^2 + 1\right]e^{-F\cdot\sigma}, \tag{1}$$

where ε_m, ε_{oil}, and ε_w are the dielectric constants of the oil-water mixture, oil, and water, respectively; F is the water holdup of the mixture; and σ is a fitting parameter.

The parameters ε_{oil} and ε_w are determined by the full oil ($F = 0$) and full water conditions ($F = 1$). The remaining parameter σ is optimized by fitting to experimental data in such a way that ε_m are reproduced as accurately as possible.

The parameter σ is determined by fitting to experimental results over the whole range of concentration. The experimental data of dielectric constants of oil/water or other organic solvent-water mixtures have been obtained by several works (1)–(4). Hanai measured the dielectric constants of oil-in-water, water-in-oil, and nitrobenzene-in-water emulsions (4). Hanai's work provided the comparison of dielectric constants of theoretical curves and observed values. From the data set, we find the following. (1) The experimental data points distribution confirms the parameters ε_w and ε_{oil} at the full oil condition and full water condition. (2) The sigmoid function curve is able to catch the data points which describe the relationship between the dielectric constant and water holdup. (3) The data curves of oil-in-water phase mixture (high water fraction) are much higher than water-in-oil phase mixture (low water fraction). In current well logging case, the oil content is much less than water. In addition, high temperature (around 125°C) causes dielectric constant increase greatly. The dependence of dielectric constant on temperature effect and oil-in-water phase condition are taken into consideration at the same time. The σ value are estimated with experiment data sets and the resulting parameter $\sigma = 0.1$ is adopted in the present study.

The MTL probe is shown in Figure 1. The S-parameter of the ports c_1 and c_2 is related to the radius, length, and the location of the fluid outlet of the probe. The probe is also

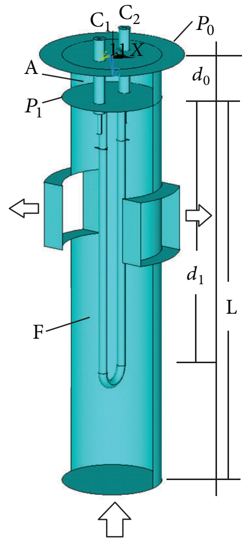

FIGURE 1: A water holdup measurement device with a terminal short-circuit dual coaxial transmission line. P_0 is port 0, and P_1 is port 1. A is the upper cavity filled with air as medium 0. F is the lower filled with mixed fluid as medium 1. C_1 and C_2 are conductors 1 and 2. The arrows indicate fluid flow inlet and outlet.

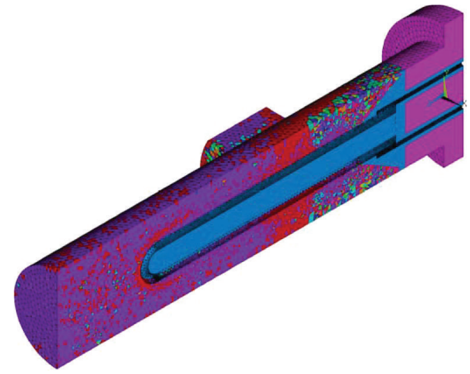

FIGURE 2: Stratified multiphase fluid flow in space. The grid colors represent the various dielectric constants of the fluid. The inlet flux is 5 m^3/day. Average water volume fraction in the mixed fluid is 80%.

a function of the distribution of the dielectric constants of the mixed fluid.

As shown in the figure, the outer shell is composed of metal conductors. The two inner cylinder conductors are short-circuited at the end. The space between port 0 and port 1 is filled with a known medium (i.e., air in this study) which has a RDC ε_{r0}. The distance between port 0 and port 1 is d_0. The distance between port 1 and the short-circuited end is d_1. Voltage and current are present in port 1 because of the excitation of voltage or current in port 0. Port 1 is considered as the measurement port. The oil-water mixed fluid with the RDC ε_{r1} occupies the space between port 1 and the short-circuit load. The mixed fluid flows in through the inlet at the bottom and flows out through the outlet at the top. The influence of the flow outlets is disregarded in the electromagnetic analysis because the outlets are small and far from the short-circuit load.

When the oil-water mixture flows into the shield shell, the fluid field becomes complex; the dielectric constant of the mixed fluid is a function of the spatial coordinates. A disturbance in the fluid flow causes the dispersion of the mixture, followed by the local concentration of the oil phase. Fluid velocity and water holdup distributions depend on the locations of the inlet and the outlet. Numerical calculations of the fluid field indicate that stratified distributions of the oil-water mixture often occur near the outlets (Figure 2).

This study focuses on oil-water mixture stratification caused by the complex fluid flow and the stratified distribution of the dielectric constant. The transmission line model is built using idealized stratified media layers (Figure 3). Let N be the number of stratified layers. The transmission line is short-circuited at $z = d = \sum_{n=1}^{N} d_n + d_0$. The media in the range $z = 0 \sim d_0$ are identified as media 0 with a RDC ε_{r0}. The mixture to be measured is located between port 1 and the end of the transmission line. (Port 1 to port n are the interfaces of the media.) The medium of each layer in $[d_0 + \sum_{n=1}^{N} d_{n-1} \sim d_0 + \sum_{n=1}^{N} d_n]$ with a RDC ε_{rn} is labeled n. The media are assumed to be lossless, with the dielectric constant being a real number. The relationship between the S-parameter at port 1 and the dielectric constants of each layer is derived in this section.

