A Void Fraction Measurement Method of Gas-water Flow Based on Microwave Method

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Abstract

In the natural gas industry, measuring void fraction with high accuracy is challenging, because the flow pattern of gas-flow is complicated and changeable. This research presents a microwave sensor to measure void fraction of gas-water flow based on the microwave transmission line method. The sensor contains horizontal and vertical electrodes resulting in a spatial orthogonal transmission line combination structure, so that the gas-water flow regime can be detected and its influence on the measurement can be accounted for. The electromagnetic fields inside the sensor for stratified and annular distribution structure are simulated and analyzed using COMSOL software. Furthermore, the variation characteristics of the horizontal and vertical electrode phase outputs of the stratified distribution structure are investigated by static experiments. Finally, flow experiments covering stratified, wavy, slug, annular gas-water flow regimes, indicates that the void fraction are positive correlated to the sensor outputs and can be predict by the sensor.

1. Introduction

In the natural gas industry, gas-water flow is very common. In the production of natural gas, the void fraction is a crucial indicator. Precise measurement of void fraction (i.e. ratio of the area occupied by air to the cross-section area of the pipe) in gas-water flow plays important roles for the production[1]. Because of the complex flow process of gas-water flow and wide range of void fraction, it is challenging to measure void fraction with high accuracy. Due to its continuous, rapid, and steady sensing capability, the microwave sensor system has gotten a lot of attention and gradually being employed to monitor void fraction [2-6].

Castle et al. [7] firstly proposed a microwave sensor for water fraction measurement, they categorized the microwave sensing principles into electromagnetic wave transmission, reflection and resonance. Oon et al.[8] developed a cylindrical cavity resonator to monitor the percentage fraction change of air-water and oil-water stratified flow. The experimental and simulated results demonstrated that the amplitude of the output shows a linear relationship with the water fraction, and the resonator successfully detect the variation of the water fraction inside the pipeline between 0 and 100 %. Al-Kizwini et al.[9] based on the resonant frequencies shifts of a microwave cavity sensor to determine the percentage volumes of gas-water and oil-gas flow in the pipeline, and constructed and tested the sensor prototype system. Experimental results were in good correlation with simulated results by HFSS software. Yang et al.[10] designed a cavity resonator focusing on the gas-water flow with water fraction 0 ~ 10 %. The theoretical analysis and HFSS simulation results indicated that the resonant frequency decreases with the water fraction increase. Then they carried out static experiments for the stratified distributed structure. The relative errors between the experimental and the simulated results are less than 7%.

The cavity resonators above mentioned are non-intrusive structure. Since the flow regimes of gas-water flow are complicated and changeable during transfer process, the non-intrusive structure has difficulty in sensing flow regimes changes, which will reduce the accuracy of void fraction measurement. A microwave sensor with consideration of flow regime influence is urgently needed for natural gas industries.

In this study, a sensor based on the microwave transmission line method is designed to measure void fraction of gas-water flow. For figure out the effect of flow regimes on the measurement, a spatial orthogonal combination structure with two transmission lines is created by two orthogonal cross assembled metal electrodes and its internal electromagnetic fields are simulated and analyzed using COMSOL software. The variation characteristics of the horizontal and vertical electrode phase outputs of stratified distribution structure are investigated by static experiments. Moreover, dynamic experiments involving stratified, wavy, slug and annular gas-water flows are performed in the range of gas superficial velocities from 0 to 20 m/s. The void fraction is obtained by a quick-closing valve calibration facility (QCV).

2. Structure, principle and internal electromagnetic field of sensor

2.1 Sensor Structure

The difference between relative permittivity of gas and water is large, this can be differentiated by microwave which makes the measurement of the void fraction within the gas-water flow possible. A void fraction microwave sensor is designed on the basis of microwave transmission line method, as shown in Figure 1. Two metal rods with diameter of 2 mm are orthogonally inserted with a distance of 20 mm into a metal tube (50 mm in diameter). Drawing an analogy between the configurations of the microwave coaxial line and the sensor, the rods and tube are respectively similar to the excitation inner conductor and grounding outer conductor of the coaxial line. The structure of the designed sensor can be considered as a spatial orthogonal combination structure with two transmission lines. In the sensor, the microwave signal is excited from Port 1 and received at Port 2.

