Void Fraction Measurement Using the Coaxial Line Phase Technique in the Vertical Gas-Liquid Slug Flow

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Abstract

Based on the electromagnetic wave propagation principle, a prediction model based on the phase difference of coaxial lines to measure the void fraction of the slug flow is proposed, and experiments on vertical pipe slug flow are conducted under 70 working conditions. A new mixing dielectric constant measurement model is established by adding a phase mixer device to the sensor to stir the slug flow into a popular and stable homogeneous flow. The homogeneous flow under the same experimental conditions is used as the reference true value of the slug flow measurement section void fraction model, and the prediction model is validated and optimized. The results show that the MAPE value of the optimized measurement model is reduced from 2.96% to 1.02% without the addition of a phase mixer, and the prediction of the void fraction of the slug flow is improved compared with the previous one.

1. Introduction

Slug flow widely exists in petroleum industry, chemical engineering, power engineering and nuclear reactor engineering, and has a broad engineering application background. The study of the characteristic parameters of slug flow in vertical pipes, such as the length of liquid slug, void fraction, and velocity of liquid slug, not only helps to fully grasp the flow characteristics of slug flow, but also has great guiding significance for engineering applications. void fraction is an important parameter to describe the phase distribution of multiphase flow and an important symbol of flow pattern conversion.

In recent years, the microwave technology has been widely used in communication, medical treatment, food and petrochemical industry[1-3]. As a kind of microwave transmission mode, the coaxial transmission widely used in instruments and equipment, which can complete the transmission of high-frequency signals. The coaxial transmission has the advantages of low cost, strong anti-interference ability, and it is not easy to leak electromagnetic waves. It has been widely used in the field of multiphase flow testing[4-6]. In 1976, Kraszewski A et al.[7] measured the moisture content of sand on the conveyor belt by detecting the amplitude attenuation and phase shift of microwave, and proposed and verified a measurement model for predicting the moisture content. In 2005, Abbas Z et al.[8] designed a coaxial sensor to detect the moisture content of oil palm fruit, and carried out experiments on oil palm fruit with different maturity. The dielectric properties of fruit were calculated by quasi-static admittance model and dielectric mixing model. In 2013, Makeev Y V et al.[9] proposed a microwave method and device for measuring the moisture content of flowing crude oil. Two modifications had been made to the device, which could be used to measure moisture content in the range of 0.01-30% and 0.01-100%, respectively. In 2014, Wang C et al.[10] proposed a new coaxial sensor for measuring oil-water volume fraction, which proved that Maxwell model was the best model when oil volume fraction was less than 50%. In 2017, Chen X et al.[11] measured the moisture content of low-speed oil-water two-phase flow by coaxial capacitive sensor in vertical upward oil-water two-phase flow, and optimized the sensor distribution characteristics and geometric size by finite element analysis. In 2018, Zhao C J et al.[12] established the DNN model based on Adam algorithm to predict the moisture content of crude oil. Combined with the neural network model to predict the relationship between moisture content and oil-water mixed dielectric constant, successfully eliminating the influence of conductivity. In 2019, Woszczyk A et al. [13] designed and optimized an open probe for measuring soil moisture content based on HFSS. The probe had been tested for soil moisture measurement in the frequency range from 50MHz to 350MHz. In 2022, Wang Y S et al.[14] studied a new coaxial capacitive sensor network, which is characterized by parallel bending electrodes and non-parallel plane electrodes. The theoretical model of coaxial capacitive sensor is established, and the relationship between two capacitive sensors in sensor network is analysed. At present, the coaxial line technology has done a lot of research in the field of multiphase flow detection, especially in the oil-water two-phase flow. Microwave technology responds well to oil-water two-phase flow. However, there are few studies on the application of coaxial phase technology to gas-liquid two-phase flow to measure void fraction. In addition, the solution of the mixed dielectric constant of two-phase flow is mostly complicated and expensive.

In this paper, the slug flow is effectively stirred and mixed by a phase mixer. A mixed dielectric constant measurement model based on homogeneous flow is established. A prediction model for measuring void fraction is put forward, and the prediction model for slug flow void fraction without a mixer is verified and optimized.

