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International Journal of Multiphase Flow 28 (2002) 2007–2016

International Journal of Multiphase Flow

www.elsevier.com/locate/ijmulflow

Fluctuation characteristics of two-phase flow splitting at a vertical impacting T-junction

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Received 11 March 2002; received in revised form 1 September 2002

Abstract

In order to investigate the fluctuation characteristics of two-phase flow splitting at a T-junction, particular attention was paid on Churn flow which had the strongest fluctuation comparing with bubble flow and annular flow. The main tube of the T-junction was vertical and the two branches were horizontal. All three pipes connecting to the junction were of 15 mm inner diameter. A statistical analysis based on Root Mean Square (RMS) was applied to temporal differential pressure signals and gas flow rate signals. The Power Spectral Density (PSD) was also employed to reveal their peculiar features in frequency domain as well. The effects of the extraction flow ratio and the gas and liquid superficial velocity upstream on fluctuation characteristics of gas-liquid two-phase flow splitting at the T-junction were investigated in detail. It is found that there is a wide fluctuation in both differential pressure and gas flow rate downstream at every extraction ratio (W_3/W_1) and the fluctuation intensity increases as W_3/W_1 increasing. It is also made clear that increasing either water superficial velocity or gas superficial velocity in inlet causes fluctuation to become more intensive.

Keywords: Fluctuation; Two-phase flow; T-junction; Churn flow; Extraction ratio

1. Introduction

T-junctions are commonly used in distributing two-phase flow by piping networks. These networks are essential components of many facilities in the power and process industries, such as conventional steam power plants, boiling-water and pressured water nuclear reactors and a wide variety of chemical and petroleum applications. Understanding the behavior of two-phase flow

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0301-9322/02/$ - see front matter
PII: S0301-9322(02)00104-0

splitting at a T-junction is extremely important since it can have significant effects on the operation, maintenance and efficiency of all components downstream from the junction.

Numerous studies on T-junction have been conducted in the past decades. If limited to impacting T-junction, Hong (1978), Azzopardi et al. (1987, 1988), Hwang et al. (1989), Chien and Rubel (1992), Fujii et al. (1995), Hong and Griston (1995, 1997) and Asano et al. (2001) have contributed to our present understanding of the behavior of two-phase flow at an impacting T-junction. However, few of them in the literature deal with time-dependent parameters. Although the idealized case of the true steady state will probably have to be well understood before the more complicated case including fluctuation can be considered, the neglect of the fluctuation of these parameters is acknowledged to be a departure from the physical reality. So it is vital of importance to understand fluctuation characteristics of two-phase flow passing through a T-junction at different extraction rate. On the other hand, transient operation in pipeline containing T-junctions can be encountered in many fields, as mentioned above. Fluctuation of two-phase flow splitting at T-junctions may cause tube vibration, which will lead to tube failures by fatigue and fretting-wear. If one of the branch tubes is in repair, the others will have to tolerate unusual fluctuation or vibration due to reconstructed extraction flow rate.

Against this background, the purpose of the present work is to investigate the fluctuation behavior of two-phase flow splitting at an impacting T-junction through time-dependent differential pressure signal and gas flow rate signal at different extraction rate W_3/W_1, where $W_1 = W_{G1} + W_{L1}$, $W_3 = W_{G3} + W_{L3}$, W_1 is inlet mass flow rate, W_3 is the branch mass flow rate, W_{G1} is inlet gas mass flow rate, W_{L1} is inlet liquid mass flow rate, W_{G3} is branch gas mass flow rate and W_{L3} is branch liquid mass flow rate. The results will provide useful information for controlling the fluctuation causing by two-phase flow in a pipe system.

The effect of gas and liquid superficial velocity upstream on fluctuation characteristics was measured and observed as well. In addition, a time-dependent parameters database was setup for establishing valid models.

2. Experimental facility and measurement

A schematic diagram of the two-phase flow-splitting loop is shown in Fig. 1. The flow loop consisted of a branch test section, open air and water loops, the related instrumentation and computer data acquisition system. The apparatus was operated under the following conditions: inlet gas superficial velocities, J_{G1}, ranging between 0.09 and 7.08 m/s, inlet liquid superficial velocities, J_{L1}, ranging between 0.09 and 0.19 m/s, and mass extraction rates, W_3/W_1, from 0 to 1, where W_1 and W_3 are the inlet and branch mass flow rates. All tests were carried out at nominally ambient pressure and temperature.

