

Experimental Study on the Velocities, Length and Frequency of Liquid Slug in Horizontal Curved Tube

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Abstract. In order to explore the characteristics of slug flow in horizontal curved tube, four kinds of curved tubes are researched in this paper of which are with 0.5m circumference, 26mm inner diameter. When the superficial liquid velocity or the superficial gas velocity increases, the probability distribution of the average velocity, average length and average frequency of liquid slug conform to the Gaussian distribution at all of the experimental conditions. The average velocity, average length and average frequency of liquid slug increase with the increase of superficial gas velocity. In addition, as the radius of curvature of the pipeline increases, the average velocity, average length, and average frequency of the fluid plug increase.

1. Introduction

Slug flow, most commonly encountered in multiphase pipe flow, is an alternative flow of the liquid slug and the long bubbles in space and time and slug flow units (composed with the liquid slug and long bubbles) movement along the pipeline. Multiphase pipeline often appears slug flow in many operating conditions. The actual physical process of slug flow is a complicated stochastic process. The process has no strict periodicity and the intermittent which is the typical characteristics. The slug frequency is only able to simulate approximatively the intermittent of slug flow with the periodicity^[1,2].

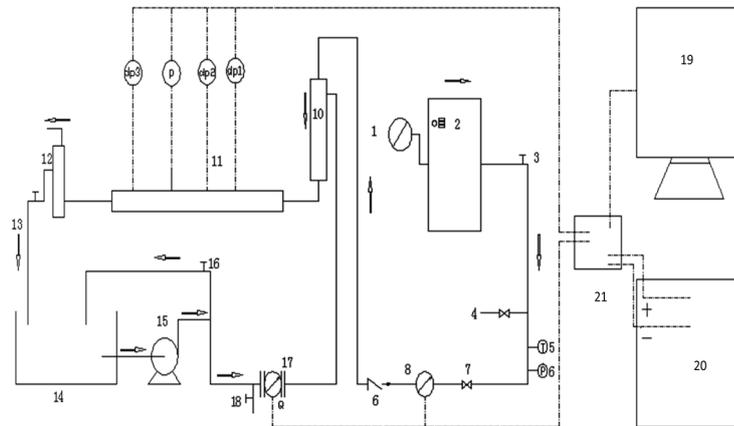
As a common flow pattern in mixing oil and gas pipeline, slug flow can be characterized as one kind of alternative flow that full of the liquid slug in the entire pipe and big bubble, it belongs to the unstable flow. In the process of production, the slug flow can cause the water hammer and jump of pressure in the pipeline^[3]. At the same time, the liquid slug that leaves the pipe end can cause sharp fluctuations of liquid level in the downstream oil and gas processing equipment^[4,5,6].

At present, there were many studies of characteristics of the slug flow in the horizontal pipe, vertical pipe and inclined pipe, but relatively few studies in the horizontal curved tube. While the bent pipe has more practical application in production process, so it is necessary to study characteristics of the slug flow in horizontal curved tube.

2. Experimental System

Experimental system consists of three units(Figure 1), namely the fluid supply unit, test unit, and fluid recovery unit.





Test parameters:

- (1) Experiment medium: water and air;
- (2) Experiment temperature: 10~25 °C;
- (3) Flow velocity: superficial gas velocity, 1 ~ 12 m/s. superficial water velocity, 0.19~2 m/s;
- (4) Work pressure: 0.1~0.25 MPa.

1. The electrical source; 2. Air Compressor; 3. Air Compressor Export control valve; 4. Air Compressor bypass; 5. Thermocouple (with digital display); 6. The pressure gauge; 7. The gas flow control valve; 8. Gas mass flowmeter; 9. The gas flow control valve; 10. The gas-liquid mixer; 11. The bend test section; 12. The gas-liquid separator; 13. Gate valves; 14. The water tank; 15. Centrifugal pump; 16. Liquid bypass; 17. Liquid flow meter; 18. The fluid flow controls valve; 19. Computer hosts; 20. 24V DC power supply; 21. Data acquisition board

Figure 1. Experimental system diagram.