Although the practical mixture fluid flow is not in a perfect stratified state, the oil and water phase show obvious spatial segregations. Under the low-speed flow condition, computational fluid mechanics simulations show that quasistratified layers can be observed in the flowing channel (Figure 2). In this study, the device is designed to measure the water holdup in high temperature, high water content, and low production well logging. With a flux less than 8 m^3 per day in the pipe, the flowing speed is usually very low.

For more complicated cases, one can utilize fine layers to describe the flowing pattern and build a model based on what is developed here. If the flow contains much more turbulence and there are no obvious layers, simulation software incorporating coupling effect between fluid flow and electromagnetic field is still waiting to be developed. Actually, to develop an applicable device for industrial usage in high-water holdup low-production well logging, such a complicated model is not always necessary in most situations. The stratified model is a rather reasonable and simple model for theoretical analysis and for application.

The input impedance of the transmission line with length d and terminated load Z_L is given by [18]:

$$Z_{\text{in}}(d) = Z\frac{Z_L + jZ\tan(\beta d)}{Z + jZ_L\tan(\beta d)}, \quad (2)$$

where $Z = \sqrt{L/C} = \sqrt{L_0/C}$ is the characteristic impedance of the transmission line. L and C denote the inductance and the capacitance, respectively. The medium of the transmission line is the oil-water mixture, which is not a permeable material; thus, the inductance of the transmission line exhibits

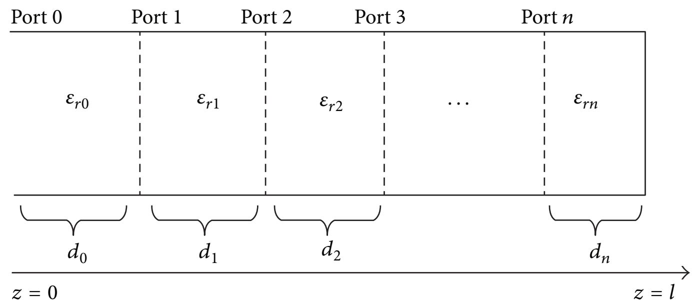

Figure 3: Transmission line model for stratified dielectric constant distribution in mixed fluid.

no relation to the media. The propagating constant of the electromagnetic wave in the transmission line is expressed as

$$\beta = \omega\sqrt{\mu_0\varepsilon_0\varepsilon_r} = \omega\sqrt{LC}, \tag{3}$$

where $\omega = 2\pi f$ is the angular frequency of the electromagnetic wave, such that f is the frequency of the electromagnetic wave; μ_0 and ε_0 are the permeability and the dielectric constant in the vacuum, respectively; ε_r is the RDC of the medium in the transmission line.

Assuming that the input impedance of port n is $Z_{\text{in}}(n)$, then

$$S_{11} = \frac{Z_{\text{in}}(1) - Z_0}{Z_{\text{in}}(1) + Z_0}, \tag{4}$$

where $Z_{\text{in}}(1)$ can be calculated by

$$\begin{aligned} Z_{\text{in}}(n-1) &= Z_0\sqrt{\varepsilon_{r,n-1}} \\ &\quad\times \frac{Z_{\text{in}}(n) + jZ_0\sqrt{\varepsilon_{r,n-1}}\tan\left(\beta_0 d_{n-1}\sqrt{\varepsilon_{r,n-1}}\right)}{Z_0(n)\sqrt{\varepsilon_{r,n-1}} + jZ_{\text{in}}(n)\tan\left(\beta_0 d_{n-1}\sqrt{\varepsilon_{r,n-1}}\right)}, \\ &\qquad (n = 2, \ldots, N) \\ Z_{\text{in}}(N) &= jZ_0\sqrt{\varepsilon_{rN}}\tan\left(\beta_0 d_N\sqrt{\varepsilon_{rN}}\right). \end{aligned} \tag{5}$$

Z_0 denotes the characteristic impedance of medium 0. β_0 represents the phase constant of the electromagnetic wave in medium 0. The parameters of the nth layer are Z_n, β_n, and ε_{rn}. The dielectric constant in the vacuum is ε_0. If the medium 0 is air, then $\varepsilon_{r0} \approx 1.0$ and β_0 is nearly the same as in vacuum.

The dielectric constant of the mixed fluid can be obtained from (4) and (5) with the S-parameter measured at port 1. By substituting the electric constants into (1), water holdup can be easily estimated.

Under the assumption of lossless media, the amplitude of the S-parameter measurement in port 1 is 1. The angle of the S-parameter is related to the propagating constant of the electromagnetic wave, length of each layer, and RDC of each layer. The S-parameter depends on the thickness d_n of each stratified layer and the propagating constant β. We define the parameter $\phi_0 = fd$ to represent the initial phase angle.

