Effect of upstream conditions on the two phase flow in the large diameter vertical pipe

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Abstract

Two phase flow in large diameter vertical pipes is of considerable importance to various fields of multiphase flows. Recently, due to increase in demand in various energy sectors considerable attention has been paid in understanding the flow behavior in large diameter vertical pipes.

This paper reports the experimental results of flow pattern identification in relatively large diameter (254mm) vertical pipe. The present work also investigates the effect of upstream conditions on the flow patterns occurring in the vertical test section. The observed flow patterns are classified as bubbly, agitated bubbly, unstable slug and churn/froth flow. Absence of hydrodynamic slugging i.e. non occurrence of Taylor bubble in the riser is also reported. It is found that agitated bubbly and churn/froth type of flows dominates in the vertical large diameter pipe under the condition where conventional small diameter pipe indicates slug flow. Experimental results demonstrate the sensitivity of the flow patterns occurring in the vertical section with the upstream conditions in the flowline. The statistical analysis performed on the data along with visual observations, suggests that liquid slugs formed in flowline dissipate as they travelled up the riser, due to the high velocity distorted bubble clusters.

1. INTRODUCTION

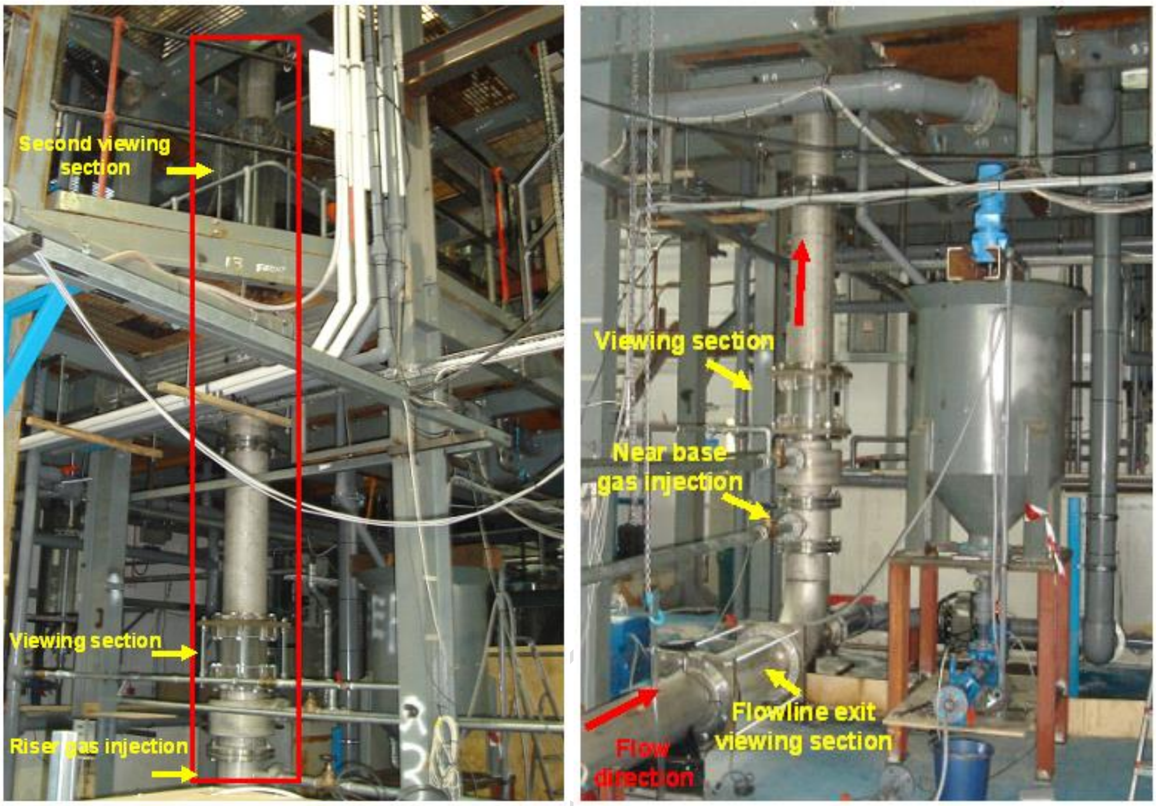
The two phase flow behaviour in large diameter (D> 100mm) vertical pipe as yet, an unresolved issue despite of its practical importance in many different industrial applications and processes. Although this field of the multiphase flows has received much attention in Oil & Gas and Nuclear industry as for the former interest lies in the economics (1) while for the latter the concern is safety requirements (2, 3). It is surprising that most of this research was confined to predicting the flow behaviour in pipe diameter less than 100mm. Currently, with the rise in production in Oil and Gas industries, along with the safety and economics involved within Nuclear industry, both industries are opting for larger diameter pipes.

Application of the larger size diameter, challenges the existing modelling methods and tools developed, as they are based on the experimental and field data that is mostly confined to more conventional smaller diameter pipes. Although, there are some exceptions also (2, 4 and 5). Additionally some previous research works suggests that the characteristics of multiphase flow in larger diameter vertical pipes are likely to be different from small diameter (1). For example slug flow, an alternate flow of liquid slugs and large elongated Taylor gas bubbles that are highly complex in nature, may not exist for large diameter vertical pipes (1, 2 and 5). This notion further introduces the uncertainty behind the predictive accuracy of the modelling tools as the best estimate codes are based on flow regime dependent constitutive equations. Moreover additional limitations of the above studies are that they have been restricted to identifying flow patterns in diameters less than 200mm and were performed on isolated riser's i.e. gas-liquid introduction in the vertical pipe base. Hence these studies do not include the effect of the flow path which is typical for certain applications like flowline-riser system, hot leg of a nuclear reactor or once through steam generator path that may have a horizontal inlet pipe connected to a vertical pipe. Here it is acknowledge that the results obtained in this paper may not exactly apply to field case of flowline-riser system due to the length constraints as the actual ratio of *L/D* in field cases are quite large in comparison to the experimental facility.

The current investigation was undertaken to determine the effect of inlet conditions on flow patterns occurring in large diameter vertical riser. The experiments were performed with two different inlet conditions namely near riser base gas injection and horizontal flowline inlet gas injection. The former represents the gas-liquid introduction in the riser base area while the latter corresponds to the gas-liquid introduction at the inlet of the flowline prior to the riser base. From these inlet conditions, the entrance effect on the two-phase flow regimes in the riser was studied. Here selected results of the experiments under two different inlet conditions are reported with emphasis to gas bubble disintegration phenomenon resulting into full or partial dissipation of liquid slugs in the vertical riser section. No Taylor bubble in the vertical riser section was observed under the both inlet conditions.

