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A New Contactless Method for Velocity Measurement of Bubble and Slug in Millimeter-Scale Pipelines

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ABSTRACT Combining C^4D technique and cross-correlation velocity measurement technique, a new measurement method, which is suitable for the bubble/slug velocity measurement in millimeter-scale pipelines, is proposed. Based on the series resonance principle and the simulated inductor technique, a new C^4D sensor is developed. With two conductance signals obtained by two new C^4D sensors (the upstream sensor and the downstream sensor), the bubble/slug velocity measurement is implemented by the cross-correlation velocity measurement technique. Experiments are carried out in three pipelines with different inner diameters of 4.50, 5.46, and 6.44 mm, respectively. The experimental results show that the proposed bubble/slug velocity measurement method is effective, the development of the new C^4D sensor is successful, and the velocity measurement accuracy is satisfactory. The relative error of bubble velocity measurement is less than 5.41% and the relative error of slug flow velocity measurement is less than 4.90%.

INDEX TERMS Gas-liquid two-phase flow, bubble flow, slug flow, capacitively coupled contactless conductivity detection (C^4D), cross-correlation velocity measurement, velocity, measurement.

I. INTRODUCTION

With the development of modern industry, there exists a trend of miniaturization of industrial devices. The study and application of gas-liquid two-phase flow in the millimeter-scale pipeline have become more and more important [1]–[3]. Bubble flow and slug flow are common phenomena of gas-liquid two-phase flow in millimeter-scale pipeline. The online measurement of the bubble/slug velocity is of great importance for academic research and industrial application [1]–[3]. However, with the decrease of pipe scale, the parameter measurement becomes more and more difficult, the conventional bubble/slug velocity measurement methods cannot meet the higher and higher requirement of academic research and industrial application of gas-liquid two-phase flow in millimeter-scale pipeline [1]–[5].

Combing the conductance sensors and the cross-correlation velocity measurement technique to implement the velocity measurement is a classic method and has been widely studied and applied by scientists and engineers for many decades in the research field of gas-liquid two-phase flow [1], [6]–[13]. Many achievements and technical progresses have been obtained [1], [6]–[13]. However, the conventional conductance sensors still have two disadvantages: 1) Most of the sensors are developed for the gas-liquid two-phase flow in normal-scale pipelines , the studies and applications on the bubble/slug velocity measurement for the gas-liquid two-phase flow in millimeter-scale pipelines are relatively limited [1], [6]–[13]. 2) Most of the sensors are developed on the basis of contact conductivity measurement technique, the electrodes are contacting directly with measured fluid, which will cause polarization effect and electrochemical erosion effect. Meanwhile, if the electrodes are contaminated, unpredictable measurement errors may arise [1], [6]–[17].

Capacitively coupled contactless conductivity detection (C^4D) technique is a contactless conductivity measurement technique and its electrodes are not directly in contact with the measured fluid. With this kind of conductivity measurement technique, the disadvantages of the conventional contact conductance sensors (polarization effect and electrochemical erosion effect) can be avoided [14]–[23]. However, as a developing technique, C^4D is mainly studied and applied in the research field of analytical chemistry for measuring ion concentration or solution conductivity in capillaries (the inner diameter of capillary is usually less than 0.2 mm). Up to date, research works on the application of C^{4}D in two-phase flow research field are very limited [14]–[23].

This work aims to propose a new bubble/slug velocity measurement method by combining C^{4}D technique and cross-correlation velocity measurement technique. Firstly, a new C^{4}D sensor which is suitable for bubble/slug velocity measurement in millimeter-scale pipelines is developed. In this new sensor, series resonance principle is introduced to overcome the unfavorable influence of coupling capacitances and simulated inductor technique is introduced to overcome the disadvantages of a practical inductor. Secondly, based on the cross-correlation velocity measurement technique, a bubble/slug velocity measurement system is developed. Finally, with two conductance signals obtained by two C^{4}D sensors (the upstream sensor and the downstream sensor), the bubble/slug velocity is determined by the cross-correlation velocity measurement technique.

