Analysis of Transition from Bubble Flow to Slug Flow in Rolling Vertical Tubes

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ABSTRACT

The mechanism of the transition from bubble flow to slug flow with co-current gas and liquid flowing through vertical tubes under rolling condition is studied. According to the experimental observation, it is found that the dispersed bubble flow pattern is periodically changed with the rolling motion. When the test section is deviated from the vertical condition, bubbles tend to flow at the upper part of the tube, and the bubble density reaches its maximum while test section rolling to the place with maximum incline angle. Besides, through the analysis of forces acted on moving bubbles under rolling condition, it is also found that the radial components of forces keeping dispersed bubbles at the upper part of the tube reach their maximums at maximum incline angle. Therefore, the transition from bubble flow to slug flow is most likely to take place at this moment. Based on the experimental data, a new correlation for predicting the transition from bubble flow to slug flow is proposed. The results show that the model predictions coincide well with the experimental data when gas superficial velocity is larger than 0.4 m/s.

1. INTRODUCTION

When co-current gas-liquid flow through tubes, a variety of flow patterns can exist depending on the gas and liquid flow rates, and the bubble flow is a typical flow pattern among these. At the present, most known studies on the transition of bubble to slug flow are devoted to stabilize horizontal, vertical or inclined tubes (Yan, 1995[1].) Based on previously published data, three major mechanistic models for estimating the transition from bubble flow to slug flow pattern are given as follows:

1. At lower liquid flow rate, the void fraction exceeds a critical value for $\alpha \geq 0.25$. (Taitel and Barnea, 1980[2])

2. At higher liquid flow rate, buoyant forces overcome the turbulent force, which cause bubble breakup, to agglomerate the gas phase into big bubbles. (Taitel and Dukler, 1976[3]; Barnea, 1986[4])

3. The transition to dispersed bubble flow based on a balance between the turbulent kinetic energy of the liquid phase and the surface free energy of dispersed bubble flow. (Chen et al, 1997[5]; Zhang et al, 2003[6])

Actually, many gas-liquid flow systems are usually operated under unstable conditions, such as the flow in marine reactors, marine boilers and aerial equipment etc. In the rolling tubes, an inertial force imparted by the rolling condition is imposed on the two-phase flow, and the movement of two-phase flow is different from that in stable conditions. So above three models may not give a good prediction under rolling condition, and it is necessary to carry out studies on transition from bubble flow to slug flow under rolling condition. The purpose of the present
study is to analyze the forces acting on bubbles with different rolling angles and periods, and finally a new appropriate transition correlation is given to predict the transition from bubble flow to slug flow under rolling condition.

2. EXPERIMENTAL APPARATUS AND METHOD

The experiments are conducted on rolling platform (see Fig. 1), and the test section is set on the middle axis of transverse orientation. During the experiments, rolling platform wiggly moves (along x axis) depending on automatic control system, and the horizontal position is the balance. The diagram of the experimental apparatus is shown in Fig.2. The major components include test section, air loop and water cycle loop. Water is pumped from water tank, then passes through turbine flow meters, and flows into the test section; Air from compressor is measured by float flow meters, it mixes with water at the entrance of test section, then the mixture flow through the test section.

![Fig.1 sketch map of rolling platform](image)

The Test section is a 15mm diameter, 4m long glass tube in which the flow pattern can be observed visually. The maximal rolling angles $\theta_m$ of the test section are $10^\circ, 20^\circ$, and rolling periods $T$ are 5s, 10s and 15s. During the experiments, void fraction is measured by two quick closing pneumatic operated valves. The inner pressure and pressure drop are measured respectively by pressure transducer and pressure difference transducer over a distance of 2000mm. All the dynamic data of the pressure drop, pressure and flow rate are collected at 0.1s using IMP acquisition system, and transferred to personal computer for real-time recording and monitoring, then are processed by a specific program.

Experiments are operated at atmosphere condition, the air and liquid volumetric fluxes range from $0.44 \times 10^{-4} \, m^3/s$ to $0.694 \times 10^{-2} \, m^3/s$ and from 0 to $0.28 \times 10^{-2} \, m^3/s$ respectively. Keeping air flow rate constant, and the liquid flow rate is gradually decreased to find the onset of transition from bubble to slug flow. Then increase air flow rate to a next constant value, and decrease liquid flow rate gradually to find next transition point. So after a series of experiments with the same method, the transition boundary can be determined.

3. ANALYSIS OF FORCES ON MOVING BUBBLE UNDER ROLLING CONDITION

3.1 flow patterns of dispersed bubble under rolling condition

Comparing with the stable condition, flow patterns of dispersed bubble change with the tube swaying to and fro, as is shown in Figure.3. After the tube deviate from the vertical position, bubbles no more uniformly exist in the tube; on the contrary, they tend to flow at the upper part of the tube. When the tube sways to the place of maximal inclination angle, the density of bubbles at the upper part of the tube gets its maximum. When the tube returns to the vertical position, bubbles disperse in the tube again.