The fluid supply unit consists of a main water tank, an air compressor, a centrifugal pump, a gas-liquid mixer, a regulator, a thermocouple, pressure gauge, a gas flowmeter, a liquid flowmeter and a gas-liquid mixer. The experimental medium is water and air. The centrifugal pump brings the water in the water tank to the flowmeter measurement place, and then sends it to the gas-liquid mixer. The air is measured by the compressor through the gas flowmeter and sent to the gas-liquid mixer. The mixed gas and liquid enters the test section and slug flow is obtained by adjusting the flow of gas and liquid.

Experimental section has two parts: a horizontal straight pipe and horizontal curved tube. The horizontal straight pipe is 3m long and 26 mm in diameter which is made of organic glass tube. The circumference of curved tube is 0.5m and the central angle of bent section are respectively 30°, 45°, 60°, 90° and the curvature radius are 955mm, 637mm, 477mm and 318mm respectively. The size of the experimental section is shown in Figure 2.

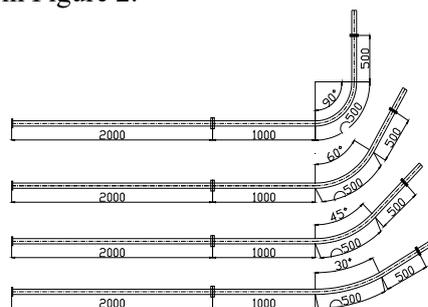


Figure 2. Experimental section size diagram.

3. The results and Discussions

3.1 liquid slug velocities

When the superficial gas velocity u_{sg} is 5.89m/s and the superficial liquid velocity u_{sl} is between 0.75 and 1.5 m/s, the time series diagram of liquid slug velocity according to the differential correlation method as shown in Figure 3 (a) and (b).

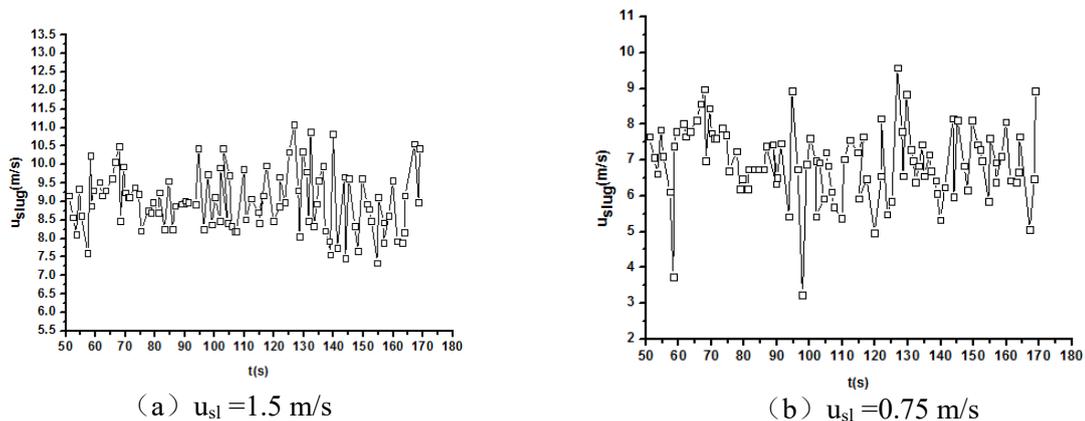


Figure 3. Liquid slug velocity time sequence.

The distribution diagram of probability density of the liquid slug velocity under different superficial velocity according to the time sequence diagram calculation are shown in Figure 4. When the superficial gas velocity $u_{sg} = 5.89$ m/s, superficial liquid velocity $u_{sg} = 1.5, 0.75, 0.5,$ and 0.25 m/s , the liquid slug velocity histogram and distribution function curve as shown in Figure 4 (a), (b), (c) and (d). The liquid slug velocity is accord with Gaussian distribution in every work condition. The distribution curve as shown in Figure 4 (a) and the distribution function as shown in equation when $u_{sg} = 5.89$ m/s, $u_{sl} = 1.5$ m/s.

$$P(f_i) = 0.913 + \frac{4.41}{0.28\sqrt{\pi/2}} e^{-2\left(\frac{f_i - 0.36}{0.28}\right)^2} \quad (1)$$

When superficial liquid velocity $u_{sl} = 0.75$ m/s, superficial gas velocity $u_{sg} = 3.04, 5.89,$ and 8.79 m/s, the liquid slug velocity histogram and distribution function curve as showed in Figure 4 (e), (b) and (f).The liquid slug velocity distribution also conforms to Gaussian distribution in the various experimental conditions.

