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Experimental study on pressure fluctuation characteristics of slug flow in horizontal curved tubes①

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Abstract

In order to study the pressure characteristics of slug flow in horizontal curved tubes, two kinds of curved tubes with central angle 45° and 90° respectively are studied, of which are with 0.5m circumference and 26mm inner diameter are used. When the superficial liquid velocity or the superficial gas velocity is constant, the pressure fluctuations and the probability distribution of the average velocity of slug flow are clear for all of the five experimental conditions. The results of experiment show that the pressure characteristics of slug flow in curved tubes have periodic fluctuations. With the rise of central angle, the period of pressure fluctuation is more obvious. The system pressure of the slug flow increases with the increasing of superficial liquid/gas velocity. Meanwhile, the probability distribution of pressure signal shows regularity, such as unimodal, bimodal or multimodal.

Key words: slug flow, horizontal curved tube, pressure fluctuations, central angle

0 Introduction

Gas-liquid two-phase flow is a very common but complicated phenomenon of flow in many industries, such as petroleum, chemistry engineering, energy power. Different flow patterns will be formed with various parameter diversities, such as gas-oil ratio, tube diameter, shape and topographic relief.

Slug flow, a most common flow pattern, often appears in multiphase pipeline in many operating conditions, such as normal operation, the start-up of the equipment, operating condition change and pigging. The intermittent changes (liquid slug, pressure and mass flux) are the typical unstable characteristic. Because of its intermittent flow, the liquid holdup and pressure of pipe fluctuate dramatically, the pipe-run in the flow pattern will endure intermittent impact of stress[1]. The slug flow also causes irregular vibration of instrumentation or meter and affects normal operation of equipment, mixture pumps and auxiliary piping[2-5].

Based on the amplitude and frequency of the pressure and the shape of the timing signal, Weisman, et al[6] pointed out fluctuation characteristics of slug flow in horizontal pipes. Nishikawa, et al[7] investigated the pressure fluctuation of two-phase flow in vertical riser tubes. It was found that the distribution curve of frequency and pressure of slug flow were always bimodal and fluctuation of pressure was bigger. Zhao, et al[8] proposed the probability density of different pressure of slug flow generally showed unimodal, while the pressure signal had a variety of distributions. Annu-nziat, et al[9] obtained the recognition criteria of flow pattern by studying the fluctuation character of two-phase differential pressure of horizontal tubes. Sganss, et al[10,11] put forward an interesting model for the static pressure fluctuation of wall of two-phase flow in a horizontal rectangular tube, also proved the identification of transition from bubble flow or plug flow to slug flow with signal characteristic of pressure and differential pressure as the discriminant basis[12,13].

Lately, there are many studies[14-18] about the characteristics of slug flow in the horizontal pipe, vertical pipe and inclined pipe, but relatively few studies in the horizontal curved tube. The curved pipe is often used in production process, so it is necessary to study characteristics of the slug flow in horizontal curved tubes.

1 Experimental system and process

1.1 Experimental system

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

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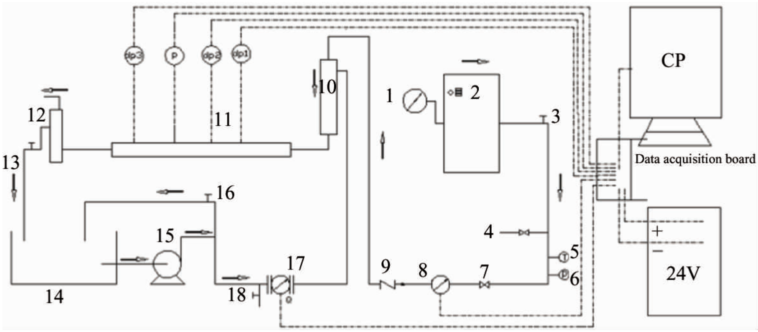


1. The electrical source of air compressor mechanical; 2. Air Compressor;
3. Air Compressor Export control valve; 4. Air Compressor bypass;
5. Thermocouple (with digital display); 6. The pressure gauge; 7. The gas flow control valve;
8. Gas mass flowmeter; 9. The gas flow control valve; 10. The gas-liquid 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

Fig. 1 Experimental system diagram

Experimental medium is water and air, the centrifugal pump takes the water from tank (14) to flowmeter (17) to measure and then send to it gas-liquid mixer (10), air through compressor (2), gas flowmeter (8) to measure and then send to it gas-liquid mixer, the mixing gas-liquid to enter it test section (11) than the slug flow is obtained by adjusting gas and liquid flow rate.