2.2 Working principle

Assuming that the transmission line impedance matches, the phase shift of the microwave signal, *Δφ*, transmitted from Port 1 to Port 2, as shown in Equation (1):

$$\Delta\varphi = 2\pi L\sqrt{\varepsilon_0\varepsilon_r}\, f / c \tag{1}$$

where L is the length of the transmission line, ε_0 and ε_r represent respectively the permittivity under vacuum (ε_0=8.854×10^{-12} F/m) and the relative permittivity of the medium inside the transmission line, f is the microwave frequency, c is the propagation velocity of the microwave under vacuum (c=3×10^{8} m/s). When the gas-water flow with different void fraction flows in the pipeline, driven by the variation of its permittivity distribution, the phase shift will also change, thus the void fraction can be estimated by the designed sensor.

2.3 Electromagnetic field analysis

The finite element simulation of the sensor is carried out by using COMSOL Multiphysics 5.5 software. The geometrical configuration and material settings of sensor are the same as described in section 2.1. The Port type is coaxial and its matching impedance is 50 Ω. Figure 2 and 3 illustrate the electromagnetic field inside sensor at 0.36 GHz for the stratified and annular distribution structure, respectively, both of which have the void fractions of 0.0 %, 53 % and 100.0 %. The front view and left view of the electric field intensity are in (a) and (b), and those of the magnetic field intensity are in (c) and (d). In order to ensure that the electromagnetic fields around the vertical and horizontal electrodes can be displayed simultaneously in (b) and (d), the transparency of the color map is set to 50 %.

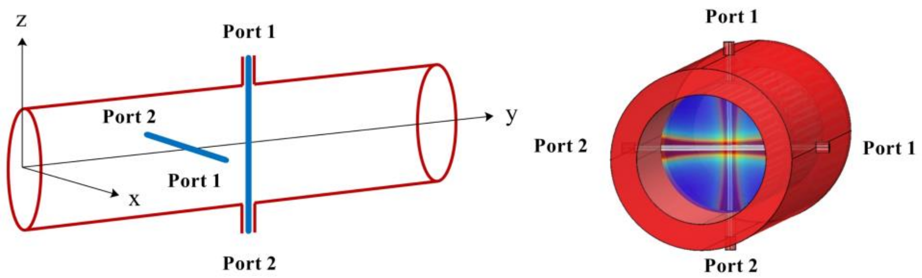
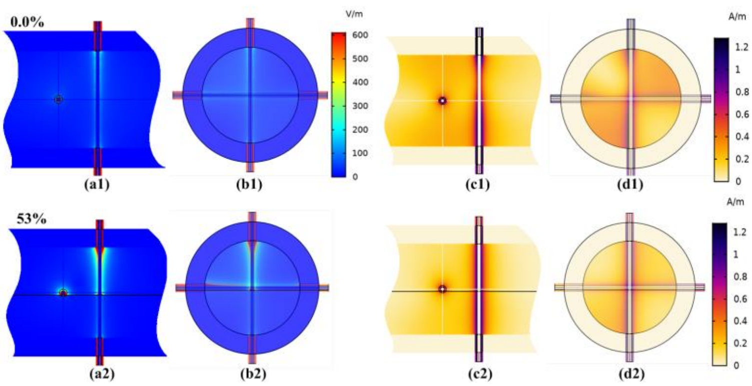


Figure 1: Schematic diagram of sensor.



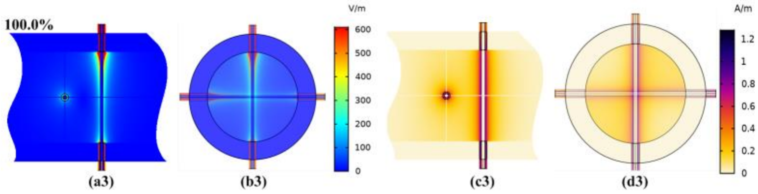


Figure 2: Electromagnetic field inside sensor (flow regime: stratified distribution structure; void fraction: 0 %, 53 %, 100 %), where electric field intensity in front view (a) and in left view (b), magnetic field intensity in front view (c) and in left view (d).