For each flow condition, the flow rates of two-phase flow through side branches was gradually altered by controlling regulating valves at the outlet of the T-junction.

Pressure drop (ΔP_{13}) from inlet to the branch was obtained by Validyne DP15, a differential transducer with maximum range approximately ± 225 kg/cm^2 and a Validyne CD-280 pressure demodulator. Output from the pressure transducers was in the form of a DC voltages signal (range ± 12.29 V) and was fed into the data-acquisition system. An appropriate calibration equation was then used to convert the voltages into differential pressure.

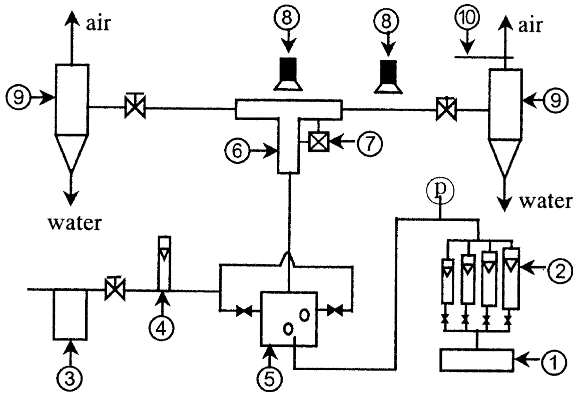

Fig. 1. Schematic diagram of experimental apparatus: (1) compressor, (2) air flowmeters, (3) filter, (4) water flowmeter, (5) mixingroom, (6) T-junction, (7) differential pressure sensor, (8) high speed video camera (9) separator, (10) hot wire anemometer.

Gas flow rate at the branch outlet was measured by a hot-wire anemometer sampled simultaneously with the differential pressure waveform. Both of the gas flow rate signal and the differential pressure signal were obtained from samples taken over 60 s at a rate of 200 samples/s. Two high-speed video cameras were employed for visual observation. One was set at 250 frames/s to record the behavior of the splitting flow at center area of the T-junction. The other was set at 125 frames/s to get the behavior of two-phase flow in the branch tube. Both of the videos were recorded simultaneously with differential pressure signal and gas flow rate signal. Water flow rate at the branch outlet was measured by weighting timed efflux. A steady interface in the separator was maintained while measurement was executed. About 30 min should be waited before each test run to reach the steady state.

3. Results and discussion

3.1. Time series of the parameters

Fig. 2 shows the differential pressure signal and the gas flow rate signal in the time domain. Since all of the other tests ($W_3/W_1 = 0$–1) showed the similar pattern in time series, only typical one ($W_3/W_1 = 0.43$) was chosen herein. We can see that these two parameters are significantly time dependent. But no more information can be taken except for changes in amplitude of two signals. Therefore, statistical analysis using root mean square (RMS) and the power spectral density (PSD) was applied to those signals to obtain the feature of the fluctuations in both time domain and frequency domain.

3.2. RMS amplitude of differential pressure fluctuation and gas flow rate fluctuation

RMS was chosen to evaluate the intensity of the differential pressure fluctuation and gas flow rate fluctuation at each extraction ratio.

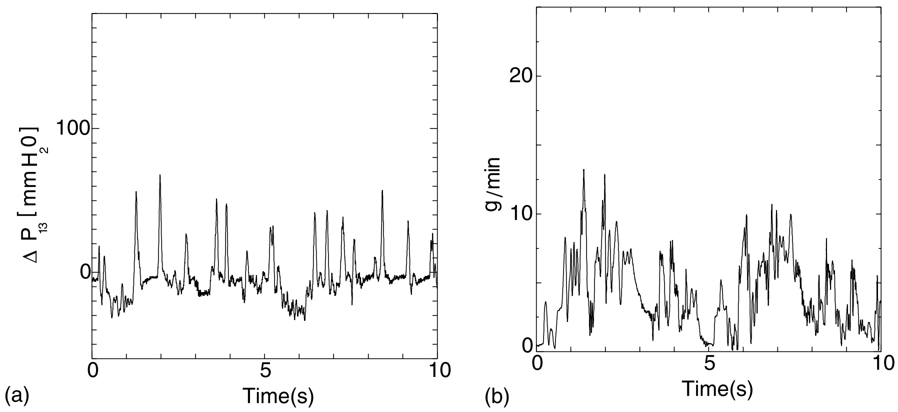

Fig. 2. Typical time series: (a) pressure drop ΔP_{13}; (b): gas flow rate at branch outlet.

