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SLUG FREQUENCY AND LENGTH INCLINED LARGE DIAMETER MULTIPHASE PIPELINE

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ABSTRACT

Experimental investigations on slug frequency and slug length are carried out in 10-cm I.D., 18-m long pipe at inclinations of ±2° at atmosphere pressure with tap water and carbon dioxide as working fluids. The superficial liquid velocity ranged from 0.1 to 1.7 m/s with superficial gas velocity between 0.5 m/s to 15 m/s. New results for slug frequency and slug unit length are obtained. The effects of superficial liquid velocity, superficial gas velocity and inclination on slug frequency and slug unit length are considered.

From the experimental results, it is shown that slug frequency increases with increasing liquid flow rate for all test conditions. Interesting results are seen with increasing the gas flow rate. In upward flow, at lower liquid flow rate, slug frequency decreases with increasing gas flow rate at lower superficial gas velocity and then increases with an increase of gas flow rate. Slug frequency is almost independent of superficial gas velocity at moderate liquid flow rate. However, slug frequency increases with increasing gas velocity at high superficial liquid velocity. In downward flow, slug frequency is almost independent of superficial gas velocity at moderate liquid flow rate. However, at higher superficial liquid velocity, slug frequency decreases with increasing superficial gas velocity at lower superficial gas velocity and then increases with increasing gas velocity.

Slug unit length decreases with increasing liquid flow rate at same gas flow rate. However, at same liquid flow rate, slug unit length will increase with increasing gas flow rate. Inclination has significant effect on slug unit length. Increasing the inclination leads to a decrease of slug unit length.

A new model is used to predict the slug frequency; good agreement is achieved with experimental results.

1. INTRODUCTION

The flow of liquid and gas is being encountered more and more in the offshore production of oil and gas. Although there is a large number of experimental and theoretical results on gas-liquid flow, known results for gas-liquid multiphase flow in large diameter pipelines are small. In particular, the region of slug flow is of great interest in the offshore production of hydrocarbons and also in some other areas, such as in the power plant and chemical industry.

The first comprehensive experimental investigations on slug frequencies were performed by Hubbard [1], who investigated the flow of air and water in an I.D. 35.1mm horizontal pipe. He pointed out that the frequency of liquid slug increased with increasing the superficial water velocity. The measured slug frequencies have a minimum as a function of the volumetric flux of the gas phase. These results were confirmed by the experimental investigations of Gregory & Scott [2] and Taitel & Dukler [3]. Gregory and Scott [2] proposed a model for predicting the slug frequency based on their experimental results.

$$f_s = 0.0157\left[\frac{V_{sl}}{gd}\left(\frac{36m^2/s^2}{V_t}+V_t\right)\right]^{1.2} \qquad (1.1)$$

In equation (1.1), V_{sl} is superficial liquid velocity, V_t is translational velocity and d is the diameter of pipeline.

Tronconi [4] considered the slug frequency based on his experimental results. He assumed that the waves on a liquid surface would grow according to the Kelvin-Helmholtz instabilities, but only waves characterized by a critical growth rate cause the formation of a stable liquid slug. Based on the theory of Mishima & Ishii [5], Tronconi [4] obtained a correlation for calculating the slug frequency:

$$f_s = 0.305\,C_w^{-1}\frac{\rho_G V_G}{\rho_f h_G} \qquad (1.2)$$

In Equation (1.2), h_G is the height of the gas phase layer in the stratified flow, and V_G is the average gas velocity within the gas layer cross section of the pipe. ρ_G and ρ_f denote the densities of gas phase and liquid film. The proportionality factor C_w in equation (1) is equal to 2.

Hill and Wood [6] also created a commonly used slug frequency model based on their experimental results. Their model was based upon the equilibrium film height.

$$f_s = 0.275\frac{V_m}{d}10^{\left(2.68\cdot\frac{h}{d}\right)} \qquad (1.3)$$

In Equation (1.3), V_m is the velocity of mixture, d is diameter of pipeline and also h is film height.

Wilkens [7] investigated the slug frequencies with carbon dioxide and sea water in large diameter inclined pipelines. The aim of this investigation is to develop a model to predict the slug frequency for large diameter pipeline and also to determine the effects of gas and liquid velocities and pipeline inclination on slug frequency.