2. EXPERIMENTAL FACILITY

Figure 1 shows the large diameter horizontal pipeline-vertical riser facility built in School of Engineering at Cranfield University. The rig comprises of an air compressor system (air loop) and water pump system (water loop), horizontal pipeline and vertical riser, upper plenum consisting of overhead/return tank, downcomer and a return line to sump. The horizontal pipeline section is of 36m in length (254.5 mm nominal diameter) while riser section is of same size with 12.2m in height. The large diameter riser rig is built with enough flexibility so that various parametric effects could be studied by changing or modifying the setup. Thus the air injection provisions are available at the start of the horizontal pipeline to study the two phase flow entering the riser and/or air injection slightly above the riser base. The air travelling from the riser section is vented to the atmosphere in the upper plenum while water flows from the side of the upper plenum into the overhead tank and than to the downcomer. The downcomer is made up of a 162.5mm diameter heavy duty PVC pipe offering a flow path either to the sump or recirculating back to the riser at the base. The pipeline-riser is equipped with special high pressure Perspex viewing sections to observe the flow pattern occurring in the pipeline-riser system. One Perspex section is installed 2m from upstream of the riser base in the pipeline that aids in visual observation of the air-water flow entering in the riser. The riser section also contains four Perspex sections of 1m in length installed at different heights for viewing the flow patterns along the riser height. Pressure transducers are installed at various locations in the pipeline-riser section to measure the pressure time series. Two differential pressure cells in the riser at the height of 5 and 7m from the ground level along with the two pressure sensors at the top and bottom of the riser were used to deduce the void fraction measurements.



(a) **(b)**

Figure 1. Photographic views of large diameter riser setup (a) the vertical riser section and (b) horizontal pipeline-riser base.

The sectional and overall void fraction from differential pressure measurements is estimated under the assumption that the differential pressure equals to static pressure by neglecting accelerative and frictional pressure losses. The over all void fractions calculated is in good agreement with values calculated from previous measurements. However for the purpose of this paper, only the readings of the two differential pressure cells at 5m and 7m height in the riser were considered. All these transducers are flush mounted, so they do not interfere with the flow and are installed near to the Perspex sections so that simultaneous signal acquisition and videoing can take place. Both water and air supply to the facility is carried out in a controlled manner with flow meters measuring individual flowrates at the inlets to the pipeline-riser system. Water measurements are performed with an electromagnetic flow meter while air flowrates is measured using Mass Probar and Vortex flow meters. All the signals are acquired through two separate data acquisition systems using DeltaV and LABVIEW. The DeltaV plant automation system was used to set and controlled the air flow rates delivered from the compressor while the signals from the instrumentation installed at various locations in the pipeline-riser setup were acquired through dedicated LABVIEW software (6).

3. RESULTS AND DISCUSSION

Experiments were carried out to study the flow patterns occurring in the flowline and the vertical riser section. The gas and liquid superficial velocities were varied over the range of 0.09 - 2.40m/s and 0.17 to 1.10m/s respectively. Figure 2 indicates the range of experiments conducted plotted on the flow pattern map (7). Here results of only selected cases (marked on Figure 2 as A, B, C, D, E, F, G and H) will be presented for both inlet conditions.

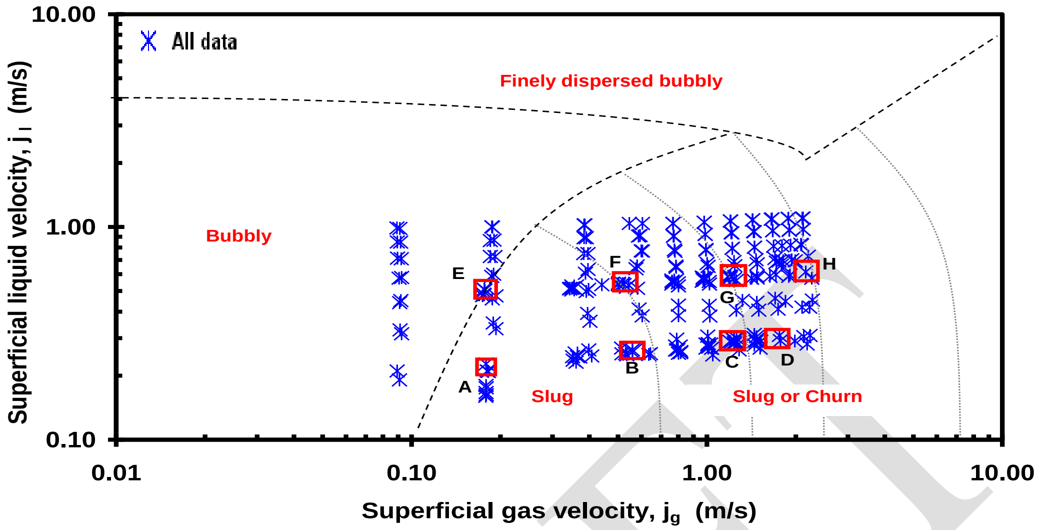


Figure 2. **Test data located on a Taitel et al. (1980) vertical flow pattern map.**

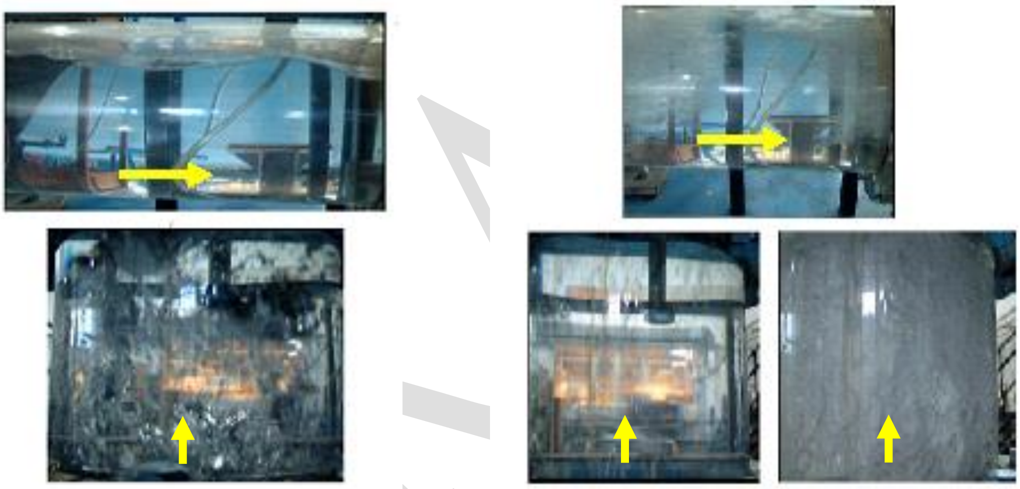
For the experimental range mentioned above, flow pattern identification has been performed by three methods: (a) visual observation of the flows from the Perspex sections installed, (b) by the pressure sensor response located at different strategic positions in the flow loop and (c) by measuring and quantifying fluctuations of the void fraction in the riser through statistical analysis. The pressure fluctuations are found to be the characteristic of the individual flow patterns hence the visual observations of flow patterns in the flowline were supplemented by the pressure measurements near the flowline exit in the riser base. In addition to these pressure measurements statistical procedures are employed to identify the prevailing flow regimes in the riser as adopted by many previous researchers (8, 9, 10 and 11). It is assumed for the identification of flow regimes that the void fraction at the measurement location is solely based on gravity pressure drop and neglecting the frictional and acceleration components. The procedure employed discriminates the two phase flow regimes based on probability density functions of void fraction fluctuations. The differential pressure signals were acquired from the riser height 5m and 7m and void fraction were estimated, these are represented as VF1 and VF2 on preceding figures.

