IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

ISO 3297:2007 Certified ⁜ Impact Factor 8.066 ⁜ Peer-reviewed / Refereed journal ⁜ Vol. 10, Issue 9, September 2023

DOI: 10.17148/IARJSET.2023.10935

Characterisation of Gas-Liquid Two-Phase Slug Flows in Horizontal Pipe

M.K. Abdullahi[1], B. Pierre[2], G.F. Hewitt[2]

Department of Chemical Engineering, Imperial College London[1,2]

Nuhu Bamalli Polytechnic, Zaria[1]

Abstract: Experiments were carried out at different stratified air-water flow settings as well as different liquid 'slug' push in rates. The experimental facility, the LOTUS (Long Tube System) facility, was then situated in the Pilot Plant area of the Department of Chemical Engineering at Imperial College London. Understanding the nature of slugs and characterizing them help significantly in slug flow modelling. Some of the properties of slug determined in this work, include liquid film height, slug film height, film holdup, slug holdup, slug front velocity and the slug length. Though, the slugs were not generated due to high gas-liquid velocities, the results compared favourably with previous work and models on characteristics of slug flow.

Keywords: LOTUS (Long Tube System), gas-liquid, slug flows.

I. INTRODUCTION

The LOng Tube System (LOTUS) rig was situated in the pilot plant laboratory of the Department of Chemical Engineering, Imperial College London. LOTUS was a general purpose air-water flow facility with test section of 32.8 mm ID and a length of 6.3 m and has been used for a very wide range of experiments.

A general flow diagram of LOTUS is shown in Figure 1 (a). For the "push-in" experiments which formed part of the current work, the principal elements of the rig which were employed are shown in the sketch in Figure 1 (b). Push-in slug flow experiments were carried out on the LOTUS facility using twin-wire conductance probes for measurement of liquid film height.

The four conductance probes were calibrated offline in order to relate the voltage (V) measured by the electronics of the probes to the liquid film heigh h_{LF} in test section. The relationship is:

$$\frac{h_{LF}}{D} = mV + C \qquad (1)$$

where h_{LF} is the liquid film height in the pipe cross-section, D internal diameter of the pipe, m is the slop of the linear relationship and C is the intercept.

In this experiment, which closely represents slug flow, a stratified gas-liquid flow was established in a horizontal test section and with the help of a 3-way valve, liquid slug was pushed over the flowing stratified flow. In the processing of the data for the experiments, the time-traces generated by the platinum twin-wire conductance probes, certain slug flow characteristics were calculated. The time-trace is normally processed following the calibration in Eqn. (1).

These characteristics were the liquid film height and slug height from the twin-wire probes which were used in calculating the film and slug holdups. The twin-wire conductance probes also helped in capturing the times for the arrival of the liquid film, slug front, slug body and slug tail at each of the probes.

These times are required to calculate the slug front velocity, the average slug liquid holdup and the slug length. These characterisations were however performed on the slug flow with stratified gas-liquid flow data only, which is the focus of this work.

It is important to restate here that all the characteristics under discussion in this paper were derived from the time-traces generated by the probes connected to the electronics and software for data collection.

DOI: 10.17148/IARJSET.2023.10935

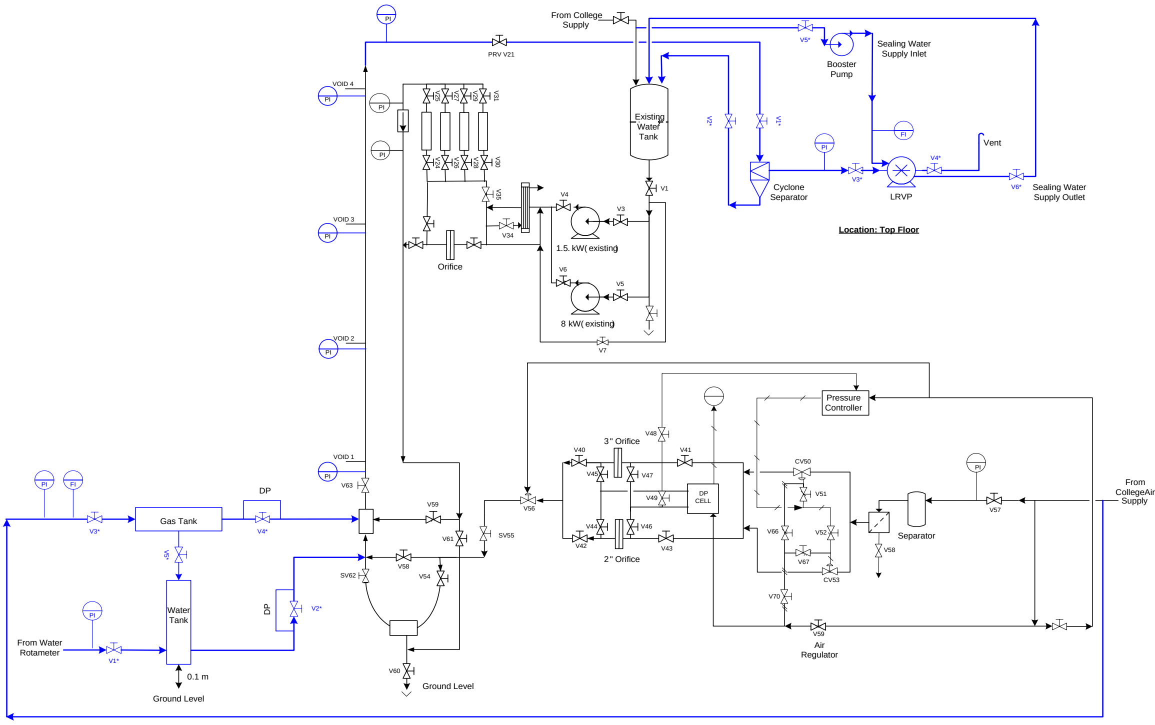

Figure 1 (a): General schematic of the LOTUS Rig

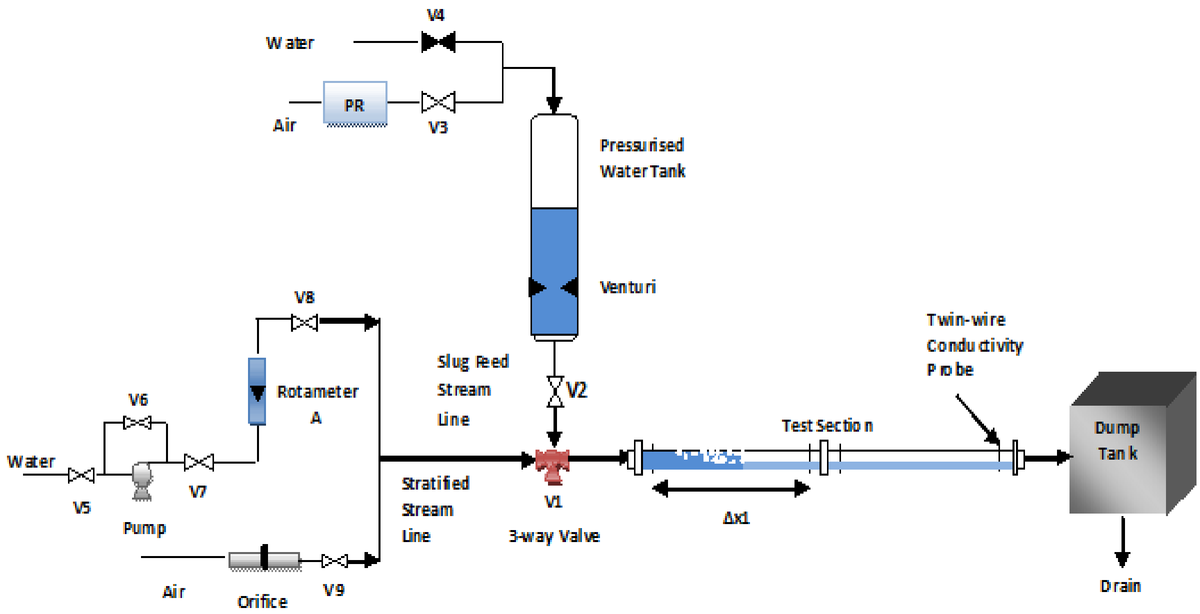

Figure 1 (b): Flow arrangement for the LOTUS “push-in” experiments

II. LIQUID FILM HEIGHT AND SLUG HEIGHT

Liquid film height and slug height are the quantities used in calculating the liquid film holdup and slug body holdup. Several runs where conducted with each over a period of about 20 seconds. Using the calibration Eqn. (1), the dimensionless liquid film was determined and plotted against time for the run of the experiment in Figures 2 (a) to (c) were plotted. Therefore, it can be deduced from these figures, that the stratified stream flows from $t = 0$ to a time $t = 7.244$s at probe 1 and $t = 7.468$s at probe 2. Then the liquid slug flows over it as indicated by sharp rise in liquid height

IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

ISO 3297:2007 Certified ⁒ Impact Factor 8.066 ⁒ Peer-reviewed / Refereed journal ⁒ Vol. 10, Issue 9, September 2023

DOI: 10.17148/IARJSET.2023.10935

to ranging between 0.7 to 0.8 due to entrained gas bubble and then rise to 1.0 at the slug tail where the liquid is pure without entrained gas bubbles. Using these two variable from the time-traces, the dimensionless liquid height and the time of arrival of the liquid at the probes the characteristics of the slug can be calculated.