II. DESIGN OF THE NEW C^{4}D SENSOR

A. PRINCIPLE OF C^{4}D SENSOR

Fig. 1(a) shows the construction of a typical radial C^{4}D sensor. Fig. 1(b) is the simplified equivalent circuit of the C^{4}D sensor. C_1 and C_2 are the coupling capacitances formed by the electrodes, the insulating pipe and the conductive fluid. R_x is the equivalent resistor of the fluid between the two electrodes. C_1, C_2 and R_x form an AC circuit. When an AC voltage U_i is applied on the excitation electrode, an output AC current I_o can be obtained. From the AC current I_o, the conductivity measurement of the fluid can be realized [14]–[20].

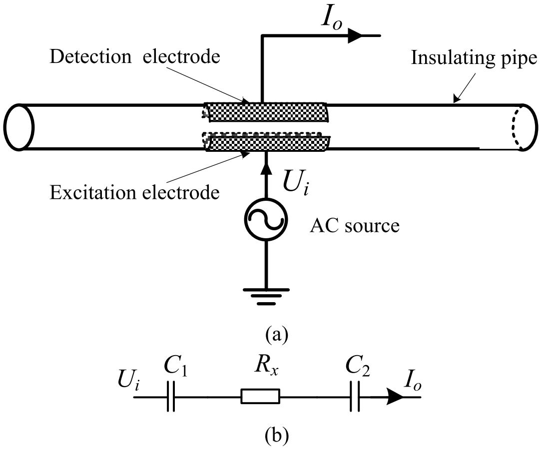


FIGURE 1. Principle of C^{4}D sensor: (a) The construction of a typical radial C^{4}D sensor, (b) Simplified equivalent circuit of C^{4}D sensor.

B. NEW C^{4}D SENSOR

As shown in Fig. 1, two coupling capacitances C_1 and C_2 are necessary for forming an AC circuit and making the conductivity detection possible [14]–[20], [22]–[24]. However, from the viewpoint of impedance measurement, the reactance introduced by C_1 and C_2 are background signals which will limit the sensitivity and the detection range of the sensor [14]–[20], [22]–[24]. Only the measured R_x is the useful signal.

Based on our previous research works on C^{4}D technique, the unfavorable influence of the coupling capacitances C_1 and C_2 can be effectively overcome by the series resonance principle [22]–[24], i.e., according to the series resonance principle, the reactance of the coupling capacitances C_1 and C_2 can be eliminated by the inductive reactance of an introduced inductor module. So, in this work, the series resonance principle is introduced. And, the influences of the background signals (C_1 and C_2) on the measurement results are overcome and the signal noise ratio (SNR) is improved.

Meanwhile, our previous research results also indicate that the simulated inductor technique is an effective way to provide the inductive reactance and a simulated inductor can overcome the disadvantages of a practical inductor (such as non-adjustable inductance value, large internal resistance and difficulties to implement large-valued inductor) [24]. So, in this work, the simulated inductor technique is adopted.

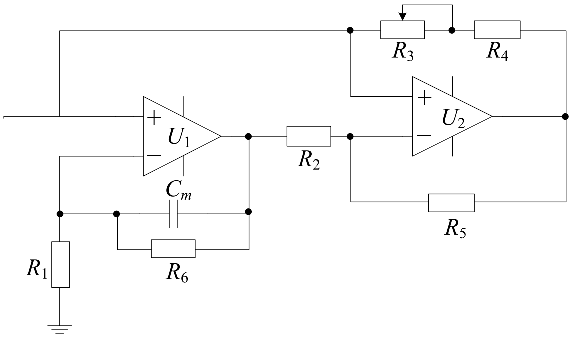


FIGURE 2. Circuit of the simulated inductor in this work.

Fig. 2. illustrates the circuit of the new simulated inductor used in this work. The new simulated inductor is developed on the basis of the classic Riordan simulated inductor [25]–[29].

The equivalent inductance L_{eq} and the internal resistance R_{eq} of the simulated inductor are:

$$L_{eq} = \frac{R_1 R_2 (R_3 + R_4)}{R_5} C_m \tag{1}$$

$$R_{eq} = \frac{R_1 R_2 (R_3 + R_4)}{R_5 R_6} \tag{2}$$

According to Equation (1), the value of the equivalent inductance can be determined by R_1, R_2, R_3, R_4, R_5 and C_m. To adjust the value of equivalent inductance linearly and conveniently, in this work, R_3 is selected as an adjustable resistance and the values of R_1, R_2, R_4, R_5 and C_m are set as fixed values, i.e., the equivalent inductance of the simulated inductor is adjusted by R_3. According to Equation (1) and (2), only R_6 is the independent resistance. So, R_6 is used to determine the value of the internal resistance without affecting the inductance. Meanwhile, from Equation (2), it can be found that if R_6 is set as a greater value, a smaller internal resistance of the simulated inductor can be realized.