(a) **(b)** **(c)**

Figure 3. Flow regimes in vertical riser with air entrance from the base observed at 5m height (a) bubbly, (b) agitated bubbly and (c) churn/froth flow – (arrows are indicating flow direction)

3.1 Visual flow pattern observation

In all the experiments of air injection near the base of the riser, the observed flow regimes were bubbly, agitated bubbly or churn/froth flow regimes (see Figure 3). Bubbly flow pattern was observed at low gas superficial velocities with gas phase distributed as distorted bubbles in water and flowing upward along with the liquid. For medium gas superficial velocities (0.2 $<U_{sg}<$ 1.18m/s) the riser flow pattern was mainly agitated bubbly at almost all liquid superficial velocities investigated. In fact the agitated bubbly flow regime with bubble coalescence/break-up and rapid agitation dominated the slug flow regime of the flow pattern map (7). The difference between the previous bubbly and this flow regime was the larger distribution of distorted bubbles flowing in clusters in the riser with rapid agitation and randomness in the liquid flow around it. For lower liquid and highest gas superficial velocities (1.2 $<U_{sg}<$ 2.2m/s) the flow transformed to churn/froth flow within the riser with highly visible chaotic oscillations by frothy mixture. It is emphasised here that for near riser base air injection <u>no slug flow</u> was envisaged in the riser during all the conducted experimental runs.



(a) **(b)**

Figure 4. Flow regimes in horizontal flowline-vertical riser (a) stratified (top) with agitated bubbly in vertical riser (below) and (b) short slug followed by gas bubble (top) with liquid slug and distorted gas bubble in riser (below) – (arrows are indicating flow direction).

For the air injection at the upstream of the riser base i.e. at the inlet of the flowline four typical flow regimes have been characterized in the riser section namely bubbly, agitated bubbly, unstable slug and churn/froth flow with stratified, elongated bubble and slug flow in the flowline (see Figure 4). Similar to near riser base gas injection bubbly and agitated bubbly flow regimes prevailed in the riser under stratified and elongated bubble flow at low to medium gas superficial velocities. However, at higher gas superficial velocities (and low liquid superficial velocities) although the flow in flowline appeared stratified, there was liquid accumulation at the base area. As this liquid pool was pushed up in the riser by incoming air bubble a more cyclic churn/froth type of the flow was observed in the riser. Based on the visual observation it is thought that gas bubble flowing behind the liquid slug attains high enough inertia due to compression by preceding slug so, when it enters the riser and expands, it rapidly break through the liquid slug preceding it (Figure 5a-b). Once the gas penetrates the liquid slug, the gas-liquid interface was no longer clearly identifiable except for a collapsing frothy interface (Figure 5c-d). The collapsing interface was mixed up with incoming liquid slug or distorted gas bubble. In the first case of liquid slug this mixture aerated the slug while moving upward and was seen to undergo similar process in subsequent sections of the riser. While in latter case this fall back of frothy mixture on distorted gas pocket made it further distorted and foamy. The flow in the riser appeared to be agitated frothy flow with rapid upward and downward motion from the Perspex walls.

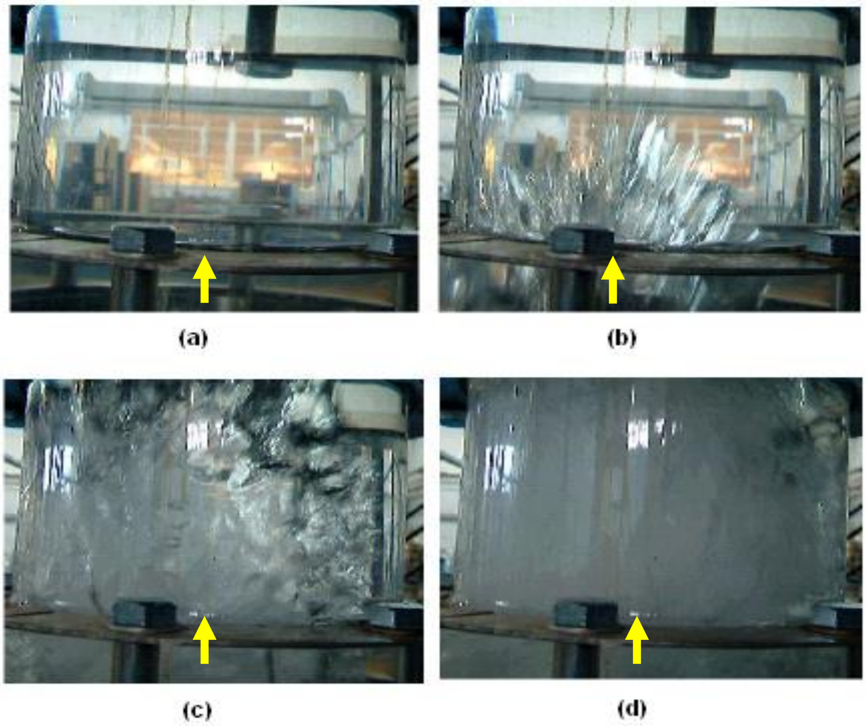


Figure 5. Liquid slug dissipation in the riser (a) liquid slug (b) distorted bubble entering the liquid slug (c) distorted bubble penetrating in the liquid slug and (d) fall back of the liquid film.