We can see from the Figure 4, the liquid slug velocity increases with the superficial liquid velocity and the superficial gas velocity. When the superficial gas velocity is constant, the average velocity of liquid slug increases monotonously and maximum liquid slug velocity increases slowly as the superficial liquid velocity increasing, but the standard deviation of the liquid slug velocity remains the same. It shows that u_{sl} has little effect on the instability of slug flow. When the superficial liquid velocity is the constant, the liquid slug average velocity increases obviously with the increasing of the superficial gas velocity and the biggest liquid slug velocity increases clearly, the standard deviation of the liquid slug velocity is also growing. As shown in Figure 4 (e), (b) and (f), this shows that the superficial gas velocity of slug flow has large effect on the instability of flow.

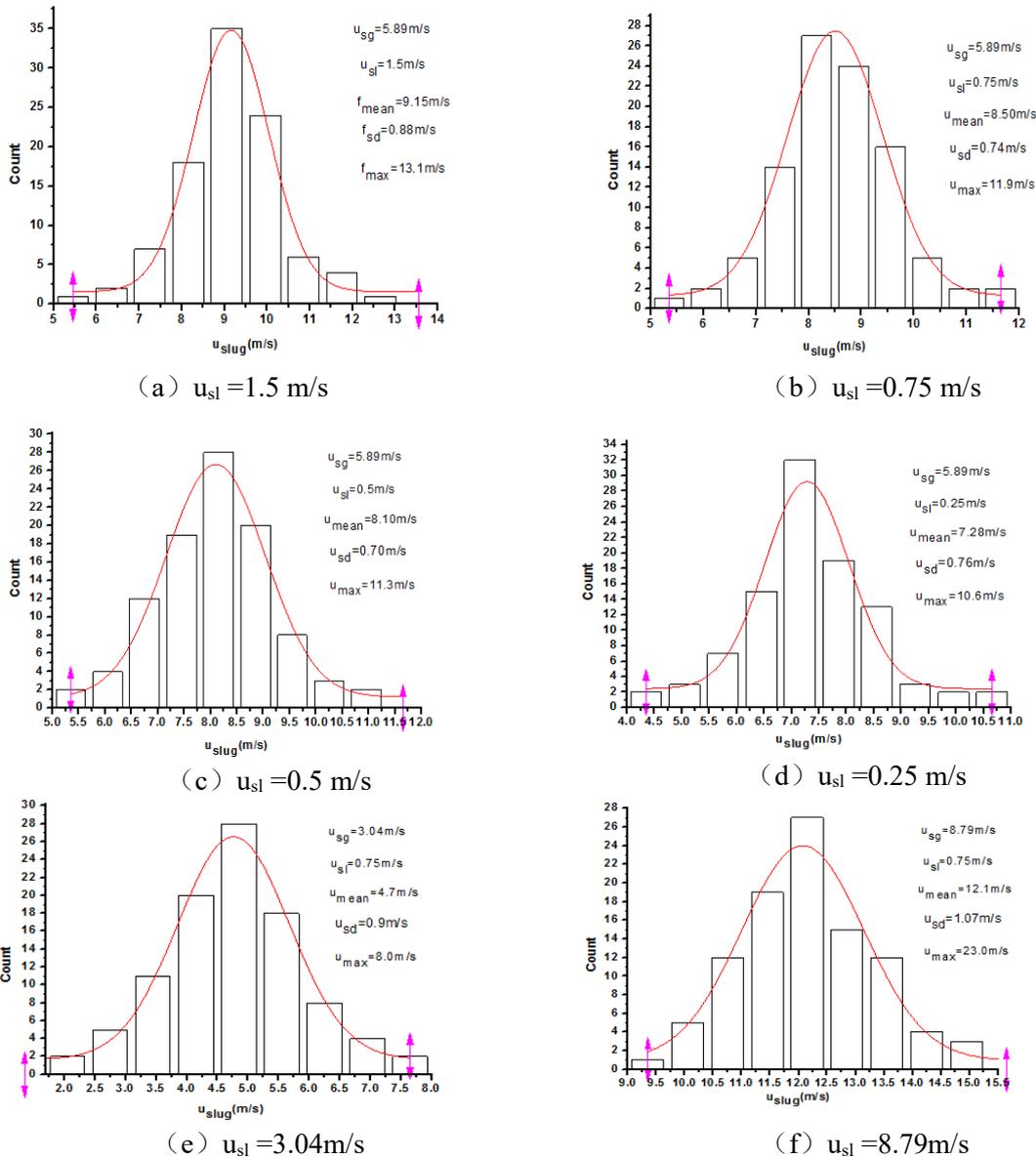
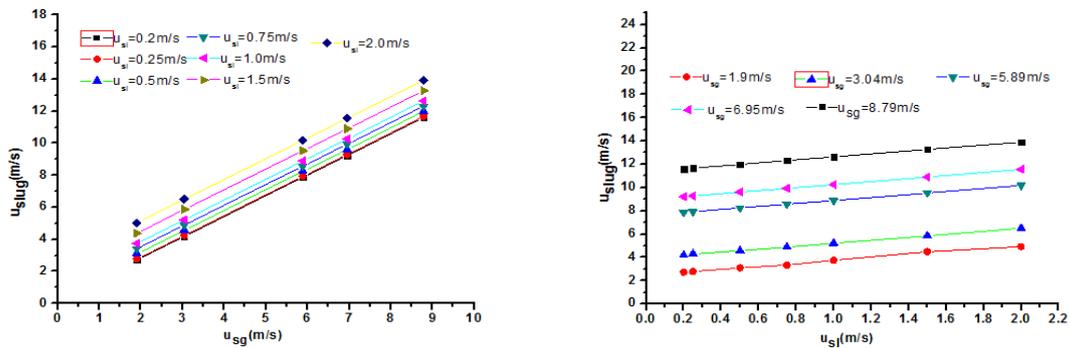