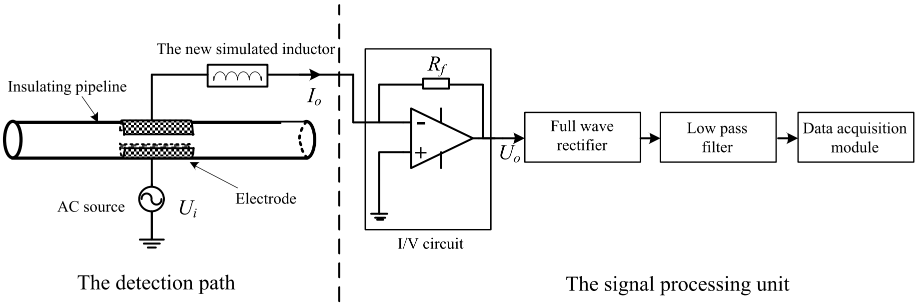


FIGURE 3. The construction of the new C^{4}D sensor.

Fig. 3 shows the construction of the new C^{4}D sensor which can be mainly divided into two parts, the detection path and the signal processing unit. The detection path consists of an AC source, an excitation electrode, an insulating pipeline, a detection electrode and the new simulated inductor. The signal processing unit consists of a current voltage conversion circuit (I/V circuit), a full wave rectifier, a low pass filter and a data acquisition module.

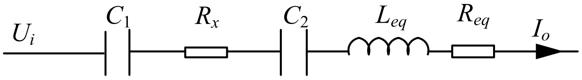


FIGURE 4. Simplified equivalent circuit of the detection path of the new C^{4}D sensor.

Fig. 4 shows the simplified equivalent circuit of the detection path of the new C^{4}D sensor. The impedance of the detection path Z is:

$$Z = R_x + R_{eq} + j(2\pi f L_{eq} - \frac{C_1 + C_2}{2\pi f C_1 C_2}) \tag{3}$$

Where, f is the excitation frequency of AC source.

At series resonance:

$$2\pi f_0 L_{eq} - \frac{C_1 + C_2}{2\pi f_0 C_1 C_2} = 0 \tag{4}$$

Where, f_0 is the resonant frequency.

The introduction of the inductor L_{eq} is to overcome the unfavorable influence of the coupling capacitances (C_1 and C_2) on the measurement results, i.e., the inductive reactance of the L_{eq} is used to eliminate the capacitive reactance of C_1 and C_2 by the series resonance principle. So, in this work, the sensor works at series resonance. The excitation frequency of AC source f is set as the resonant frequency f_0, which is determined by:

$$f = f_0 = \frac{1}{2\pi}\sqrt{\frac{C_1 + C_2}{L_{eq} C_1 C_2}} \tag{5}$$

Thus, at series resonance, the total impedance of the detection path Z is,

$$Z = R_x + R_{eq} \tag{6}$$

And the output current I_o is:

$$I_o = \frac{U_i}{R_x + R_{eq}} \tag{7}$$

Where, U_i is the voltage of AC source.

After the operation of I/V circuit the output current I_o is converted to an AC voltage signal U_o, as shown in Fig. 3.

$$U_o = -I_o R_f = -\frac{R_f}{R_x + R_{eq}} U_i \tag{8}$$

Where, R_f is the feedback resistor of the operational amplifier in the I/V circuit.

III. BUBBLE/SLUG VELOCITY MEASUREMENT

Fig. 5 shows the construction of the measurement system for the bubble/slug velocity measurement.

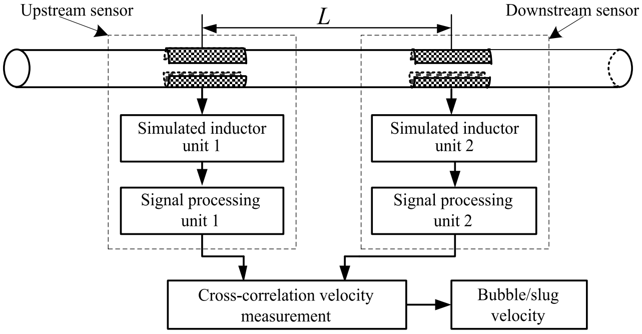


FIGURE 5. The construction of the measurement system.