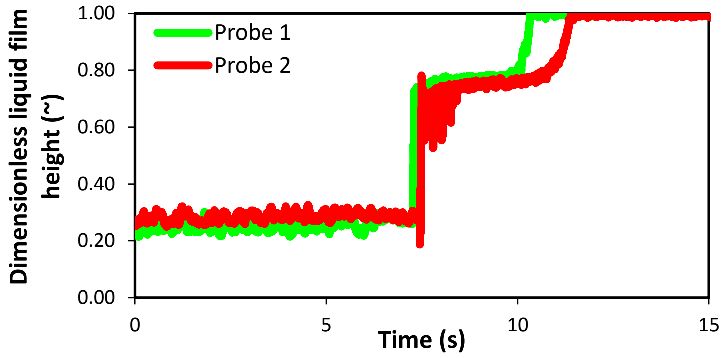

Figure 2 (a): Time traces for dimensionless liquid hold for probes 1 and 2 for U_{LS} = 2.06 m/s u_{SLF} = 0.0394 m/s and u_{SG} = 3.05 m/s in stratified stream

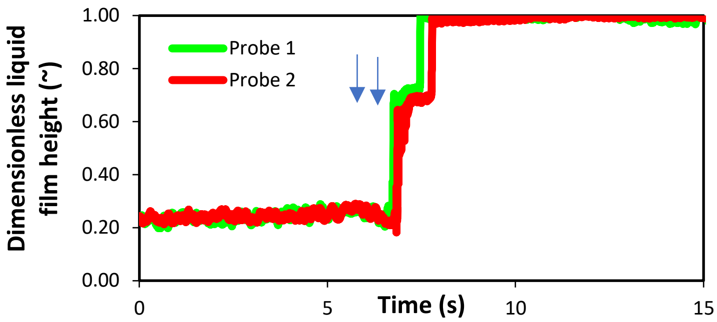

Figure 2 (b): Time traces for dimensionless liquid hold for probes 1 and 2 for U_{LS} = 3.63 m/s; u_{SLF} = 0.0394 m/s and u_{SG} = 3.05 m/s in stratified stream

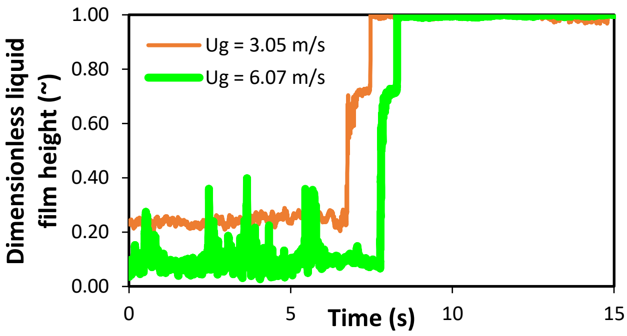

Figure 2 (c): Time traces for dimensionless liquid hold for probe 4 for U_{LS} = 3.63 m/s and U_{LS} = 3.78 m/s, u_{SLF} = 0.0394 m/s and two different u_{SG} in stratified stream

III. SLUG FRONT VELOCITY

The time dependent liquid film height was measured at three different locations approximately at the middle of the pipe using twin-wire conductance probes.
Slug front velocity u_T can be calculated using Eqn. (2).

$$u_T = \frac{\Delta x}{\Delta t} \quad (2)$$

IARJSET
ISSN (O) 2393-8021, ISSN (P) 2394-1588
International Advanced Research Journal in Science, Engineering and Technology
ISO 3297:2007 Certified ⁙ Impact Factor 8.066 ⁙ Peer-reviewed / Refereed journal ⁙ Vol. 10, Issue 9, September 2023
DOI: 10.17148/IARJSET.2023.10935

where Δx, represents the distance between the two conductance probes, Δt is the difference in the arrival time of the slug front at probe 2 and probe 1.

The velocity at which slug moves is important in modelling the slug, particularly in determining the aeration of the slug front. Slug flow causes pressure changes that lead to vibration and other flow restrictions. Therefore, it is important to experimentally determine the slug front velocity or predict it using models in order to control the devastating effects of slugging in gas-liquid two-phase flow. Figure 3. shows the changes in slug front velocity with change in the slug feed velocity at different superficial gas velocity and u_{SLF} = 0.0394 m/s in the stratified flow ahead of the slug. The effect in change in the pushing liquid rate (slug feed) on the slug front velocity can be deduced from time-traces on Figures 2 (a) and (b). In Figure 2 (a), the slug feed velocity is 2.06 m/s and the slug moves from probe 1 to 2 in 0.197s while in Figure 2 (b) the slug feed velocity is 3.63 m/s and moves in 0.108s between the two probes. Therefore, the slug front velocities in these two cases are 3.96 m/s and 7.25 m/s respectively. It clear that from Figure 2 the slug front velocity depends on the superficial gas velocity in the Tailor bubble region. The slower the gas moves the easier it could be picked up along with film beneath and accelerates it to the velocity of the fast moving slug. This is getting clearer as the slug feed velocity (nearly same as the mixture velocity) goes beyond 2.0 m/s. For u_{SG} = 3.05 m/s, the slug front velocity is higher than at u_{SG} = 6.07 m/s. This is due to the ease of entraining the slug front with slower moving gas; therefore making the slug lighter and moves faster.

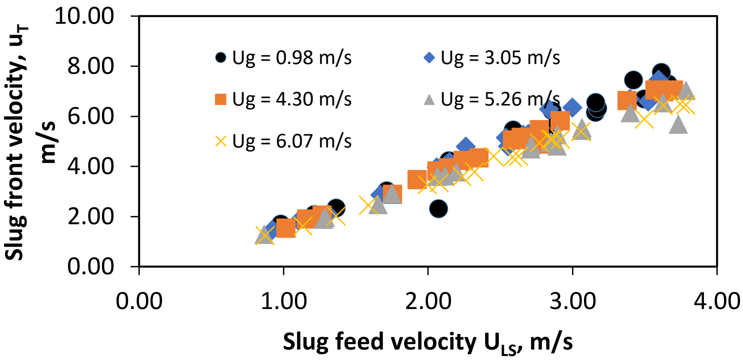

Figure 3: Slug front velocity at different superficial gas velocity and u_{SLF} = 0.0394 m/s in stratified stream with change in slug feed velocity

In Figure 4, the changes in slug front velocity at different superficial liquid velocity and u_{SG} = 0.98 m/s in the stratified flow ahead of the slug are clearly shown. However, the effect of change in liquid film velocity is not visibly noticeable in the bubble region on the slug front velocity.

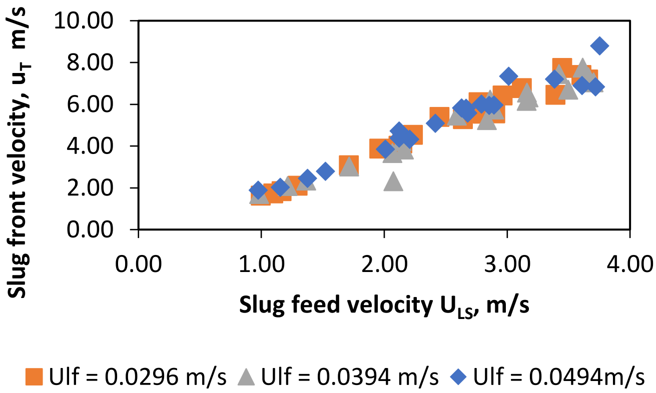

Figure 4: Slug front velocity at different superficial liquid velocity and u_{SG} = 0.98 m/s in stratified stream with change in slug feed velocity

The correlations of Dukler & Hubbard (1975), Bendiksen (1984) and Taitel & Barnea (1990b) for slug front velocity are compared with the experimental measurements of slug front velocity.