2. EXPERIMENTAL SETUP

Fig. 1 shows the experimental setup of the flow loops. The test section is a 10-cm I.D. pipe made of transparent glass. The volume of the tank is 1.44 m^3 which is filled with tap water. The fluid is pumped through a 7.62-cm I.D. PVC pipe and is metered using an orifice plate; Carbon dioxide gas from high-pressure storage tanks is introduced into the system and the gas velocity is measured using in-line flow meters. The multiphase mixture then flows through a 10-cm I.D. apparent pipe test section where all the measurements are made. The gas-liquid mixture reenters the tank at the top of through the pipeline. A de-entertainment plate is used to separate the gas and liquid. The gas is vented to the atmosphere and the liquid is recycled. When the system is inclined, measurements in both upward and downward flows can be made at the same time. A back pressure regulator is fitted on the top of the tank and is connected to the exhaust to control and maintain the required system pressure.

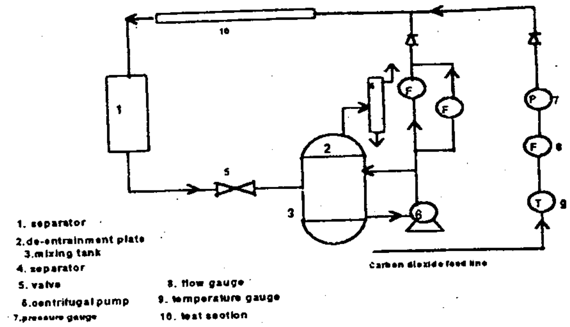

Fig. 1 Flow Loop

The flow patterns were determined with a special technique using differential pressure fluctuations. The measurements were made with 0 ~ 35 KPa OMEGA PX-750 heavy-duty differential pressure transducers. In this study, carbon dioxide was used for gas phase. Tap water was used for the liquid phase. The superficial gas velocity was varied from 0.5 ~ 15 m/s, while the superficial liquid velocity ranged from 0.1 ~ 1.7 m/s; The system temperature remained constant at 25 °C, and the system pressure was kept at atmosphere pressure. Two tape recorders were used to record all the flow phenomena, which were used to analyze the results later.

3. EXPERIMENTAL RESULTS

3.1 Results of Slug Frequency

Fig. 2 shows the results of slug frequency at different superficial liquid velocities at the same superficial gas velocity in upward flow. It is seen that slug frequency increases with increasing superficial liquid velocities for all conditions tested. The results of slug frequencies at different superficial liquid velocities at the same superficial gas velocity in downward flow are shown in Fig. 3. It is also seen that slug

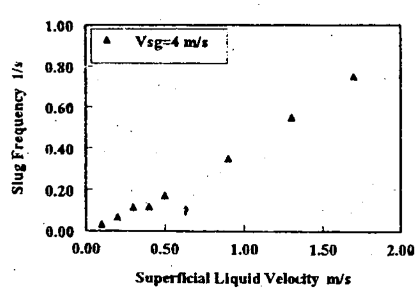

Fig. 2 Results of slug freqency along superficial liquid velocity at Vsg=4 m/s, +2 degree

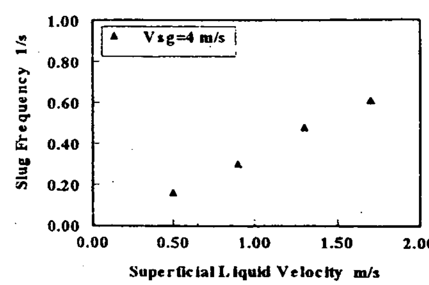

Fig. 3 Results of slug freqency along superficial liquid velocity at Vsg=4 m/s, -2 degree

frequency increases with increasing superficial liquid velocities.

Increasing superficial gas velocity generates very interesting results for slug frequency. At lower superficial liquid velocity, slug frequency decreases with increasing the superficial gas velocity at lower superficial gas velocity and then increases with increasing superficial gas velocity in upward flow (See Fig. 4). Fig.5 shows the distribution of slug frequency along superficial gas velocity at moderate and high superficial liquid velocities. From this picture, it is seen that slug frequency is almost independent of gas velocity at moderate liquid velocity of 0.9 m/s. However, slug frequency increases with increasing gas velocity at high superficial liquid velocity.