3. Numerical Examples

When two-phase mixture stratification occurs in the probe apparatus, the special effects of the complex fluid field on the electromagnetic field are considered. The effects of the complex fluid field on the electromagnetic field vary from those on the homogenous fluid field. To examine the difference before and after stratification, two models are considered: the two-layer model and the corresponding homogeneous model.

The two-layer stratification model is presented as an example. The parameters of the first layer are $v_1 = 80\%$ (the water holdup of the first layer) and $\varepsilon_{r1} = 78.93$. The parameters of the second layer are $v_2 = 0$ and $\varepsilon_{r1} = 2.3$. The first layer contains 80% water, and the second layer contains oil. The frequency of the electromagnetic wave is $f = 300$ MHz. The layer distances are represented by $d_1 = d_2 = 0.05$ m. By substituting these parameters into the equations provided in the Methods Section, we obtain the phase angle of the S-parameter $\angle S_{11} = 163.8^\circ$.

The average water holdup of the entire stratified mixture is given by $\overline{v} = (v_1 + v_2)/2 = 40\%$. If a homogenous fluid field with the same amount of water holdup $\overline{v}$ is assumed for comparison, the corresponding dielectric constant is approximately 61.5. Let the initial phase angle be $\phi_0 = \pi/\sqrt{80}$ (the angle of the S-parameter varies monotonically within the RDC range [2.23, 80]). In accordance with the equations above, the angle of the S-parameter is calculated as $\angle S_{11} = 179.94^\circ$, which is 20 degrees greater than the calculated S-parameter angle of the two-layer model. This example leads to the conclusion that the stratifications of the oil/water mixture exert nonnegligible effects on S-parameter measurement.

Under high water holdup conditions (i.e., with water holdup above 70%), the dielectric constant varies narrowly from 75 to 80. In the homogeneous model, a slight change in the S-parameter angle caused by variations in water holdup is almost impossible to identify. However, the stratification of the mixed fluid in real-life scenarios widens the range of the S-parameter angle and markedly enhances measurement sensitivity.

The three-layer model is presented as an example. When water holdup ranges from 70% to 90%, the dielectric constant of the fluid in the homogeneous model varies from 77 to 79. In the three-layer model, we suppose that the middle layer has a water holdup of 20% and a dielectric constant of 27.4,

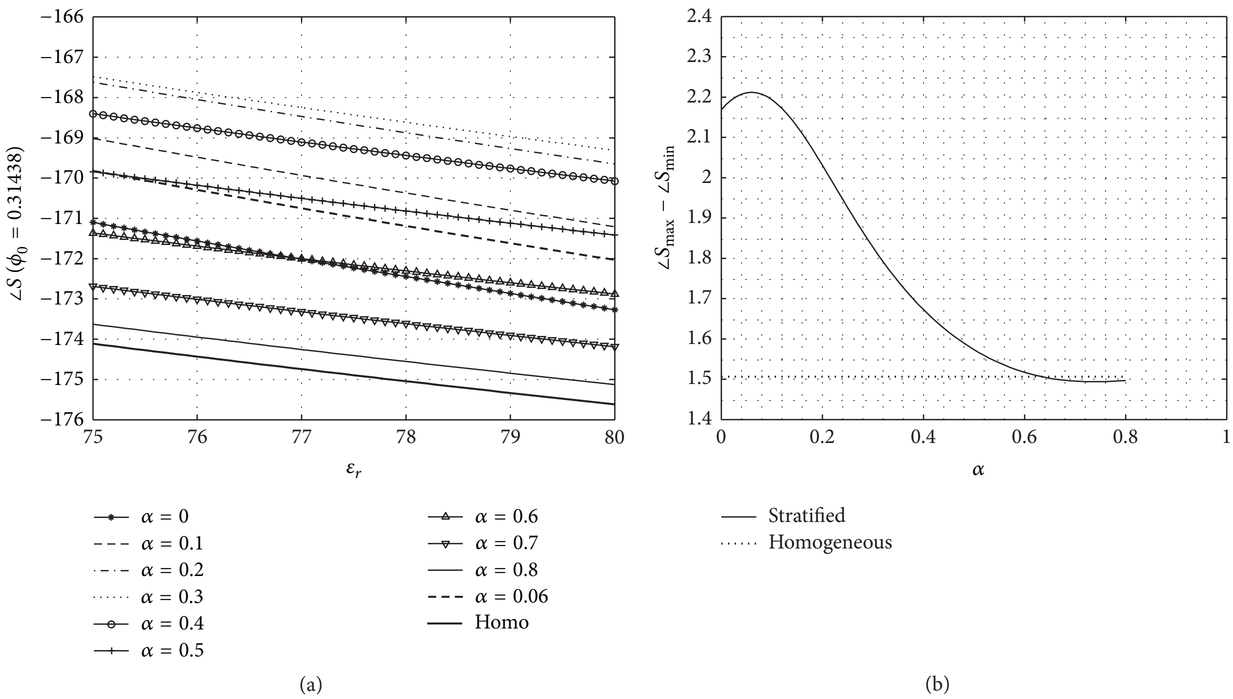

Figure 4: S-parameter curves for the stratified model of the mixed fluid under a high water content condition. The initial phase angle ϕ_0 is approximately $\pi/10$. The RDC of the oil layer is 27.4. The mixed fluid transmission line length is 0.05 m. (a) S-parameter phase angle versus dielectric constant variations in the mixed fluid. (b) Difference in the maximal-minimal phase angle versus stratification location.