The bubble/slug velocity measurement is implemented by the cross-correlation velocity measurement technique.

Two same new C^{4}D sensors are installed on the upstream and the downstream of the pipeline respectively to obtain two independent signals (the upstream signal x and the downstream signal y). By cross-correlating the two signals, the cross-correlation coefficient of the two signals can be calculated by [8], [9]:

$$R_{xy}(i) = \frac{1}{N}\sum_{n=1}^{N} x(n\Delta t) y[(n+i)\Delta t] \tag{9}$$

Where, Δt is the sampling interval, and N is the number of samples.

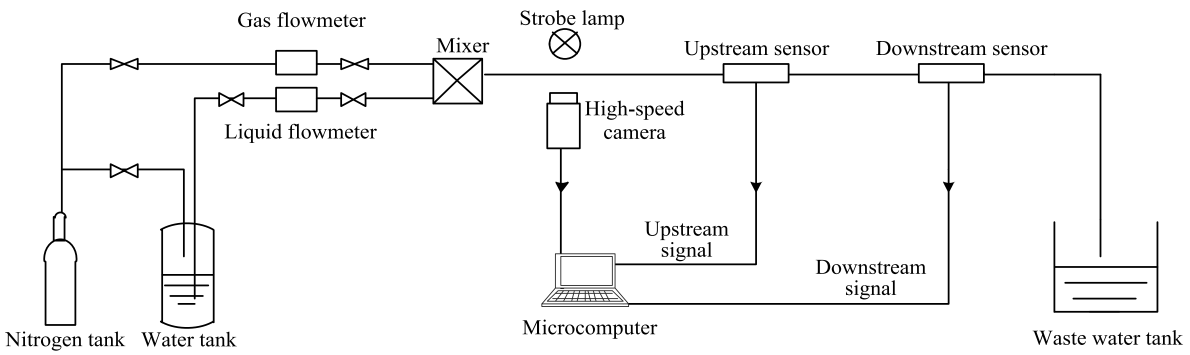


FIGURE 6. The experimental setup for bubble/slug velocity measurement.

TABLE 1. The detailed information of the C^4D sensors.

Inner diameter (mm)	Outor diameter (mm)	Electrode length (mm)	Electrode distance (mm)	Electrode angle (°)	Frequency of AC source (KHz)
4.50	7.04	10.5	21.1	125	206.9
5.46	8.12	12.1	24.3	125	198.4
6.44	9.20	13.8	27.6	125	196.3

By searching the time position of the maximum cross-correlation coefficient, the transit time τ (the time delay between the two signals) can be determined.

Finally, according to the cross-correlation velocity measurement principle [8], [9], the bubble /slug velocity v can be calculated by:

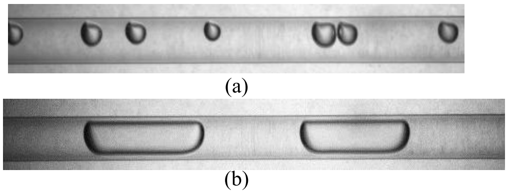
$$v = k\frac{L}{\tau} \tag{10}$$

Where, L is the distance between upstream and downstream sensors, k is the calibration coefficient.

IV. EXPERIMENTAL SETUP

Fig. 6 illustrates the experimental setup for the bubble/slug velocity measurement.

The velocity measurement experiments are carried out in three horizontal glass pipes with inner diameters of 4.50 mm, 5.46 mm and 6.44 mm respectively. Correspondingly, three pairs of C^4D sensors are developed. Table I lists the detailed information of the C^4D sensors used in the velocity measurement experiments. The AC source is the signal generator RIGOL DG 1022. The data acquisition module is the NI cDAQ-9172. The bubble velocity measurement of bubble flow and the slug velocity measurement of slug flow in millimeter-scale pipelines are investigated. Fig. 7(a) is a photo of typical bubble flow in 4.50 mm pipeline, Fig. 7(b) is a photo of typical slug flow in 4.50 mm pipeline; Fig. 8(a) is the measured signal without bubble/slug in 4.50 mm pipeline, Fig. 8(b) is the measured signal with bubble in 4.50 mm pipeline, Fig. 8(c) is the measured signal with slug in 4.50 mm pipeline.