Figure 4. Liquid slug velocity columnar distribution and probability distribution.

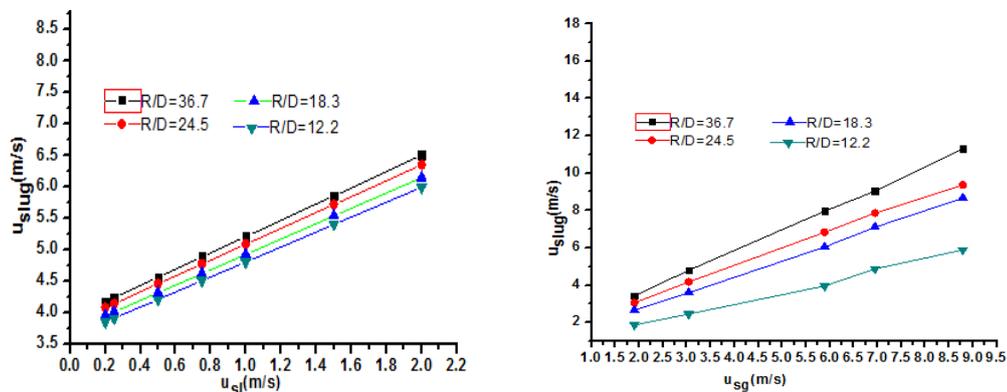
Figure 5 shows the relationship of the liquid slug velocity with the superficial velocity. The average liquid slug velocity has a linear relationship with superficial gas velocity u_{sg} , the average liquid slug velocity increases linearly with the increase of superficial gas velocity u_{sg} shown in Figure 5 (a). It indicated that the average liquid slug velocity have a linear relationship with superficial liquid velocity u_{sl} . With the increase of liquid conversion velocity u_{sl} , average liquid slug velocity increases linearly, but the standard deviation of the liquid slug velocity remain same.



(a) Superficial liquid velocity is constant (b) Superficial gas velocity is constant

Figure 5. The relationship between the average of the liquid slug velocity average and the superficial velocity.

In order to determine the change trend of the slug flow through the different horizontal bend pipe, changing the R/D (R for the bend radius, D for experimental section inner diameter) of the pipe were respectively 36.7, 24.5, 18.3 and 12.2mm in the process of experiment, under four different R/D: (1) constant superficial gas velocity ($u_{sg}= 3.04$ m/s), changing the superficial fluid velocity(u_{sl}); (2) constant the superficial fluid velocity($u_{sl}=0.75$ m/s), changing the superficial gas velocity (U_{sg}), the differential pressure signal is used to determine the liquid slug velocity in time sequence diagram under different working conditions, and the average values of the liquid slug velocity in different R/D were obtained finally as shown in Figure 6.