indicating high oil content. The other two layers are filled with a background oil-water mixture, with a dielectric constant ranging from 77 to 79. When the location of the middle layer changes along the z-axis, the sensitivity of the S-parameter markedly changes as well.

We first select $f = 300$ MHz, the length of the mixed fluid transmission line as $d = 0.05$ m, and the high oil layer thickness as $d/5$ with a RDC of 27.4. The location of the high oil layer is represented by $x = \alpha d$. The variation in the S-parameter angle above the background dielectric constant and the location of the high oil layer is shown in Figure 4. Figure 4(a) shows the S-parameter angles above the dielectric constant of the mixed fluid at different oil layer locations. The S-parameter phase angle markedly changes by approximately 2.2 degrees as shown in Figure 4(b) within the dielectric range, whereas the change in the homogeneous model is only approximately 1.5 degrees (Figure 4(a) when $\alpha = 0.06$).

As shown in Figure 4(b), the S-parameter angle variations reach the largest value at approximately $\alpha = 0.06$; that is, the location of the oil layer is about $0.06d$ from port 1. Water holdup measurement under this condition is most sensitive. d denotes the thickness of the mixed fluid layer in the transmission line probe apparatus. Nevertheless, the change in the S-parameter angle remains insufficient because of the small initial phase angle ϕ_0 (the product of the electromagnetic frequency and the length of the transmission line).

We select $f = 300$ MHz and extend the length of the mixed fluid transmission line to $d = 0.1$ m. The thickness of the oil layer remains at $d/5$. The variations in the S-parameter angle are shown in Figure 5.

Figure 5(b) indicates that the S-parameter phase angle obtains the largest value at approximately 70 degrees when the oil layer is located $0.54d$ from port 1. Similarly, the change in the homogeneous model is only approximately 5 degrees (Figure 5(a)), which is markedly smaller than the change in the three-layer model. The results suggest that the measurement sensitivity can be enhanced by increasing the range of the S-parameter phase angle if the stratification in the oil-water mixed fluid field can be controlled.

Using the numerous calculations of the different models, we have determined that the S-parameter angle variations can reach the largest values if the oil layers are at optimized locations. The initial phase angle is another factor that controls the largest phase angle. When the transmission line length is adequately long and the electromagnetic wave frequency is sufficiently high, the variation in the S-parameter angle can be significantly increased by adjusting the oil layer locations. No generalized oil layer locations for enhancing the measurement sensitivity exist. The optimized locations depend on the frequency of the electromagnetic wave and the length of the transmission line.

In addition to the locations of the stratified oil-water mixture, the dielectric constants of the oil layers significantly affect the S-parameter phase angle. The change in the S-parameter angle is investigated using different oil layer dielectric constants and a fixed initial phase angle. Let $\phi_0 = \pi/5$ and the dielectric constants of the oil layers vary from 2.23 to 80. Figure 6 shows the variations in the S-parameter phase angle. The optimized initial phase of the S-parameter is determined to be approximately $\alpha = 0.5$. The optimized location of the oil layer approaches port 1 as the dielectric constant of

