Interfacial wave patterns and their transitions in gas-liquid two-phase flow through horizontal ducts*

Li Guang-Jun, Guo Lie-Jin and Chen Xue-Jun
(National Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049)

Abstract The interfacial wave patterns and their transition characteristics in gas-liquid two-phase flow through rectangular and circular horizontal conduits are investigated. The interfacial waves were traced and recorded by using conductance probes. With the experimental observation and the analysis, some kinds of different interfacial waves were distinguished and defined, and then the interfacial wave patterns were given, which were compared with previous results. The interfacial wave transition mechanism between each interfacial wave pattern was discussed and a set of transition equations were presented to predict the interfacial wave pattern transitions. The predictive results are in good agreement with the experimental data.

Keywords Gas-liquid two-phase flow, Horizontal channels, Interfacial wave, Wave patterns

1 Introduction

A stratified two-phase flow pattern, which is characterized by the liquid moving along the bottom of the flow channel and the gas above it, exists for low gas and liquid flow rates in horizontal or inclined flow channels. When the gas velocity is sufficiently low, there is no wave on the gas-liquid interface, a smooth stratified flow occurs.[1~2] However, as the gas velocity is increased within the regime of the stratified flow, waves appear on the gas-liquid interface, which was defined as wavy stratified flow.[2]

For these stratified wavy flow patterns, the structure and dynamics of the interface greatly influence the rates of the mass, momentum and heat transfer as well as the stability of the system[3~5]. Therefore, a better knowledge of the interfacial wave formation, the wave patterns, their transition characteristics and the interfacial wave properties is essential to the eventual understanding of interfacial transfer mechanisms and two-phase flow pattern transitions in many engineering applications.

For the purpose of providing the basic knowledge about the interfacial waves and their transition characteristics, an experimental investigation on the occurrence of the interfacial waves and their transitions in horizontal gas-liquid two-phase flows through rectangular and circular flow channels was conducted. The interfacial waves were traced and recorded by using conductance technique. Then the interfacial wave patterns were given. The transitions between every different interfacial wave pattern were examined and the predictive methods were proposed.

2 Experimental procedure and techniques

2.1 Flow system

This experiment was carried out on an air-water two-phase flow loop as shown in Fig.1. Air and water were used as working fluids.

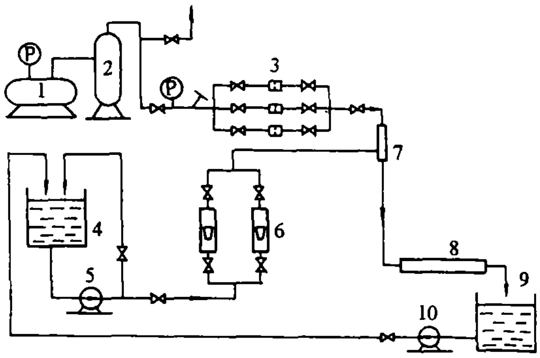

Fig.1 Schematic diagram of test loop
1 Air compressor, 2 Air tank, 3 Gas orifices, 4 Water tank, 5 Water pump, 6 Water orifices, 7 Mixture, 8 Test section, 9 Water tank, 10 Water pump.
P Pressure tap, T Thermocouple

The flow rates of water and air were measured with two Model LB ratemeters and three ori-

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fices, respectively. The test equipment includes two different geometrical cross-section test sections, which are all made of plexiglass materials so that the visualization of the interfacial waves is possible. One is a circular tube test section with a diameter of 50 mm and length of 6680 mm. The other is a test section with rectangular cross section, which is made of plexiglass plate with wall thickness of 12 mm, whose cross-section is 25×150 mm. The test section is about 6690 mm in length (see Fig.2). The temperature and pressure of the working fluids in the test sections are measured at both inlet and outlet of the test sections.

2.2 Experimental technique

The two-parallel wire conductance probe technique was used to measure the basic characteristics of interfacial waves. Fig.3 gives schematic diagrams of the probes. In this experiment three similar probes were used. The distance between the first probe and the second one is 10.0 cm in circular pipe and 30 cm in rectangular channel and the third probe is located at 10 mm and 9.7 mm far from the second one, respectively. Each of them consists of two parallel platinum wires of 0.1 mm in diameter and 1.5 mm apart. The sensors were aligned perpendicular to the direction of flow.

