

Dynamic Characteristics of the Slug Flow in Energy System

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ABSTRACT: The slug flow regime in two-phase flow, a transition between the bubbly flow regime and annular flow regime, is investigated experimentally to study its interrelation between the drift velocity and the length of the Taylor bubble. Due to the complicated shape and dynamics of the tail of the bubble and the tiny bubble generation due to the vortex shedding, the measured data of the bubble length has large scattering. By synchronizing the high speed image recording system with the impedance void meter, the drift velocity and the length of the Taylor bubble were measured accurately. The data gave us the results that the model of drift velocity of the bubble is agree well with the experimental data. However, the model for the estimation of the bubble length have large gap with the experimental data. The model of Mishima and Ishii agrees well relatively with the experimental data. A stability criterion is constructed by combining the drift velocity and the Taylor bubble length. It was found that there is a certain region where the Taylor bubble cannot exist due to the fact that buoyancy energy cannot be dissipated by the drag force effectively.

Keywords: slug flow, two-phase flow, rise velocity, Taylor bubble length

NOMENCLATURE

A flow area of a tube
 C_0 distribution parameter
 C_f a constant
 D hydraulic diameter
 f wall friction factor
 g gravity
 h distance from the nose of a slug bubble
 j superficial velocity of two-phase mixture
 m a constant
 v_{fsb} terminal film velocity in the slug-bubble section
 v_{gs} gas velocity in the slug bubble

α_{sb} void fraction corresponding to the terminal film velocity v_{fsb}
 $\Delta\rho$ absolute value of density difference
 ν_f kinematic viscosity of liquid
 ρ density

Subscripts

f liquid phase or friction
 g gas phase
 sb tail-end of the slug bubble
 SB slug bubble
 TB slug bubble

Greek symbols

α void fraction

1. INTRODUCTION

In the modern energy transfer system, two phase flow is widely used due to its superior capability of heat and mass transfer. Even for the oil transport in the pipe, two-phase

flow control is one of key issues to be considered in design and operation. Including nuclear power station, knowledge of two-phase flow is very crucial. Two-phase flow shows various flow regimes such as the discrete bubbly flow, slug flow, churn flow, and annular flow. However, the most abundant flow regimes are the bubbly flow and annular flow. It is generally accepted that the slug flow regime is the transition regime between the bubbly flow and slug flow.

However, for the pipe with the diameter less than 10 cm, the slug flow regime is one of dominant flow regime. Its periodic appearance of Taylor bubbles make the system parameter dynamic and sometimes the system response is poorer than the designed.

In spite of its importance, very few researches have been made. Existing models can be used for the analysis but generally the estimation is made in the way of regression of values of the bubbly flow and annular flow as RELAP5 mod3 in the nuclear power plant.

In the present paper, we investigate the dynamics of the slug flow regime by measuring the length and speed of the Taylor bubble. We employed high speed camera and impedance void meter to get the more accurate data. Also, we tried to evaluate existing models such as the drift model and the Taylor bubble length. We found some disagreement so that we introduce shaping factor for the better prediction.

2. MODELS

Length of Taylor bubble (Ishii, 1984)

The theoretical slug bubble length prediction is suggested by Ishii (1984). With an application of the Bernoulli equation, the local void fraction at the distance h from the nose is derived, thus

$$\alpha(h) = \frac{\sqrt{2gh\Delta\rho/\rho_f}}{\sqrt{2gh\Delta\rho/\rho_f + (C_0 - 1)j + 0.35\sqrt{\Delta\rho gD/\rho_f}}} \quad (1)$$

where, the following equation for the slug-bubble velocity is used.