(a)

(b)

FIGURE 7. (a) A photo of typical bubble flow; (b) A photo of typical slug flow.

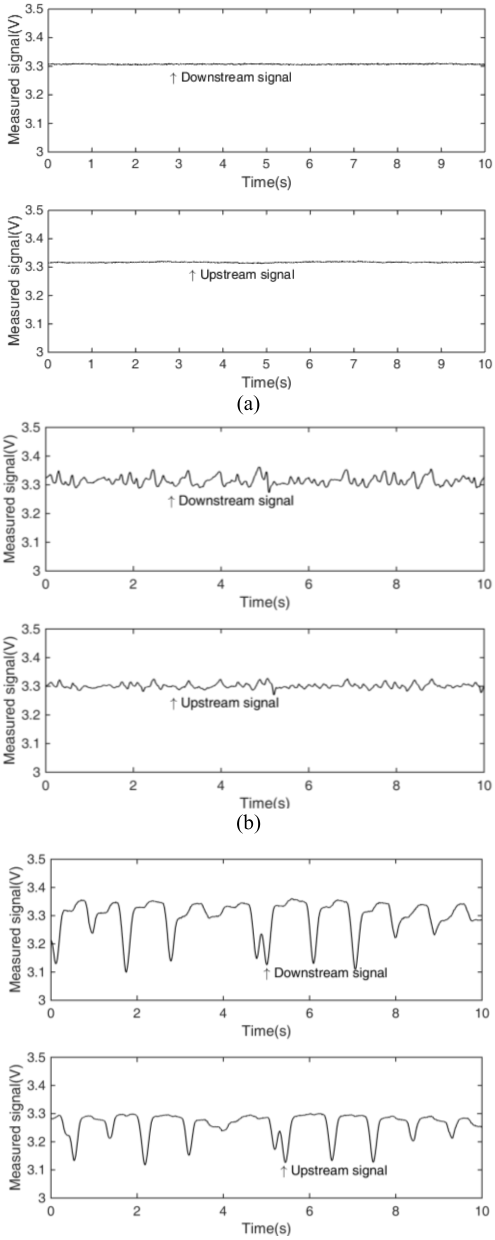
TABLE 2. The ranges of equivalent resistors with and without bubble/slug.

	Without bubble/slug	Bubble	Slug
R_x(KΩ)	63.4~125.4	63.0~128.3	65.4~155.7

The experimental materials are tap water (the conductivity of the tap water ranges from 0.17~0.19 mS/cm) and nitrogen. The ranges of the equivalent resistors of the fluid between the two electrodes R_x with and without bubble/slug are listed in Table II.

Tap water and nitrogen are driven into the pipeline by high-pressure nitrogen. The liquid flowrate is measured by an electromagnetic flowmeter (IFC-300C, Krohne) and the gas flowrate is measured by a thermal gas flowmeter (F-201 CB, Bronkhorst). By adjusting the different flowrate combinations, different flow patterns and different bubble/slug velocities can appear in the pipelines. In this work, the bubble velocity ranges from 0.09 m/s to 0.53 m/s and the slug velocity ranges from 0.06 m/s to 1.08 m/s.

The reference velocity data are obtained by a high-speed camera (MotionXtraN-4, IDT Red-lake) and a 60 mm f/2.8 D



(a)

(b)

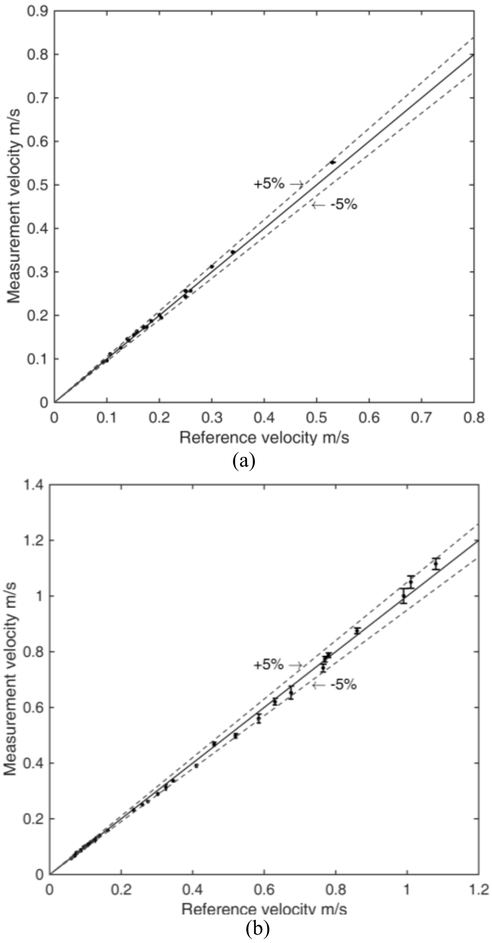
(c)