2.3 Data collection

In order to avoid the effects of ionic fluid on the measurement, the input signals to the probes were selected as 100 kHz sine signals.[6] The analog output signals from the probes were fed to an A/D converter (ADC 35) connected to an IBM microcomputer. In this investigation, a XR-5000 Cassette Tape Recorder was also used to record the film thickness fluctuations simultaneously.

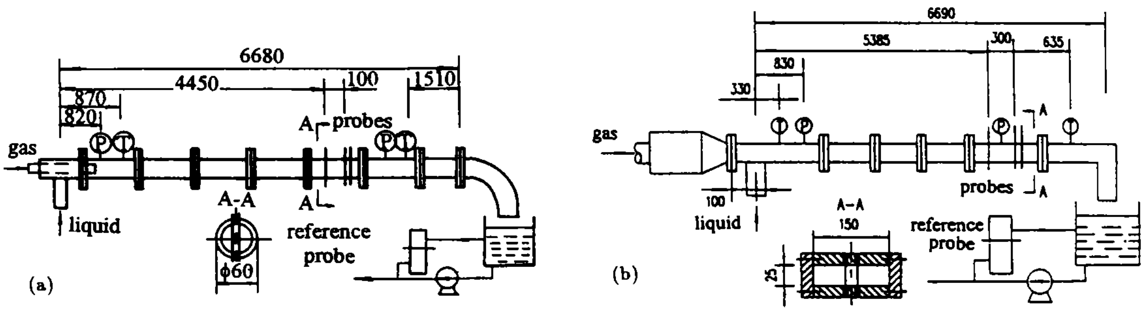

Fig.2 Schematic diagrams of test section
(a) Circular tube (b) Rectangular channel

Data were taken over a time period of 16s for ADC 35 convertor, a sampling frequency of 250 Hz was selected after trial runs. For tape recorder, the tape speed was chosen as 9.5 cm/s, which corresponds to the frequency domain of 0-5 kHz, and the sampling time of 60 s was used.

In this experiment the conductivity of liquid was measured and monitored by a reference probe located at the downstream liquid line in order to minimize the measurement errors.[7]

2.4 Experimental conditions

The experiment was carried out under quasi-steady, fully developed flow conditions. By varying the air and watêr flow rates, a wide range of stratified wavy flow pattern regions was covered. The values of liquid superficial velocity j_l ranged from 0.0141 m/s to 0.17 m/s and the air flow range was from 0 to 22.7 m/s in horizontal circular tube. The values of j_l ranged from 0.0118 m/s to 0.12 m/s and the air flow range was from 0 to 14.6 m/s in horizontal rectangular channel. The pressure of working fluids was about 0.1 to 0.12 MPa and the temperature ranged from 20 to 25°C.

3 Experimental results and discussions

3.1 Classification and description of the interfacial waves

A typical example of liquid film thickness fluctuation recorded by the probe located at a distance of 4450mm downstream from the water inlet in circular flow is shown in Fig.4. For a fixed water flow rate, with an increase in j_g, waves with small amplitude appeared and the surface of the liquid film was characterized by the regular two-dimensional disturbance, which were defined as two-dimensional waves (2D). Further increasing j_g would lead to irregular 2D waves and the interfacial structure changed gradually into irregular large amplitude waves (LA). The profile of the large amplitude waves exhibited a fairly steep front face and a relatively longer rear face.[8,9]

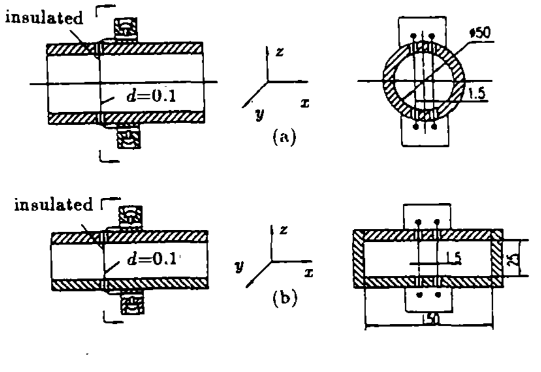

Fig.3 Structure of the conductance probes in circular pipe(a) and in rectangular channel (b)