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

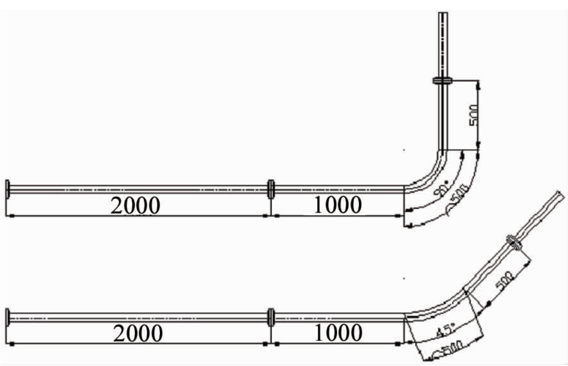


Fig. 2 Experimental section size diagram

1.2 Experimental program

Each test follows the following procedures:

(1) Before each test, fill the water tank with water. Check and examine all the test meters and devices carefully and then start the experiment.

(2) Open the compressor and control pressure to the set pressure, adjust gas volume to the experimental flow.

(3) Open the centrifugal pump gradually and adjust regulating valve slowly, increase liquid flow rate to the set value gradually, and then observe the flow pattern of horizontal tube test section until there arise slug flow in the test section.

(4) Measuring pressure, pressure differential, temperature and mass flow rate, record the key observed values.

(5) First, record the steady-state data and then gradually increase flow rate of the fluid to the set flow until the stable slug flow appears. Meanwhile, the data is automatically gathered by the computer gathering program at a given frequency, after the test working condition completed, close the water valve first and then close the gas valve. After that, implement the next test working condition.

1.3 Test parameters

Experiment medium: water and air;

Experiment temperature: 10℃ ~25℃;

Flow velocity: superficial gas velocity, 1m/s ~ 12m/s. superficial water velocity, 0.19m/s ~2m/s;

Work pressure: 0.25MPa.

1.4 Test parameter measurement

The measurement of test parameters includes gas and liquid flow rate, system pressure, temperature, pressure drop in the test section, the liquid slug length, velocity and frequency, etc.

This experiment is carried out on the gas-liquid mixing pressure. In order to improve the accuracy of measurement point, it should be done under the center line of the pipeline and in 45° with the horizontal center line to ensure a stable condensate pipeline, but also to prevent contaminants from entering the differential pressure transducer to make the transmitter is not in normal use. The ring type pressure is taken in pressure point to ensure the pressure of gas-liquid mixing pressure. The pressure points is shown in Fig. 3.

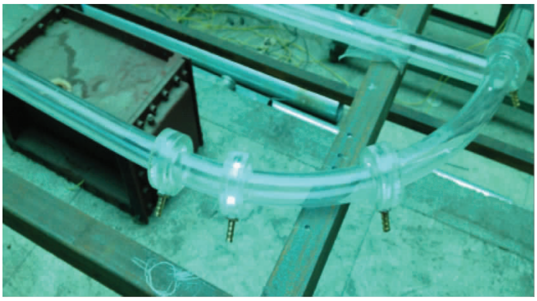


Fig. 3 thepressure points

The flow measurement

(1) The gas flow measurement:

The gas flow rate is measured by the Emerson CMF010 flow meter. The accuracy of the meter is ±0.5%. The data of gas flow is sent to the data acquisition system.

(2) The liquid flow measurement:

The liquid flow is measured by E-mag electromagnetic flow meter. The measuring accuracy of the meter is ±0.2% and the range is 0 ~ $200C_0$. The data of the liquid flow is sent to the data acquisition system.

Temperature measurement

The fluid temperature in the test section is measured by the T armored thermocouple installed at the pipeline. The measuring range of gas temperature is 0℃ ~350℃ and liquid temperature 25℃ ~45℃. The precision of the rmocouple is 0.75℃.

Pressure measurement

The pressure is measured by the Rosemount 3051 TG4A type pressure transmitter. The main parameters are as follows: the range is 0MPa ~27.6MPa and the accuracy is ±0.075%. In order to enhance the accuracy, pressure is taken a pressure point in the ring to ensure the pressure for gas-liquid mixture.

Differential pressure measurement

For different pressure points, the range of differential pressure value is different. Differential pressure transmitters are selected according to the location of the pressure measure. This selected differential pressure transmitters are Rosemount 3051 CD2A and 3051 CD1A type differential pressure transmitters. The accuracy of differential pressure transmitters is ±0.075%.