At higher gas-liquid velocities the flow became highly chaotic in nature in the riser due to collapsing gas-liquid interface, fall back and frequent arrival of long gas bubble/liquid slugs from the flowline causing temporarily blockage of the riser base. It is emphasised here that in some cases some of the structure of liquid slug survived this penetration of the gaseous phase and travelled ahead as a short aerated slug (typically around ~0.4m length). Some of the liquid slug structure did survived; hence this flow was called unstable slug flow. It is pointed out that when these liquid slug neared the exit section, the gas phase in the slug was no longer able to support and the liquid falls back again under gravity. Attention is drawn to the aspect of the fall back of the mixture near the base. Figure 6 shows the fall back at ground level near the flowline exit which appeared similar to the fall back and liquid accumulation seen in smaller diameter riser (12). This again compressed the incoming flow from the flowline there by initiating a new cycle of high velocity incoming bubble and accompanied liquid slug in the flowline. It is to be noted here that in the near riser base gas injection experiments this phenomenon was not observed for the entire set of experiments. So it can be concluded that this particular flow in riser section was encountered as consequence of slugging in the flowline. With further increase in gas superficial velocities (and higher liquid velocities) the flow was highly oscillating more like churn/froth type of flow in the whole riser.

3.2 Near riser base gas injection

Figure 7 and Figure 8 represents the PDF's plots obtained from the two riser sections under different gas-liquid superficial velocities for the near riser base gas-injection. Case A and Case E represents the void fraction Probability Density Function (PDF) plots under low gas superficial velocity. The PDF's obtained indicates thin distinct peaks at lower void fractions values implying the presence of the smaller quantity of gaseous phase in liquid. The lower section indicates smaller bubble distribution hence more peaked while the upper section (VF2) indicates a broader bubble distribution signifying gaseous expansion as it travels upwards. Case E is of higher liquid velocity then Case A and hence has a more prominent peak.

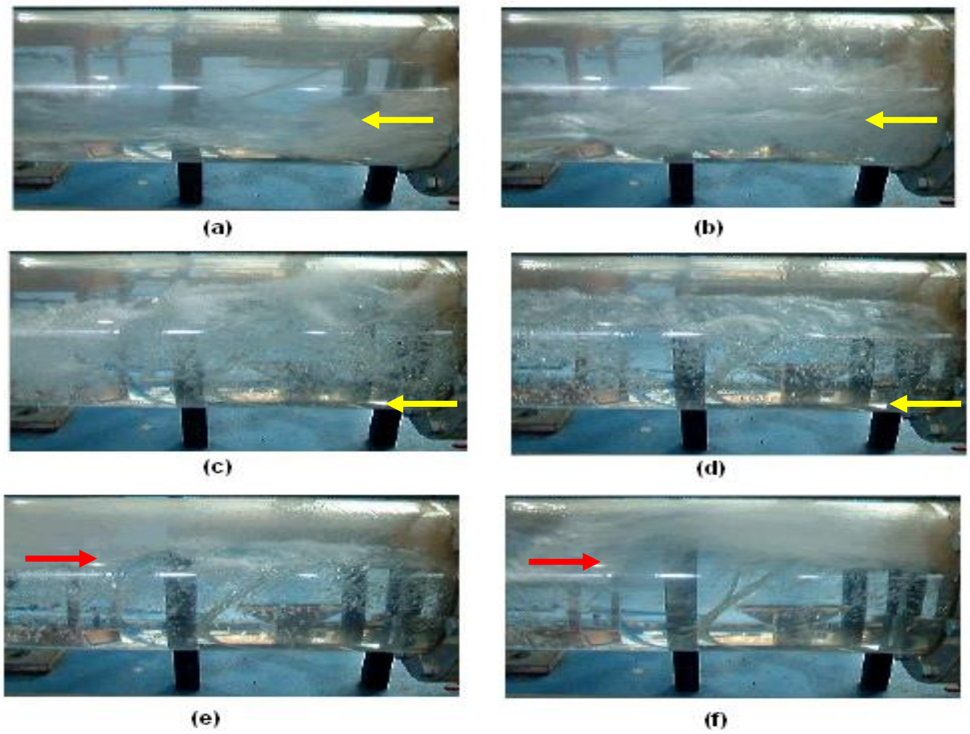


Figure 6. (a-d) Frothy mixture fall back near the base in the flowline and (e-f) compressional effect on the gaseous phase – (yellow arrows indicating fall back while red indicating flow direction).

Case B and Case F corresponds to the increase in superficial gas velocity, that has resulted in still a single peak PDF's but much broader in distribution than observed in previous case of bubbly flow. In the visual observation, this flow regime was identified as agitated bubbly flow in order to differentiate with bubbly flow found at very low gas velocities. The broad peak represents the wider bubble sizes due to the transition of flow from bubbly to agitated bubbly flow regime. The agitated bubbly flow region was observed at all intermediate superficial gas velocity range (U_{sg} = 0.2 ~1.5 m/s). The two apparent distinctions among the PDF's in this gas superficial velocity range is the difference in the mean void fraction value and broadening of the bubble distribution with increase in gas superficial velocities accompanied by rapid increase in agitation (see Case C and Case F).

Upon further increase in gas superficial velocities, i.e. Case D in Figure 7 (and Case H in Figure8) the flow transforms to churn flow. This flow was chaotic and highly turbulent with long irregular gas bubble clusters travelling upwards within the core with high velocity and the liquid film surrounding either travelling upwards and/or falling downward. The PDF's are still single peaked but there is the shift in the distribution towards higher void fraction with tick tail extending towards the lower void fraction. The presence of the large broad tail towards left of the distribution indicates the frothy nature of the flow with some liquid bridging between the irregular gas bubble clusters. With increase in water flowrate this broad tail of left subsided and more single peaked PDF at lower void fraction is observed. The PDF's in Figure 8 corresponds to these cases. All the PDF's in these cases indicates a single peak but with lower mean void fraction and less skewed towards higher void fraction due to presence of larger liquid inventory in the pipe in comparison to lower liquid velocities.