IARJSET

ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

ISO 3297:2007 Certified ⁝ Impact Factor 8.066 ⁝ Peer-reviewed / Refereed journal ⁝ Vol. 10, Issue 9, September 2023

DOI: 10.17148/IARJSET.2023.10935

$u_T = u_S + \frac{x}{\rho_L A \varepsilon_S}$ Dukler & Hubbard (1975) (3)

Where $x = (u_T - u_{LF})\rho_L A \varepsilon_{LF} = (u_T - u_S)\rho_L A \varepsilon_S$

$u_T = u_{LS} c_0 + c_1$ Bendiksen (1984) (4)

$Fr = \frac{U_{LS}}{\frac{gD\{\rho_W - \rho_G\}}{\sqrt{\rho_W}}}$

If $Fr < 3.5, c_0 = 1.2$ If $Fr > 3.5, c_1 = 0.542$

$u_T = c_0 u_M + u_D$ Taitel & Barnea (1990b) (5)

For horizontal and upward inclined pipe flows, Bendiksen (1984) model is used to describe the drift velocity u_D, and is given by,

$$u_D = 0.35\sqrt{gD}sin\theta + 0.54\sqrt{gD}cos\theta$$

The results for different flow conditions are presented in Figures 5 (a-d). Figures 5 (a) and 5 (b) are for data at constant u_{SLF} = 0.0394 m/s and u_{SG} of 0.98 m/s and 6.07 m/s respectively. And Figures 5 (c) and 5 (d) are for data at constant u_{SG} = 0.98 m/s and u_{SLF} of 0.0296 m/s and 0.0493 m/s respectively. All the models pretty well predict the experimental slug front up to an average of 2.60 m/s. Beyond this range of slug front velocity, which is within the minimum relative velocity (2.13 m/s) for the onset of gas entrainment into the slug front, sharp under prediction is observed. The best prediction by these models is in Figure 5 (b) for a case with high mixture velocity in the stratified stream ahead of the slug on which the models depend. However, among the three models, Taitel and Barnea (1990b) model gives a slightly better prediction. Average under-predictions by the models are; Dukler and Hubbard (1975) is 32.13%, Bendiksen (1984) is 32.65% and Taitel & Barnea (1990b) is 22.01%.

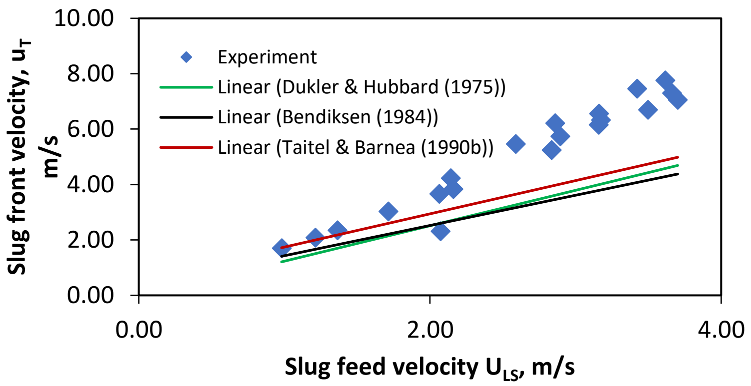

Figure 5 (a): Comparison of lug front velocity at u_{SLF} = 0.0394 m/s and u_{SG} = 0.98 m/s in stratified stream with change in slug feed velocity with some existing models

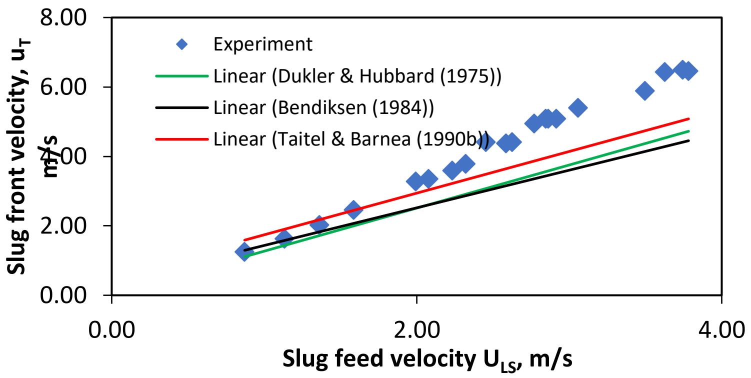

Figure 5 (b): Comparison of slug front velocity at u_{SLF} = 0.0394 m/s and u_{SG} = 6.07 m/s in stratified stream with change in slug feed velocity with some existing models

IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588
International Advanced Research Journal in Science, Engineering and Technology
ISO 3297:2007 Certified ⁜ Impact Factor 8.066 ⁜ Peer-reviewed / Refereed journal ⁜ Vol. 10, Issue 9, September 2023
DOI: 10.17148/IARJSET.2023.10935

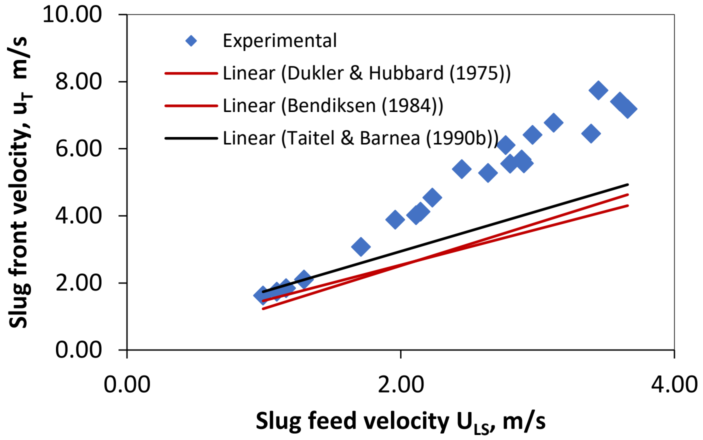

Figure 5 (c): Comparison of slug front velocity at u_{SLF} = 0.0296 m/s and u_{SG} = 0.98 m/s in stratified stream with change in slug feed velocity with some existing models

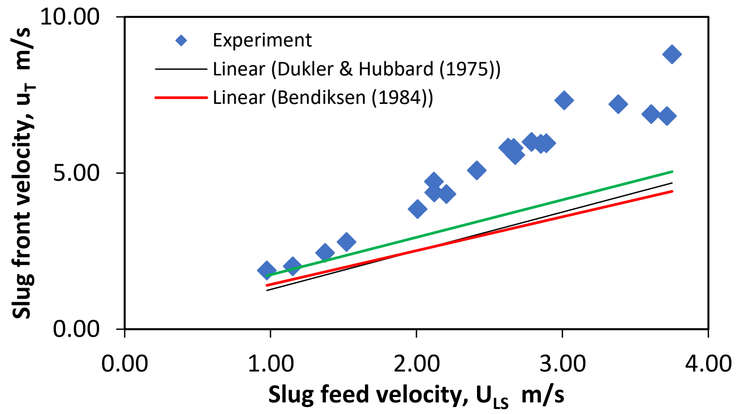

Figure 5 (d): Comparison of slug front velocity at u_{SLF} = 0.0493 m/s and u_{SG} = 0.98 m/s in stratified stream with change in slug feed velocity with some existing models

Figure 6 compares the experimental data with Manolis (1995) data. The sharp difference in the slug front velocity is due to the difference in pipe diameter. While this experiment was carried out in a 32.8 mm pipe, the Manolis (1995) data were obtained from WASP facility with a 77.92 mm test section.