2. Coaxial line phase measurement technology and void fraction measurement model

2.1 Coaxial line phase sensor

Dielectric constant and conductivity are two important parameters that affect electromagnetic signals, and the change of fluid state will lead to the change of dielectric constant. Therefore, the phase difference of electromagnetic wave signal passing through coaxial line will change when it is transmitted in mixed fluid. This principle is used to measure the void fraction of slug flow. In the vertical pipe experiment, Sulzer static mixer (SV type) is used to stir and mix the incoming flow. Its interior is assembled by a cylinder composed of corrugated plates with a certain specification, and its two ends are connected by flanges. The slug flow crosses in the phase mixer and gets effective mixing. After flowing through the phase mixer, the bullet flows to the coaxial sensor in the form of homogeneous flow. The homogeneous medium flows between the inner and outer conductors of the sensor and becomes the carrier of electromagnetic wave energy. The experimental device is shown in fig. 1, and the transmission mode of electromagnetic wave is TEM wave.

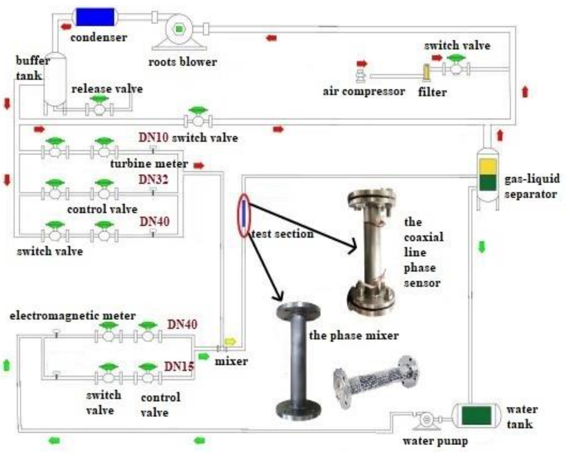

Figure 1: Experimental device diagram of coaxial line sensor.

On the basis of selecting appropriate sensor parameters, the void fraction of gas-liquid mixed fluid is obtained by measuring the phase characteristics of electromagnetic wave propagating in coaxial line.

2.2 void fraction measurement model

According to Maxwell equation, the propagation characteristics of electromagnetic waves mainly depend on the relative dielectric constant and conductivity of the medium. At 25℃, the dielectric constant of water is 78.30. the dielectric constant of air is generally about 1.00, so σ can be ignored. The electromagnetic wave propagation constant can be expressed as shown in formula (1):

$$\gamma = \alpha + j\beta \tag{1}$$

Where,

$$\alpha = \omega\sqrt{\frac{\mu_0\varepsilon_0\varepsilon_e}{2}\left[1+(tan\theta)^2-1\right]} \tag{2}$$

$$\beta = \omega\sqrt{\frac{\mu_0\varepsilon_0\varepsilon_e}{2}\left[1+(tan\theta)^2+1\right]} \tag{3}$$

Where γ is the propagation constant of electromagnetic wave, which is a physical quantity reflecting the amplitude and phase change of wave after passing through a unit length coaxial transmission line; α is the attenuation constant; β is the phase shift constant; $tan\theta = \frac{\sigma}{\omega\varepsilon_0\varepsilon_e}$ is the loss factor, σ is equivalent conductivity of medium in coaxial line, (S/m); ω is the angular frequency of the electromagnetic wave signal, (rad/s); μ_0 is permeability of vacuum, (H/m); ε_0 is the vacuum dielectric constant, (F/m); ε_e is the equivalent relative dielectric constant of the medium in the coaxial line.

Analysing the dielectric characteristics of gas-liquid mixture fluid and the response characteristics of the instrument, and considering the performance of electronic components and manufacturing process level, the working frequency of electromagnetic field is selected as 70MHz. The electromagnetic wave signal frequency is high enough to make $tan\theta \ll 1$, the attenuation constant α is 0. Assuming that the coaxial line is a lossless transmission line, the formula (3) is simplified to the formula (4), as shown in the following formula:

$$\beta \approx \omega\sqrt{\mu_0\varepsilon_0\varepsilon_e} \tag{4}$$

The phase shift of electromagnetic wave transmitted in the L-long coaxial line is shown in Formula (5):

$$\Delta\varphi = L\beta \tag{5}$$

It can be seen from equation (5) that when the electromagnetic wave emission frequency and the length of coaxial line are determined, the relative dielectric constant becomes the main factor affecting the change of phase shift constant.