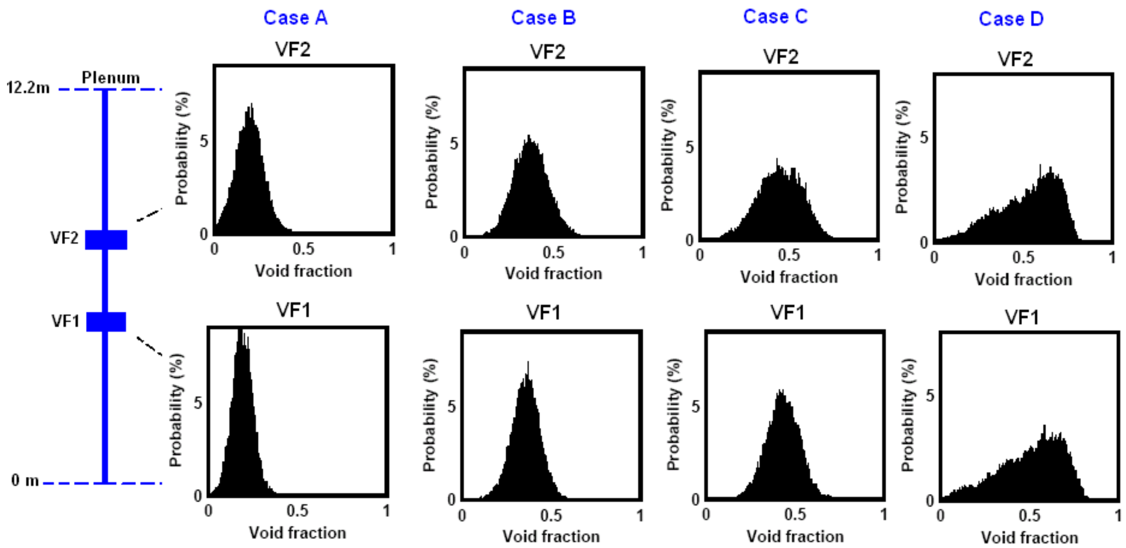


Figure 7. Probability density function plots obtained under near riser base gas injection condition for Case A: U_{sl} =0.20 U_{sg}=0.20m/s, Case B: U_{sl} =0.26, U_{sg}=0.56m/s, Case C: U_{sl} =0.30, U_{sg}=1.20 m/s and Case D: U_{sl} =0.30, U_{sg}=1.70 m/s.

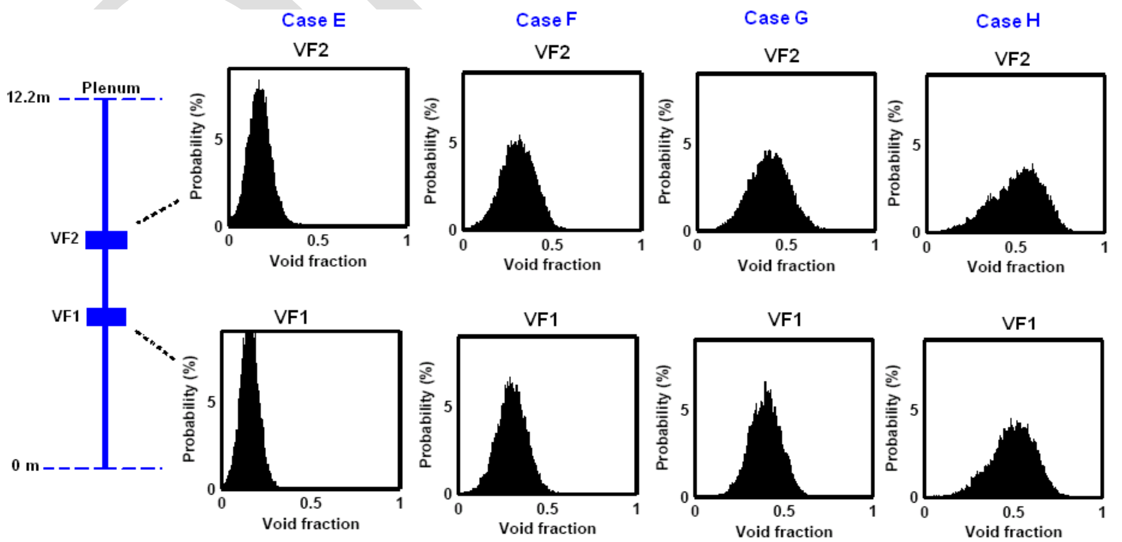


Figure 8. Probability density function plots obtained under near riser base gas injection condition for Case E: U_{sl} =0.50 U_{sg}=0.18 m/s, Case F: U_{sl} =0.53, U_{sg}=0.54m/s, Case G: U_{sl} =0.58, U_{sg}=1.20 m/s and Case H: U_{sl} =0.58, U_{sg}=2.08 m/s.

The resulting flow patterns from the above cases and others analysed in near riser base gas injection conditions are compared to typical flow pattern map of vertical flow (7) in Figure 9. The inadequacy of the current flow pattern map based on smaller diameter pipes can be clearly seen i.e. under similar conditions of gas-liquid superficial velocities the flow pattern map would indicate slug flow. However the current set of experiments proves that in this 254mm nominal diameter vertical pipe, agitated bubbly flow regime with bubble coalescence/break-up dominates the flow regime map. The statistical analysis further proves that no bi-modal or twin peak PDF representing the liquid slug and Taylor bubble is observed under these experiments validating the visual observations.

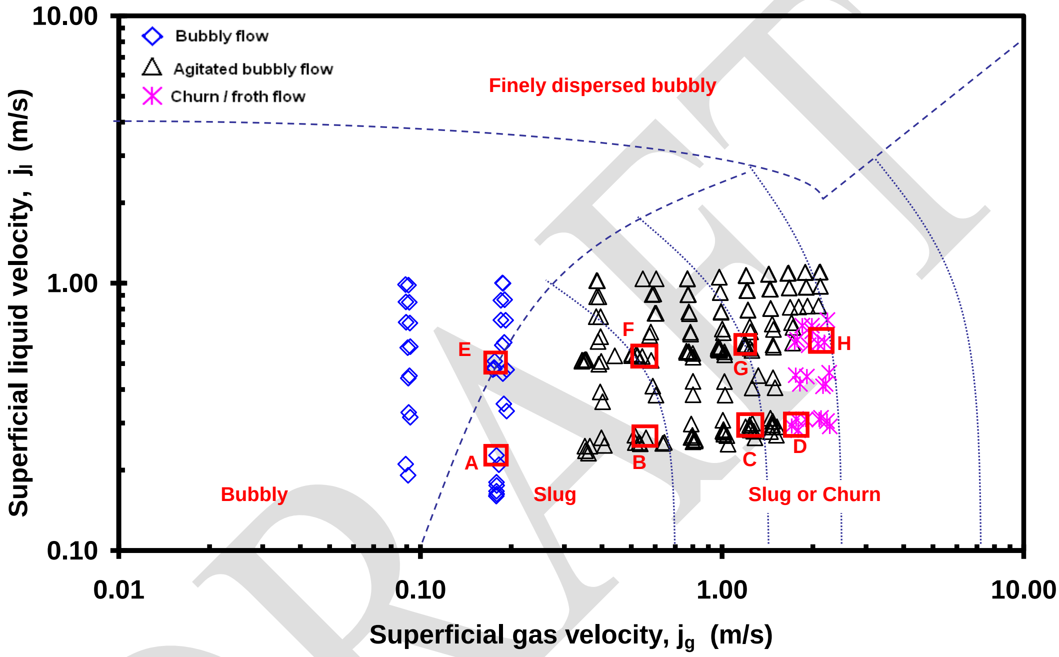


Figure 9. **Selected cases plotted on a Taitel et al. vertical flow pattern map (7).**

3.3 Upstream flowline gas injection

For upstream flowline gas injection the selected test points are presented in Figure 10 on the horizontal flow pattern of Taitel and Duckler (13). The flow patterns observed are in good agreement with the flow pattern map. In comparison to inlet conditions in section 3.2, Figure 11 and 12 illustrates the selected flowline gas injection cases. These figures also accompany the pressure profiles near the exit of the flowline along with the probability density function plots. To study the effect of the inlet conditions of the flowline gas injection, the cases of gas-liquid superficial velocities studied in Figure 11 and 12 are same as in Figure 7 and Figure 8.