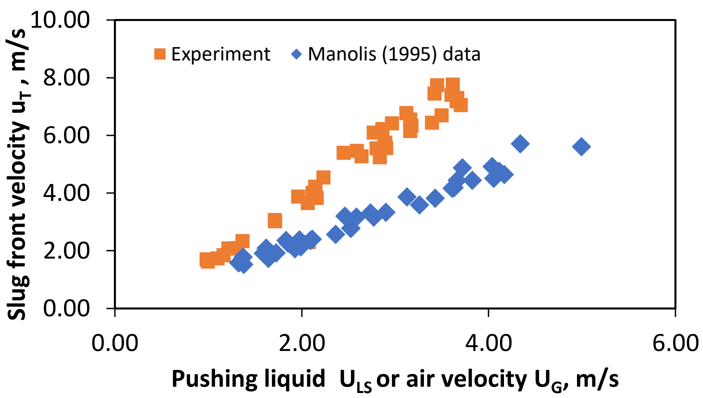

Figure 6: Comparison of slug front velocity with stratified stream with change in slug feed velocity or pushing air velocity with Manolis (1995) data

IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

ISO 3297:2007 Certified ⁜ Impact Factor 8.066 ⁜ Peer-reviewed / Refereed journal ⁜ Vol. 10, Issue 9, September 2023

DOI: 10.17148/IARJSET.2023.10935

IV. SLUG LIQUID HOLDUP

Slug liquid heights were determined from the probes time-traces in Figures 2 (a) to (c). These film heights were used in calculating the slug liquid holdup with using the Taitel and Dukler (1976) model represented in Eqn. (3)

$$\varepsilon_{LF} = \left(\frac{1}{\pi}\right)\left[\pi - cos^{-1}\left(\frac{2h_{LF}}{D} - 1\right) + \left(\frac{2h_{LF}}{D} - 1\right)\sqrt{1 - \left(\frac{2h_{LF}}{D} - 1\right)^2}\right] \qquad (6)$$

The results of slug liquid holdups are presented in Figures 6 and 7. Figure 6 shows results of slug liquid holdups for different superficial velocities in the stratified feed. Liquid film hold and slug body holdups are used in determining the fractional area occupied by each phase in the film and slug regions within the pipe cross-section.

In all the stratified flow conditions in this experiment, the slug liquid holdups decrease with increase in slug feed velocity, U_{LS}. This is due to increase in gas entrainment rate at high U_{LS}. An aerated slug moves faster than un-aerated one, which is nearly pure liquid. It is evident from the plots that at $U_{LS} < 1$, the slug liquid holdups for all the situations considered are greater than 0.9 but drop as U_{LS} increases. Figures 2 (a) and (b) for the time traces give more insight to this and the slug liquid holdups are 0.815 at slug feed velocity of 2.06 m/s and 0.718 at 3.63 m/s for the same stratified flow condition. It is clear in Figure 7 that slug body liquid holdup changes with change in gas superficial velocity. The figure shows that liquid holdup in the slug body increases with increase in gas superficial velocity in the stratified stream ahead of the slug. This is in agreement with the observation of Hale (2000). It is due to the fact that the rate of pickup of the stratified stream into the slug front depends on the relative velocity between the slug front and the stream ahead of it. The larger the relative velocity the larger the gas entrainment rate into the slug front. From the times-traces in Figure 2 (c) in which the gas superficial velocity changes from 3.05 m/s to 6.07 m/s, the estimated liquid holds are 0.718 and 0.751 respectively. This gives a change of 4.4% in the liquid holdup. Interestingly, the slug front velocities are 7.25 and 6.46 m/s respectively due to this change in liquid holdup or due to gas entrainment.

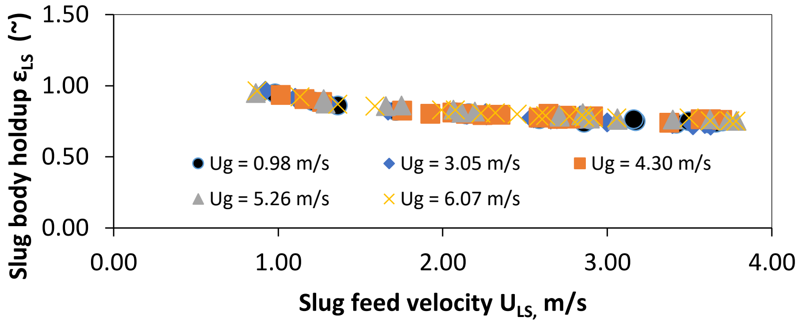

Figure 7: Slug body holdup at different superficial gas velocity and u_{SLF} = 0.0394 m/s in stratified stream with change in slug feed velocity

Figure 8 shows the change in slug body liquid holdup with change in liquid superficial velocity. Figure 6 shows that liquid holdup in the slug body increases with decrease in liquid superficial velocity in the stratified stream ahead of the slug. Though this effect is mild, but it can be observed that holdup at u_{SG} = 0.0493 m/s is slightly lower than at u_{SG} = 0.0296 m/s. High film velocity results in high film height in the pipe and also low relative velocity between the slug front and the liquid film ahead of the slug.

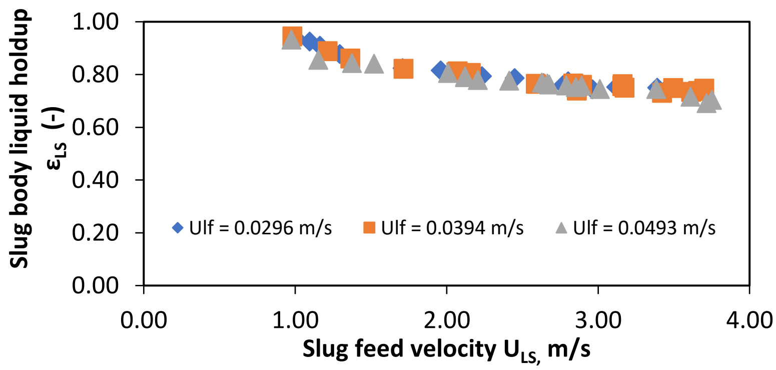

Figure 8: Slug body holdup at different superficial liquid velocity and u_{SG} = 0.98 m/s in stratified stream with change in slug feed velocity

IARJSET
ISSN (O) 2393-8021, ISSN (P) 2394-1588
International Advanced Research Journal in Science, Engineering and Technology
ISO 3297:2007 Certified ⧓ Impact Factor 8.066 ⧓ Peer-reviewed / Refereed journal ⧓ Vol. 10, Issue 9, September 2023
DOI: 10.17148/IARJSET.2023.10935

In Figures 9 (a-b) and Figures 10 (a-b); the data for the slug body hold are compared with the correlations of Gregory et al. (1978), Malnes (1982), Barnea & Brauner (1985), Andreussi & Bendiksen (1989), Abdul-Majeed (2000) and Zang et al (2003).

The liquid holdup within the liquid slug ε_S which is assumed to depend on the liquid velocity following the recommendation of Gregory et al. (1978) is,

$$\varepsilon_S = 1 - \frac{1}{1+(u_M/8.66)^{1.39}} \quad (7)$$

Barnea & Brauner (1985) also developed the following expression for slug body hold up,

$$\varepsilon_S = 1 - 0.058\left\{2\left[\frac{0.4\sigma}{(\rho_L-\rho_G)g}\right]^{1/2}\left[\frac{2f_S}{D}u_S^3\right]^{2/5}\left[\frac{\rho_L}{\sigma}\right]^{3/5} - 0.725\right\}^2 \quad (8)$$

where σ is the surface tension, f_L is the liquid friction factor and ρ_L and ρ_G are the liquid and gas densities respectively. The correlation for slug liquid holdup given by Andreussi & Bendiksen (1989) is,

$$\varepsilon_S = 1 - \frac{U_M-u_{mf}}{U_M-u_{m0}} \quad (9)$$

Where,

$$u_{mf} = 2.6\left[1-2\left(\frac{D_0}{D}\right)^2\right]\sqrt{gD}$$
$$D_0 = 2.5 \text{ cm}$$
$$u_{m0} = 2400\left[1-\frac{1}{3}sin\theta\right]Bo^{-3/4}\sqrt{gD}$$
$$Bo = \frac{\rho_L g D^2}{\sigma}$$

Abdul-Majeed (2000) also developed a slug holdup correlation which depends only on fluid viscosity and mixture velocity. The correlation is,

$$\varepsilon_S = 1.009 - \left(0.006 + 1.3377\frac{\mu_G}{\mu_L}\right)u_M \quad (10)$$

μ_G and μ_L are the gas and liquid viscosities respectively.

The plots in Figures 9 (a-b) represent the slug body holdup at constant for u_{SLF} = 0.0394 m/s and u_{SG} = 3.05 and 6.07 m/s respectively. Among the models considered for slug body holdup, Abdul-Majeed (2000) model over predicts the experimental slug body hold for all slug feed velocities considered. The models of Gregory et al (1978), Malnes (1982) and Barnea & Brauner (1985) predict the slug body holdup fairly well. However, there is a sharp under prediction by Barnes and Brauner (1985) model beyond slug feed velocity of 2.50m/s. The models of Andreussi & Bendiksen (1989) and Zang et al. (2003) generally under predict the experimental slug body liquid holdups.