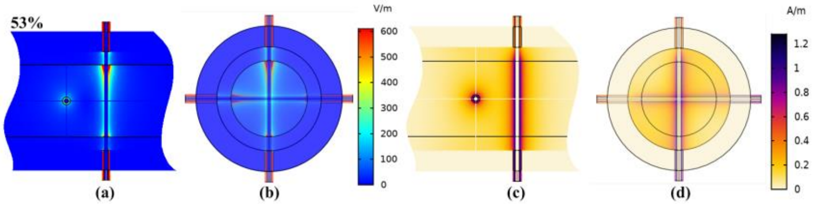


Figure 3: Electromagnetic field inside sensor (flow regime: annular distribution structure; void fraction: 53 %), where electric field intensity in front view (a) and in left view (b), magnetic field intensity in front view (c) and in left view (d).

It can be seen from the two figures that electric and magnetic fields near vertical and horizontal electrodes are very strong comparing with other regions. Because the horizontal electrode is parallel to air-water interface, when water surface approaching the electrode, a small addition of void fraction will lead to a sharp change of its phase. The electric field in air is stronger than that in water, duo to the conductivity of tap water are 0.027 S/m. However, the magnetic field in air is smaller than that in water. This is because the relative permittivity of water is 78, which is much larger than that of air, resulting in high current density in water and high magnetic field strength. In addition, when the void fraction is 0 %, the magnetic fields on the upper left and lower right sides in Figure 2 (d) are relatively large. The reason is that the magnetic field in the water is large and revolves around the electrode. The direction of the magnetic field of both electrodes are the same on the upper left and lower right sides, and the magnetic field accumulates. However, the magnetic field decreases due to the opposite direction on the lower left and the upper right. In essence, the electromagnetic fields inside sensor are similar at different void fraction.

3. Experiments

3.1 Static experiments

The sensor prototype is made and its static measurement system for stratified distribution structure is shown in Figure 4. A VNA (DEVISER E7200A) is used to excite microwave signal with a power of 1 mW and a frequency of 360MHz to Port 1 of each electrode, and measure the S21 phase of Port 2 of each electrode. In the static experiments, injecting 40 ml of water (7.77 % of water fraction) to sensor at every step and waiting for the water to be still, the stratified distribution structure can be implemented, and then measuring the S21 phase. Repeat the above steps until the water fraction reaches 100 %, and then dry sensor.

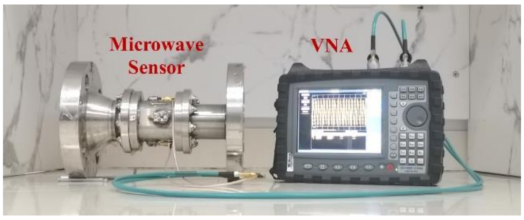


Figure 4: Static measurement system.

The normalized phase of horizontal and vertical electrodes versus void fraction in range of 0 ~ 100% for stratified distribution structure are plotted in Figure 5, respectively. The normalized phases of both electrodes decrease with an increase in void fraction. When the void fraction approaches to 50%, i.e. the height of the water in the sensor is 25mm, the normalized phase of horizontal electrode sharply jumps. The void fraction within 0-100% can be obtained by using the relationship between the phases and the void fraction.

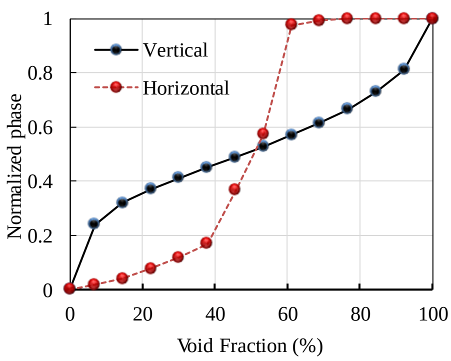


Figure 5: Relationship between normalized phase and void fraction.