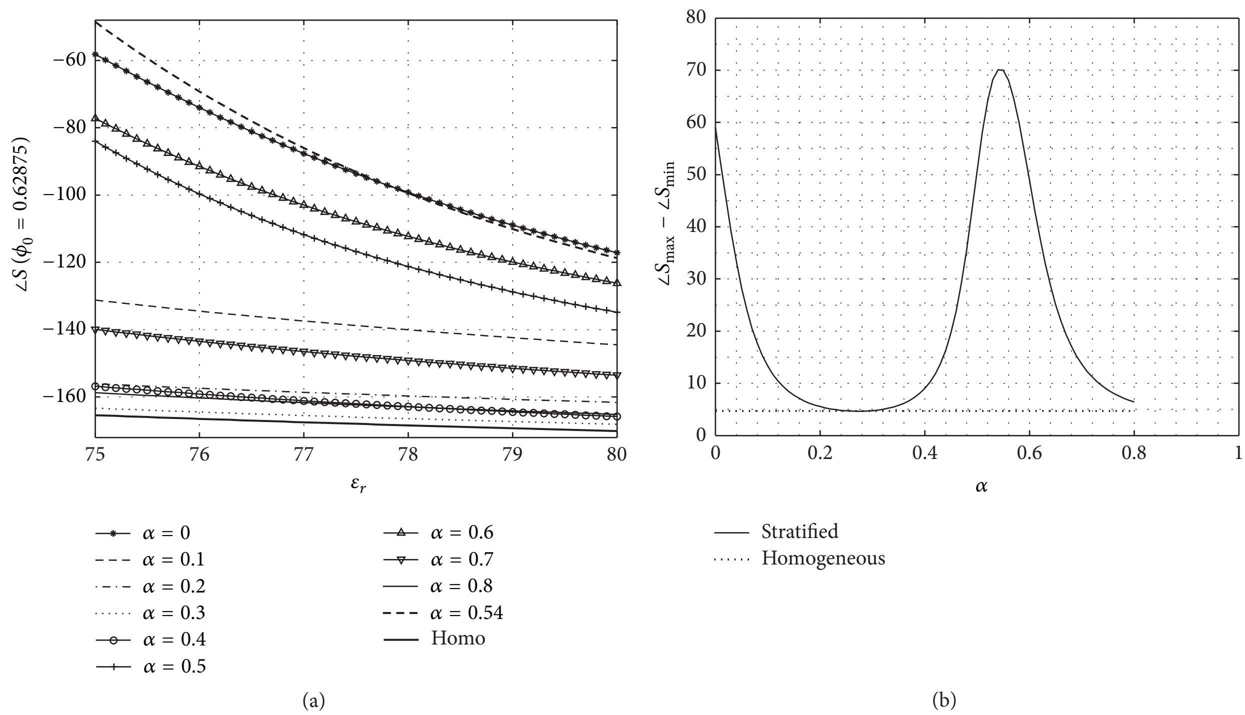

FIGURE 5: S-parameter curves for the stratified model of the mixed fluid under high water content conditions. The initial phase angle ϕ_0 is approximately $\pi/5$. The RDC of the oil layer is 27.4. The mixed fluid transmission line length is 0.1 m. (a) S-parameter phase angle versus dielectric constant variations in the mixed fluid. (b) Difference in the maximal-minimal phase angle versus stratification location.

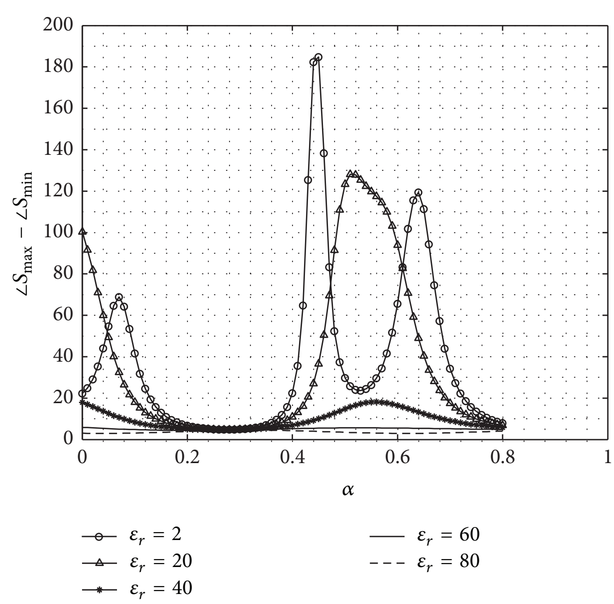

FIGURE 6: S-parameter curves for stratified model of the mixed fluid under high water content conditions. The initial phase angle ϕ_0 is approximately $\pi/5$. The RDCs of the oil layers vary from 2 to 80.

the oil layer increases. The results provide another possibility to enhance the measurement sensitivity by changing the structure of the probe apparatus. By adjusting the outlet locations, we can actively influence the fluid field patterns. The optimized oil/water layer distribution can increase the range of the S-parameter phase angle.

4. Discussion

4.1. Multiple-Solution Problem of S-Parameter Inversion. When no oil-water stratification is present, that is, $N = 1$, the S-parameter of port 1 can be expressed as

$$S_{11} = \frac{j\beta_0 \tan(\beta_1 d_1) - \beta_1}{j\beta_0 \tan(\beta_1 d_1) + \beta_1}. \tag{6}$$

A multiple-solution problem may occur because the S-parameter phase angle and the RDC exhibit a non-monotonic relationship. Multiple dielectric constants can be obtained from one S-parameter phase angle, hindering the determination of the unique water holdup. To solve the problem, we analyze the S-parameter formula as follows.

The periodic function $\tan(x)$ in the S_{11} formula results in a nonmonotonic S-parameter phase angle. The monotonic trend is found only in part of the entire definition domain. The analyses in the sections above show that the relationship between the S-parameter phase angle and the RDC depends on the initial phase angle, that is, the product of the electromagnetic frequency and the stratification section thickness. Thus, the S-parameter phase angle corresponding to the same ϕ_0 exhibits the same variations with respect to the dielectric constant. The S-parameter phase angle surface versus the RDC ε_{r1} and the initial phase angle ϕ_0 is shown in Figure 7.

