Experimental Study on the Pressure-Difference Fluctuation Characteristics of Slug Flow in Horizontal T-Junction Tube

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Abstract. In practice, two-phase fluids may be often mixed or separated in T-junction tube, and alternating flow of liquid plug and gas plug may cause its working condition to be complex and changeable, so the study on it needs to be improved at present. Based on air and water, the characteristics of response to differential pressure of gas-liquid two-phase slug flow in two kinds of transparent horizontal T-junction PMMA tubes with different diameters are studied in depth and systematically, and data collection and processing are conducted by LabVIEW platform to obtain the probability density function (PDF) and the power spectral density function (PSD) characteristics of slug flow in different periods and forms. All characteristics provide reliable slug flow identification for flow pattern recognition.

1. Introduction
The gas-liquid two-phase slug flow is a kind of flow phenomenon that the liquid slug and large bubble formed in the pipe flow forward alternately along the pipeline. It will give rise to the wild fluctuation of pressure in the pipe due to the intermittency and instability of its flow and the pipe is subjected to intermittent stress shock [1]. Therefore, it is of great important to identify the slug flow and analyze its characteristics, thus ensuring the safe operation of the pipeline. Most of the relevant researchers use the signal characteristics of pressure difference to distinguish the flow patterns of multiphase flow. Weisman [2] et al concluded the fluctuation characteristic of slug flow through comprehensive analysis based on pressure-difference fluctuation amplitude, liquid slug frequency and form of sequence signal while researching the gas-liquid two-phase flow pattern in horizontal pipe. Chinese scholars Xiao Quansheng [3] and Zhu Ruian [4] studied the phase separation in equal-diameter T-junction tube and believed that the phase separation were mainly influenced by the flow pattern of two-phase flow at inlet, mass quantity of inlet, total mass inhalation ratio of bypath, inlet flow rate and geometrical parameter of bypath, etc. CHARRONY and WHALLEYPB [5] studied the phase separation in T-junction tube by using the air and water as the medium. All above scholars does not study the flow distribution of the mixture when gas-liquid two-phase slug flow goes through fork of horizontal T-junction tube and the response characteristics of pressure difference under such circumstances, so this paper conducts relevant research on this aspect.
2. Test equipment and process

2.1. Physical test system

The physical system for this test is mainly composed of gas path metering system, water path metering system, gas-liquid two-phase mixing system, visual test section and gas-liquid mixture loop system. The gas path metering system mainly includes imported spiral lobe compressor, gas storage tank with volume of 1.5m³, gas dryer, gas mass flow meter, vortex street flowmeter and air flow regulating valve. The water path metering system has water storage tank with volume of 1.5m³, multiple-stage centrifugal pump, liquid mass flowmeter, vortex street flowmeter and water regulating valve. The test process is shown in the Figure 1.

![Figure 1. The test process](image)

First, the multiple-stage centrifugal pump takes the water from the water storage tank to the water path circulation system and the water inside the circulation system entries into the gas-liquid mixing stage after it is measured by vortex street flowmeter. Next, the spiral lobe compressor compresses the air in the external environment to the gas storage tank and then flows into gas-liquid mixing stage after the buffer of gas storage tank, drying of dryer, record of thermometer temperature, pressure measurement of pressure gauge, and measurement of vortex street flowmeter.

Then, the water supplied by water storage tank and gas supplied by spiral lobe compressor are fully mixed in the gas-liquid mixing section and then flow into visual test section, in which the fluid mixing flows into open water tank via two loops after the data collection. Finally, the liquid can be reused for circulation system and the gas is emptied directly. The visual test section is composed of transparent PMMA pipe with inner diameter of 25mm and wall thickness of 10mm, 9 ring pressure measuring kits and 1 tee joint.

2.2. Data acquisition and analysis system and analysis theory of test data

2.2.1. Analysis theory of test data. The dynamic parameters, such as pressure and pressure difference, are fluctuating with the flow of two-phase flow mixture inside the pipe, and if multiphase flow mixture is different, the fluctuation characteristics of the parameters are different. The fluctuation process of these parameters contains rich information about the flow structure and so on. The flow pattern can be identified by the fluctuation analysis of the parameters.