3.2 Flow experiments

Flow experiments of gas-water flow were conducted on wet gas flow facility at Tianjin University, China, as illustrated in Figure 6. Compressed air and water, as experimental mediums, are respectively transported to the mixer by reciprocating compressor and water pump. The fully developed gas-water flow in the pipeline flows into the test section and then into a separation tank. The air and water are separated, and finally go back to their own loop. More details about the facility can be found in[11, 12].The microwave sensor is horizontally mounted on the test section with an internal diameter of 50mm (D).

In order to measure the void fraction of gas-water flow, a quick-closing valve calibration facility (QCV) is installed in the test section, and is 20D from the mixer, as shown in Figure 6. QCV consists of three electromagnetic valves. The valves 1 and 2 with a distance of 2 m are respectively mounted on the upstream and downstream of the main pipeline, and the valve 3 is mounted on the side pipeline. The void fraction can be calculated from the gas-water mass ratio in the pipe section between valves 1 and 2.

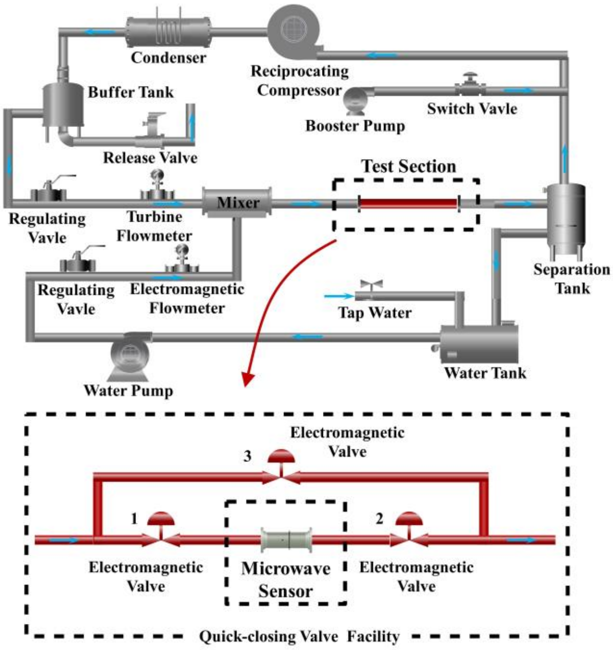


Figure 6: Sketch of wet gas flow facility [11, 12] and quick-closing valve facility.

Table 1: Experiment conditions

U_{sg} (m/s)	LVF (%)	Void Fraction (%)
1	0, 3, 5, 7, 10, 15, 20, 30, 49	100, 41, 34, 32, 25, 25, 26, 32, 28
3	0, 0.5, 1, 2, 3, 5, 7, 10, 15, 20, 30	100, 68, 60, 51, 45, 41, 40, 38, 41, 40, 35
5	0, 0.2, 0.3, 0.5, 0.7, 0.8, 1, 2, 3, 5, 6, 7, 8, 10, 15, 20	100, 86, 79, 76, 72, 67, 63, 59, 57, 55, 54, 53, 51, 49, 48, 46
10	0, 0.3, 0.5, 0.8, 1, 2, 3, 5, 6, 7, 8, 10, 12	100, 88, 85, 82, 79, 71, 67, 62, 59, 56, 55, 53, 50
15	0, 0.3, 0.4, 0.7, 0.9, 1.7, 2.6, 3.5, 4.4, 5, 6	100, 89, 85, 83, 80, 74, 69, 66, 63, 62, 61
20	0, 0.5, 1, 2, 3, 5	100, 86, 80, 75, 70, 64%

The selected range of gas superficial velocity, U_{sg}, is 1 ~ 20 m/s and liquid volume fraction (LVF) started from 0 to a maximum of 49 %. The design conditions of flow experiments are shown in Table I. The flow regimes of gas-water flow cover stratified, wavy, slug and annular, as shown in Figure 7. The flow regimes taken from the transparent tube during the experiments are given in Figure 8

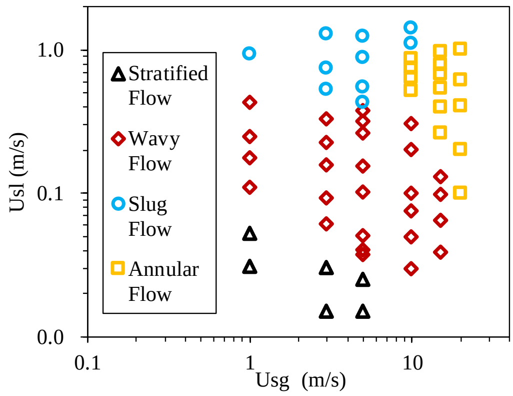


Figure 7: Flow regimes at different gas superficial velocity, U_{sg} and water superficial velocity, U_{sl}.