(a) Constant superficial gas velocity (b) Constant superficial liquid velocity

Figure 6. The relationship between the liquid slug velocity and the value R/D.

The average velocity of liquid slug increases with increase of superficial liquid velocity under constant superficial gas velocity and same R/D as shown in Figure 6 (a). This is due to the linear increase in the average velocity of the plug and the surface fluid velocity at the same R/D. Otherwise, the average velocity of liquid slug decreases with decrease of R/D under constant superficial gas velocity and different R/D, but the change is less. This is because when the fluid flows through the pipe, centrifugal force happen and cause pressure increase and velocity decrease near the outer wall. Meantime, pressure decrease and velocity increase near the medial wall. Because of inertia, the fluid flow will produce larger whirlpools area near the medial pipe and less whirlpool zone near the outer wall, which accelerates separation of gas-liquid and the flow chaos.

3.2 The length of the liquid slug

The time series of liquid slug length is obtained through the differential correlation method. When the superficial gas velocity is 5.89 m/s, superficial liquid velocity is 0.2 and 0.97 m/s, the change of liquid

slug length with times is shown in Figure 7. The liquid slug length decreases with the superficial liquid slug increasing, but the extent of the change was less.

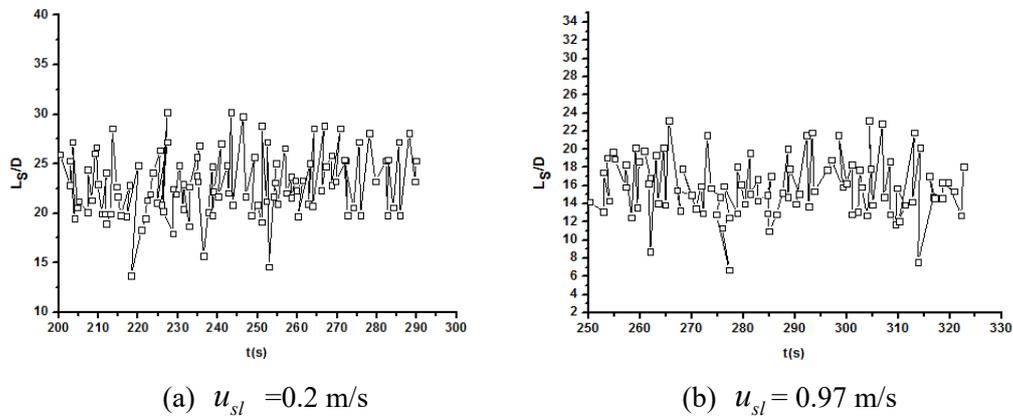


Figure 7. The time series of liquid slug length($u_{sg} = 5.89\text{m/s}$).

Figure 8 denotes the relationship of the liquid slug length and the superficial velocity. It can be seen from Figure 8 (a) that the average liquid slug length increases with increasing of superficial gas velocity, but the degree of increase gradually slow down. It can be seen from Figure 8(b) that average of liquid slug length decreases with slowly increasing of superficial liquid velocity.

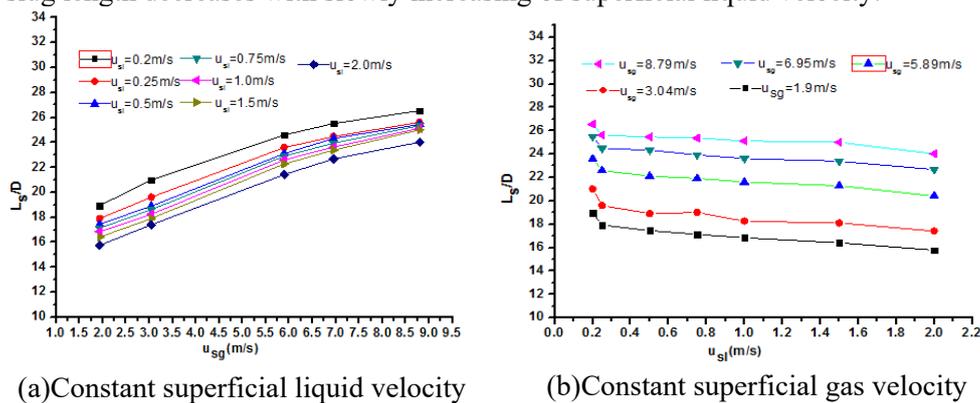


Figure 8. The relationship diagram of liquid slug length and the superficial velocity.

