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.2023.10906

Slug Flow Visualisation Studies

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Abstract: Slug flow visualization studies are described and presented. The experimental facility called the Low Pressure (LOWPRESS) rig was domiciled at Imperial College London. This study is aimed at a visual investigation of the nature of slugs as it move a long pipeline with respect to their aeration.

Flows were studied for three situations, in a horizontal pipe with stratified flow ahead of the slugs, in 1 inclined pipe with downward stratified flows towards the slugs, and in a horizontal pipe with stationary liquid film, These three experiments will reveal how slug front is entrained with gas as it moves along a pipeline.

Keywords: slug flow, visualisation, high speed camera, gas entrainment

I. INTRODUCTION

This paper presents experimental studies relating to gas-liquid slug flows in horizontal and near-horizontal pipelines. In such flows, liquid-continuous regions ("slugs") pass along the pipe separated by regions of stratified flow ("elongated bubbles"). Gas may be entrained at the slug fronts and is subsequently discharged into the elongated bubble at the slug tail. Using a low-pressure rig (LOWPRESS), flow visualisation with Olympus high-speed camera was successfully carried out.

The LOWPRESS rig located in Room 111 in the Department of Chemical Engineering, Imperial College London has two test sections available on the LOWPRESS facility, namely one 9 m long and 74 mm in diameter and the other 8 m long and 32.8 mm in diameter. Only the 32.8 mm test section.

The rig is depicted in Figure 1: In the results presented in this paper, the 32.8 mm diameter and 8 m long test facility was used. Three sets of experiments were carried out on the LOWPRESS rig.

Experiments for the visualisation of slug flow in horizontal pipe with stratified flow ahead of the slug. This is the true representation of slug flows, it was achieved through the use of a 3-way valve.

The second experiment was a repeat of the experiments earlier conducted on the WASP (Water, Air, Sand, and Petroleum) facility in the Department of Chemical Engineering at Imperial College by Manolis (1995) to enable an investigation of the flow of up to four phases along a 77.92 mm internal diameter, 37 m long stainless-steel test section at pressures up to 30 barg.

In this experiment, the rig was inclined upward by 1o to facilitate the downward flow of stratified flow towards the slug. The last experiment was also a repeat of another experiment by Hale C.P., (2007) with a stationary liquid ahead of the slug, in which the liquid was held using a weir.

Gas entrainments were earlier calculated in the work of Abdullahi (2013) for these three experiments and the plots agree with the visual images shown in this paper.

IARJSET
ISSN (O) 2393-8021, ISSN (P) 2394-1588
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ISO 3297:2007 Certified ⁜ Impact Factor 8.066 ⁜ Peer-reviewed / Refereed journal ⁜ Vol. 10, Issue 9, September 2023
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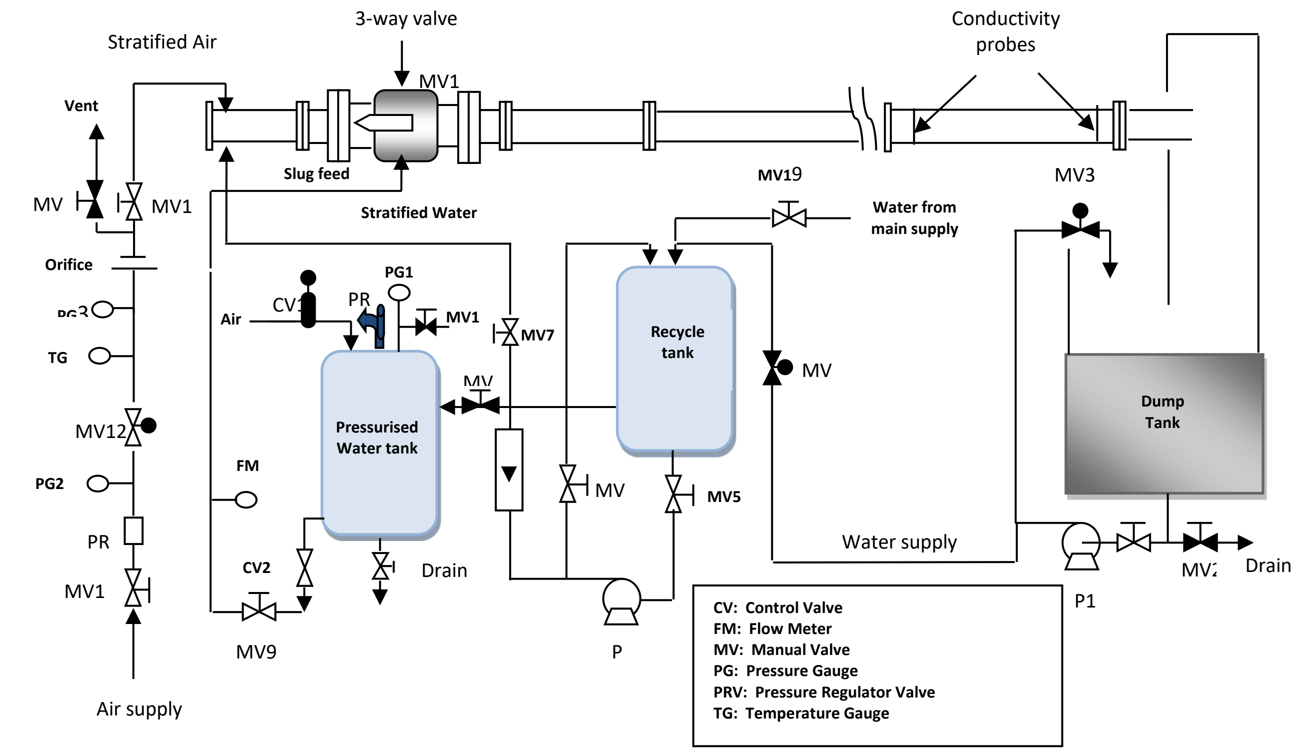

Figure 1: Flow arrangement for the LOTUS "push-in" experiments

II. SLUG FLOW VISUALISATION STUDIES USING HIGH-SPEED CAMERA

Movies were recorded using the Olympus high-speed camera. A full-resolution recording for 2,000 fps (Images per second) was used throughout the experiments in this section. The i-SPEED 3 high-speed video camera provides high resolution and extremely low light sensitivity. It is one of the additions to the Olympus i-SPEED range and can record up to 150,000 fps. Recorded movies are saved in a removable micro memory disk or to a PC. Images are converted into movies using i-SPEED Suite software. Using high-speed camera equipment and transparent components for the displacement chamber, M. Petzold et.al (2013), determined cavitation effects in pumps. Wanderley F. et,al (2013) using visualization technique with a high-speed digital camera identified flow patterns and measured interfacial parameters in two-phase natural circulation.

