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Technical Note

An experimental study of the statistical parameters of gas–liquid two-phase slug flow in horizontal pipeline

Xin Wang, Liejin Guo *, Ximin Zhang

State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China

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Abstract

Experiments were performed in a horizontal test loop with inner diameter 50 mm to study the gas–liquid slug flow. The translational velocities of elongated bubbles, lengths of liquid slugs and elongated bubbles, and slug frequencies were measured using two pairs of conductivity probes. Correlations are presented for elongated bubble translational velocity, length of elongated bubble and slug frequency, respectively. It was found that the translational velocity of elongated bubble is not only dependent on Froude number, but also is significantly affected by the distance from the entrance of pipeline in the higher mixture velocity range. Mean liquid slug length is relatively insensitive to the gas and liquid flow rates in the higher mixture velocity range, however in the lower mixture velocity range, the mean liquid slug length is affected by the mixture velocity. Mean slug frequency clearly increases as the liquid superficial velocity increases but it weakly depends on the gas superficial velocity.

Keywords: Multiphase flow; Slug flow; Liquid slug length; Slug frequency

1. Introduction

Gas–liquid two-phase flow occurs frequently in many industry fields. The slug flow pattern exists over a wide range of liquid and gas flow rates. It is characterized by a sequence of elongated bubbles separated by liquid slugs that may contain small bubbles. For its transient and intermittent nature, it is difficult to predict the flow characteristics correctly.

Cook and Behnia [1] studied this effect and the statistical distribution of slug lengths by conductivity electrodes in a 16 m long near horizontal pipe. They reported that the minimum stable slug length was close to ten diameters of the pipe in length and claimed that the development length for slug flow was about 500–600 diameters and the average slug length was about 1.5 times the minimum stable length. von Hout et al. [2] investigated the statistics and hydrodynamics of slug flow in a 10 m long pipe for many inclination angles from horizontal to vertical. They found that the measured length distributions were peaked near the pipe inlet and more widespread with increasing standard deviation further down the pipe and the coalescence rate of slugs became negligible for the distance after the entrance longer than 60 diameters and independent of flow rates.

For space limitations, most experimental researches of slug flow were carried out in short pipes and for lower range of liquid and gas flow rates. But, it is found that the initial developing length for slug flow is longer than the test section in some cases and even after the development length the liquid slug length still increases. In this work, the slug flow was experimentally studied in a 133 m long horizontal test loop. The hydrodynamic parameters, such as translational velocity of elongated bubble, liquid slug length, elongated bubble length and slug

* Corresponding author. Tel./fax: +86 29 82663895.
E-mail address: lj-guo@mail.xjtu.edu.cn (L. Guo).

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Nomenclature

D	internal pipe diameter (m)
f	slug frequency (Hz)
Fr	Froude number
g	gravitational acceleration (m/s^2)
L_S	length of liquid slug (m)
L_B	length of elongated bubble (m)
St	Strouhal number
V^*_{LS}	dimensionless liquid superficial velocity
V^*_{GSO}	dimensionless gas superficial velocity
V_t	translational velocity of elongated bubble (m/s)
x	axial distance from the mixer (m)
X_L	liquid volume fraction
Greek symbols	
ρ_G	gas density (kg/m^3)
ρ_L	liquid density (kg/m^3)

frequency are determined along the test loop for a wide range of input flow rates.

2. Experimental facility and measurement method

The experimental facility was consisted of a 133 m long horizontal test section and a 16 m vertical pipe. The inner diameter of the test loop was 50 mm. Two pairs of conductivity probes were used to detect the gas–liquid interfaces. The first pair was located at $x/D = 1157$ after the inlet and the second pair was located at $x/D = 2609$. More detailed information about the facility and the measurement method can be found in the paper [3]. In this study, air and water were used as the test fluids. The water and air superficial velocities varied in the range of 0.16–1.5 m/s and 1–20 m/s, respectively. The flow regime was slug flow in the horizontal pipeline.