In the process of test, we change the R/D of pipe at 36.7, 24.5, 18.3 and 36.7 respectively. Under different the R/D: (1) constant superficial gas velocity at 3.04 m/s, changing the superficial fluid velocity; (2) constant superficial liquid velocity at 0.75 m/s and changing the superficial gas velocity, the relationship of liquid slug length with R/D were obtained(as showed in Figure 9).

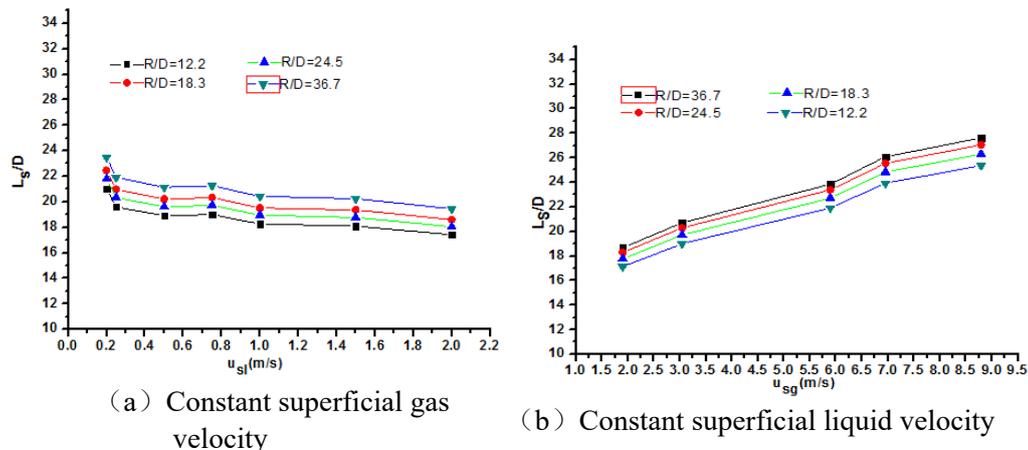


Figure 9. The relationship diagram of liquid slug length and R/D.

It can be seen from the Figure 9 that the average length of liquid slug decreases continuously with the increase of superficial liquid velocity under constant superficial gas velocity and same R/D. The average length of liquid slug increases continuously with the increases of R/D under constant the superficial gas velocity and different R/D, as showed in Figure 9 (a). When superficial gas velocity are constant and R/D are same, the average length of liquid slug increases continuously with the increase of superficial liquid velocity. The average length of liquid slug decreases continuously with the decreases of the superficial liquid velocity under constant the superficial gas velocity and different R/D, as it showed in Figure 9 (b). The main reason is that the effect of centrifugal force makes the superficial gas velocity decreases, and thus makes the average liquid slug length decreases.

3.3 The liquid slug frequency

The liquid slug frequency is relative to the entrance of gas and liquid flow, liquid level fluctuation and fluid structure factors. Therefore, results from different researchers are imparity. The experimental study determines the liquid slug frequency through manual counting and the differential correlation method.

Figure 10 show the curve of liquid slug frequency change with time when the superficial gas velocity is 5.89 m/s and superficial liquid velocity are 0.25, 0.5, 1.0, and 1.5 m/s. The liquid slug frequency presents a drastic fluctuations characteristics as time goes on, and with superficial liquid velocity increasing, the liquid slug frequency also increases gradually.

Figure 11 displays the relationship of the slug flow liquid slug frequency and the gas liquid flow. As Figure 11(a), the average liquid slug frequency increased with the increasing of superficial gas velocity. The change of liquid slug frequency is not obvious and smaller when the liquid slug velocity is small. On the contrary, when the liquid slug velocity increased gradually, the liquid slug frequency increases quickly. It can be seen from Figure 11(b) that the change trends of the average liquid slug frequency with increasing of the liquid slug velocity is similar to that with the change trends of superficial gas velocity, it also increased with the increase of superficial gas velocity, but the increase margin is comparatively small, which shows that the value of the liquid slug frequency was mainly affected by superficial liquid velocity.