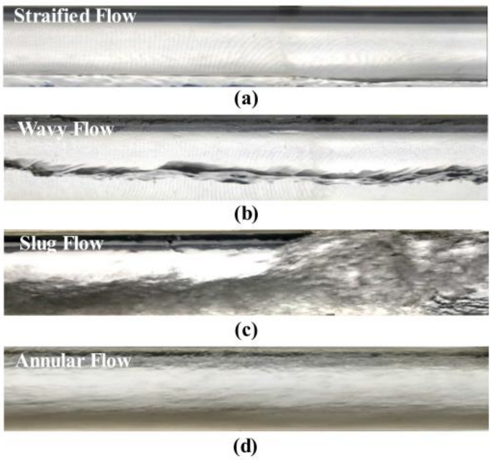


Figure 8: Pictures of flow regime (a) stratified flow at U_{sg} = 5m/s and LVF = 0.2% (b) wavy flow at U_{sg} = 5m/s and LVF = 0.8% (c) slug flow at U_{sg} = 10m/s and LVF = 5% (d) annular flow at U_{sg} = 20m/s and LVF = 3%

4. Results and discussion

Figure 9 and Figure 10 show the horizontal and vertical normalized phases of the sensor outputs, P_{hor} and P_{ver}, under different LVF respectively. At low LVF, P_{hor} and P_{ver} decreased with increasing LVF, but for large LVF, P_{hor} and P_{ver} changed irregularly. P_{hor} and P_{ver} are weakly correlated with LVF. Figure 11 and Figure 12 show P_{hor} and P_{ver} under different void fractions obtained by QCV, respectively. It is found that with an increase of void fraction, P_{hor} and P_{ver} increase, and P_{ver} varies gently than P_{hor}. When U_{sg} are 1 m/s, 3 m/s, and 5 m/s, P_{hor} changes violently at 25 ~ 60 % void fraction, but gently at 60 ~ 100 % void fraction. When U_{sg} are 10 m/s, 15 m/s, and 20 m/s, due to the existence of annular flow, the variation characteristic of P_{hor} is different from that U_{sg} are 1 m/s, 3 m/s, and 5 m/s. Moreover, it can be concluded that, at the same void fraction, P_{ver} increases with an increase in U_{sg}, but P_{hor} decreases. This is due to flow regime gradually transitions from stratified, wavy to annular flow as U_{sg} increases. In conclusion, P_{hor} and P_{ver} are strongly correlated with void fraction and will change accordingly when the flow regime changes. P_{hor} and P_{ver} are complementary to each other and can be used to predict void fraction.