III. SLUG FLOW MOVIE RECORDING

Experiments for slug flow visualization were conducted on the LOWPRESS rig (Abdullahi M.K. (2013)) in room 111 using the Olympus high-speed camera. In recording the movies for the push-in experiments, a stratified flow stream was set up in the test section and subsequently liquid slug was pushed over it. Flow visualizations were carried out for 1° inclined pipe and with a stationary film ahead of the slug. The camera was fixed to the tripod stand with the lens in place and then set to focus on the centre of the pipe cross-section at 3.5m from the pipe inlet. The flow was set into the test section and with the recording speed set at 2,000 fps the movie was made by pressing the record trigger function. Recorded movies were replayed and viewed on the display unit. The Images were saved in a removable card and then later converted into movies using i-SPEED Suite software. These Images for the various experiments are presented in this paper.

IV. PRESENTATION OF THE MOVIE IMAGES FOR THE THREE VISUALISATION EXPERIMENTS

In this section, the recorded movie Images for the push-in experiments and the bubble experiments are presented.

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V. INSTANTANEOUS IMAGES FOR PUSH-IN EXPERIMENTS WITH STRATIFIED FLOW

Air-water stratified flow was set up in a horizontal pipe as shown in Figure 2 (a) and when the flow is fully established, with the use of the 3-way valve, the slug feed was introduced. This is depicted in Figure (b) in which the slug flows over slow slow-flowing stratified flow, picking it up and accelerating it to its velocity thus leading to entrained gas at the slug front. At this time, the stratified air and water were shut as shown in Figure 2 (b). Using the highspeed Olympus camera, images were recorded and presented in Figures 3 (a) and (b).

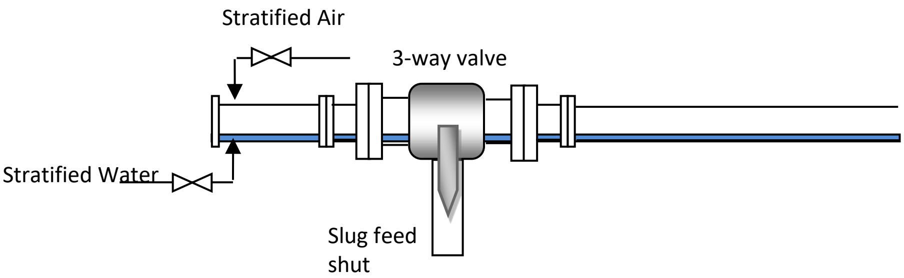


Figure 2 (a): Stratified flow flowing in horizontal test section

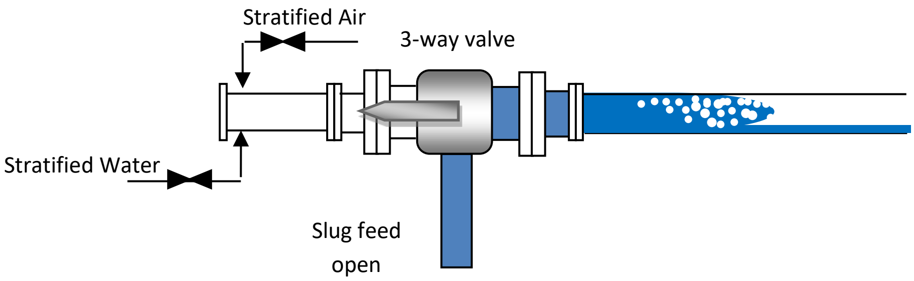
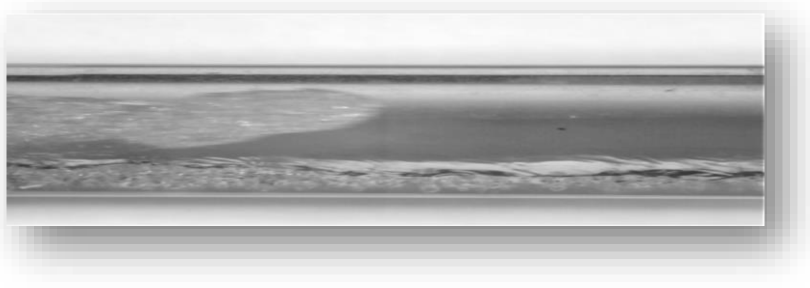


Figure 2 (b): Slug flowing over stratified flow in horizontal test section

Instantaneous images (a) to (d) in Figure 3 (a) are for an advancing slug flowing over a stratified stream at different stages. Images (a) and (b) show an aerated slug with the front abnormally lifted above the stratified stream.

This further shows the complexity of slug flows in pipes. In this run, the stratified stream was for superficial velocities of 1.54 m/s and 0.0395 m/s for air and water respectively, and a slug feed rate of 3.73 m/s. In image (c), the slug has bridged the first part of the pipe cross-section exhibiting huge gas entrainment.

Time = 0.205s	 **(a)** Aerated slug front moving over a stratified stream

DOI: 10.17148/IARJSET.2023.10906

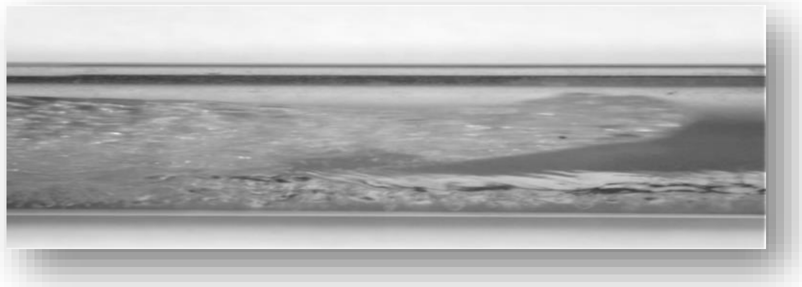
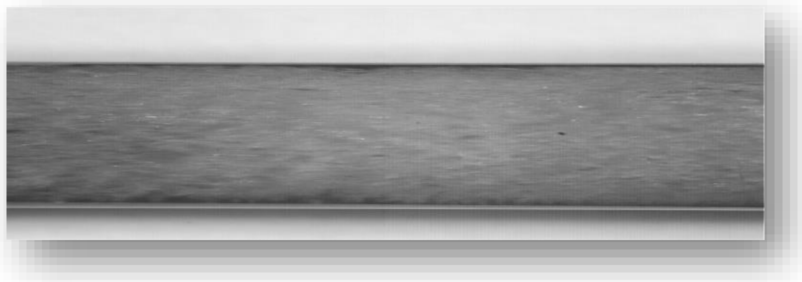
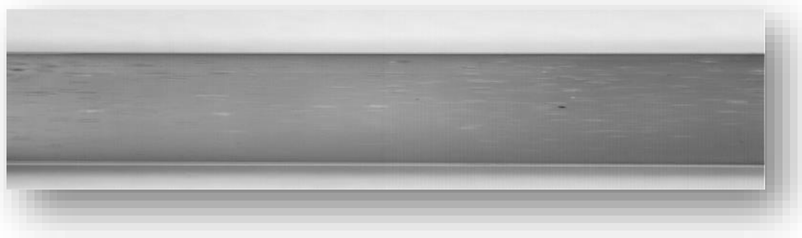
Time = 0.211s	 **(b)** Aerated slug front and slug body
Time = 0.230s	 **(c)** Slug body bridging the pipe cross section
Time = 0.380s	 **(d)** Slug body looking misty
Time 0.696s	 **(e)** Slug tail with few entrained bubbles