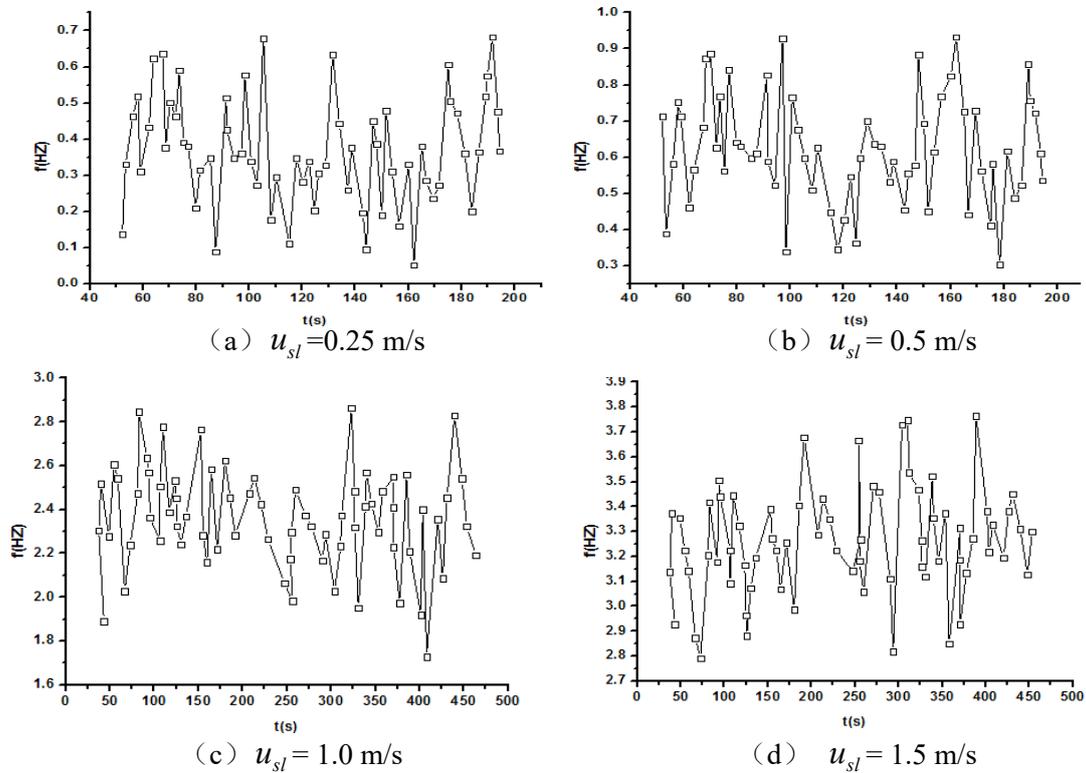


Figure 10. Time series of liquid slug frequency.

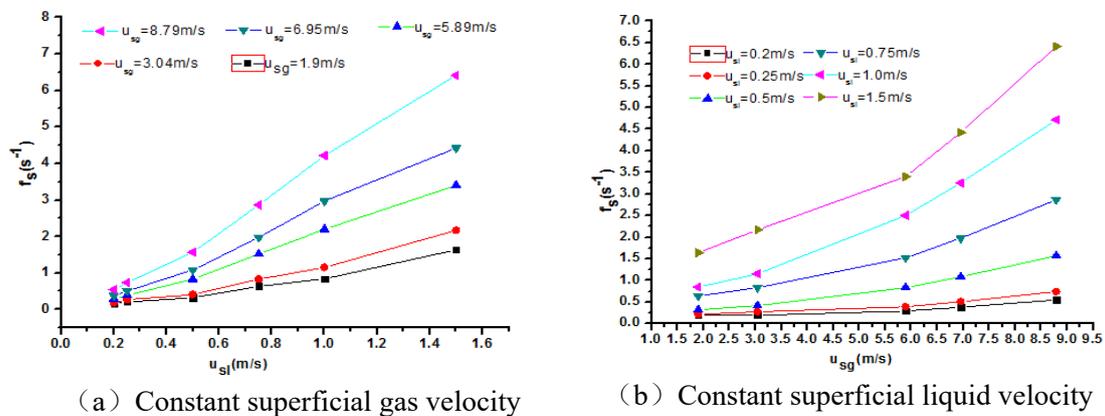


Figure 11. The distribution diagram of columnar liquid slug frequency and probability.