There are better predictions at higher superficial gas velocity because the models of depend on the mixture velocity.

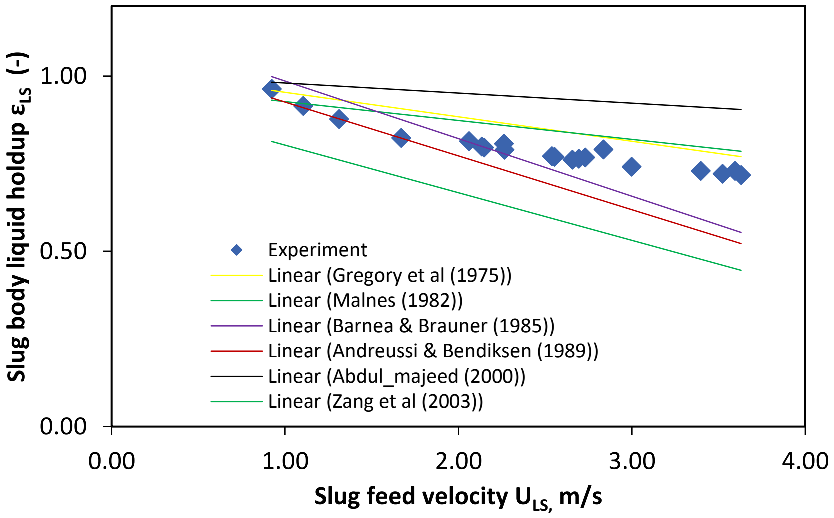

Figure 9 (a): Comparison of slug body holdup with some correlations at different slug feed velocities for stratified flow of u_{SLF} = 0.0394 m/s and u_{SG}= 3.05 m/s

DOI: 10.17148/IARJSET.2023.10935

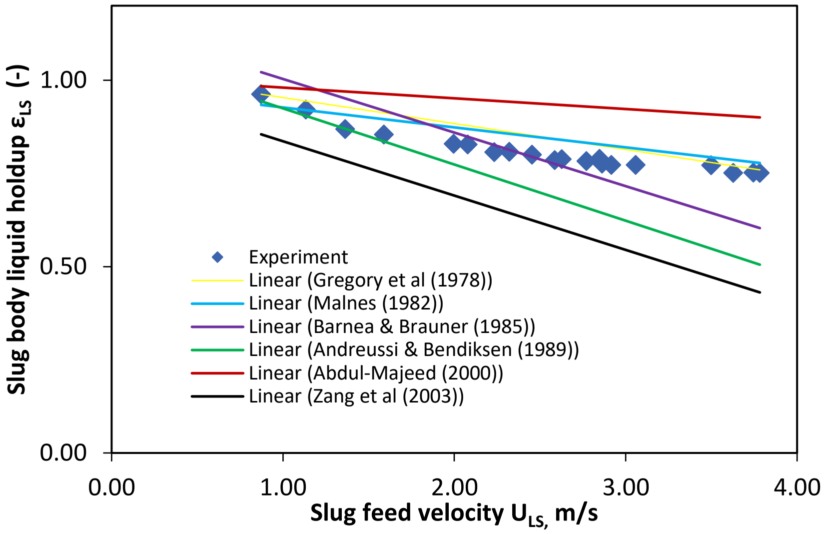

Figure 9 (b): Comparison of Slug body holdup with Some Correlations at Different Slug Feed Velocities for Stratified Flow of u_{SLF} = 0.0394m/s and u_{SG}= 6.07 m/s

Figures 10 (a-b) are data with constant for u_{SG} = 0.98 m/s and u_{SLF} = 0.0296 and 0.0493 m/s respectively. As with case for constant superficial liquid film velocity in Figures 8 (a and b), Abdul-Majeed (2000) model over predicts the experimental slug body hold for all slug feed velocities in this experiments.

Similarly the models of Gregory et al (1978), Malnes (1982) and Barnea & Brauner (1985) predict the slug body holdup fairly well. Also in this case, there is a similar under prediction by Barnes and Brauner (1985) model beyond slug feed velocity of 2.50m/s. In the same manner as in Figures 5.14 (a-b), the models of Andreussi & Bendiksen (1989) and Zang et al. (2003) under predict the experimental slug body liquid holdups for all the two conditions. The predictions are fairly same for the two conditions.

Average predictions by the models are; Gregory et al (1978) is an over prediction by 4.71%, Malnes (1982) over-predict by 4.58%, Barnea & Brauner (1985) under-predicts by 3.90%, Andreussi & Bendiksen (1989) under-predicts by 14.74%, Abdul-Majeed (2000) over-predicts by 16.05% and Zang et al (2003) under-predicts by 24.72%.

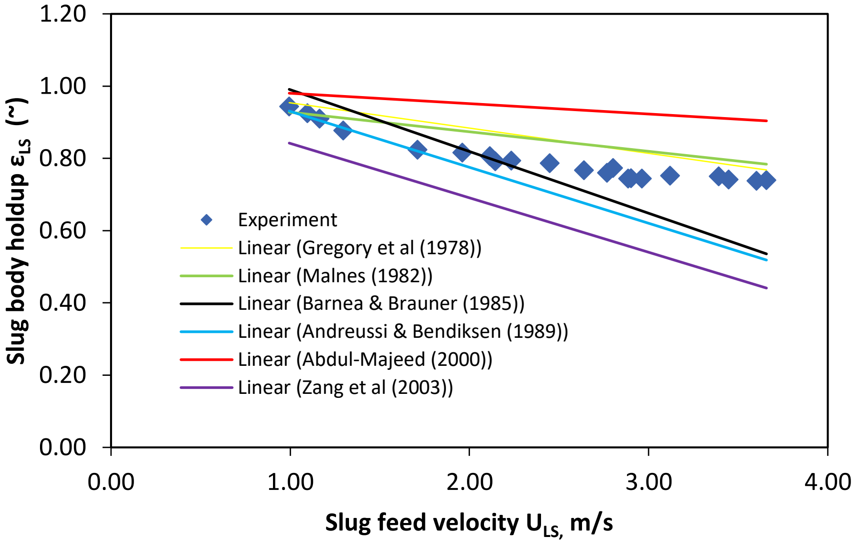

Figure 10 (a): Comparison of Slug body holdup with Some Correlations at Different Slug Feed Velocities for Stratified Flow of u_{SLF} = 0.0296 m/s and u_{SG}= 0.98 m/s

IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

ISO 3297:2007 Certified ⁝⁝ Impact Factor 8.066 ⁝⁝ Peer-reviewed / Refereed journal ⁝⁝ Vol. 10, Issue 9, September 2023

DOI: 10.17148/IARJSET.2023.10935

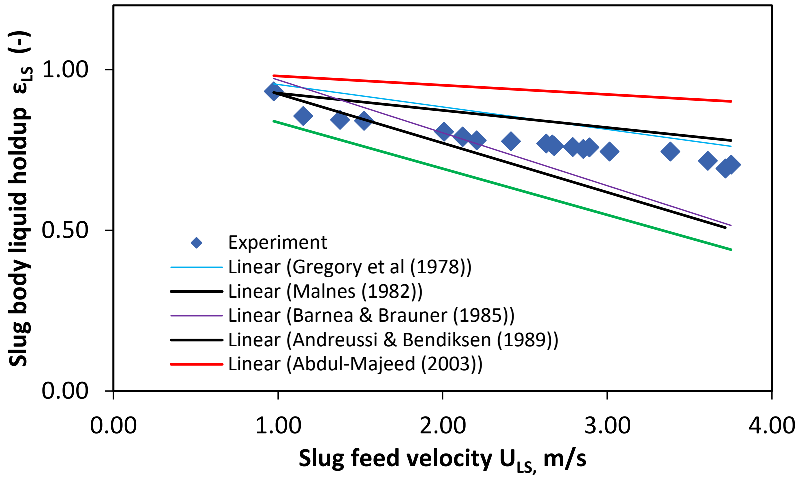

Figure 10 (b): Comparison of Slug body holdup with Some Correlations at Different Slug Feed Velocities for Stratified Flow of u_{SLF} = 0.0493 m/s and u_{SG}= 0.98 m/s

Figure 11 compares the experimental data with Manolis (1995) data. The experimental data and Manolis (1995) data of close liquid slug hold while Nydal et akl (1991) data has higher liquid holdups in the slugs.