Definition 2.1: The probability of defining the value of the random process \( x(t) \) in the range of \( \Delta x \) near the \( x \) value is as follows:
\[ P(x) = P_{\text{prob}} \left[ x < x(t) \leq x + \Delta x \right] = \lim_{\Delta x \to 0} \frac{T_x}{T} \]  

(1)

It is called PDF of \( x(t) \). The probability expression for defining the value of \( X(t) \) in the interval \([x, x + \Delta x]\) is as follows:

\[ PDF(x) = \lim_{\Delta x \to 0} \frac{1}{\Delta x} P_{\text{prob}} \left[ x \leq x(t) < x + \Delta x \right] = \lim_{\Delta x \to 0} \frac{1}{\Delta x} \left( \lim_{T \to \infty} \frac{T_x}{T} \right) \]  

(2)

It is called PDF of \( x(t) \), where \( T_x \) means the total time of \( x(t) \) in the interval \([x, x + \Delta x]\) within \( T \) time, of which the probability of its amplitude in the interval \([x, x + \Delta x]\) can be reflected by \( T_x/T \). The statistical characteristics of a random process are characterized by the power spectral density function (PSD) of the process in the frequency domain.

Definition 2.2: The discrete Fourier transform of random sequence \( x(n) \) is conducted by defining \( N \) observed value of random sequence \( x(n) \) as a set of data sequences with limited energy, to obtain \( X(e^{jw}) \).

\[ X(e^{jw}) = \sum_{n=-\infty}^{\infty} x_n e^{-jnw} = \sum_{n=0}^{\infty} x_n e^{-jnw} \]  

(3)

It is divided by \( N \) after taking the square of \( X(e^{jw}) \) to obtain:

\[ \hat{S}_x(e^{jw}) = \frac{1}{N} \left| X(e^{jw}) \right|^2 \]  

(4)

It is defined as power (PSD) of sequence \( x(n) \).

3. Measurement results and analysis

The literature shows that the frequency fluctuation characteristic of the slug flow can be more clearly characterized by pressure-difference fluctuation signal than the pressure fluctuation signal [6]. The pressure difference signal in this paper is measured by a differential pressure transmitter. According to the hydrodynamic model of slug flow, the pressure drop in the slug element is mainly concentrated in the liquid slug area, and the pressure gradient in the large bubble area is very small, which can be ignored.

For pressure difference signals, its characteristics in the time domain are mainly characterized by the probability density distribution function (PDF). Therefore, the probability density distribution function (PDF) and the power spectral density function (PSD) in the time domain are analyzed in order to further get the detailed rule of pressure difference fluctuation of main pipe, radial pipe and axial pipe after flow distribution when gas-liquid two-phase slug flow through horizontal T-junction equal diameter pipe and variable diameter pipe. The PDF of a gas-liquid two-phase slug flow through a horizontal T-junction tube after flow distribution is shown in the Figure 2, and the power spectral density functions of pressure-difference fluctuation curve for each pipe under constant superficial gas velocity and superficial liquid velocity are respectively shown in Figure 3 and Figure 4.
equal-diameter and variable-diameter main pipe  

equal-diameter radial pipe  

Note1: The yellow curve represents the PDF curves when the $V_{SL}$ is taken at 0.34 m/s;  
Note2: The black curve represent the PDF curves when the $V_{SL}$ is taken at 1.83 m/s;  
Note3: The blue, purple, and red curves respectively represent the PDF curves when the $V_{SL}$ is increased from 0.34 m/s to 1.83 m/s.