After the slug flow is mixed by the phase mixer, the gas and liquid penetrate each other and can be used as a "fluid". The equivalent relative permittivity of this "fluid" under the action of an electric polarization field is shown in formula (6):

$$\varepsilon_m = \frac{\varepsilon_w \varepsilon_g}{\varepsilon_w \alpha_g + \varepsilon_g \alpha_w} = \frac{78.3}{78.3\alpha_g + (1-\alpha_g)} \tag{6}$$

Where α_g is the void fraction, α_w is the water content, $\alpha_w = 1 - \alpha_g$, ε_g is the relative dielectric constant of gas and ε_w is the relative dielectric constant of water.

The phase difference is measured by the phase detector AD8302 using the logarithmic compression principle of logarithmic amplifier, as shown in equation (7):

$$V_{PHS} = -0.01 \cdot \left|\Delta\varphi - \frac{\pi}{2}\right| + 0.9 \tag{7}$$

Therefore, the solution formula of void fraction is:

$$\alpha_g = \frac{4\omega^2 L^2 \mu_0 \varepsilon_0 \varepsilon_w \varepsilon_g}{(180 - 200V_{PHS} + \pi)^2 (\varepsilon_w - \varepsilon_g)} - \frac{\varepsilon_g}{\varepsilon_w - \varepsilon_g} \tag{8}$$

3. Experiment testing and result analysis

The experiment is carried out in the high-precision gas-liquid two-phase flow simulation experimental device of Hebei University. The experimental medium is water and air, the experimental pipe diameter is DN50. The gas superficial velocity ranged from 0.042 m/s to 0.42 m/s, and the liquid superficial velocity ranged from 0.7 m/s to 1.12 m/s. Under this flow condition, according to Hewitt and Roberts flow pattern diagram, it can be seen that the gas-liquid two-phase flow pattern in the vertical pipeline is slug flow. All the experiments points of void fraction at different gas superficial velocity and liquid superficial velocity are shown in fig. 2.

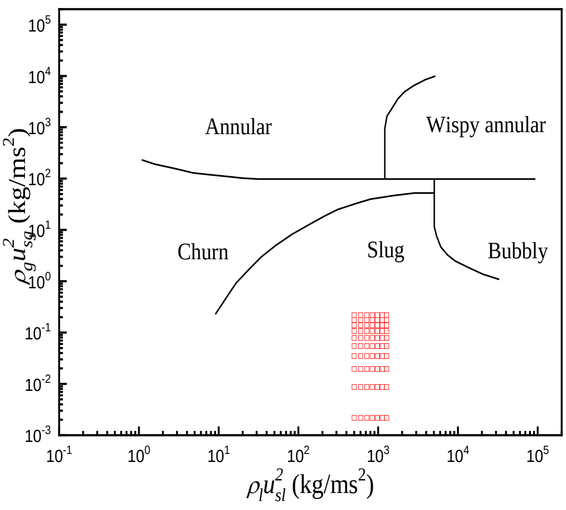

Figure 2: Hewitt and Roberts flow pattern diagram.

Perform probability density function analysis on 1000 sample data under 70 experimental points, and screen out the phase difference V_{PHS} required by the experimental model.

The experimental results show that the void fraction increases with the increase of the gas superficial velocity while the liquid superficial velocity remains constant, while the void fraction decreases with the increase of the liquid superficial velocity while the gas superficial velocity remains constant, which accords with the flow conditions of vertical pipe slug flow pattern. As shown in fig. 3.