The RMS amplitude of a signal fluctuation, Y_{rms}, can be calculated from the following equation:

$$Y_{\text{rms}} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - \bar{y})^2} \tag{1}$$

where y_i is the instantaneous value, $\bar{y}$ is the time-averaged value and N is the number of instantaneous data for each run.

A series of experiments have been performed by either a constant gas superficial velocity with different liquid superficial velocity or vice versa.

Fig. 3 shows time-averaged differential pressure ($\overline{\Delta P_{13}}$) versus RMS amplitude of ΔP_{13} at inlet condition: water superficial velocity 0.094 m/s and gas superficial velocity 0.97 m/s. The flow

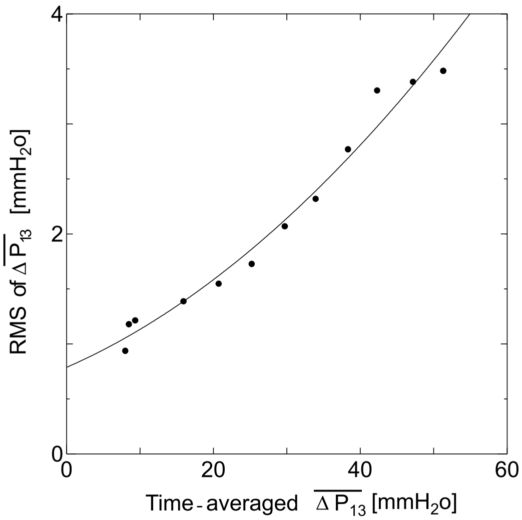

Fig. 3. Time-averaged differential pressure ($\overline{\Delta P_{13}}$) versus RMS amplitude of ΔP_{13}.

pattern in inlet tube was churn flow. It reveals that the fluctuation of ΔP_{13} became more intensive while the time-averaged pressure drop $\overline{\Delta P_{13}}$ (between inlet 1 and outlet 3 of the T-junction) became larger. Intuitively, it is reasonable for larger W_3/W_1 lead to larger pressure drop $\overline{\Delta P_{13}}$. Increasing W_3/W_1 primarily caused the fluid behavior changing in horizontal branch, the flow pattern changed complicatedly from stratify flow, plug flow, wave flow to slug flow (Fig. 4). Consequently, the RMS amplitude of the ΔP_{13} became larger and larger (see Fig. 6). This situation is similar to the results of Wambsganss et al. (1994). They tested over a mass flux range of 50–2000 kg/m^2 s and plotted RMS pressure as a function of mass quality.

In summary, while the mixture fluid is churn flow in the vertical inlet tube, the fluctuation of ΔP_{13} is attributed to followings: the first is the interaction of the reverse water from the branch to the inlet tube and the compressibility of gas in two-phase flow mixture in main tube; the second is the flow pattern's changing due to increasing W_3/W_1 (Fig. 4); the third is the uneven phase distribution (Fig. 5), which lead to the slip ratio in horizontal branch changing unevenly; i.e. while W_3/W_1 larger than 0.5, the slip ratio is larger than that in even phase distribution, on the contrary, it is smaller than that in even phase distribution condition. As a result of that, after splitting through a T-junction, the flow pattern changed more complex in horizontal branch comparing with a straight tube or a L-tube. We are going to do more experiments to find the phase separation effect on fluctuation in quantitatively.

Fig. 6(a) shows RSM of ΔP_{13} with W_3/W_1 while inlet water superficial velocity is kept constant at 0.09 m/s and gas superficial velocity are 0.94, 1.46, 1.89 m/s, respectively. The fluctuation of ΔP_{13} is increased with increasing inlet gas superficial velocity at each extraction flow ratio. It was also observed by video recording. Since the inertia of the gas increased while increasing the gas superficial velocity, the alternating competition in inlet tube between the forces of the gravity pulling the fluid downward and those due to the inertia of the gas pushing the fluid upward became more violent. On the other hand, increasing velocity of the mixture means to increase momentum of the mixture, thus the force colliding to the upper part of the T-junction became stronger, which caused stronger fluctuation of the two-phase flow in horizontal branch.