Figure 3 (a): Sequence of Images of Slug Flow over a Stratified Gas-liquid Flow u_{SG} = 1.54 m/s, u_{SLF} = 0.0395 m/s and U_{LS} = 3.73 m/s in Horizontal Pipe

Images (d) and (e) are the slug body/tail. In (d) there was approximately an even distribution of bubbles over the whole pipe cross-section in the slug body. In the image (d), which is near the tail of the slug, the entrainment level has gone down and the bubbles are at the top of the pipe due to buoyancy effects. In Figure 3 (b) typical images of an aerated slug front are presented for different stratified flow conditions and slug feed rates in a horizontal pipe.

Images (i) and (ii); and Images (iii) and (iv) are for constant stratified flow conditions with different slug feed velocities. It is clear from these Images that the slug gas entrainment increases with an increase in slug feed rate. Also in comparing

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

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Images (i) and (iii) which are for constant gas superficial velocity in the stratified stream and constant slug feed velocity but with different liquid superficial velocities, the images show that the slug gas entrainment increases with an increase in liquid superficial velocity. This agrees with the calculations in the work of (Abdullahi M.K., (2013).

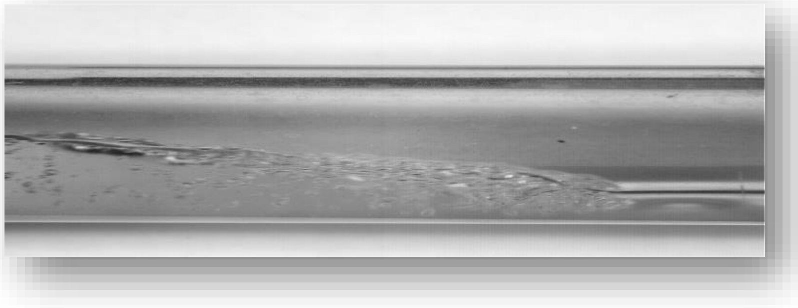
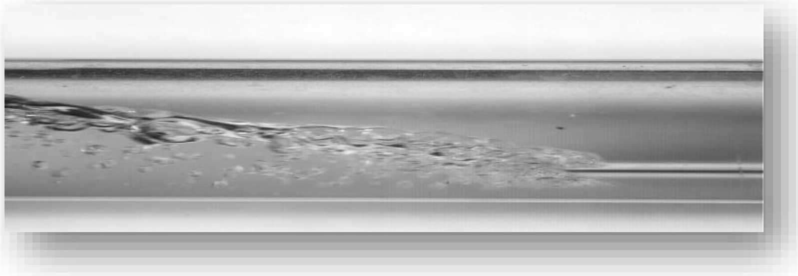
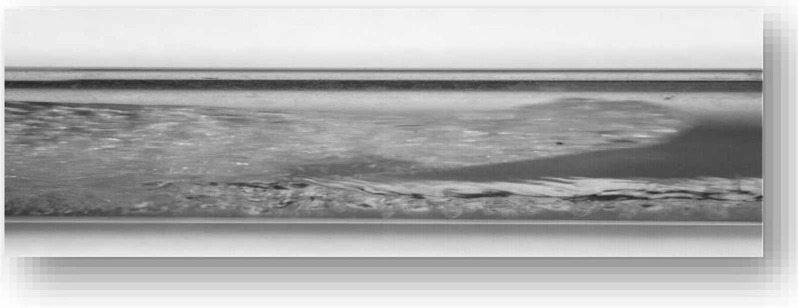
Time = 0.685s	 (i) u_{SG} = 1.54 m/s, u_{SLF} = 0.02959 m/s and U_{LS} = 1.504 m/s
Time = 0.333s	 (ii) u_{SG} = 1.54 m/s, u_{SLF} = 0.03945 m/s and U_{LS} = 1.504 m/s
Time = 0.224s	 (iii) u_{SG} = 1.54 m/s, u_{LSF} = 0.02959 m/s and U_{LS} = 3.727 m/s
Time = 0.211s	 (iv) u_{SG} = 1.54 m/s, u_{SLF} = 0.02959 m/s and U_{LS} = 3.727 m/s

Figure 3 (b): Comparison of Aerated Slug Front for Horizontal Slug Flow with Stratified Gas-liquid Flow at Constant Superficial Gas Velocity of u_{SG} = 1.54 m/s

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Figure 3 (c) compares Images for two different gas superficial velocities of 2.16 m/s and 1.54 m/s at a constant liquid superficial velocity of 0.02959 m/s in the stratified stream. From these images, it may be seen that the gas entrainment rate increases with an increase in superficial gas velocity in the stratified stream. This is evident when images (i) & (ii) and (iii) & (iv) are compared. This agrees with the calculations by (Abdullahi M.K (2013) and Hale et.al (2007).

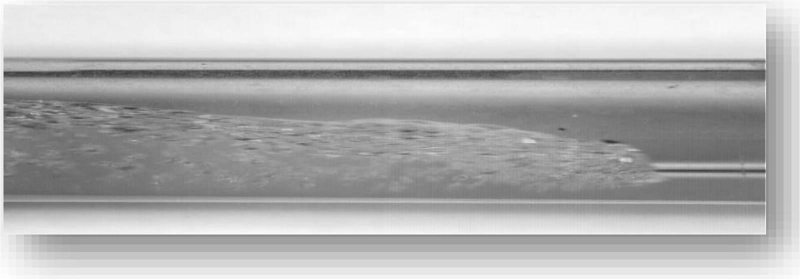
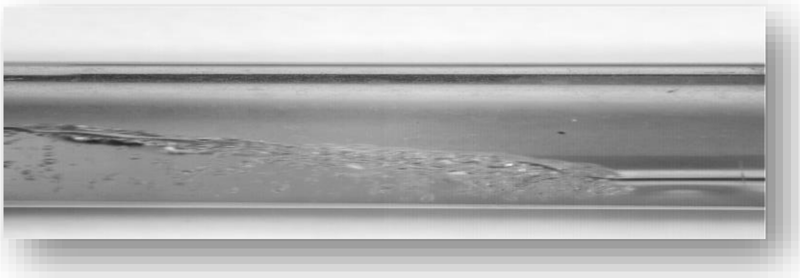
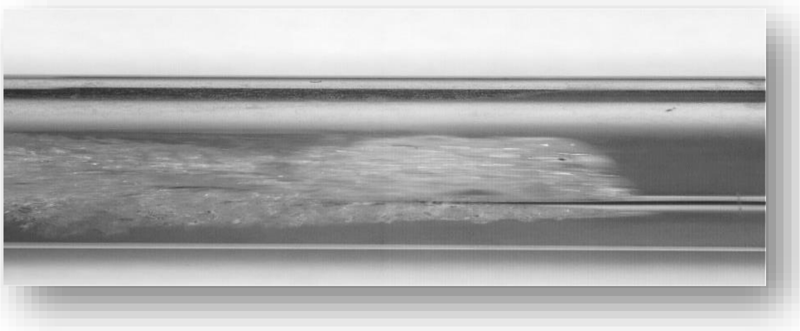
Time = 0.506s	 (i) u_{SG} = 2.16 m/s, u_{SLF} = 0.02959 m/s and U_{LS} = 1.504 m/s
Time = 0.685s	 (ii) u_{SG} = 1.54 m/s, u_{SLF} = 0.02959 m/s and U_{LS} = 1.504 m/s
Time = 0.540s	 (iii) u_{SG} = 2.16 m/s, u_{SLF} = 0.02959 m/s and U_{LS} = 3.727 m/s
Time = 0.224s	 (iv) u_{SG} = 1.54 m/s, u_{SLF} = 0.02959 m/s and U_{LS} = 3.727 m/s