The flowline pressure profiles of case A and case E in Figure 11 and Figure 12 are typical for the stratified flow condition occurring at low gas-liquid superficial velocities along with the PDF obtained from the riser showing a distinct unimodal peak at lower values of void fraction. The distinct peakness and smaller width of the distribution represents the dispersed type of bubbly flow in the riser. During the intermediate flowrates of gas ($0.4 < U_{sg} < 1.4$m/s, cases B and C) when flowline was wavy stratified, the flow pattern in the riser essentially remained agitated bubbly with single peak and broad distribution like near riser base gas injection. On the flow regime transition from these flowrates the single broad PDF distribution slightly skewed at higher void fractions indicating the presence of various sizes of bubbles in the riser test section (case C). Note the differences between Figure 7 (case B and C) and Figure 11(case B and C), the heights of PDF's are reduced and there is much broader and even void fraction distribution for flowline gas injection inlet condition. However while the near base gas injection case C (Figure 7) still indicates the agitated bubbly flow regime, Figure 11 (case C) indicates the flow transition from agitated bubbly flow regime.

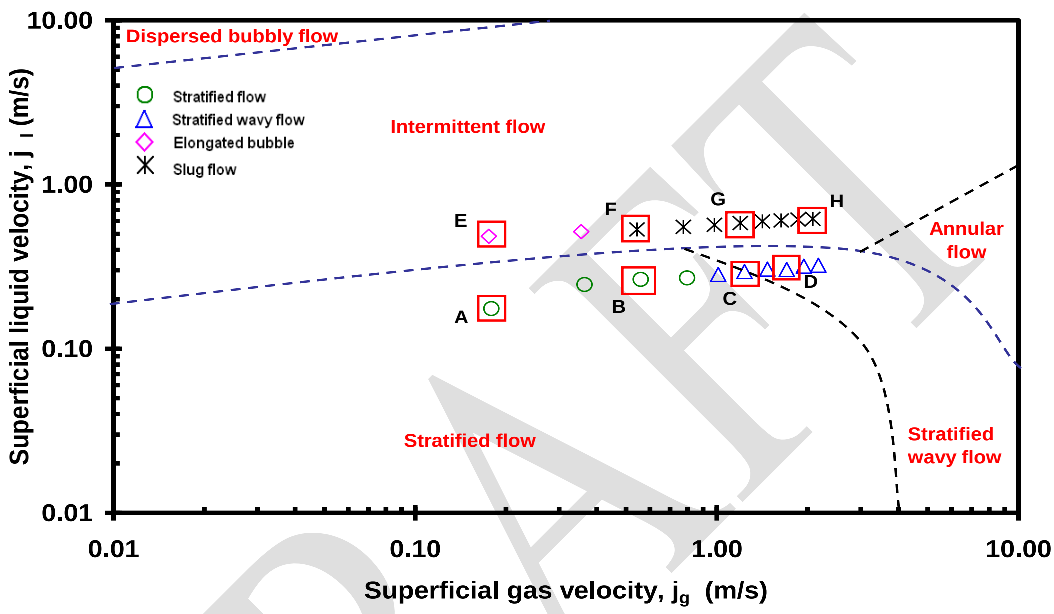


Figure 10. **Test points located on a Taitel and Duckler horizontal flow pattern map (13).**

In cases before case D (not presented here) all belonging to stratified flow regime in the flowline, liquid accumulation near the base was seen. This accumulation started when the transition in the riser appeared from agitated bubbly flow regime. Figure 11 (case D) indicates the pressure sensor response and PDF's when the flow is transformed to cyclic slugging in the near riser base vicinity. The pressure sensor near the exit indicates almost periodic/cyclic frequency of slugs having cycle of 10s. These pressure profiles are similar to the ones observed by (12 and 14) under the unstable flows in horizontal flowline-vertical riser configuration. However during this flow regime occurring in the flowline, the liquid slugs were disintegrating in the riser section. The peak of the PDF kept shifting towards higher void fraction with a clear prominent peak of gas phase at higher void fraction with long tail towards left (lower void fraction) indicating a frothy flow with some liquid bridging. For the cases C to D and onwards the gas flow rate is high compared to the liquid flow rate, consequently the accumulation or fall back from disintegration of the slugs is not enough to block the riser base and there is continuous gas penetration as suggested by the constant pressure variation in the flowline. The comparison with Figure 7(case D), i.e. both inlet conditions (Figure 7 and Figure 11 cases D) are indicating similar trends of PDF's i.e. a churn/frothy type of the flow in the riser not the slug flow or bi-modal peak in PDF's.

Case E to H in Figure 12 represents the cases under the slow moving long elongated bubble and slug flow conditions in the flowline. The increase in the liquid inventory has resulted in more distinct single peak PDF's representing bubbly flow regime in the riser in case E. The cases F, G and H in Figure 12 are essentially when highly unstable and chaotic flow in the riser was observed. Case F represents the frequent slug initiation in the flowline. During this flow regime the slug arrival continued from the flowline into the riser while the gas pocket that became highly distorted within the riser penetrated the liquid slug ahead making the slug unstable, collapsing and falling back into the lower section of the riser. Thus the PDF's (see case F) appears more flatten with much wider void fraction distribution marching towards the right (higher void fraction end). In Figure 12, case G the first void fraction PDF (VF1) does not contain a clear peak in the distribution but the second PDF (VF2) from the higher location in the riser indicates a progressive development of another peak at higher void fractions. The twin peaks have almost similar heights representing the simultaneous decay of liquid slugs and coalescence of gas bubbles in the core region. With further increase in gas flow rate the weak slug peak tends to disappear and gas dominate peak moves to further right and increase in height. It is emphasized here that this PDF is not the one that is typically observed in conventional slug flow representing liquid slug and Taylor bubble. Previous researchers (15) have referred this flow as a transitional flow encountered between conventional slug and churn/froth flow.