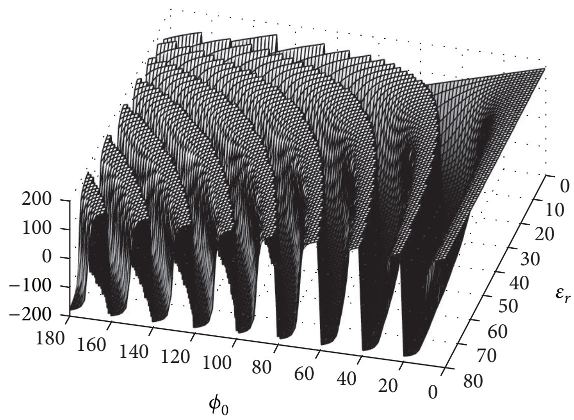

FIGURE 7: S-parameter variations versus the RDC and the initial phase angle.

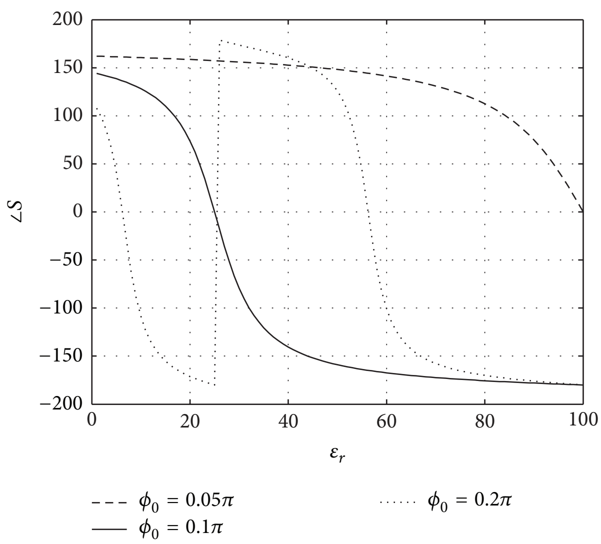

FIGURE 8: S-parameter phase angle variations versus RDCs.

When $\phi_0 = 0.1\pi$ and $\phi_0 = 0.05\pi$, the range of monotonic variation for the S-parameter is $\varepsilon_{r1} \in [0, 100]$ (Figure 8). However, a periodic behavior occurs in the range $[0, 100]$ when $\phi_0 = 0.2\pi$.

To ensure monotonic variations, the tangent function is limited to one cycle. The maximal RDC $\varepsilon_{r\max}$ satisfies the following condition:

$$\beta_0 d_1 \sqrt{\varepsilon_{r\max}} \leq \pi. \tag{7}$$

With this inequality, the S-parameter phase angle is a monotonic function in the RDC range $[0, \varepsilon_{r\max}]$. In the case of water ($\varepsilon_{r\max} = 80$), $\phi_0 \leq \pi/\sqrt{80}$ ensures the single solution within the RDC range of 0 to 80.

In accordance with the maximum RDC $\varepsilon_{r\max}$, we calculate the corresponding initial phase angle that ensures monotonic S-parameter phase angles. The monotonic angle domain is shown in Figure 9. By selecting the appropriate electromagnetic wave frequency f and the thickness d_1 of layer 1, the limit of the initial angle in the monotonic domain

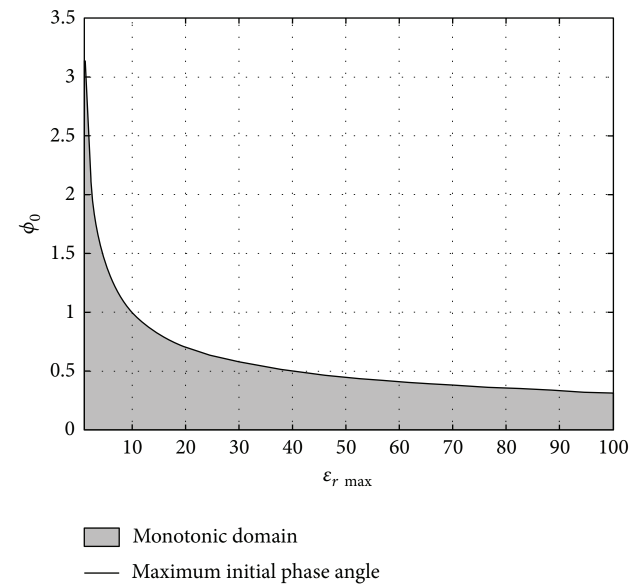

FIGURE 9: Initial phase angle distributions required by the monotonic variation of the phase angle versus the RDC.

can be easily obtained and the difficulties caused by the multiple-solution problem can be overcome.

4.2. S-Parameter Sensitivity Analysis. Figure 9 indicates that the large product of f and d_1 results in a large initial phase angle ϕ_0, which may exceed the monotonic domain boundary and result in a serious multiple-solution problem. By contrast, a small product leads to a decrease in measurement sensitivity. Balance between sensitivity and the multiple-solution problem is to be achieved. Therefore, determining the most sensitive range in S-parameter estimation while maintaining the absence of a multiple-solution problem is important.