Figure 3 (c): Comparison of Aerated Slug Front Images for Horizontal Slug Flow with Stratified Gas-liquid Flow at u_{SLF} = 0.02959 m/s

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VI. PUSH-IN EXPERIMENTS WITH DOWNWARD FLOWING FILM IN 1^{O} INCLINED PIPE

Manolis (1995) performed this experiment on the WASP high-pressure facility with a diameter of 77.92 mm at Imperial College London to study slug gas entrainment. It was here repeated in a low-pressure, 32.8 mm diameter pipe for flow visualisation.

The LOWPRESS test section was inclined upward by 1^{o}. Water was introduced through the exit section of the pipe at a known velocity into the test section as shown in Figure 4 (a). As the liquid was accumulating at the inlet section, the 3-way valve was open to introduce the liquid slug, thus pushing the accumulated liquid out of the pipe as shown in Figure 4 (b). At this time, the liquid film (water) flowing into the test section at the outlet was shut as shown in Figure 2 (b). Using the highspeed Olympus camera, images were recorded and presented in Figures 5 (a) and (b).

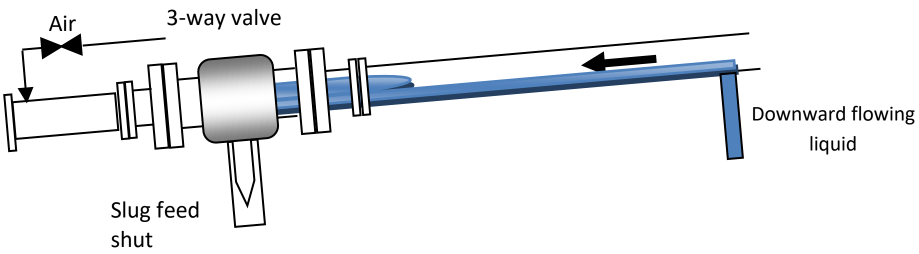


Figure 4 (a) : Liquid film flowing downward in 1^{0} inclined pipe

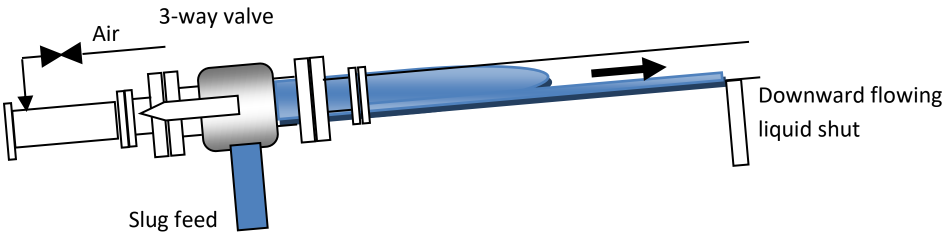
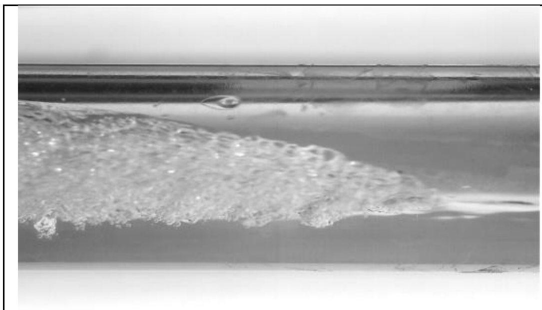
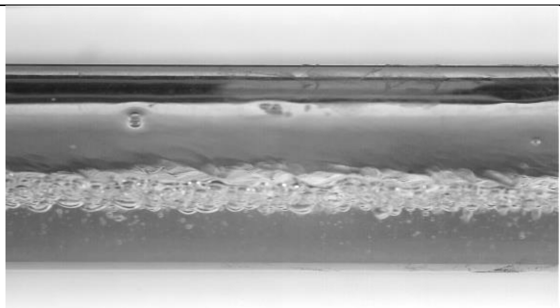


Figure 4 (b): Slug flowing over liquid film flowing downward in 1^{0} upwards inclined pipe

Figure 5 (a) is for sequence of Images (i) to (xii) for movie recorded for film flow of 0.1183 m/s and slug feed of 3.727 m/s. Images (i) to (iii) are the slug front and the bridging of the pipe cross section as the slug grows. The slug body is partly in image (iii) and fully in image (iv).