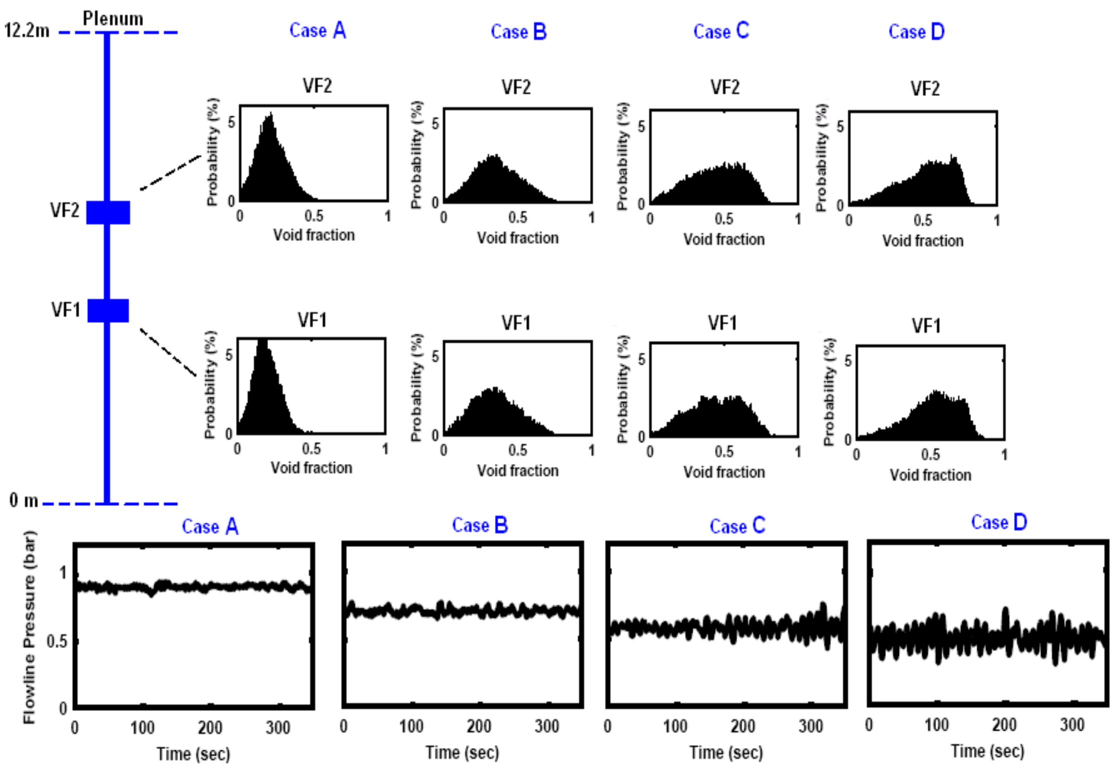


Figure 11. Probability density function plots obtained under flowline gas injection inlet condition for Case A: U_{sl} =0.18 U_{sg}=0.20m/s, Case B: U_{sl} =0.26, U_{sg}=0.56m/s, Case C: U_{sl} =0.29, U_{sg}=1.24 m/s and Case D: U_{sl} =0.30, U_{sg}=1.70 m/s.

Like case F and G, case H in Figure 12 represents the highly unstable and chaotic flow in the riser. The pressure measurements in Figure 12 represent the slugs arriving frequently to the riser base area. The interesting feature of this flow was as the liquid slug reached the riser and entered the base section, there was slowing down of the liquid accompanied by temporary accumulation of the falling frothy mixture from within the riser causing the gas bubble behind to compress. Note the liquid build up in Figure 12 (case H) is due to the rise in the liquid level within the flowline and base vicinity. The rise in the liquid level results from the accumulation of the incoming liquid slug and/or thick film of liquid with distorted bubble and from the fall back of the frothy mixture. In the latter case (fall back), the liquid accumulation (smaller peaks, Figure 11) causes partial blockage to the gas passage that then accelerates towards the riser and scoop through the short slug in base area while in former case semi-penetrates into the longer slug while travelling ahead. This is indicated well in the pressure profiles by the one or two small slugs followed by a longer slug. The flowline pressure in Figure 12 (case H) does not correspond to a completely filled riser but the pressure trend indicates that the flow in the riser and base vicinity is cyclic and unstable in nature. The pressure measurements do not have a slug production period indicating the temporary nature of the liquid build up in the base. The liquid slug formed in the base and pushed into the riser by the gas there is no liquid backup in the flowline (see Figure 6). The gas penetration in the base and liquid slug sloshing out of the riser is also not individually identifiable in Figure 12.

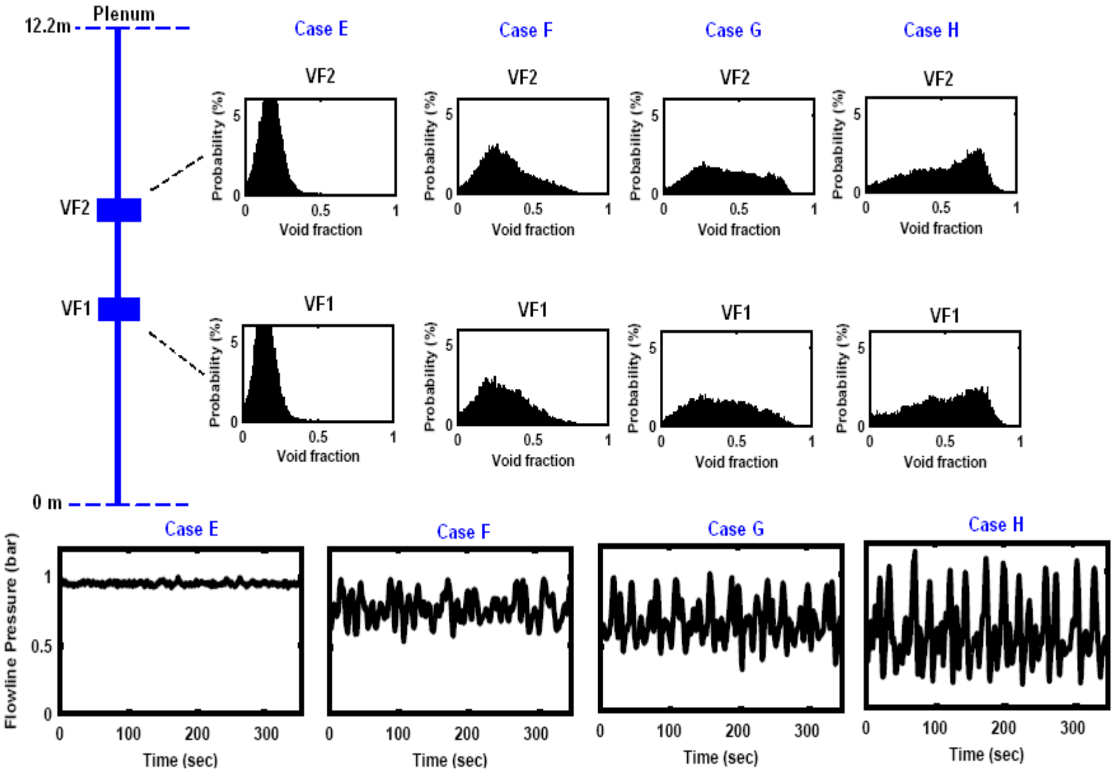


Figure 12. Probability density function plots obtained under flowline gas injection condition for Case E: U_{sl} =0.50 U_{sg}=0.18 m/s, Case F: U_{sl} =0.53, U_{sg}=0.54m/s, Case G: U_{sl} =0.58, U_{sg}=1.20 m/s and Case H: U_{sl} =0.600, U_{sg}=2.1 m/s.