$$v_{gs} = C_0 j + 0.35 \sqrt{\frac{\Delta\rho gD}{\rho_f}} \quad (2)$$

$$v_f = j - \sqrt{\Delta\rho gD/\rho_f} \quad (3)$$

The Taylor bubble length has been considered as a result of force balance between the gravity force on the liquid film and wall shear stress. Ishii suggested that because of the complete balance, there exists a small adverse pressure gradient and the liquid becomes unstable. The force balance on the liquid film around the slug bubble gives,

$$\frac{f}{2} \rho_f v_{fsb}^2 \pi D = \frac{2}{3} \Delta\rho g A (1 - \alpha_{sb}) \quad (4)$$

where, the wall friction factor f is assumed to be in the form

$$f = C_f \left[\frac{(1 - \alpha_{sb}) v_{sb} D}{v_f} \right]^{-m} \quad (5)$$

Substituting eq. (5) into eq. (4) and solving for v_{fsb} , he obtained;

$$v_{fsb} = (1 - \alpha_{sb})^{(1+m)/(2-m)} \times \left[3C_f \left(\frac{D}{v_f} \right)^{-m} \frac{\rho_f}{\Delta\rho gD} \right]^{1/(m-2)} \quad (6)$$

where, $m = 0.2$ and $C_f = 0.046$ for a turbulent flow.

Based on the condition that at the tail end of the slug bubble, the solution for the slug bubble length becomes

$$\sqrt{\frac{2\Delta\rho gL_b}{\rho_f}} = j + 0.75 \sqrt{\frac{\Delta\rho gD}{\rho_f}} \left(\frac{\Delta\rho gD^3}{\rho_f v_f^2} \right)^{1/18} \quad (7)$$

According to this equation, the slug bubble length depends on superficial velocity, tube diameter and flow properties.

This theory had been reported that it shows general trends, but it does not give well-matched prediction.

3. MEASUREMENT AND DATA ANALYSIS

In the present study, it is among the interest region not only stable and low velocity of slug bubble but also unstable slug flow with a high volumetric flux. To investigate the phenomena of slug flow precisely not only bubble rise velocity and length but also a shape change of slug bubble, its collision and acceleration, two measurement instrumentations are employed in the present research; high speed camera and impedance meter.

A high speed camera with a test frame by 36 cm in length and 5cm in width and a void-impedance was employed. Both instruments operate for same period of time by data acquisition system programmed to give a operating signal to a system. As shown in Figure. 1, HSC and impedance meter measured the slug flow with sampling frequencies of 60Hz and 180Hz, respectively. The measuring process remains for 20 seconds, and during this time, impedance signal is sensitively observed when the slug bubble is passing through the electrodes. The measuring frequencies and time duration are set to be changeable according to experimental conditions. After measuring for 20 seconds, the systems are ended at the same time, and the 1,200 images and 3,600 points of data are observed.

By comparing the signal and image one to one each other, its characteristics can be systematically analyzed to ensure a validity of a slug length extraction method. Once the reliable and accurate method of extracting slug information from the void impedance signals is developed, then it allows generating a number of dataset from existing two-phase flow signals.

Bubble rise velocity is calculated from the recorded images. The time interval between

frames is 0.0167 second as the HSC operates at 60Hz. A pixel displacement is counted and transformed to a real velocity using a ratio of pixel and metric distances.

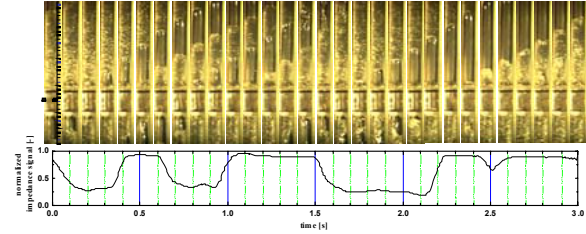


Figure 1: Rising slug bubbles and simultaneously measured impedance signal for 3 seconds

For an extraction of Taylor bubble lengths from the measured signal, we define a time interval of slug bubble passing through between electrodes as a slug bubble passing time, t_{SB} , and developed an algorithm which consists of five steps; filtering, differentiation, nose-and-tail pulse generation, nose (tn,i) detection and tail (tt,i) computation and slug bubble passing time $t_{SB,i}$ ($=tt,i - tn,i$) calculation. Then, a multiplication of the slug passing time and the bubble rising velocity from an image analysis, a slug bubble length is calculated as the eq.(8)

$$L_{TB} = v_{gs} \cdot t_{SB} \quad (8)$$

4. RESULTS AND DISCUSSIONS

4.1 Bubble rise velocity

Slug unit velocity, v_{gs} , is calculated from recorded images. Generally, the v_{gs} can be predicted by the drift flux model for slug flow regime (Zuber and Findlay, 1965; Ishii, 1977). eq. (2). Although velocity data is not enough, as Mi (2001), Mishima and Hibiki (1996) claimed, in the region that the mixture velocity, j , becomes more than 1m/s, it starts not to follow the theoretical velocity but the mixture velocity (See Figure. 2). According to Mi, it is because of physically

higher intensity turbulence that retards the Taylor bubble rising velocity when j is high. More experiments have been performed for higher j , but it was hard to distinguish the ambiguous bubble nose from the fluctuating flow.