Figure 2. (a) PDF of Pressure-Difference Fluctuation Curve for Each Pipe

According to the observation and analysis of Figure 2, with regard to the PDF for pressure-difference fluctuation curve of equal-diameter and variable-diameter main pipe, radial branch pipe and axial branch pipe, there is a common characteristic that the dispersity becomes stronger as the superficial gas-liquid velocity increases. The difference is that the PDFs of equal-diameter main pipe, equal-diameter axial branch pipe, variable-diameter radial branch pipe and variable-diameter axial branch pipe are distributed in single peak. Combined with other research, the probability density of pressure-difference signal for slug flow is distributed in single peak, which can provide theoretical basis for identifying flow pattern of the slug flow. In particular, only the equal-diameter radial pipe is transformed from single peak to multi-peak to single peak, caused by the instability of the flow pattern of the equal-diameter radial branch pipe. The observation results show that the axial branch pipe is smaller than radial branch pipe due to the influence of flow distribution, and variable-diameter pipe is smaller than equal-diameter pipe, which can provide theoretical basis for flow distribution of the gas-liquid two-phase slug flow.
Based on the above analysis, the fluctuation range of power spectral function of equal-diameter main pipe, equal-diameter axial branch pipe and variable-diameter axial branch pipe increases as another-phase superficial velocity increases, and the fluctuation range of pressure-difference fluctuation power spectral function of equal-diameter radial branch pipe is the largest if the superficial velocity of one phase is constant. The fluctuation range increases because there is a certain periodicity in gas-liquid two-phase flow, but very irregular, and there are some smaller fluctuations between each fluctuation cycle, showing that a series of two-phase flow with different local structure flows through measurement section. After the superficial gas-liquid velocity is increased, the flow pattern is more irregular, and the steam block and bubble with different shapes and sizes are unevenly distributed in the liquid phase. Therefore, the pressure-difference fluctuation process shows the characteristic of dispersive spectrum. The amplitude changing of equal-diameter radial branch pipe and variable-diameter radial branch pipe does not change obviously. This is because the gas will take precedence over the liquid into the radial branch pipe, and the pressure difference fluctuates not obviously relative to that of the main pipe and the axial pipe. Combined with other research [16], there is larger the amplitude of the power spectrum of slug flow is larger, which can provide theoretical basis for identifying flow pattern of the slug flow.

Figure 2. (b)PDF of Pressure-Difference Fluctuation Curve for Each Pipe
|                   | equal-diameter main pipe | equal-diameter radial pipe | equal-diameter axial pipe |
|-------------------|--------------------------|-----------------------------|--------------------------|
| 1                 | ![Graph 1](image1)       | ![Graph 2](image2)         | ![Graph 3](image3)      |
| 2                 | ![Graph 4](image4)       | ![Graph 5](image5)         | ![Graph 6](image6)      |
| 3                 | ![Graph 7](image7)       | ![Graph 8](image8)         | ![Graph 9](image9)      |
| 4                 | ![Graph 10](image10)     | ![Graph 11](image11)       | ![Graph 12](image12)    |
| 5                 | ![Graph 13](image13)     | ![Graph 14](image14)       | ![Graph 15](image15)    |

**Note1:** The above curves are all obtained by using equal diameter T-tube, and the $V_{SG}$ are 4.28m/s;
**Note2:** The line 1 curves represent the PSD curves when the $V_{SL}$ is taken at 0.34m/s;
**Note3:** The line 5 curves represent the PSD curves when the $V_{SL}$ is taken at 1.83m/s;
**Note4:** The line 2, 3, and 4 curves represent three PSD curves when the $V_{SL}$ increases from 0.34m/s to 1.83m/s.

(a) PSD for Pressure-Difference Fluctuation Curve of the T-junction equal diameter pipe under Constant Superficial Gas Velocity.
variable-diameter main pipe | variable-diameter radial pipe | variable-diameter axial pipe

1

2

3

4

5

**Note 1:** The above curves are all obtained by using variable diameter T-tube and the \( V_{SG} \) are 4.28 m/s;

**Note 2:** The line 1 curves represent the PSD curves when the \( V_{SL} \) is taken at 0.34 m/s;

**Note 3:** The line 5 curves represent the PSD curves when the \( V_{SL} \) is taken at 1.83 m/s;

**Note 4:** The line 2, 3, and 4 curves represent three PSD curves when the \( V_{SL} \) increases from 0.34 m/s to 1.83 m/s.