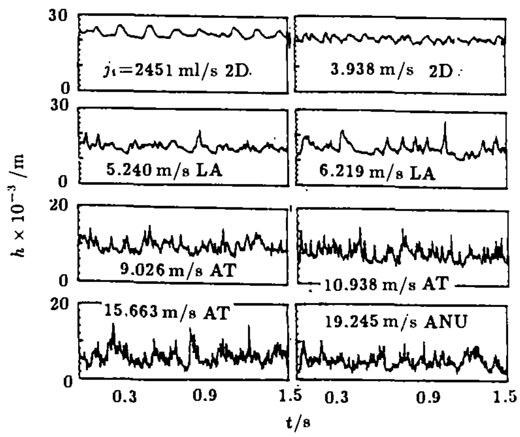

Fig.4 Liquid film fluctuations with time in horizontal circular pipe flow(j_l=0.0736 m/s)

Continuously increasing j_g up to a certain value, liquid droplets began to hit the top wall of the pipe, such liquid droplets or filaments would be separated from the liquid phase and deposited on the pipe wall. A new flow pattern of atomization(AT) would then be resulted in. When the gas velocity exceeded such an extent that a stable liquid film began to flow along the upper wall of the test section, annular(ANU) flow occurred.

With increase in liquid velocity, similar phenomena were observed, and the transitions from 2D to LA, from LA to AT and from AT to ANU occurred at lower gas velocity. When j_l was increased beyond 0.12m/s, the stratified flow pattern was replaced by an intermittent flow pattern(SLUG).

The film thickness fluctuations recorded by the probe in rectangular channel are similar to the results above, 2D, LA, AT and SLUG wave or flow patterns were distinguished and defined.

3.2 Interfacial wave pattern and comparison with previous experimental results

In present experiment, according to our observations, three kinds of the interfacial wave patterns were distinguished and defined as 2D, LA, AT in horizontal gas-liquid two-phase separated flow through circular and rectangular conduits, and also the annular and slug flow patterns were distinguished. Fig.5 shows the results for the wave and flow pattern transition of air/water two-phase flow in horizontal circular and rectangular flow channels in j_g -j_l plane and also compared with previous results[3,10] of air-water flow in horizontal tubes with 25.2 mm id and 50.3 mm id, respectively. From Fig.5 it is found that the transitions from each stratified wave pattern agree approximately well with previous results, which verifies the reliabilities of present experimental system and measurement method.

3.3 Nomenclature

- A area of channel cross-section, m^2;
- A_l' $\mathrm{d}A_l/\mathrm{d}h$;
- D diameter or hydraulic-diameter, m;
- g gravity acceleration, m/s^2;
- h liquid film thickness, m;
- N viscosity number;
- α void fraction;
- ρ phase density, kg/m^3;
- μ dynamic viscousity, Pa·s;
- ν kinetic viscousity, m^2/s;
- σ surface tension, N/m.

4 Theoretical investigation on interfacial wave transitions

4.1 Smooth stratified flow to two-dimensional wave

Two-dimensional waves are caused by the gas flow under the conditions where the velocity of the gas is enough high to form waves but slower than that needed for the rapid wave growth which causes transitions to intermittent or annular flow.

The phenomenon of wave generation is quite complicated and not completely understood. It is generally accepted that waves will be initiated when pressure and shear stress working on a wave can overcome the viscous dissipation in the waves.[2,11]

In this paper we use the ideas introduced by Jeffrey who suggested the following condition for wave generation[12]:

$$(u_g - c)^2 c > \frac{4 v_l g(\rho_l - \rho_g)}{s\rho_g} \tag{1}$$

where s is a sheltering coefficient which Jeffrey suggested that it should take a value of about 0.3, but Benjamin[13] indicated much smaller values for this coefficient ranging from 0.01-0.03 based on theory as well as on the experimental results for flow. In this work the value 0.06 of s is used.[3]

c is the propagation velocity of the waves. For most conditions where transition can be expected to take place, $u_g \gg c$. Theories concerning these waves suggested that the ratio of the wave velocity to the mean of the film velocity, c/u_l, decreases with increasing Reynolds number of the liquid, and the data of Fulford and Li confirmed this point.[7,14] The ratio approached 1.0 to 1.5 at the high Reynolds number. For simplicity, and because that a precise location of this transition boundary is not important, the relation $u_l = c$ is used.

