Two Phase Flow Patterns in Large Diameter Vertical Pipes

Shazia F. Ali and Hoi Yeung*
**Faculty of Chemical & Process Engineering,*
NED University of Engineering & Technology, Karachi 75270, PK.
Department of Offshore, Process & Energy Engineering,
Cranfield University, Cranfield, Bedfordshire MK43 0AL, UK.
sfaqazi@neduet.edu.pk and h.yeung@cranfield.ac.uk

Abstract

An experimental investigation of adiabatic upward co-current air-water two phase flow has been carried out to determine the flow patterns in a 12.2m high and 250mm nominal diameter vertical pipe. The visual observations of flow patterns were supplemented by statistical analysis of the time-averaged void fraction determined by pressure drop method. Five flow patterns were identified in the vertical test section namely – dispersed bubbly, bubbly, agitated bubbly, churn/froth flow within the experimental superficial velocity range (j_a = 0.18-2.2m/s and j_w = 0.18-1.2m/s). Conventional slug flow consisting of smooth bullet shaped bubbles (Taylor bubble) and liquid slugs was never observed, instead agitated bubbly flow was the most dominant flow pattern in relevant superficial velocity range. Based on the visual and statistically extracted information, a flow pattern map was developed and compared to the existing flow pattern maps. Available flow regime transition models compared against the present experimental data yielded poor agreement with none of the existing models predicting the transitions as a whole. A satisfactory agreement was obtained with other large diameter studies with inconsistencies mainly attributable to confusion in the identification of the flow patterns.

***Keywords**: two-phase flow, flow patterns, flow pattern transitions, large diameter, vertical flow.*

1. Introduction

Two phase flow in pipes is frequently encountered in various industrial processes, such as petroleum, nuclear, chemical, power generation, refrigeration etc. The prediction of flow patterns in these pipes is of paramount importance to the process design engineer because often the performances of the industrial processes strongly depend on it, for e.g. the simultaneous transport of gas-liquid in a pipe will result in the pressure losses, also the mass and heat transfer rates differ significantly from one flow pattern to another, therefore the knowledge of which flow pattern is occurring under which condition is important. Additionally in some cases a particular flow pattern is to be avoided, for example slug flow - an alternate flow of liquid slugs and large elongated gas bubbles is a main cause of operational problems in many gas-liquid systems; firstly because it produces large pressure drops, secondly it produces hammering affect in pipelines, thirdly this cyclic flow of liquid slugs and gas can be damaging for upstream processing facilities.

Recently, due to growing demand of comfort, various industries like power generation, nuclear, oil & gas exploration and refrigeration require increase in production rates, which directly implies the use of larger diameter piping network. Although the Oil and Gas production industry frequently employs vertical pipe sizes from 75mm to 150mm (commonly referred as risers!) in transferring the crude products from the reservoir to processing facilities, the fast depletion of near-shore fields have increased the necessity to employ diameter sizes greater than 200mm recovering hydrocarbons from much deeper seas with harsher and remote environments at an acceptable cost. The use of large diameter vertical risers is not just confined to oil and gas industry but is also relevant to nuclear and refrigeration industries. In actual nuclear reactor, the range of hydraulic diameter of pipes varies in range of 0.01 to 1m and the length of these piping also has a wide range. Even ASHRAE studies (RP-107 & RP-134) recommend the need for obtaining reliable two phase flow data on pipes sizes of 101.6 to 203.2mm due to large new industrial refrigeration systems employing wet-suction return piping in sizes as large as 609.6mm in diameter. In this context, the flow behaviour in large diameter ($D >$ 150mm) vertical pipe has become a subject of great interest. However, it is found that little studies of two phase flow in large diameter vertical pipes have been conducted and the vertical two-phase flow in large diameter pipes is still not well understood. Moreover, the experimental and field data available is mostly confined to more conventional smaller (typically less than 75mm) diameter pipes and their results are tenuously extrapolated to the larger diameter piping systems. The above extrapolations results in significant errors due to the complexity arising from interaction of the phases and are the result of lack of detailed knowledge of flow behaviour in large diameter vertical pipes. This has led the investigators to question the accuracy of existing modelling tools and recommend that additional research to be conducted with larger diameters.