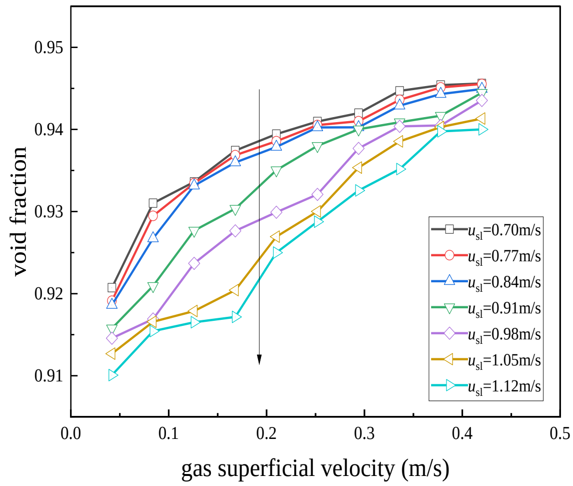

Figure 3: Relationship between gas superficial velocity and void fraction.

4. Verification and optimization of void fraction prediction model of slug flow

4.1 Prediction model of void fraction in slug flow

The slug flow experiment was carried out under the same flow conditions. Without the static mixer, the two-phase flow flows through the coaxial phase sensor in the form of slug flow, which is in a series-parallel state in the pipeline. Therefore, the equivalent relative dielectric constant of gas-liquid two-phase mixed medium under the action of electric polarization field is shown in formula (9):

$$\varepsilon_{gw} = k\left(\varepsilon_w \alpha_w + \varepsilon_g \alpha_g\right) + \frac{(1-k)\varepsilon_w \varepsilon_g}{\varepsilon_w \alpha_g + \varepsilon_g \alpha_w} \tag{9}$$

Where,

$$k = \frac{2\alpha_g}{5 - 3\alpha_g} \tag{10}$$

In this paper, the existing experimental data are used to verify and evaluate the prediction model of slug flow void fraction measured by coaxial line phase technology without adding a mixer. According to the homogeneous flow model in the experiment, the flow pattern is stable, the inlet parameters are single, and the structure is simple. The mixed medium in the state of gas-liquid two-phase flow can be regarded as a single medium. The homogeneous flow under the same experimental condition is taken as the reference truth value of the void fraction model of slug flow measurement section, and the error analysis of the void fraction model of slug flow measurement section is carried out under the same condition by using the flow characteristics of homogeneous flow. The consistency of the experimental results is expressed by mean absolute percentage error (MAPE), and the comparison between the experimental results and the model prediction results is shown in fig. 4.

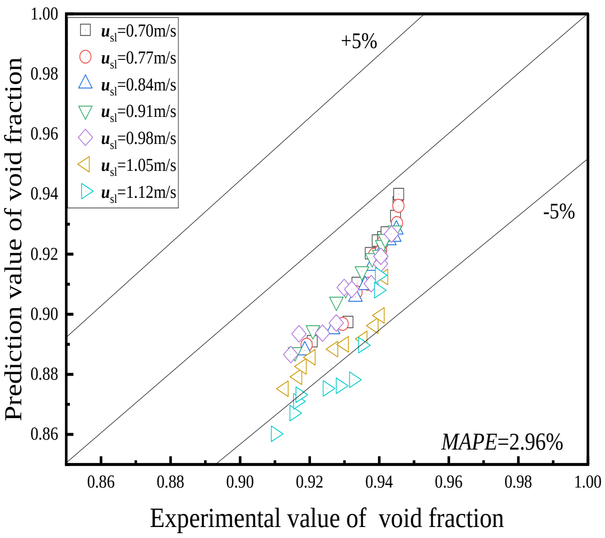

Figure 4: Comparison between experimental results and model prediction results

The two models used in the experiment represent two different correlations: uniform correlation and slip ratio correlation. The correlation between the experimental results of the void fraction model with or without a mixer shows that the MAPE is 2.96%, and 88.6% of the experimental data points are within the average absolute percentage error of 5%. It can be seen from the fig. 4, the experimental results of the measured void fraction models under the two flow patterns have certain correlation, but the experimental predicted values are low, which may be caused by two reasons. The first reason is that the flow patterns are different, and the state of the gas-liquid mixture inside the vertical pipe changes after it is added to the static mixer, which may lead to the difference of experimental data. The second reason may be the improper selection of dielectric constant of gas-liquid mixture. Series-parallel method is used to solve the gas-liquid mixed dielectric constant of slug flow void fraction model, but the series-parallel method represents two extreme cases of actual mixed dielectric constant when solving the void fraction model, that is, the upper limit and the lower limit of mixed dielectric constant are given, which will lead to a big difference between the mixed dielectric constant and the actual result. All these reasons may be the reasons for the big error between the experimental results in slug flow model and those in homogeneous flow model. Moreover, the series-parallel method is adopted in the prediction model of gas-liquid mixed dielectric constant in this paper. When the slug flow passes through, there will be not only gas slug but also liquid slug, and some liquid particles will be mixed between the gas slug and the liquid slug, so the flow pattern is complicated. Therefore, in order to improve the measurement accuracy of this model, its ε_{gw} must be optimized.