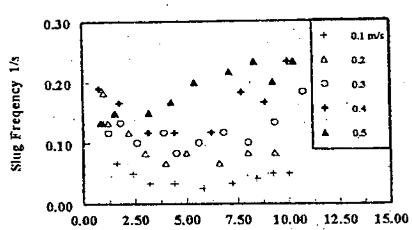

Fig. 4 Profile of slug freqency along superficial gas velocity at low superficial liquid velocities, +2 degree

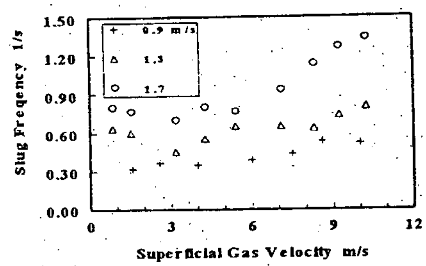

Fig. 5 Profile of slug freqency along superficial gas velocity at high superficial liquid velocities, +2 degree

Fig.6 shows the profile of slug frequency along superficial gas velocity at different superficial liquid velocities in downward flow. It is seen that slug frequency is almost independent of superficial gas velocity at moderate liquid flow rate. However, at higher superficial liquid velocity, slug frequency decreases with increasing superficial gas velocity at lower superficial gas velocity and then increases with increasing gas velocity.

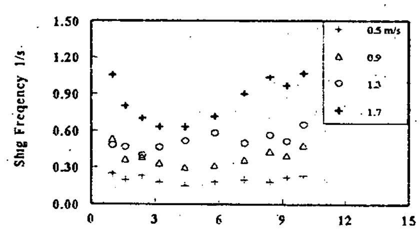

Fig. 6 Profile of slug freqency along superficial gas velocity at different superficial liquid velocities, -2 degree

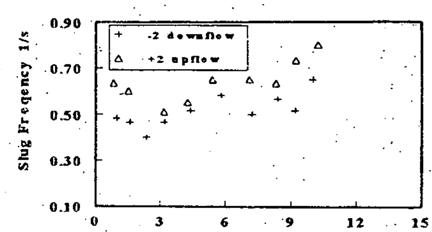

Fig. 7 Effect of inclination on slug freqency at superficial liquid velocity of 1.3 m/s

Fig. 7 shows the effects of inclination of test section on slug frequency. From this picture, it is seen that inclination of test section has significant effect on slug frequency. Slug frequency increases with increasing the inclination of test section.

3.2 Results of Slug Unit Length

In all cases tested in this paper, slug unit length was found to decrease with increasing superficial liquid velocity. Fig. 8 shows the distribution of slug unit length along superficial liquid velocity at superficial gas velocity of 5 m/s in +2 degree upflow. Fig. 9 shows the results of slug unit length along superficial liquid velocity at superficial gas velocity of 5 m/s in –2 degree downflow. Usually, the slug length remains relatively constant at about 15 to 20 times the pipe diameter. In a slug unit, mass is conserved from the input gas and liquid flow rates. If the superficial liquid velocity is increased at a constant superficial gas velocity, the ratio of liquid to gas in the slug unit must be increased. Although the film height in film region is increased with increasing the liquid flow rate, the ratio of liquid to gas is still

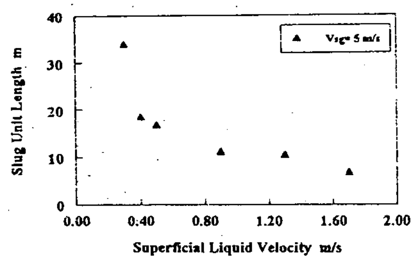

Fig. 8 Results of slug unit length along superficial liquid velocities at Vsg=5 m/s, +2 degree upflow

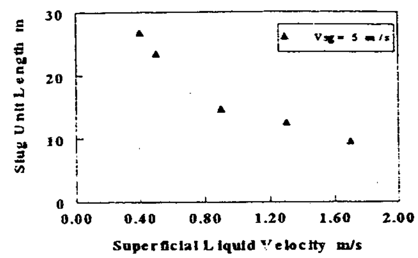

Fig. 9 Results of slug unit length along superficial liquid velocities at Vsg=5 m/s, -2 degree downflow

higher than that in the film region. Since the slug length remains relatively constant, a decrease of slug unit length corresponds to a higher ratio of liquid to gas.

Interesting results were obtained for slug unit length by increasing the superficial gas velocity at constant superficial liquid velocity. At lower superficial liquid velocity, the unit length increases greatly with increasing superficial gas velocity. Fig. 10 shows the results of slug unit length along superficial gas velocity at different superficial liquid velocities. At moderate superficial liquid velocity, the slug unit length increases slightly to a maximum with increasing superficial gas velocity. At higher superficial liquid velocity, the slug unit length increases slightly to a maximum and then decreases with increasing superficial gas velocity. These results are expected. The ratio of gas to liquid in the slug unit will be increased with increasing superficial gas velocity at constant superficial liquid velocity. Usually, higher ratio of gas to liquid leads to larger mixing zone for same slug unit length. So. increasing superficial gas velocity, the unit length will be increased. At higher gas and liquid velocities, the void fraction in the slug will be much greater. This is due to higher turbulence leads. To some extent, the mixing zone will be decreased, however the length of film region will be remained relatively constant. In this case, the length of slug unit will be decreased.