In order to study the influence that the bend curvature of slug flow to the liquid slug frequency we change experiment bend R/D was 36.7, 24.5, 18.3 and 36.7 respectively during the experiment. Under four different values of R/D: (1) constant the superficial gas velocity $u_{sg} = 3.04$ m/s, change the superficial liquid velocity u_{sl} ; (2) at two kinds of experimental conditions of constant the conversion velocity $u_{sl} = 0.75$ m/s and change of the superficial gas velocity u_{sg} , there are a total of 12 kinds of experiment conditions. We determine the changes in the relationship between the liquid slug frequency with the R/D increased gradually under different conditions using differential pressure signal (Figure 12).

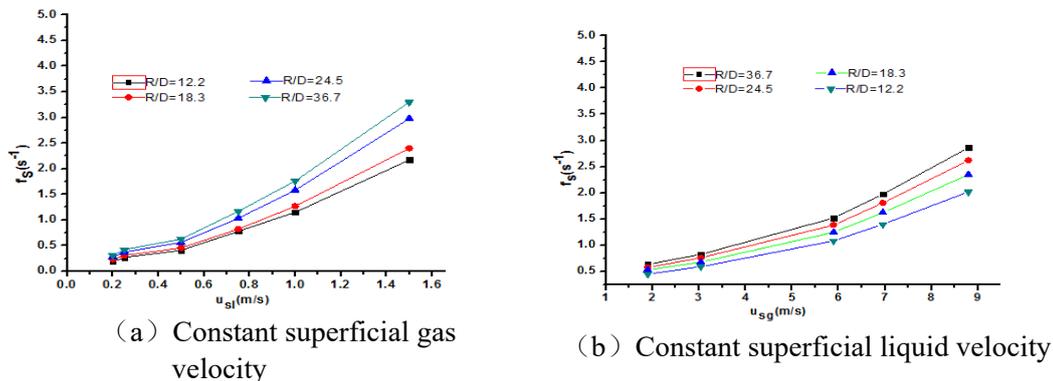


Figure 12. The variation diagram of the liquid slug frequency and R/D.

It can be seen from the Figure 12 that the average frequency of liquid slug increases continuously with the superficial liquid velocity when the superficial gas velocity is constant and R/D is same. The average frequency of liquid slug decreases continuously with the decreases of the superficial liquid velocity when the superficial gas velocity is constant and R/D is different (Figure 12 (a)). When the superficial liquid velocity and R/D is constant, the average frequency of liquid slug increases continuously with the increase of superficial gas velocity. The average frequency of liquid slug decreases continuously with the decreases of value of R/D when the superficial gas velocity is constant and R/D is different (Figure 12 (b)). The main reason is that the centrifugal force makes the superficial gas velocity decreases, and thus makes the average frequency of liquid slug decreases.

4. Conclusion

This experiment has carried on the research of the characteristic slug flow in horizontal curved tube of 26 mm inner diameter. The relevant conclusions are as follows: (1) Liquid slug velocity: The probability distribution of the average liquid slug velocity conform to the Gaussian distribution when the superficial velocity of one phase is constant, and that of another phase is increases. The average liquid slug velocity increases with the increase of superficial gas velocity and the superficial liquid slug velocity, which is mainly affected by the superficial gas velocity. The average liquid slug velocity increase with the increase in curvature radius of pipe. (2) The liquid slug length: The average length of liquid slug increase with the increase of the superficial gas velocity. The average length of liquid slug decrease with the increase of the superficial liquid velocity. Meanwhile, the average length of liquid slug increase with increase in curvature radius of pipe. (3) The liquid slug frequency: The average liquid slug frequency increases with increases of the superficial gas velocity and the superficial fluid velocity, which is mainly affected by superficial liquid velocity. Meanwhile, increases in average liquid slug frequency with increases in curvature radius of pipe.

Acknowledgments

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