![Fig.3 diagram of dispersed bubble flow patterns in one rolling period](image)
3.2 Rolling regularity

Depending on automatically control system, the rolling platform makes simple harmonic motion and the maximal rolling angle $\theta_m$, periods $T$ and the rolling regularity are as follows (Gao, 1999[7])

$$\theta = \theta_m \sin \left( \frac{2\pi}{T} t + 2k\pi \right)$$

$$\omega = \frac{\partial \theta}{\partial t} = \frac{2\pi}{T} \cos \left( \frac{2\pi}{T} t + 2k\pi \right)$$

$$\beta = \frac{\partial^2 \theta}{\partial^2 t} = -\theta_m \left( \frac{2\pi}{T} \right)^2 \sin \left( \frac{2\pi}{T} t + 2k\pi \right)$$

$$k = 0,1,2, \ldots$$

where $\theta, \omega, \beta$ denotes angle displacement, angle velocity and angle acceleration respectively.

3.3 Analysis of forces acting on moving bubble

In order to analyze the forces of moving bubbles, we assume

1. The bubbles are non-deformable spherical bubble;
2. Dispersed bubbles in high velocity liquid, and the moving trace of bubble can be assuming as straight, so the relative position of a bubble in test section is:

$$z_{\text{bubble}} = r \sin \phi = u_o t \quad (0 \leq \phi < 90^\circ)$$

where $u_o$ is the bubble relatively rise velocity. $u_o$ is given by Abdul-Majeed (1997)[8]

$$u_o = 1.4 \left( 1 - \frac{d_b}{D} \right) \left( \frac{g_{\text{eff}} \sigma (\rho_l - \rho_g)}{\rho_l^3} \right)^{1/2}$$

Bubble diameter $d_b$:

$$d_b = \left( \frac{3\sigma}{g (\rho_l - \rho_g)} \right)^{0.5}$$

3. The bubble diameter is much less than the diameter of test section, so the role of surface tension played can be neglected.

Based on these hypotheses, the forces acting on a bubble under rolling condition are shown in Fig. 4.

The total force is

$$\vec{F}_{\text{total}} = \vec{F}_b + \vec{F}_d + \vec{F}_n + \vec{F}_t + \vec{F}_k + \vec{F}_w$$

Fig.4 diagram of forces on moving bubble under rolling condition

4. Tangential inertial force $F_t$, normal inertial force $F_n$ and bulk inertial force $F_k$

To fix absolute coordinate on the earth, the rolling platform makes bulk motion relative to earth, so the inertial forces due to rolling motion affect the movement of bubble, and make bubble produces tangential, normal and bulk acceleration. Thus, based on rolling regularity, the tangential, normal and bulk inertial force are as follows.

Tangential inertial force

$$F_t = (\beta \times r) \times \frac{\pi d_b^3}{6} (\rho_l - \rho_g)$$

$$= -\theta_m \left( \frac{2\pi}{T} \right)^2 \sin \left( \frac{2\pi}{T} t \right) \cdot r \frac{\pi d_b^3}{6} (\rho_l - \rho_g)$$

Normal inertial force

$$F_n = \omega^2 r \frac{\pi d_b^3}{6} (\rho_l - \rho_g)$$

$$= \theta_m^2 \left( \frac{2\pi}{T} \right)^2 \cos^2 \left( \frac{2\pi}{T} t \right) \cdot r \frac{\pi d_b^3}{6} (\rho_l - \rho_g)$$

and $F_{nr}$ is the radial component of $F_n$ along the tube direction

$$F_{nr} = F_n \cos \phi$$

The direction of bulk inertial force $F_k$ is perpendicular to the direction of the bubble relatively rise velocity $u_o$, and the expression is
When rolling period $T = 10\, \text{s}$, and maximal rolling angle $\theta_m = 10^\circ$, curves indicating additional unit radial inertial force acting on a bubble are showed in Fig.5, Fig.6 and Fig.7, respectively. As $r \cos \phi = \text{const}$, $F_{nr}$ is not influenced by the position of bubble in test section. Thus given constant rolling period $T$ and maximal rolling angle $\theta_m$, $F_{nr}$ is the function of time $t$ as shown in Fig.5.