In last decade, experimental studies with intermediate diameter sizes ($100 < D \leq 200$mm) [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12] and higher diameter sizes ($300 < D \geq 500$mm) [13, 14, 15] have emerged. Although these studies have contributed to the topic of the large diameter vertical pipes, majority of the work was performed on isolated vertical pipes i.e. the gas-liquid were introduce in the vertical pipe base [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12]. This situation may not represent the real conditions such as the ones encountered in process industry, as the entrance effects on the flow behaviour in such cases are not explicitly included. Likewise, others studies [13, 14, 15] have mostly been confined to very small length-to-diameter ratio ($L/D < 12$), which may also not depict the true two phase flow behaviour in a longer vertical pipe as the flow is still evolving (underdeveloped). Moreover in the above studies, it is also noted that either, the way two phases are introduced in the vertical pipe were given in the vague way, if not entirely omitted or the gas distributor configurations (porous plates, perforated plates/rings, porous tubes multiple/single-orifice plates, nozzle, shower caps discs or porous sinter walls etc.) were entirely different than the configurations encountered in industrial conditions. Hence these studies do not include the industrial effect of the flow path which is typical for applications like process industry where gas inlet to vertical pipe is (i) a 90º smaller diameter pipe at the base or (ii) both gas-liquid phase flowing in long horizontal pipe attached to vertical pipe base via elbow (e.g. horizontal flowline connected to vertical pipe in oil & gas exploration or hot leg of a nuclear reactor or once through steam generator that have a certain inlet pipe/configuration connected to a vertical pipe). Additionally, it is stated that NO experimental work is reported for diameter between existing research ($100 < D \leq 200$mm) and ($300 < D < 500$mm) and hence current 250mm results extends the database into diameter and conditions where data has not been previously collected.

The major impediment to the application of large diameter vertical pipes has been the lack of experimental data defining the flow behaviour, as it is difficult to build such large scale loop at laboratory level. In view of the aforementioned, at the department of Process and Systems Engineering at Cranfield University, a large diameter (D = 250mm nominal diameter) two phase flow vertical pipe - horizontal flowline experimental facility is setup, the first of its kind in UK. The idea behind is to elucidate the flow behaviour in large diameter pipes [16]. In previous works the data from the facility was used to evaluate the existing modelling tool [17, 18] and to assess the predictive capabilities of commonly used void fraction correlations from the different fields [19]. This paper reports the two phase flow patterns, flow regime transitions and the experimental flow regime map for a large diameter vertical pipe. The comparison of different vertical flow maps/transition models against experimental data is presented and the discrepancies noted are explained. The results presented here are useful in extending the knowledge of two-phase flow behaviour in large diameter vertical pipe in general and can be regarded as a first hand tool for knowing the flow patterns and the approximate transitions in large diameter vertical pipe.

2. Experimental details

Schematic diagram of the experimental loop is shown in Figure 1. The loop comprises of an air compressor system (air loop) and water pump system (water loop), horizontal flowline, vertical pipe (i.e. test section), upper plenum consisting of overhead/return tank, downcomer and a return line to sump. The overall height of the test section is 12.2m and horizontal flowline is of 36m length, both consisting of nominal diameter of 250mm. The water is supplied to the flowline-riser section from the single phase loop by a sump pump (P3). The water flowrate is regulated via valve (VW4) and a bypass valve (VW2) and measured by an electromagnetic flowmeter with an experimental accuracy of ±0.5%. After leaving the flowmeter, water flows into the heavy duty PVC pipe with the different elevations from the ground before entering into the 36m long, 250mm nominal diameter schedule-40 stainless steel horizontal flowline at the ground level. The loop is built with enough flexibility so that various parametric effects could be studied by changing or modifying the setup. Thus the air inlet provisions are available at the start of the horizontal flowline to study the two phase flow entering the test section and/or air inlet slightly above the test section base. The air to the test section is supplied from buffer tank to minimise the pressure pulsations from the compressor installed as part of an existing multiphase flow test facility. The air flow from the buffer tank is measured by two massprobar flowmeters (FT302 & FT305) with an experimental accuracy of ±1.3%. The flow to meters is controlled by means of control valves (FIC301 & FIC302) situated upstream from the flow meters. The control valves are managed by DeltaV digital automation system. Air after metering is delivered to large diameter facility via 50.8mm pipe either to the test section base (VA1) or at the inlet to horizontal flowline (VA5). In this work only former configuration (data) was used. The two phases i.e. water entering from the base and air entering slightly above the base mixes and then flows upward into the test section. The vertical test section contains four special high pressure clear Perspex sections of approx. 1m in length installed at different heights for identifying the flow patterns along the height by the high-speed video camera. The pressure measurements were done by three high-accuracy pressure transducers (accuracy of ±0.15%) installed at the exit of horizontal flowline, near the test section entrance and at the exit of the vertical pipe. Two differential pressure cells (accuracy of ±0.04%) and a water manometer were also mounted in the test section at the height of approximately 5m, 8m and 10m to deduce the void fraction. The later sensors are installed near the perspex sections so that simultaneous signal acquisition and videoing can take place. After passing through the test section, the air 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 test section at the base. In experiments results reported here, later flow path was used. All the signals from the instrumentation installed at various locations in the flowline-vertical test section were acquired through dedicated LABVIEW software [20].