The inclination of pipeline has a slight effect on the slug unit length. Fig. 11 shows the effects of inclination on the slug length. Increasing the inclination causes the slug unit length to be decreased at the same superficial liquid and gas velocities. This is due to the fact that the slugs are shorter and more frequent in upward flow than that in downward flow at the same gas and liquid velocities. Based on the mass conservation in the slug unit, shorter slug leads to shorter film region.

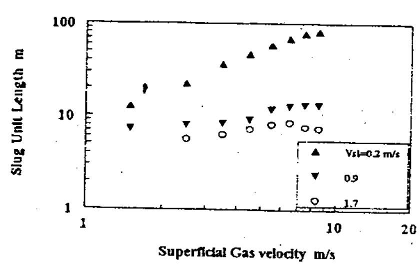

Fig. 10 Results of slug unit length along superficial gas velocity at different superfical liquid velocities, +2 degree upflow

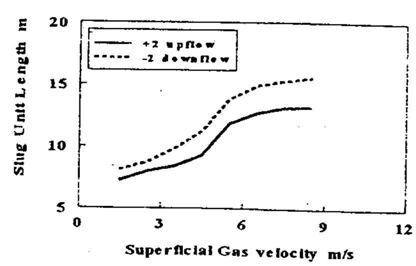

Fig. 11 Effect of inclination on slug unit length at Vsl=0.9 m/s and different superficial gas velocities

4. SLUG FREQUENCY MODELING

The Hill & Wood' model[6] includes the film height as a parameter. It is difficult to measure this accurately. It is also very hard to determine the shape of gas-liquid interface. Same problem can also be found in Tronconi's model[4]. Also, Tronconi's model [4] doesn't include the effect of pipe diameter on slug frequency. From the Gregory & Scott' model [2], it is seen that there is only one parameter V_t which is sensitive to the results. In this case, how to calculate the value of V_t for large diameter pipeline is the key to set up the slug frequency model. This model doesn't reflect the effect of inclination on slug frequency. In this paper, a new model, which reflects the effects of diameter and inclination on slug frequency, will be proposed based on the experimental results and Gregory & Scott' model.

A common way to consider the translational velocity is as a ratio with superficial mixture velocity. At low gas flow rate, Kouba & Jepson [8] and Jepson & Taylor [9] pointed out that the value of V_t / V_m was about two based on their experimental results in large diameter pipeline. At higher gas flow rate, this ratio drops to a steady value of around 1.2 to 1.3. Also Kouba and Jepson [8] specified V_t / V_m=1.25 for mixture velocities above 3 m/s. Jepson and Taylor [9] showed the ratio tapering to 1.25 as the superficial gas velocity was increased. The new model can be expressed as follows:

$$f_s = K_\theta \left[\frac{V_{sl}}{gd} \left(\frac{36m^2/s^2}{V_t} + V_t \right) \right]^{1.2} \tag{4.1}$$

In equation (4.1), K_θ is the function of inclination, which reflects the effect of inclination on slug frequency. Based on experimental results, K_θ can be calculated as follows.

$$K_\theta = 0.018 * \exp(\sin\theta) \tag{4.2}$$

In Equation (4.2), V_t can be calculated with the following equation:

$$V_t = 1.25(V_{sl} + V_{sg}) \tag{4.3}$$

Fig.12 and Fig.13 show the comparison between the experimental and predicted results in upward and downward flows. It is seen that the experimental results have a good agreement with the predicted. Fig.14 and Fig.15 show the comparison between the experimental results and the predicted by the new model and Gregory & Scott's model. It is clear that the Gregory & Scott's model under predicts slug frequency at low and high gas flow rates.

5. CONCLUSION

In this paper, experimental investigations on slug frequency and film height are carried out in 10-cm I.D., 18-m long pipe at inclinations of ±2° at atmosphere pressure with water and carbon dioxide as working fluids. New results of slug frequency and slug unit length in large diameter pipeline were obtained.