3. Results and discussion

3.1. Translational velocity of elongated bubble

Nicklin et al. [4] proposed a correlation to predict the velocity of Taylor bubble based on experiments in vertical slug flow, which has later been applied for all pipe inclinations by most researchers:

$$V_t = C_0 V_m + V_0 \tag{1}$$

where V_0 is the drift velocity of elongated bubble in stagnant liquid, and V_m is the mixture velocity defined as the sum of the liquid and gas superficial velocities V_{LS} and V_{GS}. The coefficient of C_0 was found to be close to 1.2 for fully developed turbulent flow and approaching 2 for laminar flow [4].

Fig. 1 is the translational velocity of elongated bubble as a function of the local mixture velocity measured at $x/D = 1157$ and 2609, respectively. It is shown that the mean value is linear against the mixture velocity and the standard deviation increases as the mixture velocity increases. The measured translational velocities of elongated bubble are compared with the predicted values from the model proposed by Theron [5] and Bendiksen [6]. It is shown that there is clear discrepancy between the experimental and the predicted results in the higher mixture velocity range. However, in the lower mixture velocity range the agreement between the measured values and the predictions of Bendiksen [6] is very good. From Fig. 1, it is shown that the function of elongated bubble translational velocity can be divided into two parts as suggested by Bendiksen [6]. Both parts of the translational velocity function separated by $Fr = 3.5$ can be fitted, respectively, by the following equations.

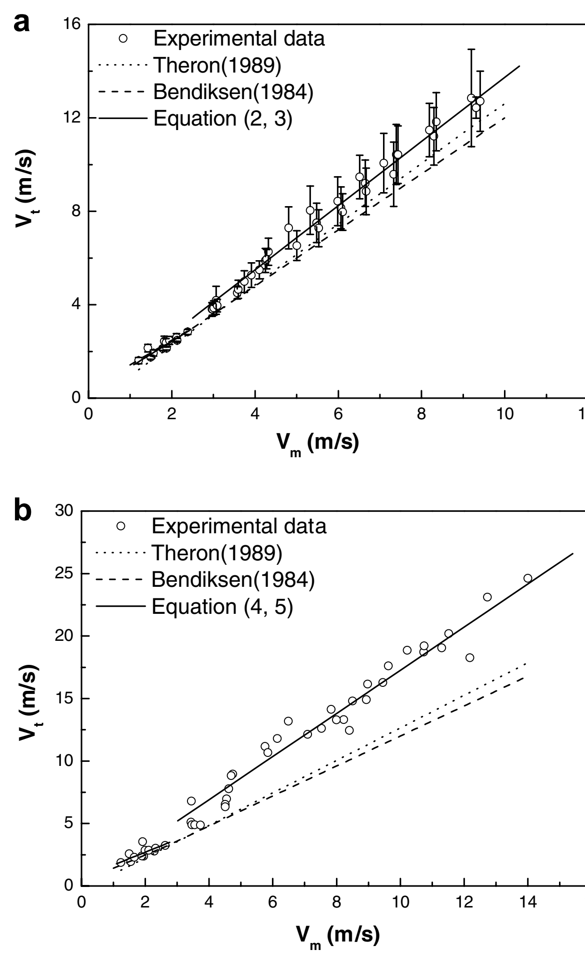

Fig. 1. Translational velocity of elongated bubble as a function of mixture velocity: comparison of measurements with model predictions. The error bar represents the standard deviation from the mean value ((a) $x/D = 1157$ and (b) $x/D = 2609$).

For $x/D = 1157$:

$$C_0 = 1.096 \quad V_0 = 0.342\sqrt{gD} \quad \text{for } Fr \equiv U_m/\sqrt{gD} \leqslant 3.5 \tag{2}$$

$$C_0 = 1.373 \quad V_0 = 0 \quad \text{for } Fr \equiv U_m/\sqrt{gD} > 3.5 \tag{3}$$

For $x/D = 2609$:

$$C_0 = 1.028 \quad V_0 = 0.927\sqrt{gD} \quad \text{for } Fr \equiv U_m/\sqrt{gD} \leqslant 3.5 \tag{4}$$

$$C_0 = 1.726 \quad V_0 = 0 \quad \text{for } Fr \equiv U_m/\sqrt{gD} > 3.5 \tag{5}$$