The adiabatic air-water flow experiments were carried out to study the flow patterns occurring in the vertical riser section. The air superficial velocity ranged from

0.18m/s to 2.23m/s and the water superficial velocity ranged from 0.18m/s to 1.1m/s. The existing set-up did not allow for the experiments in annular flow regime.

For all the results presented in the experimental range mentioned above, the void fraction in the test section was determined from pressure drop measurements. These are found to be the characteristic of the individual flow patterns hence the visual observations of flow patterns in the vertical test section were supplemented by them. The statistical procedure employed to discriminate the two phase flow regimes is based on probability mass distribution function. This method of identifying the prevailing flow regimes in vertical test section has been adopted by many previous investigators [21-25].

The void fraction was estimated from differential pressure cells installed under the assumptions that (i) the differential pressure equals to static pressure (by neglecting accelerative and frictional losses) or (ii) that the differential pressure equals to static pressure plus frictional loss. Under first assertion, both neglected terms oppositely contribute to the pressure drop hence the void fraction values obtained are slightly higher than true values, thus providing the upper limit of void fraction attainable. To validate the second assertion, frictional loss was subtracted from measured pressure drop. The frictional loss was determined from two different well known correlations; [26] and [27] for vertical flows developed from wide ranges of conditions commonly used in industry. These correlations were used as they contain the influence of mass flux, mixture density, length, equivalent diameter etc.

The Figure 2 shows the effect of frictional loss determined by the above two correlations on the measured pressure drop at different water superficial velocities. No visible effect of friction loss is observed under the given water-air superficial velocities (within 4% of total). So it can be seen that both correlations predicted friction loss component that was smaller (less than 4%) to the extent that it does not influence the total pressure drop. Thus it can be stated that because of the minimal contribution of frictional component (less than 4%) to total pressure drop, (as the total pressure drop were dominated by hydrostatic component ~ 96%) neglection of this term will not produce significant error. In this paper, only the instantaneous pressure drop readings from differential pressure cells at the height of approximately 5m (VF1) and 8m (VF2) were considered.

3. Experimental Results

In vertical two-phase flows in conventional small diameter pipes, following four basic flow patterns are identified namely bubbly, slug, churn and annular by many investigators. Researcher [4, 9, 12] have defined five types of flow patterns in their 200mm diameter vertical pipe experiments as undisturbed bubbly, agitated bubbly, churn bubbly, churn/slug and churn/froth flow. However, in the present analysis a simplified classification is employed to avoid any subjectivity by considering the flow regimes in large diameter vertical pipe air-water upflow to be composed of following distinct regimes namely: (i) Dispersed Bubbly Flow (ii) Bubbly Flow (iii) Agitated Bubbly Flow (iv) Churn/Froth Flow and (v) Annular flow (not encountered in experiments). Note that the churn/froth flow includes all the variation of churn flow defined by [4, 9]. This is been done intentionally as we planned to clear out the above delineation more clearly in later sections. Figures 3(a - d) shows the photographs of the four distinct flow patterns that were identified for the two-phase (air-water) large diameter vertical flow.

(i) ***Dispersed bubbly flow*** - This flow pattern in Figure 3(a) appeared in few experimental runs only at high water and low air superficial velocities (j_a =0.06-

0.15m/s and j_w >0.7m/s) i.e. at a very low void fraction. In this flow regime the bubbles formed were small of approximately same size, spherical and uniformly distributed by some distance in continuous water phase. The bubbles formed did not coalesce to form larger bubbles during their upward rise.

(ii) ***Bubbly flow*** **-** This flow pattern in the Figure 3(b) was obtained under low air-water superficial velocities. While many researchers have not made any distinction in above dispersed bubbly flow and this bubbly flow (also referred as non-dispersed bubble flow) [28, 29] others have classified this flow as low-liquid-input bubbly flow or non-dispersed bubbly flow [30-34]. In this flow regime, the bubbles were of distorted spheres shapes in large population closely packed in the liquid phase. There was also some localized coalescing of the distorted bubbles in the core region forming larger distorted bubbles during upward flow upon increasing air superficial velocity.