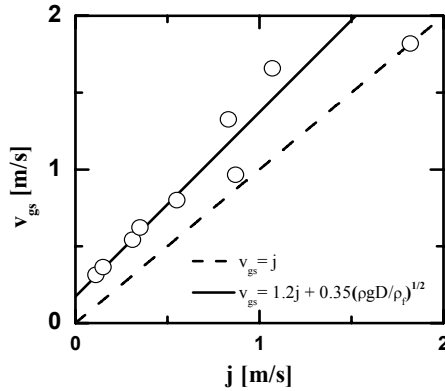


Figure 2: Experimental results of the slug unit velocity compared to those theoretical predictions

4.2 Length of Taylor bubble

In this section, the calculated slug lengths covering large area of 1 inch vertical upward slug flow regime, as a result of application of aforementioned, methods are presented and discussed. The observed slug lengths are shown in figures below presented of L_{TB}/D vs its probability. Because of the much of uncertainties and complexity of the nature, the slug lengths show various distributions.

For example, when the fluid superficial velocity is relatively low as 0.01m/s shown in Figure. 3, as gas superficial velocities increases, the slug length distribution is changed. At first, 100% of the slug bubble exists in the range of 0~15D, but the deviation gradually increases while the peak value decreases. When $j_g = 2.3\text{m/s}$ at the highest velocity in these experimental results, the peak value of the probability become the lowest, less than 10%, and a variety of slug length from 10D to 100D can be observed. These phenomena are occurred in the same way as j_f increases.

By comparing to the theoretical value, a considerable divergence between theory and the experimental results are found

especially according to the volumetric flux. When the volumetric flux is low, the theory predicts the minimum value of the experimental results. On the other side, when it is high, the theoretical value is somewhat between minimum and maximum value of the experimentally measured slug length. The model shows a general trend reasonably well, but it also has a point to be enhanced for predicting average slug length. The model shows a general trend reasonably well, but it also has a point to be enhanced for predicting

4.3 Stability analysis

Consider when if gravity force is lesser than the wall shear force, then the eq.(4) can be rewritten as. eq.(9). This is a state supposed to be stable,

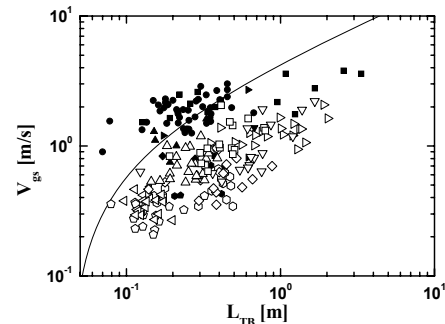
$$\frac{f}{2} \rho_f v_{fsb}^2 \pi D \geq \frac{2}{3} \Delta \rho g A (1 - \alpha_{sb}) \quad (9)$$

and in stability perspective, the slug data can be plotted in the form of L_{TB} versus v_{gs} which is a combination of eq.(2) and eq.(9). Thus,

$$\alpha(L_b) \geq \alpha_{sb} \quad (10)$$

$$v_{gs} \leq 1.2 \sqrt{\frac{2g\Delta\rho L_{TB}}{\rho_f}} + \sqrt{\frac{\Delta\rho g D}{\rho_f}} \left\{ 0.35 - (0.9) \cdot \left(\frac{\Delta\rho g D^3}{\rho_f v_f^2} \right)^{\frac{1}{18}} \right\} \quad (11)$$

It is plotted in Figure. 4. The $L_{TB} - v_{gs}$ plane can be divided into two regions in between with the criterion.