1.5 Data acquisition system

All of the voltage signals through acquisition board are sent to the computer control room. According to related literatures, the wave frequency of differential pressure signals is generally within 50Hz. The acquisition frequency is 500Hz. IMP35952A acquisition plates are selected for the experiment. The acquisition frequency is 0.1kHz ~49kHz, which can satisfy the test requirement.

2 Results and discussions

2.1 The pressure fluctuation of slug flow in bend

When superficial liquid velocity u_{sl} is equal to 0.95m/s, the superficial gas velocity u_{sg} is from 1.9m/s to 8.79m/s, the central angle of curved section is respectively 45° and 90°. The pressure fluctuation curves are shown in Fig. 4.

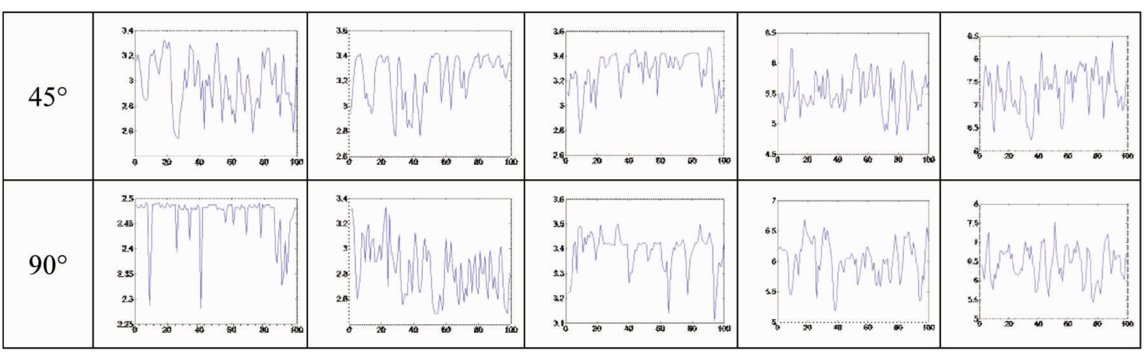


Fig. 4 The pressure fluctuation curve with constant liquid superficial velocity
(The abscissa is the time (s), the vertical axis represents the pressure (kPa))

It can be seen from Fig. 4, the pressure fluctuationisquasi-periodic. The pressure of systemincreases with increasingsuperficial gas velocity, because of the compressibility of the gas. Meanwhile, with the increase of superficial gas velocity, the period of the fluctuation of pressure signal is more obvious, since because the length of slug unit increase with the increasing of gas flow rate, but the number of slug units between measurement points is decreased. The superposition times of pressure drop of slug unit are reduced accordingly.

With the increase of superficial gas velocity, compared with pressure fluctuation curves of slug flow of the central angle of 45°, periodic signal of 90° is more obvious. This is because when fluid flows the elbow, different pressure distribution between internal and external walls of tube makes the flow lines cured. Due to the inertia of the fluid, the fluid acted by centrifugal force in makes the walls of the curved tube generate different pressure and the lateral velocity is greater than that inside.

In the curved tube, the centrifugal force of slug units increases with increase of central angle, the velocity also increases, and the pressure of external wall will increase and the length of slug units will elongate.

When the superficial gas velocity is equal to 1.9m/s, the superficial liquid velocityis from 0.25m/s to 1.5m/s, the central angle ofcurvedbent section are respectively 45° and 90°. The pressure fluctuation curves as shown in Fig. 5.

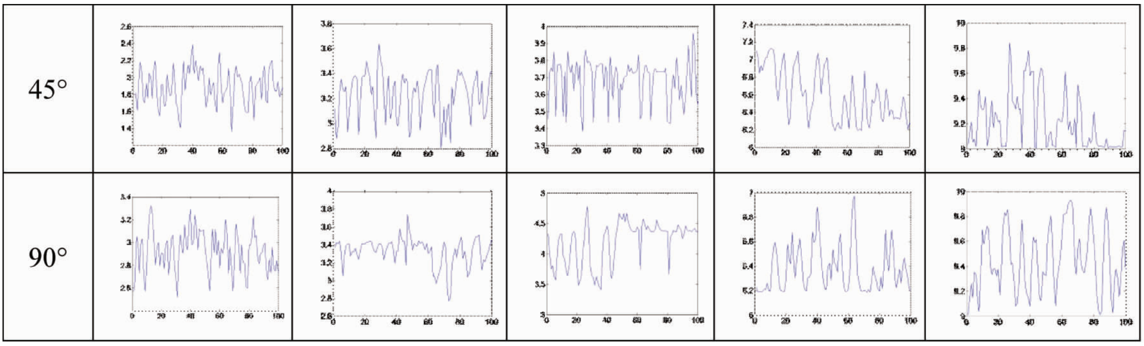


Fig. 5 The pressure fluctuation curve with constant gas superficial velocity (The abscissa is the time (s), the vertical axis represents the pressure (kPa))