(iii) ***Agitated bubbly flow*** **-** This flow was obtained under the medium air superficial velocities ($0.5 < j_a \leq 1.6$m/s) and consisted of large distorted shape bubbles flowing in clusters in the core with the small discrete bubbles flowing randomly up and down near the walls. There was rapid agitation between the water-discrete bubbles near wall causing circulatory type of motion in the vicinity. The agitation was seen to increase with increase in gas superficial velocities. As the air superficial velocity increased, the clustering and coalescence of bubbles also increased causing the gas-liquid interfaces to deform more by both phases turbulence. These bubble clusters had high rise velocity and it was observed that during their upward movement many other random moving bubbles were sucked into their wake and increased their axial lengths. The Figure 3(c) shows the image of this flow. The difference between the previous bubbly (low input bubbly flow) and this flow regime was the larger distribution of distorted bubbles flowing in clusters in the test section with rapid agitation and randomness in the liquid flow around it that increased with the increase in air superficial velocities (j_a > 1.2m/s), the flow did have some similarity with churn/froth flow as it appeared to be increasingly consisting of multiple turning and twisting distorted gas clusters, however they remained in the core and still lacked the vigour and intensity of the churn flow (encountered at j_a > 2.0m/s). The voidage characteristics (dealt in next section) of this flow are sufficiently distinct from those of bubbly or churn/froth flow to enable us to recognise and describe them separately from bubbly and churn/froth flow. The commonly encountered slug flow in small diameter vertical upflow condition was never observed in the entire experimental range; instead it was this agitated bubbly flow that was the most dominant flow pattern throughout the large diameter vertical upflow experiments with no resemblance with typical slug flow found in conventional small diameter pipes, in fact no large smooth bullet shaped bubbles like Taylor bubble (occurring in slug flow) were observed under this range of air-water superficial velocities in the test section, although a coalescence and breakup was visible around 5m height. Thus emphasising the fact that no slug flow existed in this diameter vertical upflow condition under the experimental range conducted, where under similar conditions, slug flow would be observed in smaller diameter pipes.

(iv) ***Churn/froth flow*** - This flow depicted in Figure 3(d) existed at higher air superficial velocities when $j_a \geq 2$m/s ($j_w \leq 0.8$m/s) and although originated from large group of bubbly clustering and agglomeration, was unlike the agitated bubbly flow because of its "frothy" appearance and highly oscillatory characteristics. During the flow observation it was observed that within the core region large highly distorted frothy gaseous structures with axial lengths much greater than the pipe diameter were flowing upwards in the core section of the pipe accompanied by falling and upward moving liquid film around the periphery. The flow was extremely chaotic and whole test section content appeared to be oscillating with these distorted large gaseous structures.

The flow patterns during air-water flow through a 250mm nominal diameter vertical test section have also been identified using statistical analysis of sectional void fraction. The time-varying sectional void fractions have been analyzed by probability mass function (PMF) plots in a manner similar to [21, 22, 23, 24, 35]. The plots provided a good indication of the prevailing flow regimes. Figure 4 below provides the PMF plots for increasing air superficial velocities (j_a = 0.15, 0.59, 1.77 and 2.2m/s) for three different water superficial velocities (j_w = 0.25, 0.55 and 1m/s).

Figure 4(a) shows the PMF plots obtained for increasing air superficial velocities (j_a = 0.15, 0.59, 1.77 and 2.2m/s) for j_w = 0.25m/s. The analysis of the void fraction fluctuations showed that at the lowest air superficial velocity, the flow was mainly bubbly with PMF showing a distinct sharp unimodal peak, lying close to origin having a mean around 0.15. However, with increase in air superficial velocity with flow transforming into agitated bubbly flow, this peak shifted towards higher void fraction and becomes much more broaden due to the wide distribution of bubble sizes with clustering and coalesce. This broad single peak persists for all the intermediate air-water superficial velocity range with a progressive shifting towards higher void fraction. The PMF's in this region are single peak but typically normal distributed with low values of skewness and variances than observed for churn/froth flow.