These approximations substituted into Eq.(1) give the criterion for this transition:

$$j_g \geq 2\alpha \left(\frac{(1-\alpha) v_l (\rho_l - \rho_g) g}{s \rho_g j_l} \right)^{0.5} \tag{2}$$

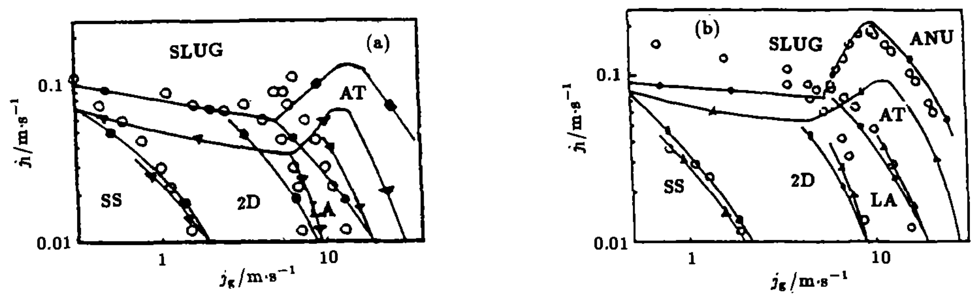

Fig.5 Interfacial wave pattern map and a comparison with some previous studies
○ Present data ▲ Shi et al[10] ● Andritsos et al[3] (a) Rectangular channel (b) Circular pipe

4.2 Two-dimensional wave to LA

The interfacial stability analysis of stratified flow is applied to the prediction of transition from stratified flow.[7] Solutions that are unstable by the VKH(Viscous Kelvin-Helmholtz) analysis and stable by the IKH (Inviscid Kelvin-Helmholtz) analysis are solutions with a low amplification factor. It was suggested that this instability results in large amplitude wave.[7] The neutral stability conditions obtained by VKH analysis were used to predict the transition from the two-dimensional wave to large amplitude wave. Refer to Li for details.[7]

$$\left(\rho_l \frac{A_l'}{A_l} + \rho_g \frac{A_l'}{A_g}\right) c_{vn}^2 - 2\left(\rho_l \frac{A_l'}{A_l}\overline{u_l} - \rho_l \frac{A_l'}{A_l}\overline{u_g}\right) c_{vn} + \rho_l \frac{A_l'}{A_l}\overline{u_l}^2 + \rho_g \frac{A_l'}{A_g}\overline{u_g}^2 - (\rho_l - \rho_g) g = 0 \tag{3}$$

where c_{vn} is the wave speed of viscous neutral stability wave obtained from VKH stability analysis.[7]

4.3 Large amplitude wave to atomization

Several different atomization detection methods and inception criteria have been used.

In this experiment visual observation is used to identify the occurrence of the atomization. The gas velocity, at which the liquid droplets were first torn from the large amplitude wave and hit on the top wall of the flow channels, was defined as the atomization gas velocity, and atomization occurred. It is known that the occurrence of atomization is related to the occurrence and development of the large amplitude waves.[9,15] The following criterion gas velocity predicting the onset of the atomization presented by Kutateladze was used in this paper[16]:

$$u_g = 36\frac{\sigma}{\mu_l}\sqrt{\frac{\rho_l}{\rho_g}}N Re_l^{-1/3} \tag{4}$$

where the viscosity number N is defined as:

$$N = \mu_l/\left(\rho_l\sigma\sqrt{\sigma/g(\rho_l-\rho_g)}\right)^{0.5} \tag{4a}$$

and the Reynolds number by

$$Re_l = \rho_l j_l D/\mu_l \tag{4b}$$

4.4 Occurrence of annular flow and slug flow

The interfacial stability analysis of stratified flow is applied to the prediction of transition from stratified flow[7]. Solutions that are unstable by the IKH analysis are solutions for which the Bernoulli amplification overcomes the stabilizing effect of gravity at the steady-state condition. These solutions are characterized by a very high amplification rate, resulting in the transition to slug flow, for high liquid holdup(h/D >0.5), and to annular flow (h/D <0.5). It was suggested that this instability results in large amplitude wave and only for high liquid level(h/D >0.5), the waves will block the pipe, causing transition to slug flow. In this paper the results of the IKH analysis were used to predict the transition from the stratified flow to annular flow, accompanying with the condition of h/D <0.5, i.e.