FIGURE 8. **(a) Measured signal without bubble/slug; (b) Measured signal with bubble; (c) Measured signal with slug.**

lens (AF Micro-Nikkor). From the captured pictures, the reference velocity of bubble/slug can be calculated by:

$$v_r = \frac{L_c}{nT_c} \tag{11}$$

Where L_c is the moving distance of the bubble/slug, T_c is the shooting interval of the high-speed camera, and n is the number of the pictures captured in the time interval corresponding to the bubble movement.



(a)

(b)

FIGURE 9. **Experimental results of 4.50 mm pipe (k=1.045): (a) bubble flow; (b) slug flow.**

V. EXPERIMENTAL RESULTS AND DISCUSSION

Fig. 9. to Fig. 11. show the bubble and slug velocity measurement results. The relative error e is used as the performance index and its definition is:

$$e = \frac{v - v_r}{v_r} \times 100\% \tag{12}$$

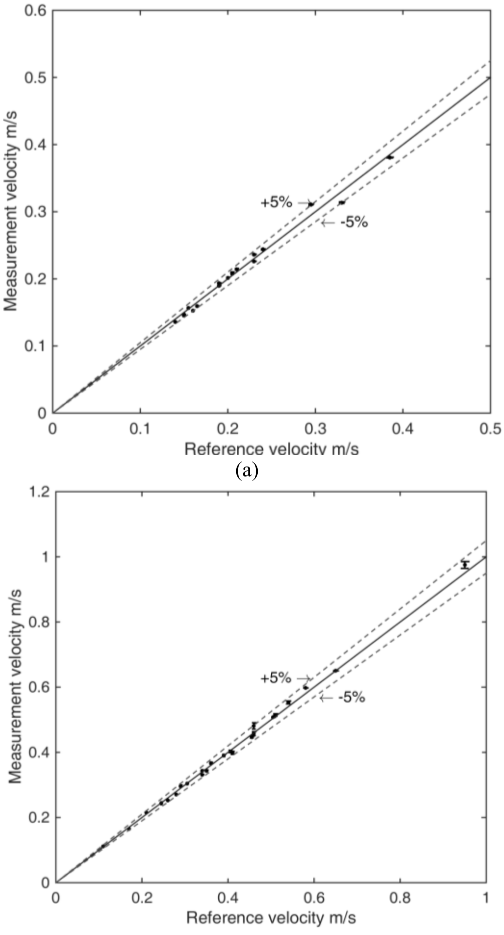
Table III lists the maximum relative errors and the velocity ranges of the bubble velocity measurement and the slug velocity measurement.

These experimental results show that the proposed method for bubble/slug velocity measurement in millimeter-scale pipelines is effective. The new C^{4}D sensor, which is developed on the basis of series resonance principle and simulated inductor technique, is successful. And, the measurement accuracy of the bubble/slug velocity measurement system is satisfactory. The maximum relative error of bubble flow velocity measurement is 5.41%, and the maximum relative error of slug flow velocity measurement is 4.90%. The maximum relative error appears in 6.44 mm pipe. 6.44 mm is a little over the range of the critical capillary size of the pipe for 'mini' (or 'micro') scale, and in this pipe, the effect of superficial tension is not high enough to ensure bubble/slug stable. Maybe, that is the reason of higher error in 6.44 mm pipe.