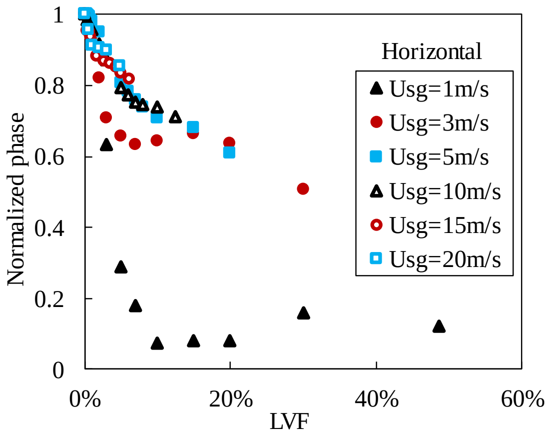


Figure 9: Relationship of P_{hor} and LVF

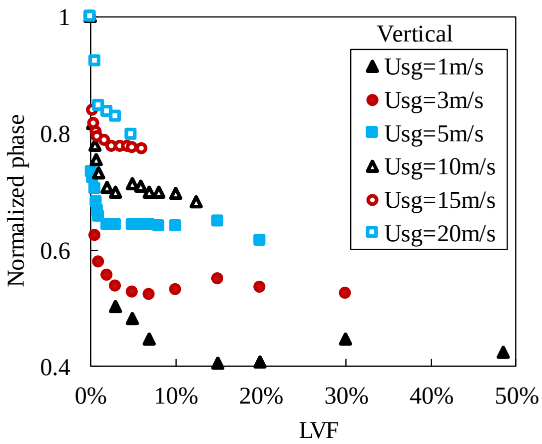


Figure 10: Relationship of P_{ver} and LVF

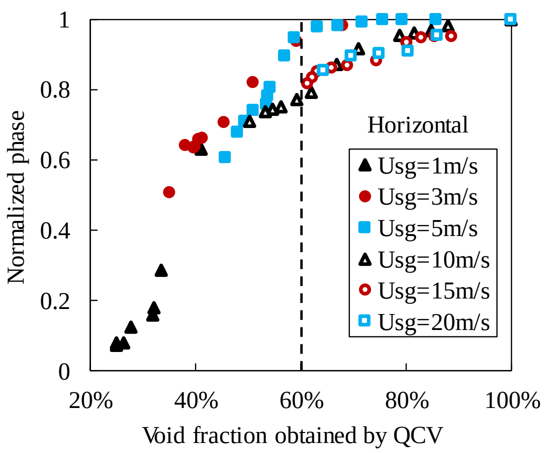


Figure 11: Relationship of P_{hor} and void fraction

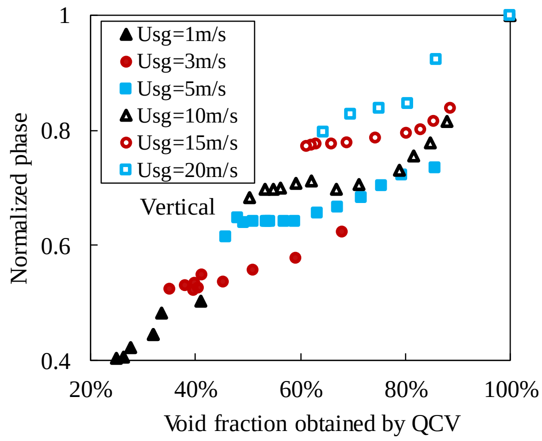


Figure 12: Relationship of P_{ver} and void fraction

5. Conclusion

This research presents a microwave sensor to measure void fraction of gas-water flow based on the microwave transmission line method. The sensor contains horizontal and vertical electrodes resulting in a spatial orthogonal transmission line combination structure, so that the gas-water flow regime can be detected and its influence on the measurement can be accounted for. The electromagnetic fields inside the sensor for stratified and annular distribution structure are simulated and analyzed using COMSOL software. Furthermore, the variation characteristics of the horizontal and vertical electrode phase outputs of the stratified distribution structure are investigated by static experiments. Finally, flow experiments covering stratified, wavy, slug, annular gas-water flow regimes, indicates that the void fraction are positive correlated to the sensor outputs and can be predict by the sensor.

In this paper, a void fraction measurement method of gas-water flow based on the microwave transmission line method is developed. To accommodate the effects of the gas-water flow regime, a microwave void fraction sensor is designed as a spatial orthogonal combination structure with two transmission lines. Flow experiments covering stratified, wavy, slug, annular gas-water flow regimes are carried out, and void fraction is obtained by a quick-closing valve calibration facility. The experimental results show that the normalized phases of the vertical and horizontal transmission lines of the sensor are weakly correlated with LVF, but strongly correlated with void fraction. Both normalized phases vary monotonically with the void fraction. In addition, the variation characteristics between the void fraction and the vertical normalized phase are different from the horizontal normalized phase for different gas superficial velocities and flow regimes. The results demonstrate the rationality and feasibility of the present method for measuring void fraction of gas-water flow with different flow regimes.

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