Fig. 6(b) shows the fluctuation of ΔP_{13} with W_3/W_1 while gas superficial velocity is kept constant at 0.94 m/s and water superficial velocity are 0.05, 0.09, 0.14 m/s, respectively. The fluctuation of ΔP_{13} became more intense while increasing inlet water superficial velocity. This is attributed to

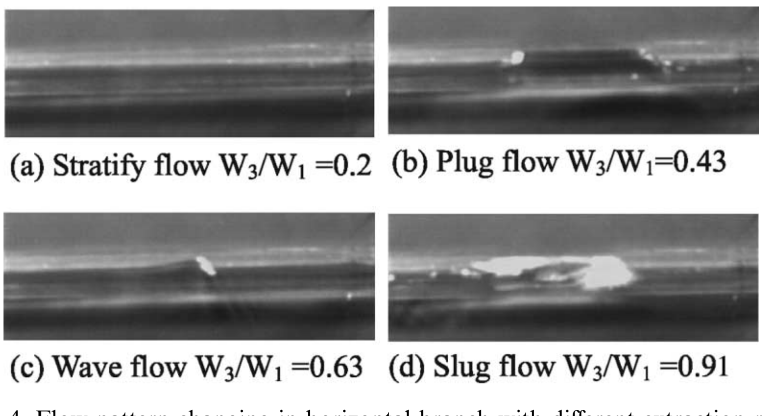

Fig. 4. Flow pattern changing in horizontal branch with different extraction ratio.

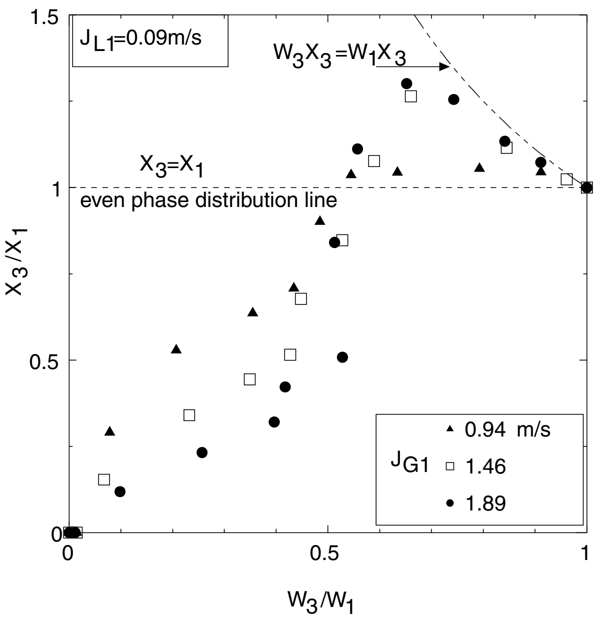

Fig. 5. Characteristics of phase distribution on churn flow.

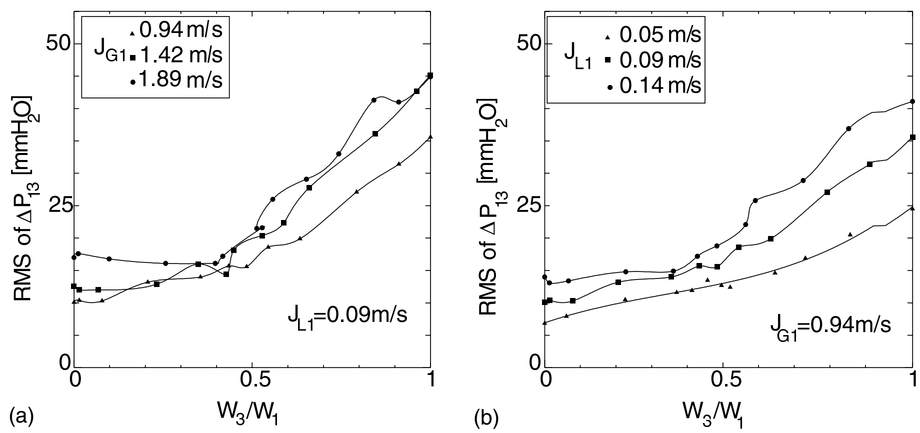

Fig. 6. RSM of ΔP_{13} with extraction ratio W_3/W_1: (a) water superficial velocity is kept constant at 0.09 m/s and gas superficial velocity are 0.94, 1.46, 1.89 m/s; (b) gas superficial velocity is kept constant at 0.94 m/s and water superficial velocity are 0.05, 0.09, 0.14 m/s.

that increasing water superficial velocity mainly increases the mass of mixture, which leads to increase mixture momentum greatly. According to momentum conservation, the force impacting to upper side of T-junction became stronger. As a result, the more intensive fluctuation happened both in inlet tube and horizontal tube (this phenomena was also observed by visualization).