Besides, it is necessary to indicate that the proposed method still has some drawbacks. When the gas-liquid

TABLE 3. **The maximum relative errors of the bubble velocity measurement and the slug velocity measurement.**

Inner diameter (mm)	The bubble velocity measurement		The slug velocity measurement	
	Velocity range (m/s)	Maximum relative error	Velocity range (m/s)	Maximum relative error
4.50	0.09~0.53	4.74%	0.06~1.08	4.85%
5.46	0.14~0.39	5.37%	0.11~0.95	3.26%
6.44	0.11~0.42	5.41%	0.08~0.46	4.90%

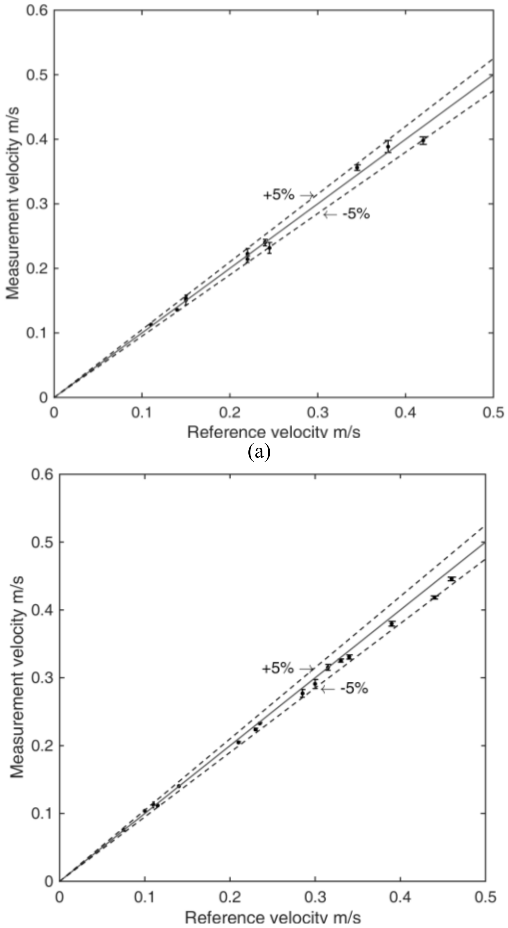


(a)

(b)

FIGURE 10. **Experimental results of 5.46 mm pipe ($k = 1.029$): (a) bubble flow; (b) slug flow.**

two-phase flow is the bubble flow with smaller bubbles and lower velocity (as shown in Fig. 12.), the accuracy of bubble velocity measurement may decrease (i.e., greater measurement error may arise) because the obtained signals is too weak to realize a successful cross-correlation velocity measurement in this situation. To further improve the measurement performance of the proposed method (and the developed new C^4D sensor) would be our research work in the future.



(a)

(b)

FIGURE 11. **Experimental results of 6.44 mm pipe ($k = 0.989$): (a) bubble flow; (b) slug flow.**

FIGURE 12. **The typical photo of bubble flow with low velocity and small bubble diameter in 4.50 mm pipeline.**

VI. CONCLUSION

This work focuses on the bubble/slug velocity measurement of gas-liquid two-phase flow in millimeter-scale pipelines.

A new bubble/slug velocity measurement method is proposed by combining C^4D technique and cross-correlation velocity measurement technique. With the introductions of series resonance principle and simulated inductor technique, a new C^4D sensor which is suitable for bubble/slug velocity measurement in millimeter-scale pipelines is developed. In this new C^4D sensor, the simulated inductor technique is introduced to develop an inductor module and hence to overcome the unfavorable influence of the coupling capacitances by series resonance principle. A bubble/slug velocity measurement system is constructed. Two independent signals are acquired by two new C^4D sensors (the upstream sensor and the downstream sensor) and the bubble/slug velocity measurement is realized by the cross-correlation velocity measurement technique.

Experiments are carried out to verify the effectiveness of the proposed method. The experimental results indicate that the new contactless method for bubble/slug velocity measurement in millimeter-scale pipelines is effective. The development of new C^4D sensor is successful. The bubble/slug velocity measurement system can realize the online and contactless velocity measurement successfully and the measurement accuracy of the bubble/slug velocity is satisfactory. The maximum relative error of bubble flow velocity measurement is 5.41%, and the maximum relative error of slug flow velocity measurement is 4.90%.

Useful knowledge and experience are obtained. The study results can provide a good reference for others' research works. However, due to the complexity of gas-liquid two-phase flow in millimeter-scale pipeline, more research works should be undertaken in this area.

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