The transition from agitated bubbly to churn/froth flow seems to occur gradually as the PMF's of increasing air superficial velocities indicate. At j_a > 1.7m/s it can be noted that the PMF plot becomes slightly skewed towards left (negatively skewed) showing transition is being approached. It is to be noted that a negative skewness value towards lower void fraction (left) indicates churn/transitional flow and conversely, a positive skewness indicates there is a tailing out toward the higher void fraction (right) i.e. for bubbly flow. It is generally observed that for bubbly and annular flows, the skewness is rather small while the skewness for slug flow has a large and positive value and the skewness for churn flow has a large but negative value. At j_a = 2.2m/s, the PMF of churn/froth flow exhibited a peak at higher void fraction representing a large gas dominant portion along with thick tail extending towards left the lower void fractions. This long thick tail towards lower void fraction indicated some aerated slugs/liquid bridging which is typical characteristic of transitional flows. The broad peak at the high void fraction represents the gas structures that are long and distorted in nature. It is to be noted that this thick tail is seen only at lower water superficial velocities with highest air superficial velocity only. With increasing water superficial velocity, this tail disappears and normal curve with broad base is observed in the PMF's plots signifying a more agitated bubbly flow.

In Figure 4(b) for j_w = 0.55m/s, the flow is still bubbly for lowest air superficial velocity which upon increase in air superficial velocity changes into agitated bubbly flow and then to churn/froth. Not much differences in PMF plots is observed for this water superficial velocity and that of in Figure 4(a), however the only difference appears to be of mean void fraction, where in Figure 4(b) due to increase in water inventory in the test section, the mean void fraction has decrease than those presented in earlier figure. Lastly, the Figure 4(c) shows the results of highest water superficial velocity of j_w = 1m/s. In comparison to the lowest air superficial velocity results presented above, this PMF shows a narrow peak at lower void fraction (α = 0.07) than indicated by bubbly flow as the latter was typically encountered when mean void fraction was greater than 0.14, thus the former is identified as dispersed bubbly flow. Another unique feature of this flow's PMF plot was a higher and more pointed peak along with high probability of pure liquid which was almost the minimum for bubbly flow (in case of j_w = 0.25 and 0.55m/s). The increase in air superficial velocities only broadens the probability mass distribution due to wider bubble size distribution with PMF plots appearing similar to those presented in the Figure 4(a & b).

Note in the Figure 4(c) that for highest air superficial velocity, a clear left skewness is not visible and PMF plot appear to more of normal distribution signifying that churn flow is not yet approached. It is to be noted also that although slug flow was never observed in these experiments its probability mass function plots represents two distinct peaks, one at higher void fraction corresponding to the probability of the gas dominant Taylor bubble and other one at lower void fraction representing an aerated liquid slug.

Some previous researchers [21 and 36] have suggested that the information available from PMF's while is sufficient to distinguish the flow patterns, it is not able to distinguish flow regime transitions. Thus the use of the statistical moments as an auxiliary tool for flow pattern transition identification is recommended. In this regard, generally use of standard deviation is employed instead of variance because while variance represents the power of the signal fluctuation, the standard deviation shows how far the signal fluctuates from the mean. Thus the standard deviation is expected to be small for bubbly and annular flows (as data points will lie close to mean), while it should assume larger values (data points are far from the mean) for intermittent flows due to the presence of the large distorted bubbles and highly chaotic liquid phase. So the standard deviation of the void fraction fluctuation signal was employed to extract information about the flow regime transitions.

The Figure 5(a-b) illustrates the standard deviation of the sectional void fraction fluctuation in the experiments for the conditions corresponding to those in Figure 4(a - c). Figure 5(a) illustrates the standard deviation of the sectional void fraction fluctuation against mean void fraction. It is observed that with an increase in average value or mean void fraction, standard deviation becomes larger signifying the transition from bubbly flow to other intermittent flows. The standard deviation range clearly lies in three different bands of values. This is in accordance to the three flow patterns observed i.e. bubbly flow showing minimum standard deviation against mean value, agitated bubbly flow showing intermediate values of standard deviation and churn/froth flow indicating highest standard deviation values against mean due to highly chaotic characteristics. It is to be noted here the rate of increase of standard deviation is slightly decreased for agitated bubbly flow due to enhance liquid recirculation because of bubble coalescence and breakup.