3.3. RMS amplitude of gas flow rate (W_{G3}) fluctuation at branch outlet

Fig. 7 shows typical RMS amplitude of gas flow rate W_{G3} with W_3/W_1. Let us choose the curve ($J_{G1} = 0.94$ m/s, $J_{L1} = 0.09$ m/s) to explain in detail. While W_3/W_1 changed from 0 to 0.35, flow pattern in branch was stratified. Although Weisman et al. (1979) reported that in a straight tube there was no fluctuation in stratified flow regime. But two-phase splitting through an impacting T-junction made the result quite different. Influence from left-side flow on right-side flow was strong enough to give rise to fluctuation. In the extreme condition, when the right-side valve was completely closed, the liquid inside did not flow but oscillated. This phenomenon was also observed clearly by high-speed video camera.

While W_3/W_1 increased from 0.35 to 0.63, fluctuation of the gas flow rate increased as a whole. The flow pattern in branch was mainly wave flow and intermittent flow (plug flow) occasionally (see Fig. 4). However, when valves on each branch were fully open, i.e. W_3/W_1 approached to 0.5, a valley appeared on abruptly. This is because the test facility was symmetric as two valves were full open and there was no asymmetric exit influence. Thus the flow configuration was relatively stable. While W_3/W_1 increased from 0.63 to 0.83, the flow pattern in branch was only wave flow. The plug flow was disappeared. So the fluctuation of gas flow rate was decreased. While W_3/W_1 increased from 0.83 to 1, the flow pattern in branch was slug flow. Thus, the RMS amplitude of gas flow rate went up slightly.

Fig. 7(a) shows RMS of W_{G3} versus W_3/W_1 at inlet condition: water superficial velocity is kept constant at 0.09 m/s and gas superficial velocity are 0.94, 1.46, 1.89 m/s. While W_3/W_1 was below 0.23, there was no difference in three curves, but while W_3/W_1 exceeded 0.23, increasing superficial velocity led to enhance the fluctuation of gas flow rate at branch outlet. It should be noticed that the ranges of gas and liquid superficial velocity were limited to churn flow in inlet tube. Fig. 7(b) shows RMS of W_{G3} versus W_3/W_1 at inlet condition: gas superficial velocity is kept constant at 0.94 m/s and water superficial velocity is 0.05, 0.09, 0.14 m/s, respectively. While W_3/W_1 was below 0.35,

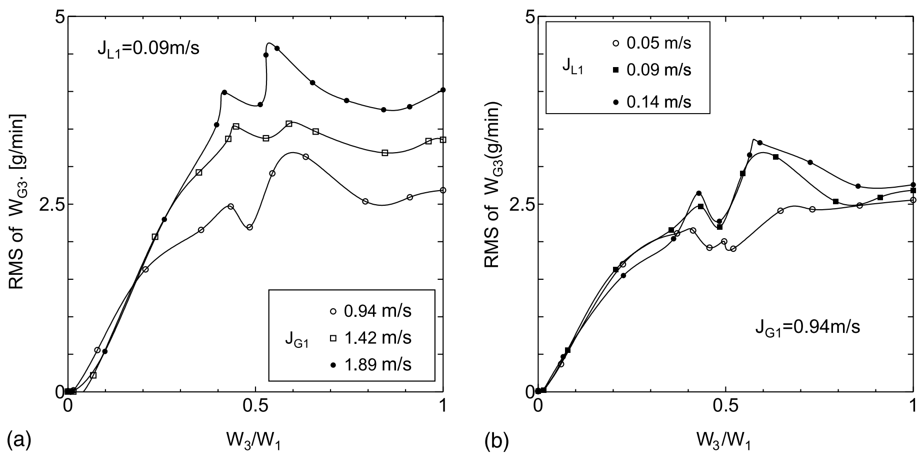

Fig. 7. RMS of W_{G3} versus W_3/W_1—(a) inlet condition: water superficial velocity is kept constant at 0.09 m/s and gas superficial velocity are 0.94, 1.46, 1.89 m/s; (b) inlet condition: gas superficial velocity is kept constant at 0.94 m/s and water superficial velocity are 0.05, 0.09, 0.14 m/s.

there was little difference in the three curves. Increasing water superficial velocity caused the fluctuation more intensive after W_3/W_1 surpassed 0.35.