(a)

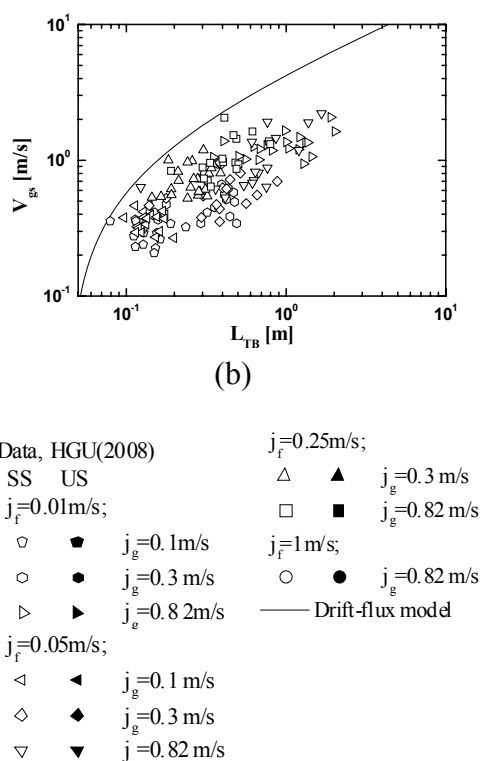


Figure 4.12: The length and velocity distribution of (a) stable slug(SS), (b) unstable slug(US) with various flow conditions, and the comparison to the drift flux model

The right side is the region where the wall shear force is stronger than gravity. The left side is vice versa. Therefore, the former region, which has a strong wall shear force, is stable. As Figure. 4 shows, when slug flow belongs to the unstable region or heading to it, bubble accelerations and collisions are frequently observed by experiment, and this phenomena are tend to occur as j increases. When j becomes higher, slug bubbles are tend to cross over the criterion from stable to unstable region. It was also experimentally observed that long slugs cut in its axial direction before it grow and have stability due to the strong effect of turbulence eddies and wakes.

5. CONCLUSIONS

The vertical slug flow regime has been studied using visualization method to

evaluate existing analytical models which has been used for the flow regime transition criteria in the inclined tube facility. High speed camera synchronized with the impedance meter to measure the void fraction provided accurate measure of the bubble length and rising velocity. The present results show that there is a small error in the model of the drift velocity but the length should be improved due to the large deviation between the present experimental data and previous model.

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REFERENCES

1. Fernandes, R.C., Semiat, R. and Duckler A.E., 1983, Hydrodynamic model for gas-liquid slug flow in vertical tubes, A.I.Ch.E J. 32, 981-989
2. Jones, N. Zuber, 1975, The interrelation between void fraction fluctuations and flow patterns in two-phase flow, International Journal of Multiphase Flow 2, 273-534
3. Lev Shemer, 2003, Hydrodynamic and statistical parameters of slug flow, International Journal of Heat and Fluid Flow, Volume 24, Issue 3, Pages 334-344
4. M.Ishii, 1977, One-dimensional drift-flux model and constitutive equations for relative motion between phases in various two-phase flow regimes, ANL Report ANL-77-47
5. Mishima, K., Ishii, M., 1983. Flow regime transition criteria for upward two-phase flow in vertical tubes. Int. J. Heat Mass Transf. 27, 723-737
6. M. Ishii, 1975, Thermo-fluid dynamic theory of two-phase flow, Eyrolles, Paris
7. Jones, N. Zuber, 1975, The interrelation between void fraction fluctuations and

- flow patterns in two-phase flow, *International Journal of Multiphase Flow* 2, 273-534
8. P. Griffith, G.B. Wallis, 1961, Two-phase slug flow, *Journal of Heat Transfer* 83, 307-320
 9. R. van Hout, L. Shemer, D. Barnea, 2003, Evolution of hydrodynamic and statistical parameters of gas-liquid slug flow along inclined pipes, *Chemical Engineering Science*, Volume 58, Issue 1, Pages 115-133
 10. R. van Hout, D. Barnea, L. Shemer, 2001, Evolution of statistical parameters of gas-liquid slug flow along vertical pipes, *International Journal of Multiphase Flow*, Volume 27, Issue 9, Pages 1579-1602
 11. R. Van Hout, L. Shemer, D. Barnea, 1992, Spatial distribution of void fraction within a liquid slug and some other related slug parameters, *International Journal of Multiphase Flow*, Volume 18, Issue 6, Pages 831-845
 12. Y. Mi, M. Ishii, L.H. Tsoukalas, 2001, Flow regime identification methodology with neural networks and two-phase flow models, *Nuclear Engineering and Design* 204, 87-100
 13. Y. Taitel, D. Barnea, A.E. Dukler, 1980, Modeling flow pattern transitions for steady upward gas-liquid flow in vertical tubes. *AIChE Journal* 26, 345-354
 14. Zuber, N., Findlay, J.A., 1965, Average volumetric concentration in two-phase flow Systems. *J. Heat Transf.* 87, 453-46