$F_{br}$ is different from $F_{nr}$, it is relevant to the position of bubble and time $t$, and the amplitude of $F_{br}$ increases with the increasing of $Z_{\text{bubble}}$, i.e. the process of bubble rising is also that of the increasing of $F_{br}$ amplitude (See Fig. 6). $F_{br}$ is the function of gas relative velocity $u_o$ and $t$, so if $u_o$ changes $F_{br}$ is different also. In Fig.7, the direction of arrow shows the direction of increasing of $u_o$.

$F_h$ can be shown as

$$F_h = \frac{1}{6} \pi d_b^3 \rho_l \frac{\rho_l - \rho_g}{T} u_o$$

When rolling period $T = 10\, \text{s}$, and maximal rolling angle $\theta_m = 10^\circ$, the curve of the unit radial component of $F_{br}$ acting on bubble is drawn in Fig. 8, and $F_{br}$ arrives at its maximum at $t = \frac{kT}{4}$.

As $F_d$ parallels to the direction of gas relative velocity $u_o$, it just prevents bubble from rising along the tube, and doesn’t influence the radial moving of bubble, so that $F_d$ can be ignored here.

$c. \text{Turbulent force } F_{rw}$

At higher liquid flow rates, the turbulent fluctuations associated with the flow can cause large bubbles breakup, so the turbulent force acting on the bubble is estimated by Levich (1962)[9]
\[ F_w = \frac{1}{2} \rho \overline{v'}^2 \frac{m d_b^2}{4} \]  

where \( \overline{v'} \) is the radial velocity fluctuation, which can be estimated using the friction velocity \( u_* \)

\[ (\overline{v'})^2 = u_* \left( \frac{f_i}{2} \right)^{\frac{1}{2}} \]

where \( u_i \) is the liquid flow rate; \( f_i \) is the liquid phase friction factor under rolling condition.

Substituting equation (16) into equation (15), the unit turbulent force can be given

\[ F_w = \frac{3 u_i^2 \rho \rho g f_i}{8 d_b \rho g} \]  

(17)

4 TRANSITION ANALYSIS OF BUBBLE TO SLUG FLOW UNDER ROLLING CONDITION

As described in the previous section, the additional radial components of tangential inertial force, normal inertial force and buoyancy force tend to keep the dispersed bubbles at the upper part of the tube and enhance the transition to intermittent flow. On the other hand, the turbulent force and bulk force tend to disperse the bubble. Thus, when bubble flow stably exists in the rolling condition, bubbles must be satisfied with the following expression

\[ F_{nr} + F_{tr} + F_{br} \geq F_{k} + F_{rw} \]  

(18)

When the inequality of equation (20) removed, the stable bubble flow is critical. Based on the analysis of bubble movement in the section 2 this paper, we know that every component of forces is the periodic function, when \( t = \frac{k T}{4} \) \( (k = 0.1,...) \), \( F_{nr} \) and \( F_{tr} \) reach their maximums, but bulk force \( F_{k} \) is in minimum. At this moment, the dispersed bubbles are easier to coalescence. Once the liquid flow rate decreases at \( t = \frac{k T}{4} \) \( (k = 0.1,...) \), the critical stable condition of bubble flow will be broken, and the transition of bubble flow to slug flow will be brought. So the transition criterion under rolling condition can be expressed

\[ t = \frac{k T}{4} \]

\( (k = 0,1,2,...) \)  

(19)

\[ F_{nr} + F_{tr} + F_{br} = F_k + F_{rw} \]

Substituting equation (9), (11), (12), (14) and (17) into equation (19), the final transition criterion becomes

\[ \left( \rho_1 - \rho_g \right) g \cdot \sin \theta_m + 6 \rho \left( \frac{2 \pi}{T} \right) \left( \rho_1 - \rho_k \right) u_i t = \frac{9 u_i^2 \rho \lambda_t}{4 d_b} \]  

(20)

Equation (20) represents a criterion for the transition from bubble to slug flow under rolling condition.

\[ \begin{array}{c}
\text{Graph 1:} \quad T=10s, \quad \theta_m=10^\circ \\
\text{Graph 2:} \quad T=15s, \quad \theta_m=10^\circ \\
\text{Graph 3:} \quad T=5s, \quad \theta_m=10^\circ 
\end{array} \]
The experimental data and theoretical results are plotted on flow pattern transition maps using superficial gas and liquid velocities as coordinates. Fig. 9 presents the results for the three rolling periods, two rolling angles. From Fig. 9, it can be seen that the predictions coincide very well with the experimental data.

5. CONCLUSION

Based on the balance between forces keeping bubbles flow at the upper part of tubes and other forces dispersing bubbles at maximal rolling angle, a method for the prediction of the transition from dispersed bubble flow to slug flow under rolling motion has been presented. The prediction results have been compared with a range of experimental data with different rolling angle and rolling period, and the agreement has been good for the gas superficial velocity larger than 0.4 m/s.

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