For horizontal or near horizontal pipe flow, there is not unified result of C_0 in the literatures and the spread is considerable. Gregory and Scott [7] reported $C_0 = 1.35$. Mattar and Gregory [8] reported 1.32. Dukler and Hubbard [9] proposed an equation to compute C_0 in their model and the range was 1.25–1.28. Singh and Griffith [10] obtained $C_0 = 0.95$. Ferre [11] reported $C_0 = 1.02 - 1.3$ from the data obtained for a pipe of 50 m length. Bendiksen [6] found that the critical Froude number was equal to 3.5: for $Fr < 3.5$, $C_0 = 1.05$; if $Fr > 3.5$, $C_0 = 1.2$ for horizontal pipe. The experimental result of Theron [5] was a correlation dependent on Froude number and the C_0 approximately equals to 1.3 for the experimental condition of this study. In general, Singh and Griffith [12], Ferre [11], Bendiksen [6] and Theron [5] support a dependence of C_0 on Froude number, as observed in this research. However, the $C_0 = 1.373$ at $x/D = 1157$ while $Fr > 3.5$ is higher than C_0 reported in all of the literatures; one reason of the difference may be that x/D is longer than that in the experiments of these literatures. Also, it is shown that C_0 increases with increasing of x/D from Fig. 1 while $Fr > 3.5$. Therefore, one of the reasons of the spread of C_0 in literatures seems to be the different x/D in the experimental facilities. Interestingly, if $Fr < 3.5$ it is shown C_0 does not depend on x/D and approximately equals to the value measured from single bubble moving in constant liquid flow [6].

3.2. Liquid slug length

The mean liquid slug lengths measured at $x/D = 1157$ and $x/D = 2609$ are shown in Fig. 2(a) and 2(b), respectively. It is found that the slug lengths from both locations are almost independent of the mixture velocities only in the higher mixture velocity range, but in the range of lower mixture velocity, the mean slug lengths are smaller than the values at higher mixture velocities and the mean slug length decreases and then increases as the mixture velocity increases. This characteristic is considered to be due to the transition of flow pattern from slug flow to plug flow, which was observed that the small bubbles in the liquid slug region disappeared in the lower mixture velocity range from the signal of conductivity probe. From both figures, it is observed that the mean liquid slugs grew from $15D$–$27D$ at the middle of the test loop ($x/D = 1157$) to $23D$–$40D$ near the pipe exit ($x/D = 2609$) in the higher flow rates range. In the experiment of Cook and Behnia [1], the maximum input mixture velocity was only 2.5 m/s. In this velocity range we observed that most of the mean liquid slug lengths measured at $x/D = 1157$ were lower than $15D$ and all of the minimum liquid slug length were lower than $10D$, therefore the slug flow was still developing even at $x/D = 1157$ and it seemed that a longer development length was needed for slug flow in the lower mixture velocity range than the development length of 500–600 diameters suggested by Cook and Behnia [1].

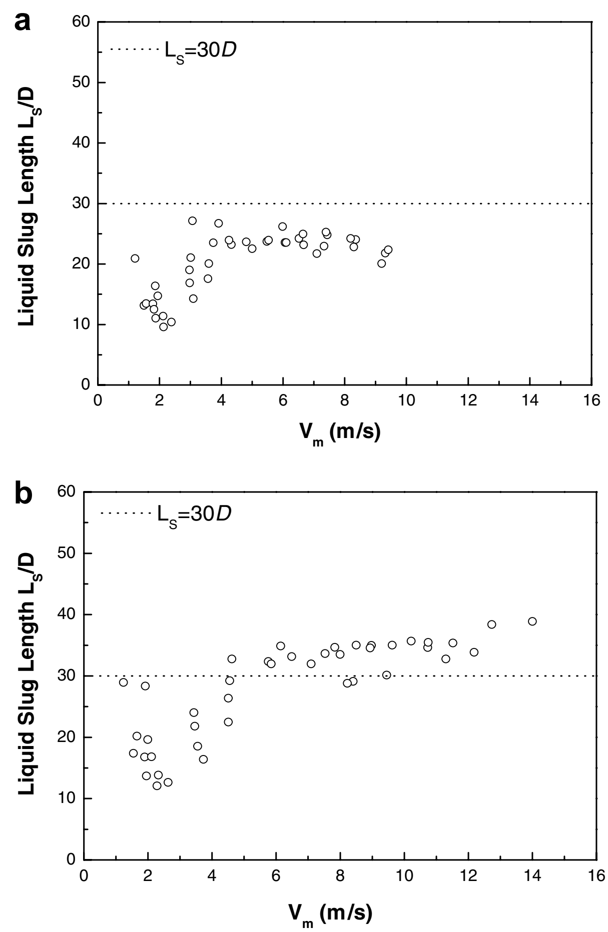

Fig. 2. Variation of mean liquid slug length with mixture velocity at two locations: (a) $x/D = 1157$ and (b) $x/D = 2609$.