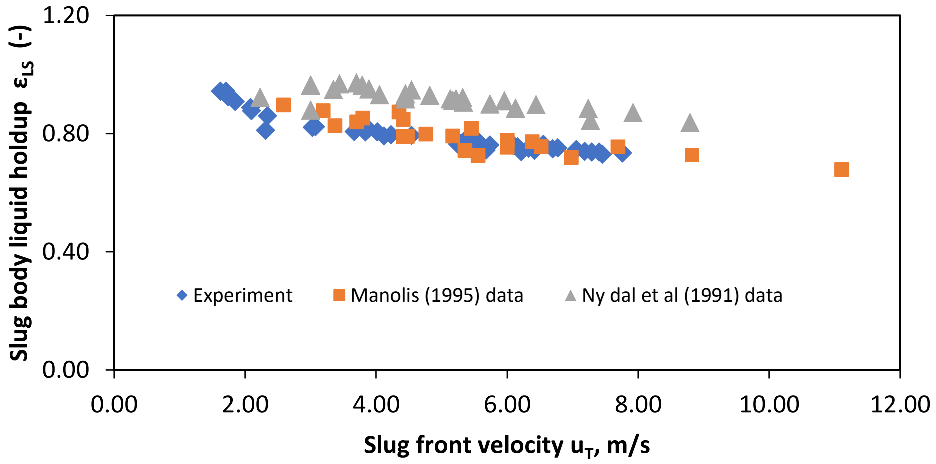

Figure 11: Comparison of slug body holdup with Manolis (1995) and Nydal et al (1991) data

In summary, the sharp under predictions by Andreussi & Bendiksen (1989), Abdul_Majeed (2000) and Zang et al (2003) models, may be related to the phenomena built into these models. Most, if not all of the correlations for the average slug body holdups were found to be unsatisfactory when applied to different geometries from those used in extracting the empirical correlations (Paglianti et al 1993).

None of the models considered slug aeration in its development, the slug body holdup for the experiments was solely calculated based on the liquid slug height measurements by the twin-wire conductivity probes.

Gregory et al. (1978) model is dependent only on the mixture velocity and the model of Barnea & Brauner (1985) expressed in depends on the fluids properties and liquid slug velocity within the slug. Though there is difference in the development of the models, the predictions are quite close.

IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

ISO 3297:2007 Certified ⁜ Impact Factor 8.066 ⁜ Peer-reviewed / Refereed journal ⁜ Vol. 10, Issue 9, September 2023

DOI: 10.17148/IARJSET.2023.10935

V. SLUG LENGTH

The determination of slug length expected during intermittent flows is essential for the prediction of pressure gradient and holdup along a gas-liquid pipeline. It is also desirable to have a knowledge of the range of slug lengths at any given flow conditions. As earlier stated, the presence of slugs in the test section was detected by the twin-wire conductance probes which were described in the work of Abdullahi M.K. (2013). Data were acquired at a sampling frequency of 500 Hz and these include the time at which the slug front and the slug tail arrive at each of the four probes.

With a known steady velocity of the slug front, u_T, the slug length at each probe can be calculated by:

$$L_S = u_T(t_T - t_F) \quad (11)$$

Where, L_S is the slug length, t_F and t_T are the times of arrival of slug front and slug tail at a probe respectively.

Figure 12 shows slug lengths at u_{SLF} = 0.0394 m/s and three different superficial gas velocities in the stratified flow region. From the Figure, it is clear that the slug length increases with increases in slug feed up to a velocity of 2.14 m/s. Beyond this feed velocity of 2.14 m/s, the slug front begins to get entrained with gas bubble and therefore becomes lighter. The fast moving slugs therefore more aerated and the time lag between the arrival of the front and the tail becomes smaller. This results in short slugs. The figure further shows that, slug length increases with decrease in superficial velocity of the gas in the stratified stream ahead of the slug. Time-traces in Figures 2 (a) and (b) which are for the same stratified flow condition can help to explain this rapid change in slug length. In Figure 2 (a), the slug feed velocity (nearly same as mixture velocity) is 2.06 m/s and the time lag for the arrival of the front and the tail is 4.57s which results in slug length of 14.28 m. While in Figure 1 (b) the slug feed is 3.63 m/s and the time lag is 0.698s giving a shorter slug length of 6.86 m.

Also considering time-traces in Figure 2 (c) which is for two superficial gas velocities and constant film velocity in the stratified region can be used to compares the effect of gas superficial velocity on slug length. The slug feed velocity is nearly the same and the slug lengths are 6.86 m and 3.77 m respectively. This shows that the slug length decreases with increases in gas superficial velocity in the stratified stream. This is obvious in Figure 12. The measurements in Figure 12 also show that the slug lengths range from 77D to 412D (D = 32.8 mm). That is the range for hydrodynamic to long slugs, Kadri et al. (2009).

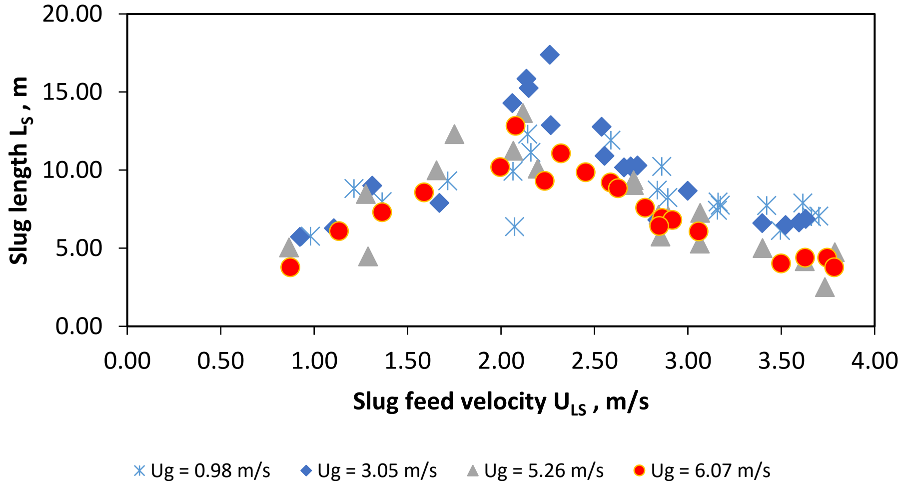

Figure 12: Slug length at different superficial gas velocity and u_{SLF} = 0.0394 m/s in stratified stream with change in slug feed velocity

Figure 13 shows slug lengths at u_{SG} = 0.0394 m/s and three different superficial liquid velocities in the stratified flow region. From the figure shows that the slug length increases with increases in slug feed up to a velocity of 2.45 m/s. Above a feed velocity of 2.45 m/s, as in the case of Figure 9, the slug front becomes aerated and moves faster. However, the dependence of the slug length on superficial velocity of the liquid in the stratified stream ahead of the slug is unclear. The data in Figure 13 also shows that the slug lengths range from 175D to 476D (D = 32.8 mm). Those are very long slugs, Kadri et al. (2009).

IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

ISO 3297:2007 Certified ⁙ Impact Factor 8.066 ⁙ Peer-reviewed / Refereed journal ⁙ Vol. 10, Issue 9, September 2023

DOI: 10.17148/IARJSET.2023.10935

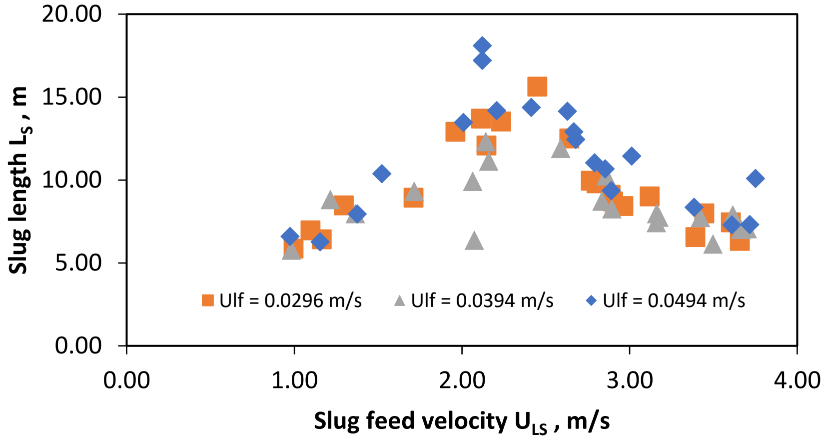

Figure 13: Slug length at different superficial liquid velocity and u_{SG} = 0.98 m/s in stratified stream with change in slug feed velocity

Figure 14 (a & b) compare a particular experimental run for constant liquid superficial velocity and two varied gas superficial velocities in the stratified stream with Dukler & Hubbard (1975) and Kadri et al (2009) correlations. The slug length range for this run is 179D- 417D.