4.2 Optimization of mixed dielectric constant prediction model

The dielectric properties of gas-liquid two-phase flow are closely related to electrical and magnetic properties. Therefore, the research on the dielectric properties of gas-liquid two-phase flow has been widely concerned. In the effective medium theory, the dielectric properties of heterogeneous media are generally described by phenomenological method, and the function of mixture components is usually expressed by the effective dielectric constant of heterogeneous media. The combination and shape of different components of the mixture will also have great influence on the dielectric constant of the mixture. In continuous media, its configuration can be roughly divided into two categories: one is a symmetric medium which is randomly mixed with spherical particles and fills the whole space (topological equivalence). Bruggeman's effective medium theory is commonly used for this medium, and the other is an antisymmetric medium structure in which one component surrounds another. The commonly used theory is Maxwell-Garnett theory. In order to make the theory more consistent with the experimental results and reduce the error, this paper improves the formula for calculating the effective dielectric constant of the mixture in the slug flow pattern of vertical pipe, and analyses the effective dielectric constant of the gas-liquid binary mixture.

The study of void fraction in gas-liquid two-phase flow is an important index in parameter research. At present, the common method to measure the void fraction of slug flow is based on the principle that the mixed dielectric constant is different under different void fractions.

The slug flow alternately flows from gas slug and liquid slug, and the gas slug is separated from the pipe wall by liquid film, and there are many small bubbles at the junction of liquid slug and gas slug, which will cause great uncertainty in the solution of ε_{gw}. In order to obtain the mixed dielectric constant accurately, the mixed dielectric constants of aeroelastic and liquid elastic are considered separately in this paper.

When the gas slug passes, the mixed dielectric constant is solved in series, and the mixed dielectric constant is expressed by formula (11):

$$\varepsilon_{\text{gas}} = \frac{\varepsilon_w \varepsilon_g}{\varepsilon_w \alpha_g + \varepsilon_g \alpha_w} \tag{11}$$

When the liquid slug with bubbles flows, the mixed dielectric constant of liquid slug is expressed by formula (12):

$$\alpha_g \frac{\varepsilon_{liquid} - a}{2a + \varepsilon_{liquid}} + (1 - \alpha_g) \frac{\varepsilon_{liquid} - b}{2a + b} = 0 \tag{12}$$

Where,

$$b = \frac{2\alpha_g}{3 - \alpha_g} \varepsilon_g \tag{13}$$

$$a = \frac{2 - 2\alpha_g}{2 + \alpha_g} \varepsilon_w \tag{14}$$

For this gas-liquid two-phase flow, the mixed dielectric constant is calculated by weighted harmonic average, and the weight is based on the gas slug frequency. Because the slug flow is a very complicated physical process with no strict regularity, the frequency of gas slug only approximates the intermittence of slug flow with periodicity. A new dielectric constant formula can be obtained:

$$\varepsilon_{gw} = t_1 \varepsilon_{gas} + t_2 \varepsilon_{liquid} \tag{15}$$

$$t_1 + t_2 = t \tag{16}$$

PSD (power spectral density function) can be used to obtain the characteristic frequencies of gas and liquid slug. PSD is the fast Fourier transform of signal autocorrelation function, which represents the energy distribution of signals at different frequencies. The power spectral density function is used to analyse the phase difference signal and reflect the energy distribution of the signal at different frequencies.

$$P(\omega) = \frac{1}{N} \left| \sum_{n=0}^{N-1} x(n) e^{-j\omega m} \right| \tag{17}$$

Where N is the number of sample segments divided by $x(t)$, and $x(t)$ is the experimental signal.