It is seen that slug frequency increases with increasing liquid flow rate for all test conditions. Interesting results are seen with increasing gas flow rate. In upward flow, at lower liquid flow rate, slug frequency decreases with increasing gas flow rate at lower superficial gas velocity and then it increases with an increase of gas flow rate. Slug frequency is almost independent of gas velocity at moderate liquid velocity. However, slug frequency increases with increasing gas velocity at high superficial liquid velocity. In downward flow, slug frequency is almost independent of superficial gas velocity at moderate liquid flow rate. At higher superficial liquid velocity, slug frequency decreases with increasing superficial gas velocity at lower superficial gas velocity and then increases with increasing gas velocity. At the same superficial gas velocity, slug unit length decreases with increasing superficial liquid velocity. Slug unit length increases with increasing superficial gas velocity at lower liquid flow rate. At moderate flow rate, slug unit length increases slightly t a maximum with increasing superficial gas velocity. However, at higher liquid flow rate, slug unit length increases slightly to a maximum and then decreases slightly with increasing gas flow rate. Increasing the inclination leads to the decrease of slug unit length.

A new model is proposed to predict the slug frequency for large diameter pipeline, and good agreement is achieved with experimental results.

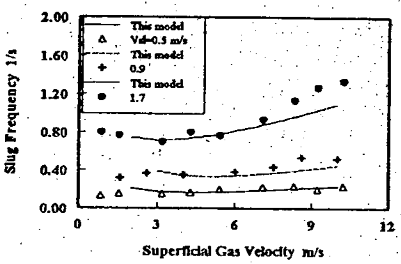

Fig. 12 Comparison between experimental results and this model at different liquid velocities, +2 upflow

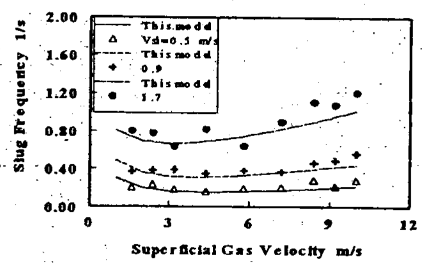

Fig. 13 Comparison between experimental results and this model at different liquid velocities, -2 downflow

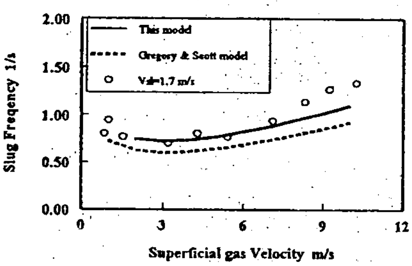

Fig. 14 Comparison of experimental results with this model and Gregory & Scott's model at +2 degree upflow

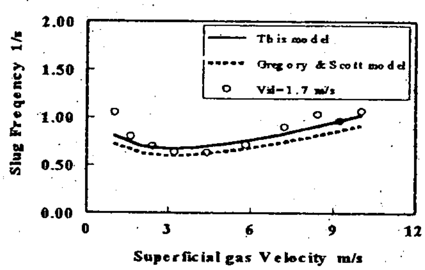

Fig. 15 Comparison of experimental results with this model and Gregory & Scott's model at -2 degree downflow

REFERENCES

1. Hubbard, M., An analysis of horizontal gas-liquid slug flow, Ph.D thesis, University of Houston, TX., 1965.
2. Gregory, G. & Scott, D.S., Correlation of liquid slug velocity and frequency in horizontal co-current slug flow, *AICHE JL* Vol.15, pp.933-935, 1969.

3. Taitel, Y. & Dukler, A.E., A model for slug frequency during gas-liquid flow in horizontal and near-horizontal pipes, *Int. J. Multiphase Flow* Vol.3, pp.585-596, 1977.
4. Tronconi, E., Prediction of slug frequency in horizontal two phase slug flow, *AICHE JL* Vol.36, pp.701-709, 1990.
5. Mishima, K. & Ishii, M., Therotical prediction of onset of horizontal slug flow, *J.Fluids Engng* Vol.102,pp.441-445, 1980.
6. Hill, T.J. and D.G. Wood, A new approach to the prediction of slug frequency, *SPE Annual Technical Conf.*, pp.141-149, 1990.
7. Wilkens, R.J., Prediction of the flow regime transitions in high pressure large diameter inclined multiphase pipelines, Ph.D thesis, Ohio University, OH, 1997.
8. Kouba, G.E. and Jepson, W.P., The flow of slugs in horizontal two phase pipelines, *Tran. ASME*, Vol.112, pp.10-24,1990.
9. Jepson, W.P. and Taylor, R.E., Slug flow and its transition in large diameter horizontal pipes, *Int.J.Multiphase Flow*, Vol.19, pp411-420, 1993.

NOMENCLATURE

C	coefficient
d	diameter of pipeline, m
f	frequency, s^{-1}
g	acceleration of gravity, m/s^2
h	height, m
V	velocity, m/s
θ	inclination of pipe section, degree
ρ	Density, Kg/m^3

Subscripts

G	gas phase
m	mixture
s	slug flow
sg	superficial gas velocity
sl	superficial liquid velocity
t	translational