It can be seen from Fig. 5, the pressure fluctuation is quasi-periodic. The pressure of system increases with increase of superficial liquid velocity. This is because the average density in the system increases with the increase of liquid, the compression function of the gas increases with the increase of average density.

At the same time you can see, with the superficial liquid velocity increases, the amplitude of pressure fluctuation more serious, the quasi-period of the fluctuation of pressure signal is more obvious. This is because that with the increase of fluid flow, the velocityincreases, the system compressibility enhances, and the cross-sectional area of gas reduces, the rate of gas flow and the length of the bubble increases, but slug frequency is reduced, the fewer slug units between measurement points, the less the superposition times of pressure drop of slug unit.

Compared with the central angle of 45°, the quasi-period of the signal of pressure fluctuation, 90° is obvious.

2.2 Probability density function of pressure fluctuation for slug flow in bend

When superficial liquid velocity u_{sl} is equal to 0.95m/s, the superficial gas velocity u_{sg} is from 1.9m/s to 8.79m/s, the central angle of curved section is 45° and 90° respectively. The pressure fluctuation curves of probability density function is shown in Fig. 6.

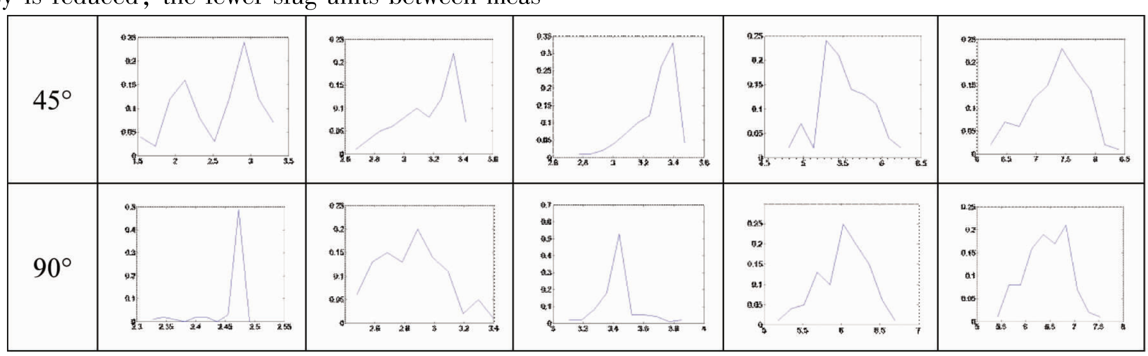


Fig. 6 Probability density function of pressure fluctuations with constant liquid superficial velocity (The abscissa is the pressure (kPa), the vertical axis represents the probability density function)

It can be seen from Fig. 6, with the increase of superficial gas velocity, probability density distribution of pressure fluctuations are transformed between unimodal and bimodal. This is due to the function of the centrifugal force. In the bend, the lateral pressure is greater than that inside, when the superficial gas velocity is less, the number of slug units and superposition times of pressure drop of slug unit are relatively bigger between the point and the exit of pipe. When the superficial gas velocity increases, the gas content and slug length of tube increase too, but the function of the centrifugal force decreases.

Compared with the central angle of 45°, probability density distribution of the tube with central angle of 90° appears multimodal more often. Meanwhile, with the increase of superficial gas velocity, the probability density tends to be divergent.

When superficial gas velocity u_{sg} is equal to 1.9m/s, the superficial liquid velocity u_{sl} is from 0.25m/s to 1.5m/s, the central angle of curved section are respectively 45° and 90°. The pressure fluctuation curves of probability density function are shown in Fig. 7.