The sensitivity of the S-parameter depends on the RDC. The most sensitive point can be achieved when the slope of the S-parameter phase angle reaches the largest value. The S-parameter phase angle formula can be derived from (6):

$$\angle S = \arctan\left(\frac{2\sqrt{\varepsilon_{r1}}\tan\left(\beta_0 d_1 \sqrt{\varepsilon_{r1}}\right)}{\tan^2\left(\beta_0 d_1 \sqrt{\varepsilon_{r1}}\right) - \varepsilon_{r1}}\right) + k\pi, \tag{8}$$

where k depends on the signs of the real and the imaginary parts of the S-parameter. $k = 0$ if the real part is positive; $k = -1$ if both the real and the imaginary parts are negative, and $k = 1$ if the real part is negative and the imaginary part is positive. By obtaining the second derivative of the equation above and then equating the result to zero, we can obtain the following optimal sensitivity equation:

$$\varepsilon_{r1p} = \left(\frac{\pi}{2} \cdot \frac{1}{\beta_0 d_1}\right)^2. \tag{9}$$

Here ε_{r1p} denotes the RDC for which the device is most sensitive. The slope of the $\angle S$ curve reaches the largest value

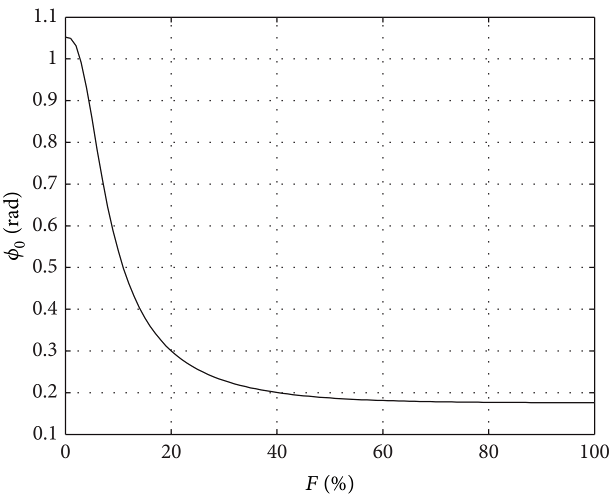

Figure 10: Initial angle versus water content for the most sensitive measurement.

when $\beta_0 d_1 \sqrt{\varepsilon_{r1}} = \pi/2$. Thus, one can determine the most sensitive point at which

$$\angle S\left(\varepsilon_{r1p}\right) = 0,$$
$$\left.\frac{d\angle S\left(\varepsilon_{r1}\right)}{d\varepsilon_{r1}}\right|_{\varepsilon_{r1}=\varepsilon_{r1p}} = \beta_0 d_1. \tag{10}$$

The measurement sensitivity is maximized at this point. This condition indicates that the variation of ε_{r1} can be measured most sensitively when $\beta_0 d_1 \sqrt{\varepsilon_{r1}} = \pi/2$ is satisfied.

To achieve best accuracy, the measured S-parameter must be sensitive with the RDC changes. If the large changes in RDC lead to small changes in the S-parameter, the method could not work. So in order to get an accurate value of relative constants, the method must work around the most sensitive range.

We propose a procedure to optimize water holdup measurement. The following steps ensure the accurate measurement of relative constants. (1) Estimate the maximum RDC values to measure the media, such as $\varepsilon_{r\max} = 80$. (2) Select the proper electromagnetic wave frequency and the proper length of the transmission line (i.e., the proper initial phase angle) to ensure a monotonic phase angle function for the S-parameter. According to initial phase angle distributions (Figure 9), choose the appropriate ϕ_0 to guarantee monotonic S-$\varepsilon_{r\max}$ functions. (3) By adjusting the frequency and the length of the transmission line, the most sensitive range covers the range of the RDC to be measured. (4) By measuring the phase angle of S-parameters in full oil and full water cases in lab, a S-ε_r template is calibrated by relative dielectric constant in high resolution. (5) The measured S-parameter data in well logging will be plot in S-ε_r template and then the corresponding ε_r are determined. The accurate measurement of the relative constant is ensured because this S-ε_r template is created with the most S-ε_r sensitivity.

To calculate the most sensitive points under different water holdup conditions, the relationship of the RDC with water holdup is substituted into (1). The relation of the most sensitive initial phase ϕ_0 to water holdup is reflected in the following function:

$$\phi_0 = \frac{\pi}{2\sqrt{\varepsilon_m}} = \frac{\pi}{2\sqrt{80 - 38.885\left(0.01F^2 + 0.2F + 2\right)e^{-0.1F}}}, \tag{11}$$

where $\varepsilon_w = 80$ and $\varepsilon_{\text{oil}} = 2.23$, and F is the water holdup for the mixture. The most sensitive initial angles for water holdup in the range of 0% to 100% are shown in Figure 10.

We can easily select the proper electromagnetic wave frequency and the length of the transmission line from this curve in accordance with the water holdup estimation. Furthermore, we can adjust the most sensitive range to increase the measurement accuracy.