$L_U = u_T T_U = \frac{u_T}{v_S}$ Dukler & Hubbard (1975) (12)

Kadri (2009) reported that the final slug length is reached when the extension of the tail becomes equal to the bubble length,

$L_U = L_{Bf} + L_{Sf}$ (13)

By making a volumetric balance between the stratified flow and the fully developed slug flow, a relationship between the bubble and slug length is obtained as follows:

$$L_{Bf} = L_{Sf} \frac{A - A_{Lmax}}{A_{Lmax} - A_{Lmin}}$$

When $A_{Lmax} \rightarrow A_{Lmin}$ then $L_{Bf} \rightarrow \infty$ which means there are no slugs formed.

In Figure 14 (a), the correlation of Dukler & Hubbard (1975) grossly under predicts the experimental slug length up to a slug feed velocity of 2.5 m/s and then increases linearly as the slug feed velocity increases.

A slug length range of 54D – 803D were predicted by Dukler and Hubbard (1975) model. This shows a three-fold lower limit and twice the upper limit to the experimental values. Kadri et al (2009) model reasonably predicts the experimental results with good agreement having slug length ranging between 163D – 305D.

Figure 14 (b), has the superficial gas velocity increased from 0.9 m/s to 2.16 m/s while keeping the liquid superficial velocity at 0.0296 m/s.

There is a better prediction of slug length by both models at higher gas superficial velocity particularly at low slug feed velocities. The slug length ranges are 116-406D for the experimental run, 59-1295D for Dukler & Hubbard (1975) model and 82-364D for Kadri et al (2009) model.

IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

ISO 3297:2007 Certified ⁒ Impact Factor 8.066 ⁒ Peer-reviewed / Refereed journal ⁒ Vol. 10, Issue 9, September 2023

DOI: 10.17148/IARJSET.2023.10935

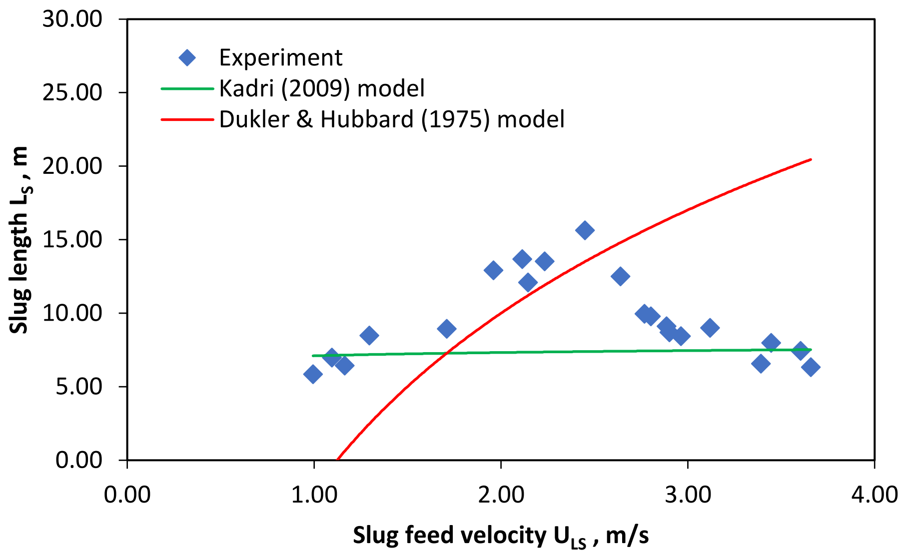

Figure 14 (a): Comparison of slug length with correlations of Dukler & Hubbard (1975) and Kadri et al (2009) at different Slug Feed Velocities for stratified flow of u_{SLF} = 0.0296 m/s and u_{SG}= 0.98 m/s

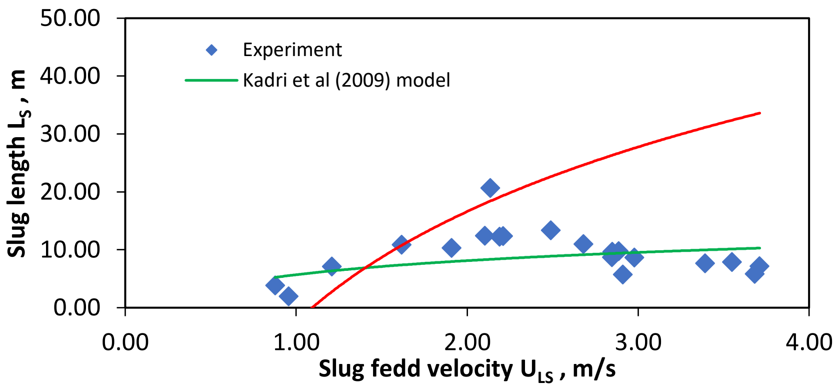

Figure 14 (b): Comparison of slug length with correlations of Dukler & Hubbard (1975) and Kadri et al (2009) at different Slug Feed Velocities for stratified flow of u_{SLF} = 0.0296 m/s and u_{SG}= 2.16 m/s

Figure 15 (a & b) compare another experimental run for constant gas superficial velocity and two varied liquid superficial velocities in the stratified stream with Dukler & Hubbard (1975) and Kadri et al (2009) correlations. The slug length range for this run is 176D- 363D.

In Figure 5.19 (a), the correlation of Dukler & Hubbard (1975) grossly under predicts the experimental slug length up to a slug feed velocity of 2.5 m/s and then directly increases linearly as the slug feed velocity increases. A slug length range of 34D – 545D was predicted by Dukler and Hubbard (1975) model. This shows a three-fold lower limit and twice the upper limit to the experimental values. Kadri et al (2009) model reasonably predicts the experimental results with good agreement having slug length ranging between 154D – 251D.

Figure 15 (b), has the superficial liquid velocity increased from 0.0394 m/s to 0.0493 m/s while keeping the gas superficial velocity at 0.0296 m/s. The slug length ranges are 201-551D for the experimental run, 49-783D for Dukler & Hubbard (1975) model and 45-350D for Kadri et al (2009) model.

IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

ISO 3297:2007 Certified ⁒ Impact Factor 8.066 ⁒ Peer-reviewed / Refereed journal ⁒ Vol. 10, Issue 9, September 2023

DOI: 10.17148/IARJSET.2023.10935

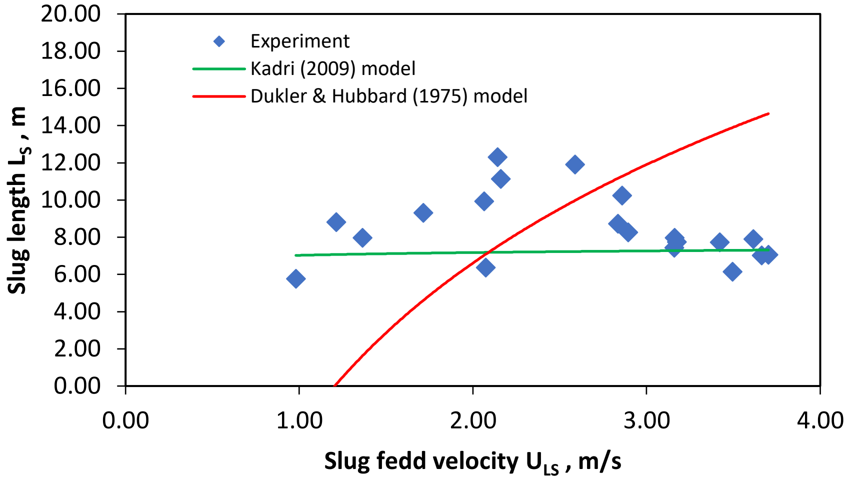

Figure 15 (a): Comparison of slug length with correlations of Dukler & Hubbard (1975) and Kadri et al (2009) at different Slug Feed Velocities for stratified flow of u_{SLF} = 0.0394 m/s and u_{SG}= 0.98 m/s