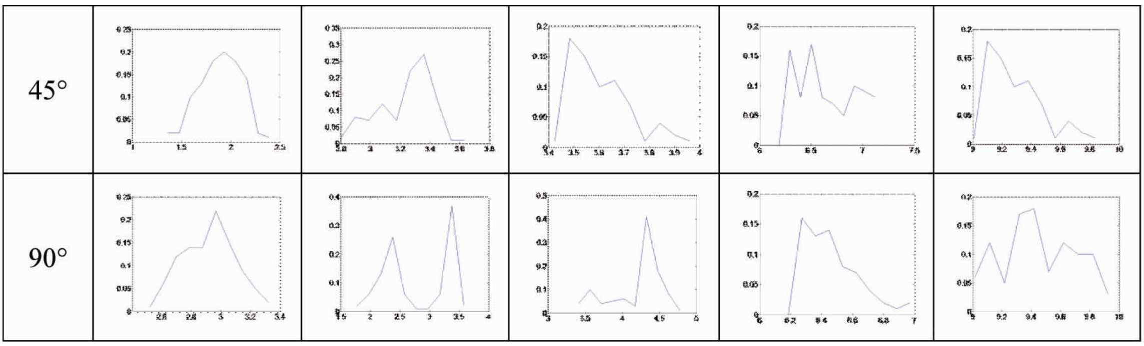


Fig. 7 Probability density function of pressure fluctuations with constant gas superficial velocity (The abscissa is the pressure (kPa), the vertical axis represents the probability density function)

Probability density of 45° bend transforms from unimodal to multimodal. This is because the centrifugal force of the inner has less pressure when liquid slugs through the bend when the superficial liquid velocity is small, the probability density shows unimodal and approximately normal distribution. But with the increase of superficial liquid velocity, the compression of gas within the pipe is enhanced by liquid, the system pressure and flow rate are growing, which makes the centrifugal force increase when liquid slugs through pipe.

During compression, the velocity of forward bubbles presents random states like larger and smallerdue to compression, and the probability density distribution is multimodal.

As for the bend with 90°central angle, the probability density is multimodal with the increase of superficial liquid velocity. With the increase of superficial liquid velocity and system pressure, the centrifugal force of liquid slug increases with increass of the central angle, so the probability density distribution become multimodal. At meantime, its distribution tends to be diversed.

2.3 Comparison of the characteristics of the horizontal pipe and curved tube

In the same position, the effect of slug frequency on liquid superficial velocity in horizontal curved tube and horizontal tube is more visible than that on gas superficial velocity. This is because the average density in the system increase with the increass of liquid, the compression function of the gas increases with the increass of average density.

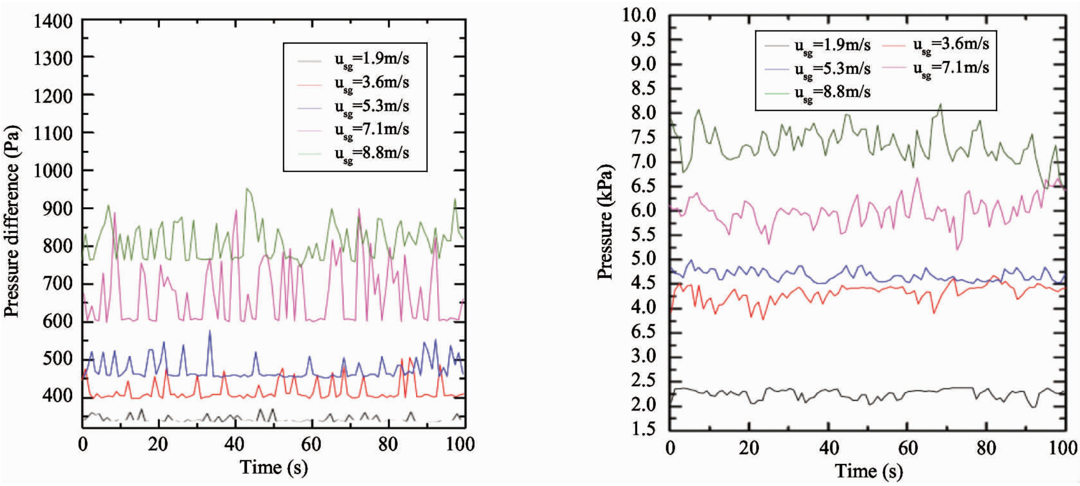
The increase of the amount of gas, liquid, or both in the horizontal pipe and curved pipe will increase in pressure and pressure difference and the maximum pressure. The pressure of system increases with increase of superficial gas velocity or superficial liquid velocity, because of the compressibility of the gas and the increase of average density.