 **Time = 0.445s (i)** Aerated slug front	 **Time = 1.02s (vii)** Bubble body

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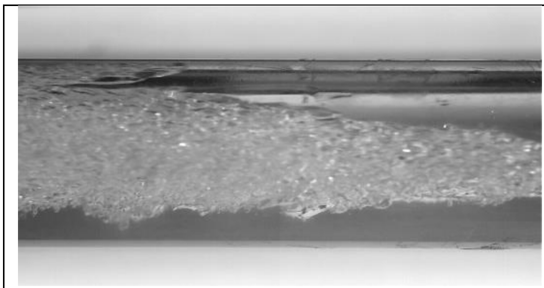
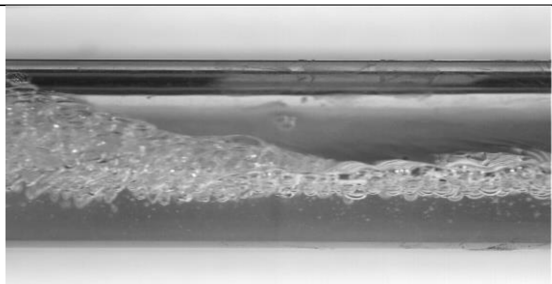
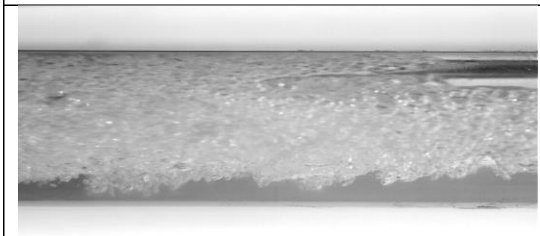
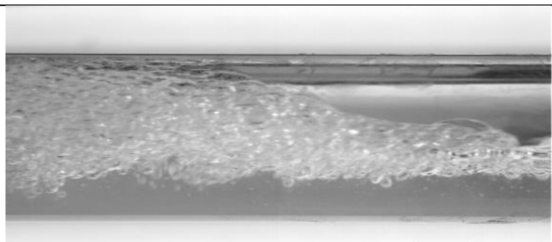
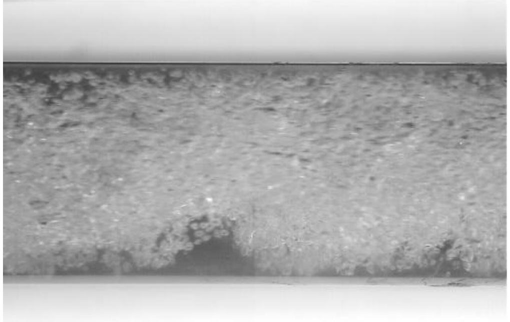
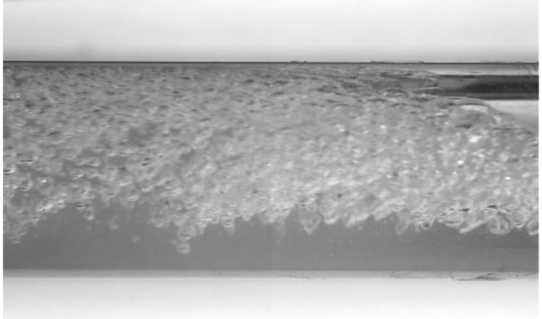
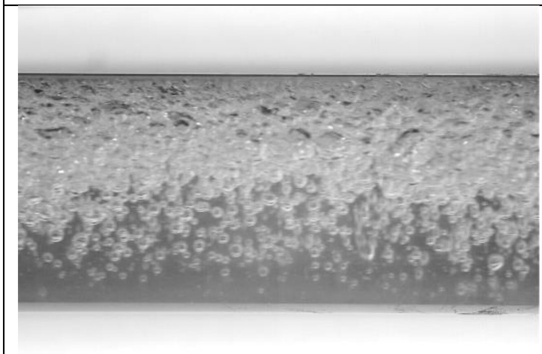
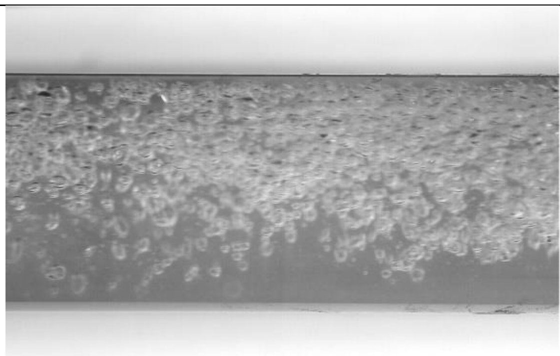
 **Time = 0.456s (ii)** Aerated slug front/body	 **Time = 0.767s (viii)** Second slug front with entrained gas
 **Time = 0.468s (iii)** Aerated slug front bridging up pipe	 **Time = 0.830s (ix)** Second slug front with entrained gas
 **Time = 0.500s (iv)** Full slug body with entrained gas	 **Time = 0.841s (x)** Fully entrained second slug body bridging pipe
 **Time = 0.584s (v)** Slug body with bubble moving up	 **Time = 0.853s (xi)** Second slug body with entrained gas

IARJSET

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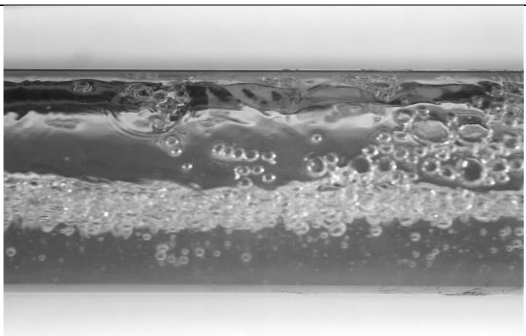
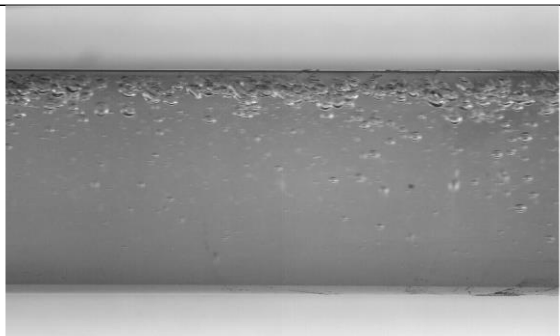
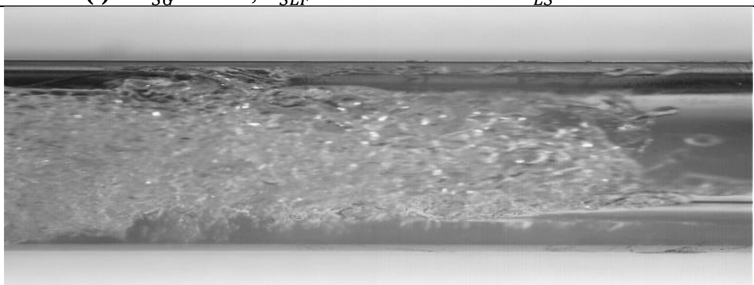
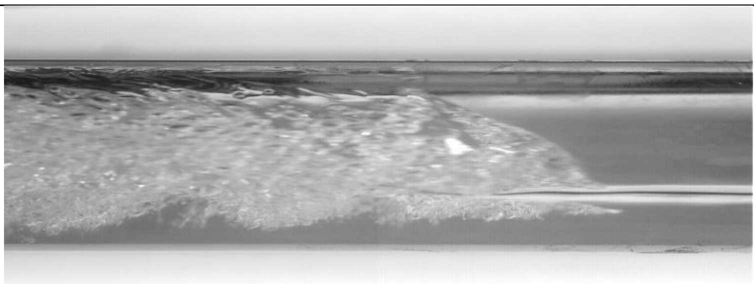
 **Time = 0.660s (vi)** Bubble front and slug tail	 **Time = 0.870s** (xii) Second slug tail with few bubbles