The characteristic frequency is used to represent the time $t=1/f$ when the gas slug and liquid slug appear. According to the relationship between the occurrence time and formulas (15) and (16), the values of t_1 and t_2 can be obtained. At the same time, according to the relationship between the change of values of t_1 and t_2 and the dimensionless gas-phase Froude number, the functional expression of t_1 and t_2 is obtained as follows:

$$t_1 = f(Fr_g, Fr_l) \tag{18}$$

Froude number is a dimensionless parameter that represents the relative magnitude of gravity and inertia of fluid. In order to verify the time t_1 and t_2 of gas slug and liquid slug flowing in one cycle, it is characterized by dimensionless number. The basic parameters of Froude number are determined according to the experimental inlet parameters, perform function fitting on t_1 and t_2. Get the correlations of t_1 and t_2:

$$t_1 = 5.84606 + 0.37302 Fr_g + 15.90535 Fr_l \tag{19}$$

$$t_2 = \frac{1}{f} - t_1 \tag{20}$$

To sum up, the optimization model of slug flow void fraction can be obtained.

4.3 *Verification of optimization model of cross-section void fraction*

According to two different flow patterns of slug flow, gas slug and liquid slug, the mixed dielectric constant measurement model is optimized, and a new dielectric constant measurement model is obtained, and the optimized model of slug flow void fraction in vertical pipe is obtained. The homogeneous flow under the same experimental condition is taken as the reference truth value of the slug flow measurement void fraction model, and the error analysis of the slug flow measurement void fraction optimization model is carried out.

The comparison between the optimized void fraction prediction model and the experimental measurement results is shown in Figure 5. The experimental results show that the correlation between slug flow void fraction optimization model and experimental model has been strengthened. It can be seen from the fig. 5 that MAPE is reduced to 1.02%, and the experimental data are all within the average absolute percentage error of 5%. The new prediction model improves the sensing ability and measurement accuracy of coaxial line sensor.

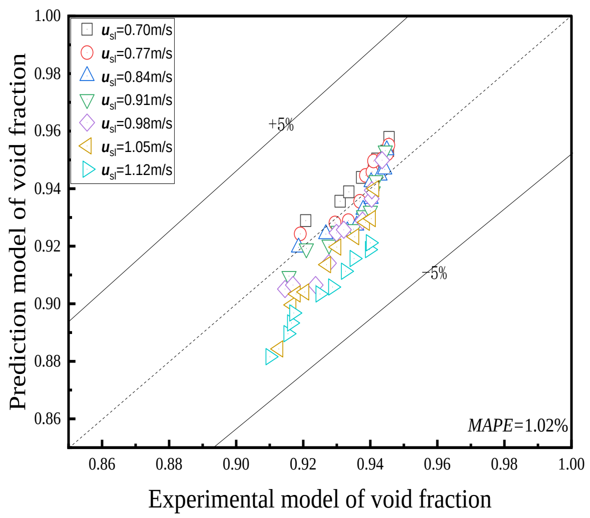

Figure 5: Comparison between experimental model of void fraction and optimized prediction model

5. Conclusion

In this paper, the void fraction of slug flow (without static mixer) and homogeneous flow (with static mixer) under vertical pipe was measured by electromagnetic coaxial line phase sensor measuring device, and its dielectric constant was optimized.

1. According to the different dielectric constants of gas-liquid mixture under different flow patterns, the correlations for solving different dielectric constants are given, and the correlations among void fraction, mixed dielectric constant and phase difference are obtained.

2. The slug flow is stirred into a homogeneous flow by using a mixer. According to the stable flow pattern of homogeneous flow, the two-phase flow can be regarded as a single fluid. Taking the experimental data of the void fraction measured by homogeneous flow as the reference true value, the experimental data of the void fraction by slug flow is analyzed.

3. The optimized and modified mixed dielectric constant prediction model is obtained by analyzing two different flow patterns of gas slug and liquid slug and PSD (power spectral density function) under the slug flow pattern. The error of void fraction measurement model and optimization model is compared and analyzed, and the correlation of the comparison results is strengthened. MAPE decreased from 2.96% to 1.02%, and the experimental data were within the average relative error of 5%.

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