In a word, increasing either gas or liquid superficial velocity increased the mixture momentum in inlet tube. According to momentum conservation, the force impacting to the upper side of the T-junction increased dramatically. This force induced stronger fluctuation of the two-phase flow in the branch.

3.4. PSD analysis

The PSD is usually employed to extract the periodic feature of a signal. In this work, the PSD of the gas flow rate fluctuation at the branch outlet were computed by the fast Fourier transform (FFT) technique.

Fig. 8 shows the PSD of ΔP_{13} at extraction ratio $W_3/W_1 = 0.2$, 0.43, 0.63, 0.91. Inlet condition was as following: gas superficial velocity was 0.94 m/s and liquid superficial velocity was 0.09 m/s. Summarizing figure (a)–(d), the magnitude of PSD increased as a whole with W_3/W_1 increasing. Dominant frequency of (a)–(c) decreased with W_3/W_1 increasing even though there was a slight discrepancy in (d), and the strong peaks of PSD became more and more with W_3/W_1 increasing. All of the PSD distributions showed a broad band in the low-to-moderate-frequency regimes. At the high frequency, the power spectra showed a clear power-law fall off. This phenomenon

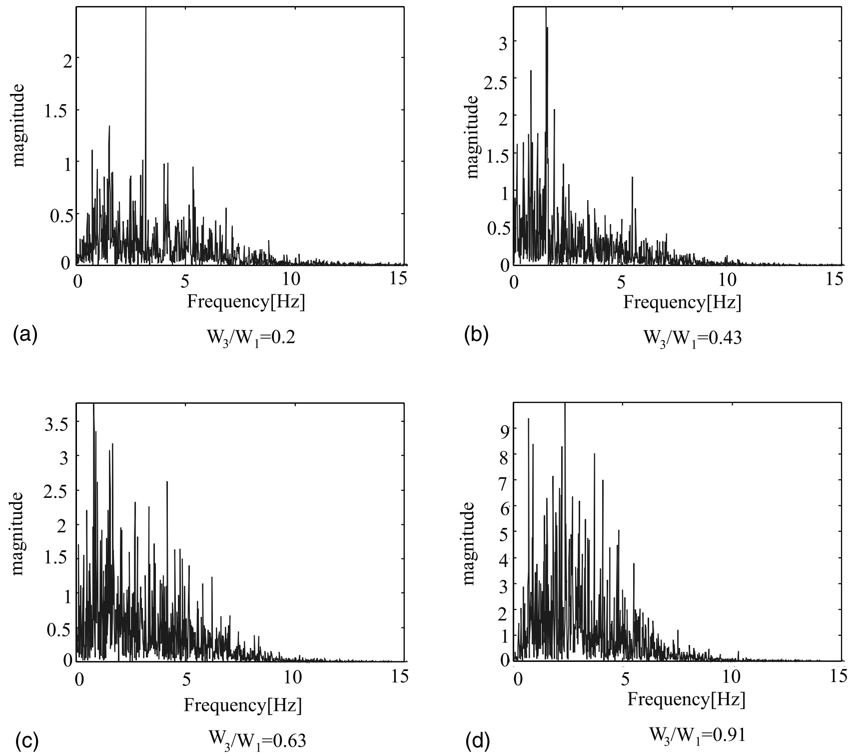

Fig. 8. Typical PSD distribution of ΔP_{13}.