Figure 5 (a): Sequence of Movie Images for Slug Flows with back-flow of liquid film at of u_{SLF} = 0.118 m/s and of u_{SG} = 0 m/s in 1^0 Inclined Pipe

In image (iv), the entrained bubbles are distributed throughout the pipe cross-section. Then a large bubble followed the tail of the slug [see Images (vi) and (vii)]. This may be due to the shedding of the entrained bubbles at the tail of the slug. Then a second slug followed the bubble [Images (viii) and (ix)]. The slug clearly contains some entrained bubbles. Images (x) and (xi) are for the slug body while image (xii) is the slug tai

Time = 0.974s	 **(i)** u_{SG} = 0.00, u_{SLF} = - 0.0789 m/s & U_{LS} = 1.504 m/s
Time = 0.275s	 **(ii)** u_{SG} = 0.00, u_{SLF} = - 0.0789 m/s & U_{LS} = 3.727 m/s
Time = 0.212s	 **(iii)** u_{SG} = 0.00, u_{SLF} = - 0.1183 m/s & U_{LS} = 1.504 m/s

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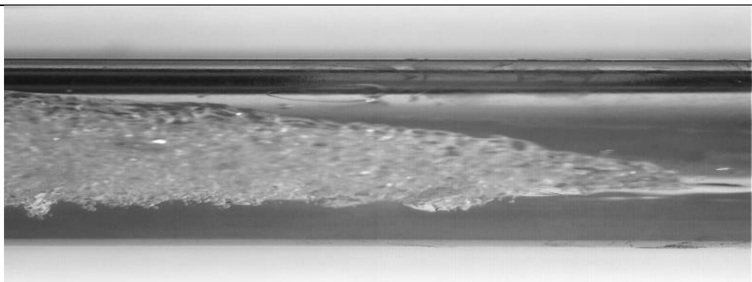
Time = 0.445s	 **(iv)** u_{SG} = 0.00, u_{SLF} = - 0.1183 m/s & U_{LS} = 3.727 m/s

Figure 5 (b): Comparison of Aerated Slug Fronts Images for Slug Flows with back-flow of liquid film in 1^0 Inclined Pipe

Figure 5 (b) compares slug front gas entrainment with changes in flow conditions for back-flow of liquid film of 0.0789 m/s and 0.1183 m/s and slug feed velocity of 1.504 m/s and 3.727 m/s. Comparison between Images (a) and (b) or (c) and (d) in Figure 5.3(b) shows that the entrainment of gas into the slug increases (as in all previous cases above) with increase in slug feed velocity. Also considering the change in liquid film velocity ahead of the slug, looking at Images (a) and (c) or (b) and (d) in each case the slug feed velocity being constant, the gas entrainment decreases with increase in the liquid film velocity in 1^o inclined pipe. This was what the calculations in the work of also depicted (Abdullahi, M.K. (20130)..

VII. PUSH-IN EXPERIMENTS WITH STATIONARY FILM

Hale (2007) performed this experiment on WASP high pressure facility with a diameter of 77.92 mm at Imperial College London to study slug gas entrainment. Using a weir, the liquid film was kept stationary. It was here repeated in a low pressure, 32.8 mm diameter pipe for flow visualisation.

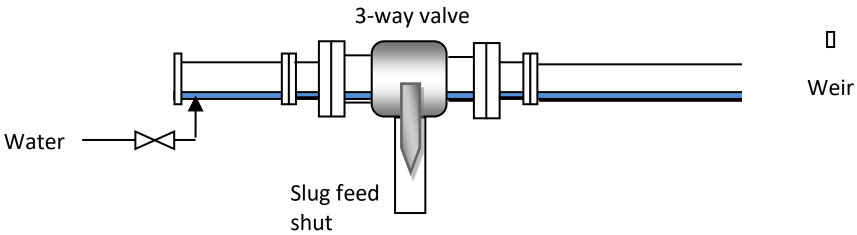


Figure 6 (a): Stationary liquid in horizontal test section

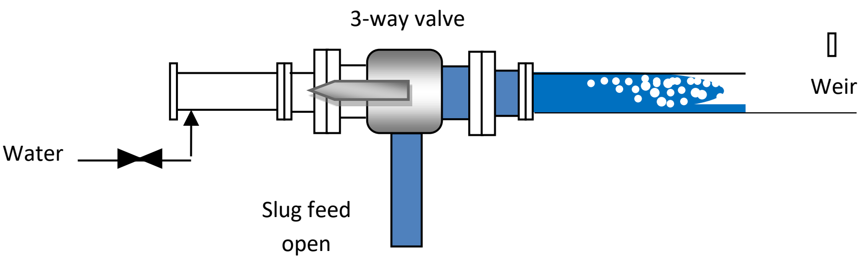


Figure 6 (b): Slug flowing over stationary liquid film in horizontal test section

The LOWPRESS test section was inclined upward by 1^o. Water was introduced through the exit section of the pipe at a known velocity into the test section as shown in Figure 4 (a).

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

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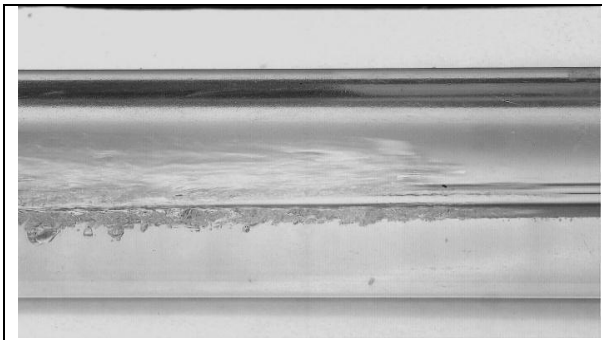
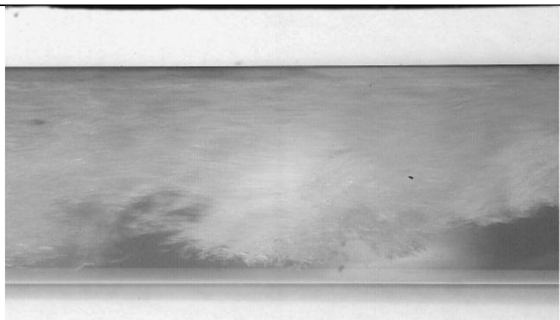
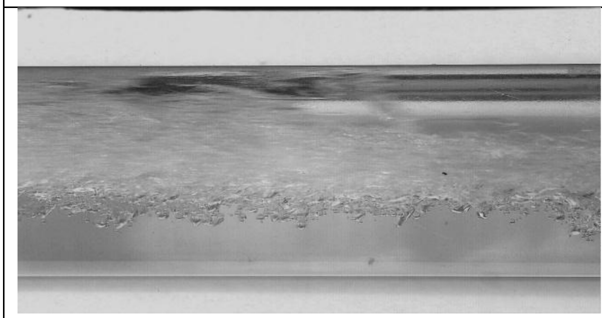
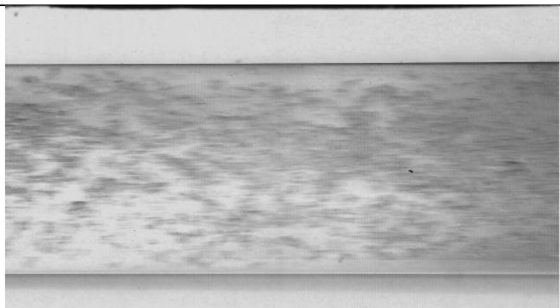
DOI: 10.17148/IARJSET.2023.10906

As the liquid was accumulating at the inlet section, the 3-way valve was opened to introduce the liquid slug, thus pushing the accumulated liquid out of the pipe as shown in Figure 4 (b). At this time, the liquid film (water) flowing into the test section at the outlet was shut as shown in Figure 2 (b). Using the highspeed Olympus camera, images were recorded and presented in Figures 5 (a) and (b).