3.3. Elongated bubble length

Fig. 3 presents the mean elongated bubble length measured at $x/D = 1157$ as a function of gas superficial velocity for various liquid superficial velocities. It is shown that the mean elongated bubble length increases linearly with the increasing of gas flow rates in the range of $2 < V_{GSO} < 10$ m/s at the log–log plot. However, the mean elongated bubble length seems weakly sensitive to the gas flow rates in the range of $V_{GSO} > 10$ m/s or $V_{GSO} < 2$ m/s. The reason may be that the flow pattern is near the

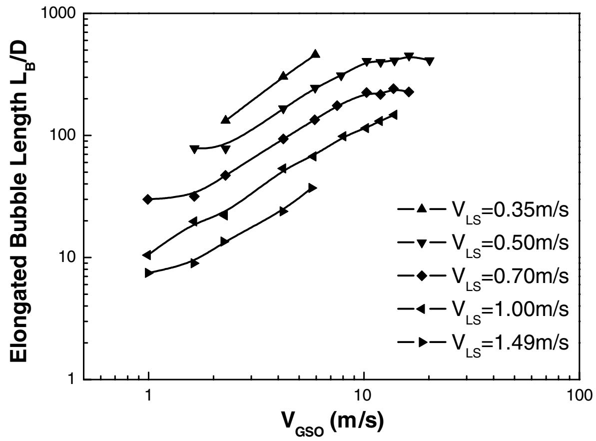

Fig. 3. Mean elongated bubble length at $x/D = 1157$ as a function of gas superficial velocity for various liquid superficial velocities.

transition boundary between annular flow and slug flow or between bubble flow and slug or plug flow.

The measured data at $x/D = 1157$ were processed for power law correlation in log–log plots of elongated bubble lengths vs. dimensionless gas and liquid superficial velocities as shown in Fig. 4. It is found that the data in the range of $2 < V_{GSO} < 10$ m/s can be correlated by

$$V^*_{LS} = \frac{V_{LS}}{\sqrt{gD\left(1 - \frac{\rho_G}{\rho_L}\right)}} \tag{6}$$

$$V^*_{GSO} = \frac{V_{GSO}}{\sqrt{gD\left(1 - \frac{\rho_G}{\rho_L}\right)}} \tag{7}$$

$$\frac{L_B}{D} = 12.07 {V^*_{LS}}^{-1.67} {V^*_{GSO}}^{1.14} \tag{8}$$

3.4. Slug frequency

The slug frequency f is defined as the reciprocal of slug unit period T_u in this research, $f = 1/T_u$. Fig. 5 presents the effects of gas and liquid flow rates on the mean slug

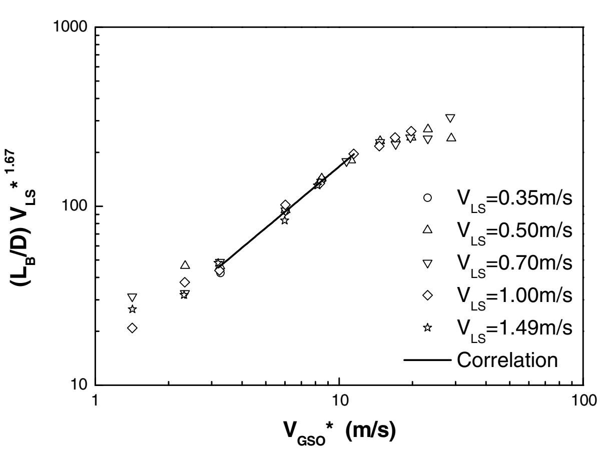

Fig. 4. Correlation of mean elongated bubble length: $x/D = 1157$.