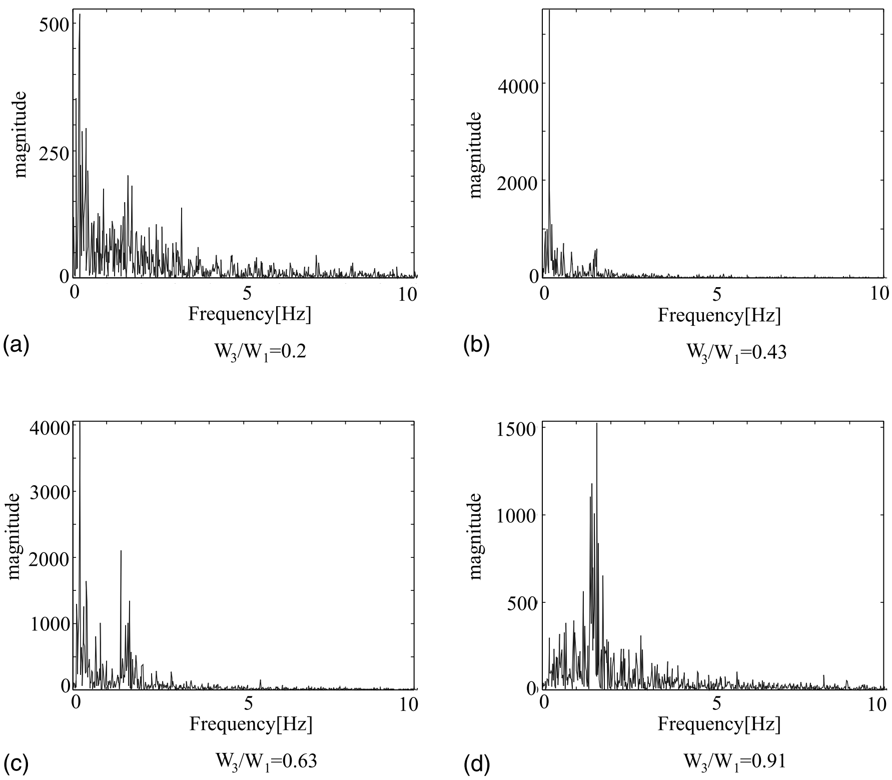

Fig. 9. Typical PSD distribution of gas flow rate at branch outlet.

indicates the behavior of two-phase flow through a T-junction is a high-dimensional chaos rather than a stochastic process (Cai, 1996).

Fig. 9 shows PSD of gas flow rate at $W_3/W_1 = 0.2$, 0.43, 0.63, 0.91. Inlet condition was as following: gas superficial velocity was 0.94 m/s and liquid superficial velocity was 0.09 m/s. The PSD of gas flow rate was concentrated on low-moderate-frequency regime and fall off at range of high frequency just as the same with ΔP_{13}. It means that two-phase flow in horizontal branch is chaotic, too. Dominant frequency kept constant at about 0.18 Hz during $W_3/W_1 = 0.2$–0.7, which means an obvious periodic fluctuation appeared within range 0.2–0.7. However, when extraction ratio W_3/W_1 exceeded 0.7, dominant frequency increased to approximately 1.6 Hz. On the other hand, the band of the frequency became very narrow while W_3/W_1 approached to 0.5. It means that the more symmetric the flow configuration, the more monotonous of the fluctuation in horizontal branch is and the larger the power becomes. Contrarily, while W_3/W_1 is far from 0.5, the power becomes smaller and the band of frequency becomes broad.

4. Conclusions

Several experiments were carried out to investigate the fluctuation characteristics of two-phase flow splitting at a T-junction. A statistical analysis RMS was applied to temporal differential pressure signals and gas flow rate signals. PSD was also employed to reveal their peculiar feature in frequency domain. The effect of the extraction flow ratio and the gas and liquid superficial velocity upstream on fluctuation characteristics of gas-liquid two-phase flow splitting at the T-junction was presented, respectively. The main conclusions can be summarized as follows:

(1) Pressure drop ΔP_{13} and gas flow rate at branch outlet is extremely time dependent.
(2) Fluctuation of ΔP_{13} increases while time-averaged value of ΔP_{13} increasing.
(3) Fluctuation of ΔP_{13} increases monotonously with extraction flow ratio increasing.
(4) Fluctuation of gas flow rate increases with increasing extraction flow ratio W_3/W_1 relative sharply to a maximum then fall off slowly. While the extraction ratio is larger than 80%, the fluctuation returned to increase slightly.
(5) Increasing either gas superficial velocity or liquid superficial velocity lead to more intensity fluctuation of both ΔP_{13} and W_{G3}.
(6) In frequent domain, dominant frequency of ΔP_{13} became lower while extraction ratio W_3/W_1 became larger. But dominant frequency of W_{G3} approximately kept constant during $W_3/W_1 =$ 0.2–0.7, and increased while W_3/W_1 exceeded 0.7.
(7) In the horizontal branch, the more symmetric the flow configuration, the more monotonous the fluctuation is and the larger the power is.
(8) The characteristics of power spectra on both ΔP_{13} and W_{G3} reveals that the behavior of two-phase flow splitting through a T-junction is a high-dimensional chaos rather than a stochastic process.

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