Figure 7 (a) shows sequence of entrained slug images (i) – (xiv) from a movie for slug flow over a stationary film in horizontal pipe. There is a progressive increase in slug gas entrainment from the front to the slug body (see Images (i) to (vi)).

Then there is a clear decrease in the slug aeration towards the tail (see Images (vii) and (viii). After image (viii), a large bubble came up, may be due to the shedding of entrained gas at the slug tail [Images (ix) to (xi)]. The bubble then entrained the liquid behind it [Images (xiii) and (xiv)].

 **Time = 0.021s (i)** Slug front penetrating stationary film	 **Time = 0.168s (viii)** Slug scooping liquid film beneath it
 **Time = 0.031s (ii)** Slug front becoming entrained with bubble	 **Time = 0.178s (ix)** Fully entrained slug body
 **Time = 0.041s (iii)** Slug front bridging the pipe cross section	 **Time = 0.187s (x)** Slug near the tail

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.2023.10906

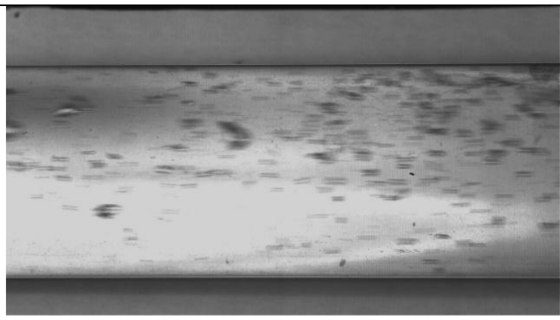
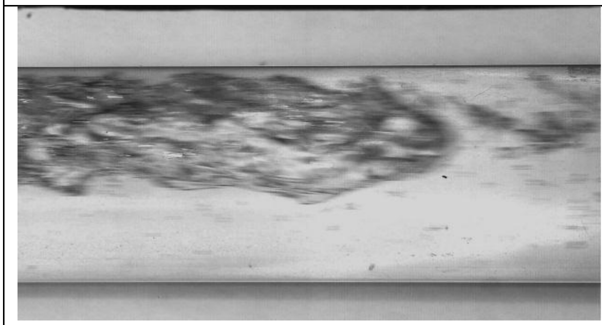
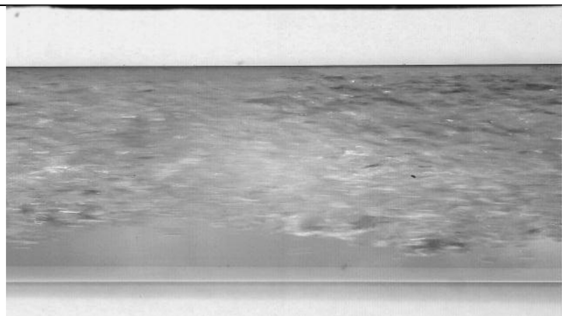
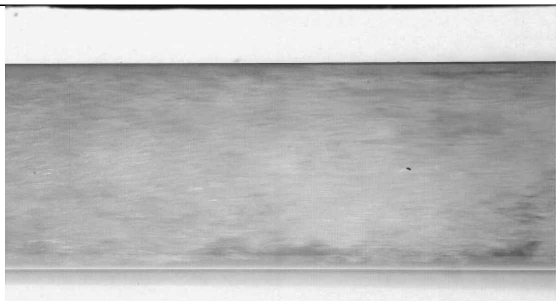
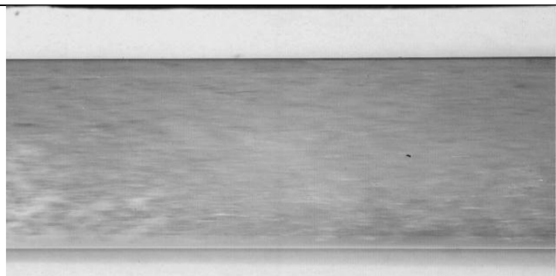
 **Time = 0.050s (iv)** Entrained slug body over a stationary film	 **Time = 0.200s (xi)** Slug tail sparsely aerated
 **Time = 0.058s (v)** Bubble behind slug tail	 **Time = 0.204s (xii)** Bubble mixing up with liquid slug
 **Time = 0.065s (vi)** Bubble over a liquid film	 **Time = 0.225s (xiii)** Fully entrained slug
 **Time = 0.118s (vii)** Bubble growing and film getting thinner	 **Time = 0.250s (xiv)** Slug body with entrained bubbles

Figure 7 (a): Sequence of instantaneous images for horizontal slug flows over a stationary liquid film

By increasing the weir height, the film held within the pipe also increases and this result in lower gas entrainment rate. This is clear by comparing image (i) or (ii) with (iii) or (iv) in Figure 7 (b). There appears to be high gas entrainment in image (a) than in image (d) which has a clear liquid beneath the aerated slug. The slug front also becomes irregular in shape with increase in film height and slug feed velocity. There is a good agreement with the calculations in Figure 3.3.20(c) with the slug gas entrainment decreases as the liquid film height increase (Abdullahi M.K. (2013).