5. Conclusion

Based on the stratification model of the oil/water mixture at a low flow rate, the S-parameter for the shielded two-wire transmission line with a short-circuit load is derived. The coupling effect between the fluid field and the high-frequency electromagnetic field is analyzed, which shows the dependence of the S-parameter on the multiphase flow pattern. The RDC of the mixed fluid can be obtained from the S-parameter measurement. The water holdup of the mixed fluid can be estimated using the relationship between the dielectric constant and the water fraction. A theoretical analysis shows that the multiple-solution problem can be avoided and that the measurement sensitivity can be improved by adjusting the electromagnetic wave frequency and the length of the transmission line. The analysis of the stratification phenomenon in the oil-water fluid flow indicates that the coupling between the fluid field and the electromagnetic field significantly influences the S-parameter measurement. The local dispersion of the water and oil phases is an important factor in improving the sensitivity and accuracy of the water holdup probe apparatus.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

This research is supported by the Major National Science and Technology Programs in the "Twelfth Five-Year" Plan period (2011ZX05020-008) and Open Foundation of SINOPEC Key Laboratory of Geophysics.

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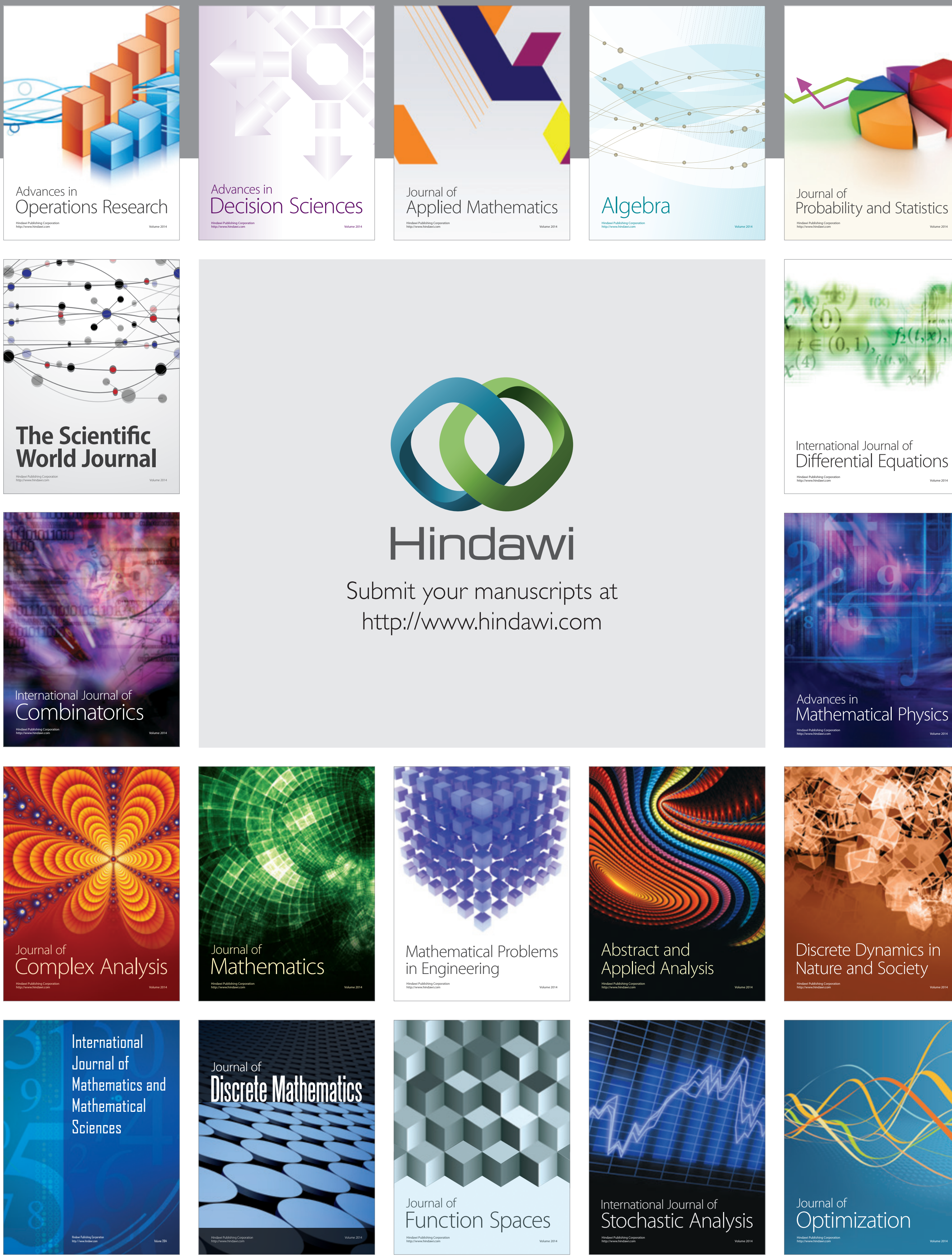
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