It can be concluded from the Figures 12 that when the flowline was experiencing hydrodynamic slugging, some of the liquid slugs were dissipated while travelling upward, due to long and highly distorted gas bubble clusters that penetrated through them. This can be verified by the occasional appearance of a weak peak at lower void fractions along with strong prominent peak at higher void fractions in the PDF's. From the Figure 12 (case H) it can also be noted that the liquid fall back results in the reduction of the gas phase (void fraction) in lower sections and showed indistinct peaks in PDF plot at location 1 in the riser. Also note that the peak at the high void fraction (VF2) is not only higher than rest of the distribution but also broader indicating that the gas bubbles are longer and distorted. There is also long thick tail extending towards lower void fraction indicating some of the survived liquid slugs and frothy air-water mixture which is typical characteristic of transitional flows.

Figure 13 indicates the flowline gas injection cases on the vertical flow pattern map. It is observed that under low liquid velocities (with 0.18 <Usg< 2.2m/s), the flow patterns observed are in conformity to the ones observed at inlet condition of near riser base gas injection. At higher liquid superficial velocity though the agreement between the two conditions still exist for low gas superficial velocities some disagreement is observed in the range of 1.2 <Usg< 1.63 m/s. This range consisted of unstable slug flow regime of collapsing slugs with the PDF's not containing the clear bi-modal peaks. However with any further increase in gas superficial velocities, the flow regime transformed to churn/froth type of flow as seen in near riser base injection.

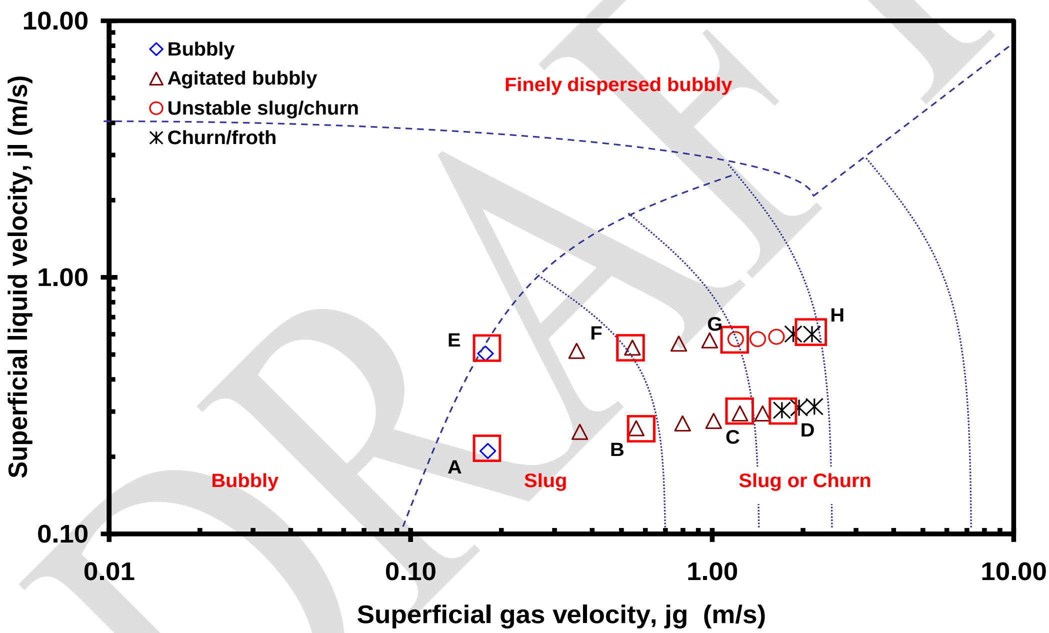


Figure 13. Flowline gas injection test points located on a Taitel et al. vertical flow pattern map (7).

4. CONCLUSION

Following conclusion can be drawn based on the experimental results:

- Three different flow patterns were observed in the vertical riser namely bubbly, agitated bubbly and churn/froth flow in near riser base gas injection. In contrast to the slug flow regime indicated by vertical flow regime map (7) based on smaller diameter data, agitated bubby flow regime is found to dominate this (slug flow) region in our experiments.
- Flowline gas injection inlet condition indicated bubbly, agitated bubbly, unstable slug and churn/froth flow. Unstable slug was detected in some runs between gas superficial velocity range of 1.2 <Usg< 1.63 m/s only.

- No effect of inlet conditions is observed at low gas superficial velocities; however some differences are seen in the limited range of liquid and gas superficial velocities ($U_{sl} = 0.59$m/s and $1.2 < U_{sg} < 1.63$ m/s) where some unstable slug flow is detected. This can be considered as the flow regime where the flow exhibited the remains of slug flow structure (from the flowline) but was less stable as the flow transformed into churn/froth flow upon increase in gas flow rates.
- The overall results of the probability density function plots obtained in the experiments are in agreement with earlier works. The probability density function plots indicate that all flow pattern transitions took place over a range of flow rates. This work also corroborates the absence of conventional slug flow in large diameter vertical riser as the slug flow is not observed neither the bimodal peak associated with it in probability density function plots.
- From the experiments it is demonstrated that the intermittent flow behavior in flowline influences the riser flow pattern characteristics and thereby controls the riser dynamics. It is postulated that three forces namely gravitational force, compressional forces of succeeding bubble and turbulent forces associated with two phase are responsible for the slug collapse into churn/froth type of flow in large diameter pipes.
- It is seen that as the gas superficial velocity increases at the low liquid flowrate, periodic instability sets in. However when liquid superficial velocity increases this periodic instability is taken over by more chaotic instability within the riser, the severity of which increases with gas superficial velocity because of the increase in liquid holdup within the riser base and flowline. The distinction of this instability at higher gas flow rates is not clear with riser flow pattern alone but it seems that riser flow pattern influences the flowline behaviour to generate this instability.

5. REFERENCES

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