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.2023.10906

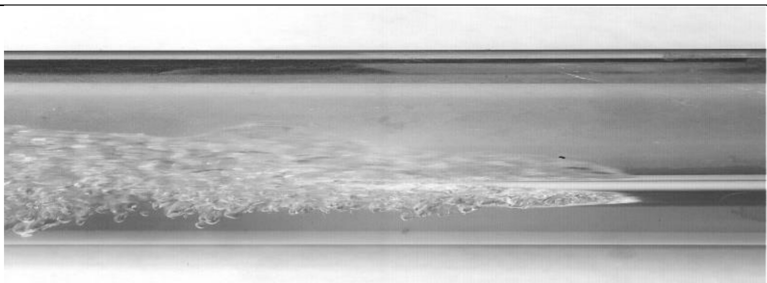
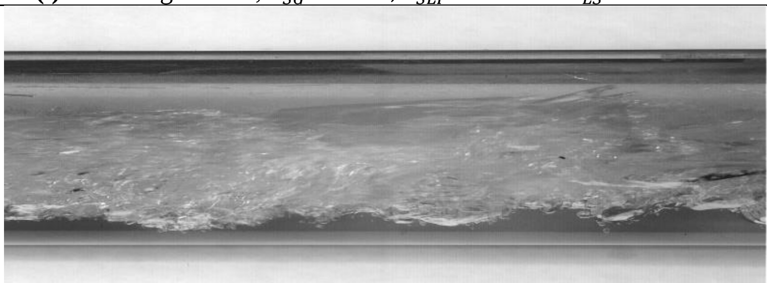
Time = 0.148s	 **(i)** Weir height 5mm, u_{SG} = 0.00, u_{SLF} = 0.00 & U_{LS} = 1.504 m/s
Time = 0.049s	 **(ii)** Weir height 5mm, u_{SG} = 0.0, u_{SLF} = 0.00 & U_{LS} = 3.727 m/s
Time = 0.114s	 **(iii)** Weir height 10mm, u_{SG} = 0.0, u_{SLF} = 0.00 & U_{LS} = 1.504 m/s
Time = 0.031s	 **(iv)** Weir height 10mm, u_{SG} =0.0, u_{SLF} = 0.00 & U_{LS} = 3.727 m/s

Figure 7 (b): Comparison of Movie Images for Horizontal Slug Flow over Stationary Liquid Film

VIII. COMPARISON OF SLUG FRONT GAS ENTRAINMENT FOR THE THREE METHODOLOGIES

Figure 7 compares, images of the slug front for similar conditions for the slug flow over a stratified gas-liquid flow, then over a back-flow of liquid film and finally over a stationary liquid film at slug feed velocity of 1.504 m/s. Looking down from image (a) to (c), it is clear that the slug front becomes less dense as the amount of bubbles increase. Image (a) looks more rigid and (b) looks foamy while in (c) there are clear bubbles in the slug front.

This shows that the slug is getting more aerated moving from stratified stream flow condition to stationary film flows. This situation is similar to the comparison made by (Abdullahi, 2013), which shows the plots of calculated gas entrainment for the three methodologies. The figure shows that there was more gas entrainment at the slug front for the stationary film experiments particularly at high relative velocities. This was also exhibited in Hale (2007) experiments and Hale et.al (2005).

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.2023.10906

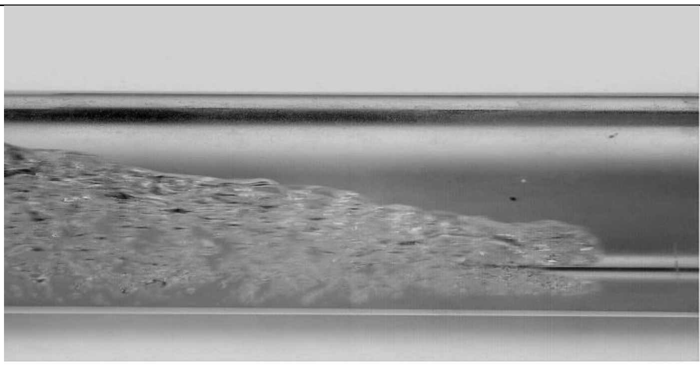
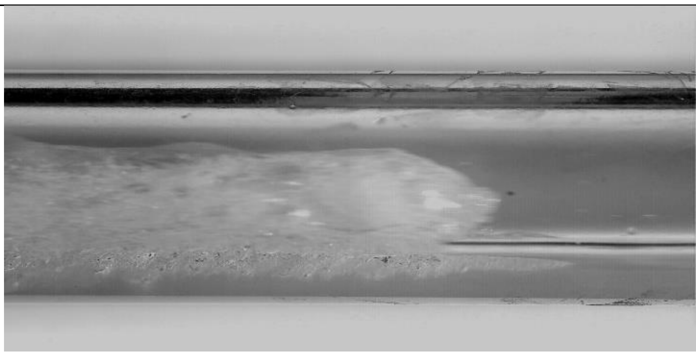
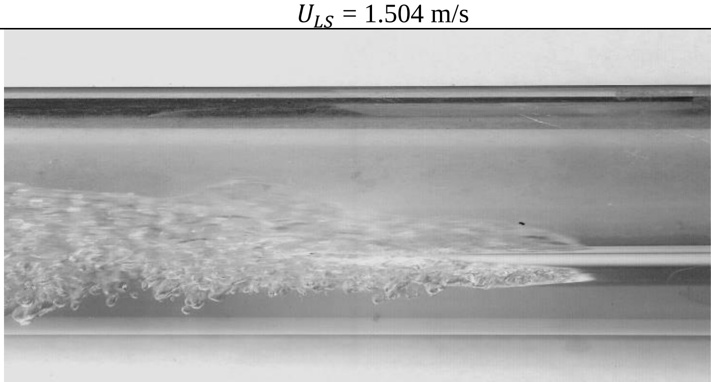
Time = 0.285s	 **(a)** Stratified Stream: u_{SG} = 2.16 m/s, u_{LF} = 0.03945 m/s & U_{LS} = 1.504 m/s
Time = 0.898s	 **(b)** Back-flow of Liquid Film: u_{SG} = 0.00 m/s, u_{LF} = -0.03945 m/s & U_{LS} = 1.504 m/s
Time = 0.148s	 **(c)** Stationary Liquid Film: U_{SG} = 0.00, U_{LF} = 0.0 & U_{LS} = 1.504 m/s

Figure 7: Comparison of Slug Front Aeration for the Three Methodologies at U_{LS} = 1.504 m/s

IX. CONCLUSION

Experiments were performed to visualise slug flow gas entrainment in pipes for different flow conditions. Instantaneous images from the four methodologies (slug with stratified flow, stationary flow, and back-flow of liquid and bubble experiments) show the occurrences of gas entrainment in slug flows. As earlier shown by calculations, images also show an increase in gas entrainment with increase in slug feed velocity. There are good agreements between what the images reveal, and calculations based on the concepts presented in Section 3.2.1 (Abdullahi M.K. (2013). For slug moving over stratified gas-liquid flow, images show that the entrainment rate increases with increase in both gas and liquid superficial velocities. Likewise, as calculations show, gas entrainment rate decreases with increase in back-flow of liquid in 1^o inclined pipe. Instantaneous images from the dog-leg experiments show that slug gas entrainment decreases with increase in slug feed velocity as shown by calculations in Chapter 4 (Abdullahi M.K. (2013)). Also, images show the occurrence of multiple slugs in both back-flow of liquid film and stationary film experiments (see Figures 5 (a) and 7 (a) respectively).

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

DOI: 10.17148/IARJSET.2023.10906

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