The comparison chart is shown Fig. 8.

It can be seen from Fig. 9, the difference is that the probability density distribution of differential pressure signal is mainly characterized by a unmoral distribution, normal distribution of horizontal slug flow, and a bimodal distribution of bend slug flow. Obvious difference exists between them.

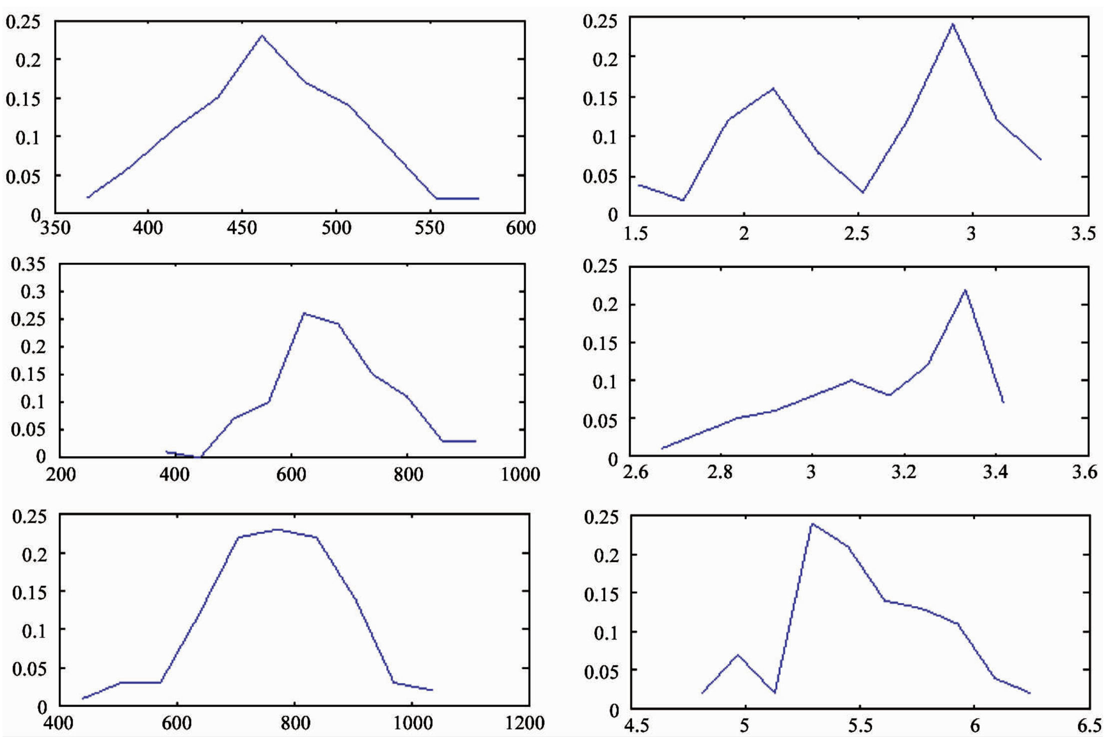
The probability distribution of pressure signal in curved tube shows regularity, such as unimodal, bimodal or multimodal.

This is because the pressure fluctuation at a measurement point is the superposition of all the liquid slug



(a) Horizontal tube (b) Curved tube

Fig. 8 Pressure fluctuation curves when superficial liquid velocity is constant



(a) Horizontal tube (b) Curved tube

(The abscissa is the pressure difference, the vertical axis represents the probability density function)

Fig. 9 Probability density function of pressure fluctuations with constant liquid superficial velocity

and long bubble pressure fluctuation between the measuring point and the outlet of the pipe. When the fluid flows into the elbow of a specific radius of curvature, the fluid will be affected by the centrifugal force, the liquid slug and the liquid film length, the gas flow rate of the liquid slug and the gas content in the liquid film region.

3 Conclusion

(1) The pressure fluctuation of slug flow in curved tube presents quasi-periodically. Meanwhile, its quasi-period is more obvious with the increase of the central angle. At the same time, the pressure of system increases with increase of superficial liquid velocity or superficial gas velocity.

(2) Probability density of the pressure signal shows diversity of distribution such as unimodal, bimodal and multimodal. With the increase of the central angle, gas superficial velocity or liquid superficial velocity, the probability density distribution shows multimodal. This is because the centrifugal force has a greater influence on the system pressure. Furthermore, the dispersity of probability density increases with increasing of superficial liquid velocity or superficial gas velocity.

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