(b) PSD for Pressure-Difference Fluctuation Curve of T-junction variable diameter pipe under Constant Superficial Gas Velocity

**Figure 3.** PSD for Pressure-Difference Fluctuation Curve of Each Pipe under Constant Superficial Gas Velocity
| equal-diameter main pipe | equal-diameter radial pipe | equal-diameter axial pipe |
|--------------------------|-----------------------------|---------------------------|
| ![Diagram 1](image1)     | ![Diagram 2](image2)        | ![Diagram 3](image3)      |
| ![Diagram 4](image4)     | ![Diagram 5](image5)        |                           |

**Note1:** The above curves are all obtained by using equal diameter T-tube, and the VSL are 1.03 m/s;
**Note2:** The line 1 curves represent the PSD curves when the VSG is taken at 4.32 m/s;
**Note3:** The line 5 curves represent the PSD curves when the VSG is taken at 11.03 m/s;
**Note4:** The line 2, 3, and 4 curves represent three PSD curves when the VSG increases from 4.32 m/s to 11.03 m/s.

(a) PSD for Pressure-Difference Fluctuation Curve of T-junction equal diameter pipe under Constant Superficial Liquid Velocity
Note 1: The above curves are all obtained by using variable diameter T-tube, and the VSL are 1.03m/s;

Note 2: The line 1 curves represent the PSD curves when the VSG is taken at 4.32m/s;

Note 3: The line 5 curves represent the PSD curves when the VSG is taken at 11.03m/s;

Note 4: The line 2, 3, and 4 curves represent three PSD curves when the VSG increases from 4.32m/s to 11.03m/s.

(b) PSD for Pressure-Difference Fluctuation Curve of T-junction variable diameter pipe under Constant Superficial Liquid Velocity

Figure 4. PSD for Pressure-Difference Fluctuation Curve of Each Pipe under Constant Superficial Liquid Velocity

4. Conclusions
This paper studies the response characteristics of response to gas-liquid two-phase slug flow in equal-diameter and variable-diameter horizontal T-junction tube, radial branch pipe and axial branch pipe under different working conditions in a transparent horizontal T-junction PMMA tube by taking multiphase flow test room of Xi’an Shiyou University as the platform and using the water and air under normal temperature as the medium. The pressure-difference fluctuation curve and PDF of slug flow under different working conditions for each section are collected, drawn and analyzed respectively, of which the conclusions are as follows:

1. Flow pattern change: The flow pattern of mixtures in equal-diameter main pipe and axial branch pipe is the slug flow in the case of low superficial gas-liquid velocity, and that of radial branch pipe is not the slug flow because of more gas in it. As the superficial gas-liquid velocity increases, the flow pattern of mixture in equal-diameter horizontal T-junction tube main pipe, radial branch pipe and axial
branch pipe is the slug flow. Similarly, since there is a lot of air in the radial branch pipe, the flow pattern of the mixture in the whole pipeline system is not the slug flow as the superficial gas-liquid velocity continues to increase. For the variable-diameter pipe, the flow pattern of gas-liquid two-phase mixture in main pipe, radial branch pipe and axial branch pipe is the slug flow in the case of low superficial gas-liquid velocity, and the slug flow bubble in radial branch pipe is more obvious than that of axial branch pipe. The flow pattern of slug flow in radial branch pipe disappears first, and then the flow pattern of the whole pipeline system is not the slug flow as the superficial gas-liquid velocity continues to increase. These conclusions can provide theoretical basis for identifying flow pattern of the gas-liquid two-phase slug flow.

2. Characteristics of pressure-difference fluctuation: there is greater difference in pressure-difference fluctuation between main pipe, radial branch pipe and axial branch pipe when the gas-liquid two-phase slug flow flows through the fork of horizontal T-junction tube: ① The PDF of equal-diameter main pipe, equal-diameter axial branch pipe, variable-diameter radial branch pipe and variable-diameter axial branch pipe has a single peak distribution, and that of equal-diameter radial branch pipe is distributed in multi-peak. As the superficial gas-liquid velocity increases, the dispersity is stronger. ② The fluctuation range of power spectral function of equal-diameter main pipe, equal-diameter axial branch pipe and variable-diameter axial branch pipe increases with the increase of another phase superficial velocity, and that of the equal-diameter radial branch pipe is the largest if the superficial velocity of one phase is constant, without obvious amplitude changing. The fluctuation range and amplitude of pressure-difference fluctuation power spectrum function of variable-diameter radial branch pipe are not obvious. These conclusions can provide theoretical basis for increasing service life of downstream equipment and long-distance pipework and identifying the flow pattern of the slug flow.

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