$$\left(\rho_l\frac{A_l'}{A_l}+\rho_g\frac{A_l'}{A_g}\right)c_{in}^2-2\left(\rho_l\frac{A_l'}{A_l}\overline{u_l}-\rho_l\frac{A_l'}{A_l}\overline{u_g}\right)c_{in}+\rho_l\frac{A_l'}{A_l}\overline{u_l}^2+\rho_g\frac{A_l'}{A_g}\overline{u_g}^2-(\rho_l-\rho_g)g=0 \tag{5}$$

where c_{in} is the velocity of the inviscid neutral stability wave obtained for IKH stability analysis, which is defined as follows.

$$c_{in}=\frac{\rho_l\overline{u_l}A_g+\rho_g\overline{u}_gA_l}{\rho_lA_g+\rho_gA_l} \tag{5a}$$

The results of the VKH analysis were used to predict the transition from the stratified flow to slug flow, accompanying with the condition of h/D >0.5, i.e.

$$\left(\rho_l\frac{A_l'}{A_l}+\rho_g\frac{A_l'}{A_g}\right)c_{in}^2-2\left(\rho_l\frac{A_l'}{A_l}\overline{u_l}-\rho_l\frac{A_l'}{A_l}\overline{u_g}\right)c_{in}+\rho_l\frac{A_l'}{A_l}\overline{u_l}^2+\rho_g\frac{A_l'}{A_g}\overline{u_g}^2-(\rho_l-\rho_g)g=0 \tag{6}$$

4.5 Comparison with experimental data

The following viewpoints can be found from Fig.6.

4.5.1 The predictive gas velocities by Eq.(2) is little higher than the experimental data, which is more apparent under the high liquid flow rate region. Because the liquid flow is inevitably affected by the vibration of the test section and the disturbance of the inlet of the gas and liquid, so the waves appear at the relatively lower gas velocity compared with the predictive velocity.

4.5.2 It is proper to predict the transition from two-dimensional wave to large amplitude wave by using the neutral stability condition deduced from the linear stability theory.

4.5.3 Eq.(4) is reasonably used to predict the occurrence of atomization. It is known that there are the following five basic types of atomization mechanisms[15]: (1) shearing off of the tops of roll waves by gas flow; (2) undercutting of the liquid film by gas flow, (3) bursting of gas bubbles, (4) impingement of large drops, (5) disintegration of liquid bulge by gas flow in counter-current situations. Under the present flow conditions, the first two mechanisms are important. The transitions from stratified flow to annular flow are well predicted by using the results of IKH analysis together with the condition of dimensionless liquid holdup h/D <0.5. And the transitions from stratified flow to slug flow are well predicted by using the results of VKH stability analysis together with the condition of $h/D > 0.5$.

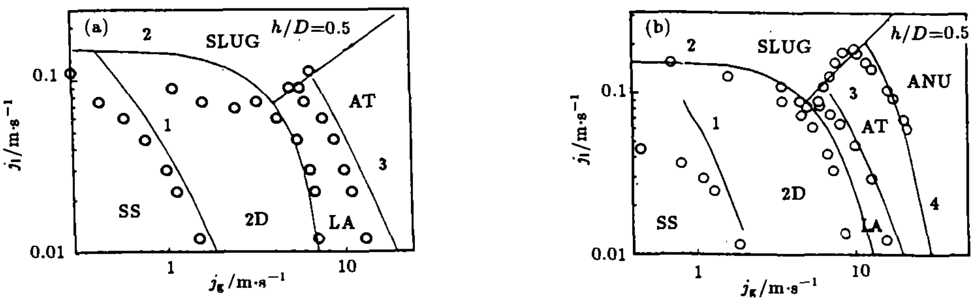

Fig.6 Comparison between the experimental data and theories
O Experimental data, 1— Eq.(2), 2—Eq.(3), 3—Eq.(4), 4— Eq.(5); (a)Rectangular channel (b) Circular pipe

5 Conclusion

In this paper the experimental and theoretical studies of the interfacial wave patterns and their transition characteristics were conducted. The following conclusion remarks can be made through the analysis and discussion.

5.1 Within the present experimental range, six different types of flow or interfacial wave patterns were distinguished, i.e., smooth stratified flow(SS), two-dimensional waves (2D), large amplitude waves(LA), atomization(AT), slug flow (SLUG) and annular flow (ANU). The interfacial wave patterns were given and compared with the previous results, which show a good agreement.

5.2 A set of the transition criteria was proposed in this paper to predict the appearances of the interfacial waves. The mechanism of interfacial waves occurring or wave pattern transition was discussed carefully. The predictive results were compared with the experimental data, they agreed quite well.

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