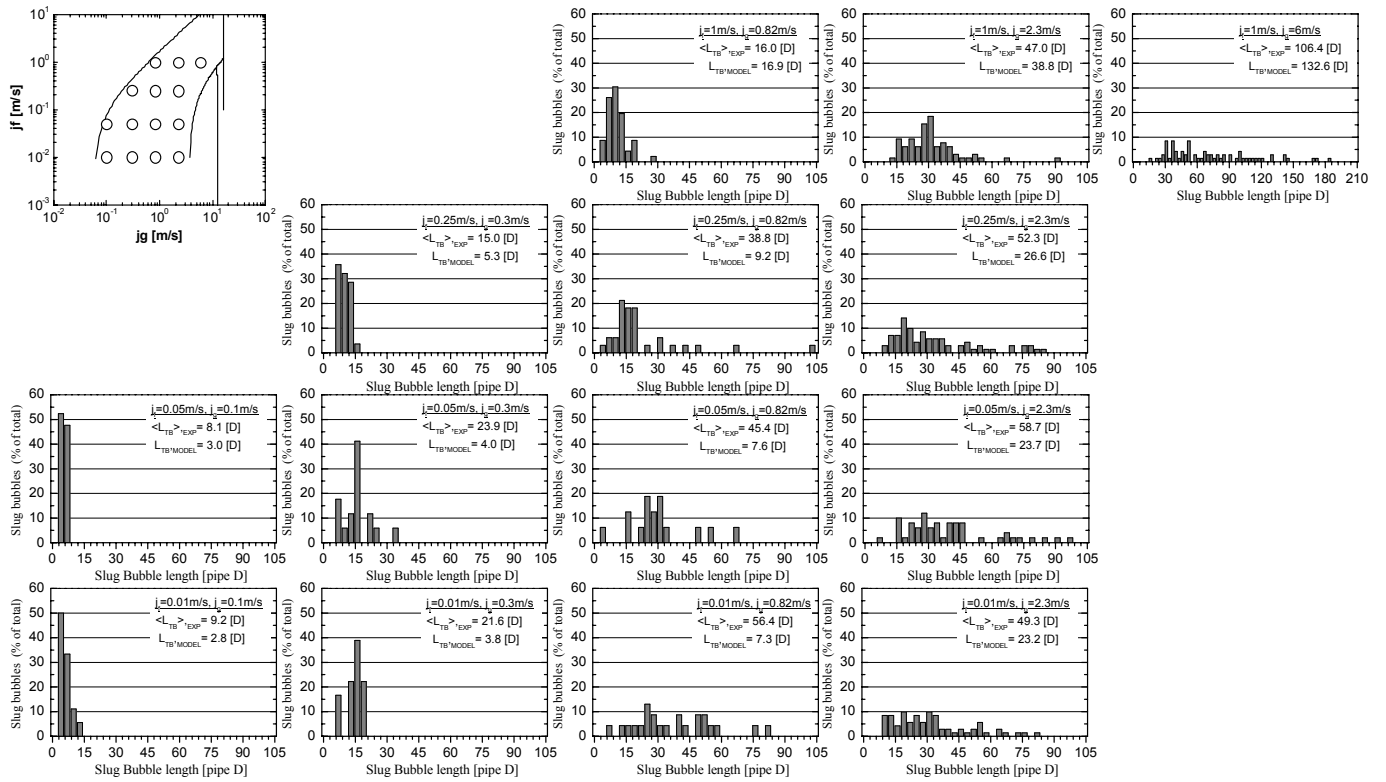


Figure. 3: Slug bubble distribution with various flow condition