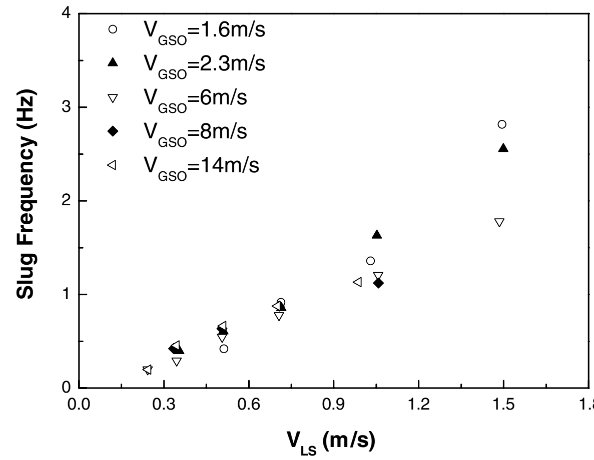

Fig. 5. Mean slug frequency at $x/D = 1157$ as a function of liquid superficial velocity for various gas superficial velocities.

frequency. It is found that the mean slug frequency weakly depends on the gas superficial velocity for various liquid superficial velocities except $V_{LS} = 1.49$ m/s, but the mean slug frequency clearly increases as the liquid superficial velocity increases. Some investigators, including Gregory and Scott [7], Dukler and Hubbard [9], Woods [13], reported a minimum in the slug frequency at $V_{GSO} = 4$ m/s, however it is not observed by us.

The measured slug frequency data at $x/D = 1157$ and $x/D = 2609$ are processed with dimensionless parameters and plotted in Fig. 6, in which the Strouhal number St is shown as a function of the liquid volume fraction X_L. It is observed that the relation can be correlated by the equation of the following form, as reported by Fossa et al. [14]:

$$St = \frac{fD}{V_{GSO}} \tag{9}$$

$$X_L = \frac{V_{LS}}{V_{LS} + V_{GSO}} \tag{10}$$

$$St = \frac{0.05 X_L}{1 - 1.675 X_L + 0.768 X_L^2} \tag{11}$$

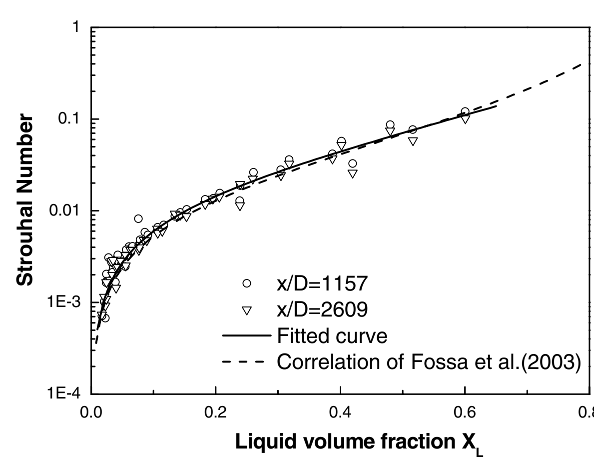

Fig. 6. Correlation of slug frequency measured at $x/D = 1157$ and $x/D = 2609$: comparison with the correlation of Fossa et al. [14].

Although the length of the test section was only 12 m long and the maximum x/D was 255 for the experiment of Fossa et al. [14], the agreement between the correlation of this study and that of Fossa et al. [14] is quite good.

4. Conclusions

An experimental study of the slug flow in horizontal test loop was presented. The characteristic parameters, such as translational velocity of elongated bubble, liquid slug and elongated bubble length, and slug frequency, were determined by the conductivity probes located far from the entrance of the pipeline. Correlations are presented for translational velocity of elongated bubble, length of elongated bubble and slug frequency, respectively. It was found that C_0 in the correlation of translational velocity of elongated bubble is not only dependent on Froude number, but also is significantly affected by x/D in the higher mixture velocity range. However in the lower mixture velocity range, C_0 is not influenced by x/D. The mean liquid slug lengths are relatively insensitive to gas and liquid flow rates only in the higher mixture velocity range. But in the lower mixture velocity range, the mean liquid slug length decreases and then increases with V_{m}. The elongated bubble length is clearly affected by the gas and liquid flow rates and the slug frequency is mainly influenced by the liquid flow rates. The correlation for slug frequency is weakly affected by x/D and quite well agrees with the correlation in literature.

Acknowledgement

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