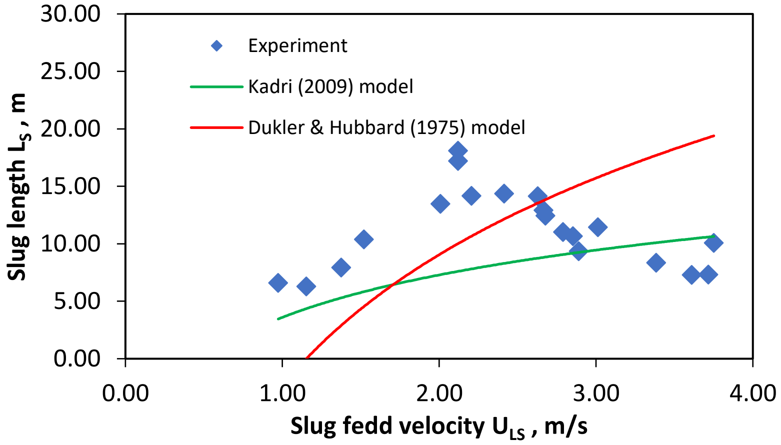

Figure 15 (b): Comparison of slug length with correlations of Dukler & Hubbard (1975) and Kadri et al (2009) at different Slug Feed Velocities for stratified flow of u_{SLF} = 0.0493 m/s and u_{SG}= 0.98 m/s

In developing the model for dynamic slugs in gas-liquid horizontal pipe, Kadri et al (2009) categorised slugs into three types: long slugs with length up to 100D, short hydrodynamic to long slugs and short slugs being 8D – 16D in length. They concluded that very long slugs, reaching 500D have been observed.

Average predictions by the models are Kadri et al. (2009) under predicts by 16.62% and Dukler & Hubbard (1975) under predicts in the region of no gas entrainment by 47.22% and within the gas entrainment velocity regime over-predict by 99.11%.

Figure 16 compares slug lengths for this experiment with Manolis (1995) WASP data. It is clear that the experimental slug lengths on 32.8 mm pipe are much longer than those obtained on WASP's 77.9 mm pipe. Slug length depends on slug front velocity which in turn depends on the slug body liquid holdup.

Figure 5.16 shows that the slug holdups for this experiment and those of Manolis (1995) are similar but the slug front velocities shown on Figure 5 are twice those of Manolis (1995) data due to pipes diameter difference. For this wide gap in slug front velocity, the slug length in this experiments are much longer. Manolis (1995) slug lengths range falls within short slugs from 13.72D to 25.13D.

IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

ISO 3297:2007 Certified ⁘ Impact Factor 8.066 ⁘ Peer-reviewed / Refereed journal ⁘ Vol. 10, Issue 9, September 2023

DOI: 10.17148/IARJSET.2023.10935

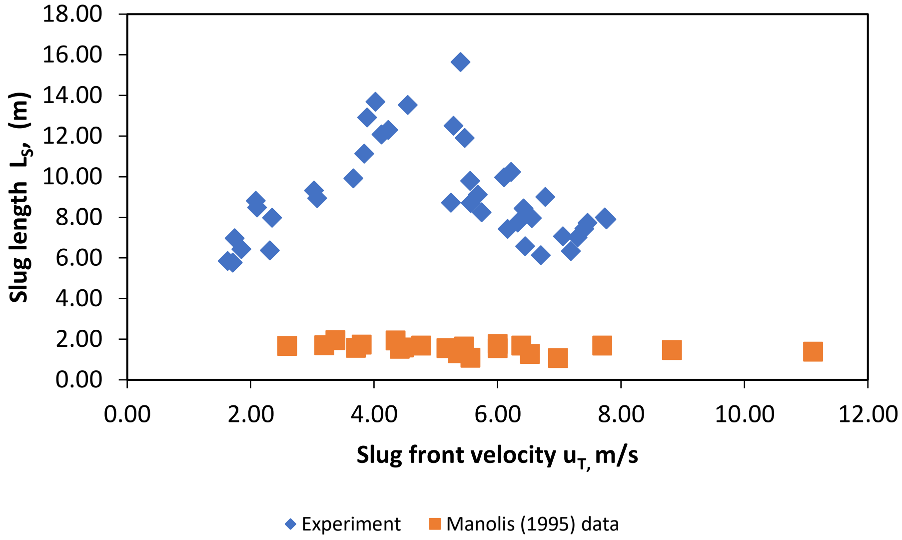

Figure 16: Comparison of slug length with Manolis (1995) data

VI. CONCLUSION

The measured slug characteristics such as slug liquid holdup and slug length agreed with some previous data and correlations to an acceptable extent. However, it is important to note that measured length of slug depends on the discrimination level. In this experiment the conductivity probes were placed near the exit of the test section which is of 8m length.

Analysis of the slug characteristics such as slug front velocity, slug liquid holdup and the nature of the flow in the gas region ahead of the slug determine the rate of volumetric gas entrainment. This has shown that the nature of the flow ahead of the slug has significantly affects the entrainment rate, with stratified wavy leading to high gas entrainment than stratified smooth.

REFERENCES

[1]. Abdullahi M.K (2013: Slug front gas entrainment in gas-liquid two-phase flow in horizontal and near horizontal pipe
[2]. Abdul-Majeed G.H. (2000): Liquid slug holdup in horizontal and slightly inclined two-phase slug flow. Journal of Petroleum Science & Engineering, vol. 27, pp. 27-32.
[3]. Andreussi P. & Bendiksen K. (1989): An investigation of void fraction in liquid slugs for horizontal and inclined gas-liquid pipe flow. *Int. J. Multiphase Flow*, Vol. 15, No. 6, pp. 937-946
[4]. Barnea D. & Brauner N. (1985): Holdup of the liquid slug in two-phase intermittent flow. *Int. J. Multiphase Flow*, Vol. 11, No. 1, pp. 43-49.
[5]. Bendiksen K. H. (1984): An Experimental Investigation of the Motion of Long Bubbles in Inclined Tubes. International Journal of Multiphase Flow, vol. 10, No. 4, Pages: 467-483, 1984.
[6]. Dukler A.E. & Hubbard M.G. (1975): A model for gas-liquid slug flow in horizontal and near horizontal tubes. I & EC Fundamentals, vol. 14, pp. 337-347.
[7]. Gregory G.A.**,** Nicholson M.K**.** & Aziz K. (1978): Correlation of the liquid volume fraction in the slug for horizontal gas-liquid slug flow. *Int. J. Multiphase Flow*, Vol. 4, pp. 33-39.
[8]. Hale C.P., Hewitt G.F., Manolis I.G., Mandes M.A., Richardson S.M. and Wong W.L., (2007): Experimental and Analytical Studies of Gas Entrainment Phenomena in Slug Flow in Horizontal and Near Horizontal Pipes. Multiphase Science and Technology, Volume 17, Nos. 1-3, pp. 1-22.
[9]. Kadri, U., Zoeteweiji, M.L., Mudde, R.F. & Oliemans, R.V.A. (2009a): A growth model for dynamic slug in gas-liquid horizontal pipes. Int. J. of Multiphase Flow, vol. 35, pp. 439-449.
[10]. Malnes D. (1982): Slug flow in vertical, horizontal and inclined pipes. *Report IFE/KR/E-83/002, V. Inst. for Energy technology, Keller, Norway.*
[11]. Manolis I. G. (October 1995): High Pressure Gas-Liquid Slug Flow. PhD Thesis, Department of Chemical Engineering and Chemical Technology, Imperial College London.

IARJSET ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

ISO 3297:2007 Certified ⁙ Impact Factor 8.066 ⁙ Peer-reviewed / Refereed journal ⁙ Vol. 10, Issue 9, September 2023

DOI: 10.17148/IARJSET.2023.10935

[12]. Paglianti A., Andreussi P. & Nydal O. J. (1993): The Effect of Fluid Properties and Geometry on Void Distribution in Slug Flow. 6th International Conference on Multiphase Production, Cannes, France, 16-18 June, 1993, Pages: 193-203.

[13]. Taitel Y. & Barnea (1990b): Two-phase slug flow. Advances in Heat Transfer, vol 20, pp. 83-132.

[14]. Taitel Y. & Dukler A.E. (Jan. 1976): A model for predicting flow regime transitions in horizontal and near horizontal gas-liquid flow. *AIChE Journal*, Vol. 22, No. 1, pp. 47-55.

[15]. Zhang H., Wang Q. Sarica C. & Brill J.P. (2003a): Unified Model for Gas-Liquid Pipe Flow via Slug Dynamics – Part 1: Model Development. J. Energy Res Tech, vol. 125, pp. 266-273.