This observation is also consistent with initial observation of gradual transition from bubbly flow by an increase in the rate of coalescing and breakup of bubbles with an increase in air superficial velocity. However with an increase in mean void fraction (due to increase in air superficial velocity), the local liquid recirculation are damped out promoting bubble coalesce and again a gradual flow transition from agitated bubbly to churn/froth flow. Hence, the changes of slope of standard deviation with an increase in mean void fraction are representing the three different flow regimes. A further explanation of above may also be found if the same standard deviation is plotted against air superficial velocity, see Figure 5(b). The figure illustrates that standard deviation of the sectional void fraction fluctuation increases with air superficial velocity at constant water superficial velocity. While standard deviation does increases with j_a, the differences in water superficial velocity is not significant at lower j_a but only becomes dominant at higher air superficial velocity (j_a >1.2m/s). It is to be noted that with an increase in water superficial velocity the standard deviation seems to decrease which is in accordance to the visual observation (and PMF's) that indicated that the flow remained agitated bubbly for j_w > 0.7m/s due to increase liquid inventory and suppression of bubble induced turbulence.

The flow patterns information thus obtained from the visual and statistical analysis is represented graphically in the form of a flow pattern map in Figure 6 with superficial velocity of air and water as the axes of the map. The figure depicts the flow patterns and flow pattern transition boundaries. At low values of j_a and j_w, the flow is mainly bubbly while for low j_a and high j_w, it is dispersed bubbly. Agitated bubbly flow occurs predominantly for intermediate values of j_a. For high j_a, the flow transition occurs from agitated bubbly to churn/froth flow.

The above flow patterns and the transitions in large diameter vertical upflow condition were compared with the theoretical predictions of some well known flow pattern maps/ models [29-34, 37, 38] derived from small diameter vertical upflow condition. For the sake of brevity, the related equations are not presented here and can be obtained from the original work of the researchers.

The flow regime map in Figure 7 illustrates the comparison between experiments and various model predicted transitions from bubbly to dispersed bubbly flow. In present work, the dispersed bubbly flow not only occurred at lower air superficial velocities but also at lower liquid velocity than predicted by some models. Our experimental observation is consistent with the observation of Ohnuki and Akimoto [4] for 200mm diameter vertical upflow condition. In fact the predictions of Taitel *et al.* [30] models occurred at a water superficial velocity of approximately one order of magnitude higher than experimentally observed transitions.

It is be noted here that even Costigan and Whalley [35] also found this transition boundary to be higher than observed in their small (32mm) diameter vertical upflow experiments. McQuillan and Whalley [32] flow map for vertical flow also could not predict the dispersed bubbly flow observed in the experiments. Only Weisman and Kang [31] and Chen *et al.* [37] predictions did come closer to predicting the boundary between bubbly and dispersed bubbly flow. Weisman and Kang [31] work suggest that this transition is independent of gas superficial velocity and only depends upon the liquid superficial velocity, fluid properties and diameter of the pipe. The current results observed are also consistent with the observation of Chen *et al.* [37] that the critical liquid superficial velocity for the transition to dispersed bubble flow increases monotonically with an increase in gas superficial velocity, hence at low air superficial velocity range this transition will also be at lower values of liquid superficial velocity unlike the trends suggested by Taitel *et al.* [30].

The Figure 8 illustrates the results for the bubbly-to-slug flow transition. It is interesting to note from the experimental results that for large diameter pipes bubbly flow region became much larger compared with conventional size pipes. Taitel *et al.* [30] and Mishima & Ishii [29] models underestimated this transition to be occurring at lower gas superficial velocities. However latter predictions are closer to actual transition then former. While both the above models predict an early transition to slug flow from bubbly, experiments results indicate that there is **NO** slug flow instead there is transition from bubbly flow to its variation agitated bubbly flow where a coalescence and break up process is clearly visible along with the local liquid recirculation near the walls. The deviation of the Taitel et al. [30] and Mishima and

Ishii [29] models may be attributed to the use of the constant critical void fraction (α_c = 0.25 & 0.3) value at which transition is expected to occur. This is in contradiction to various studies [39, 40, 41] done in past where this transition is found to be dependent upon the initial bubble size rather than fixed void fraction value.

In comparison of constant critical void fraction approach, Weisman and Kang [31] approach resulted in the improved performance. This can be attributed to the larger degree of freedom offered by an increase in diameter size that results in increase in free rise velocity of gas phase. The correlation is based on the Froude numbers of gas and total volumetric flux and is independent of physical property effect but do include the diameter effect. Note that Weisman and Kang [31] did not define slug flow in vertical flow condition but rather referred the region between bubbly flow and annular flow as intermittent flow (consisting of all plug, slug and churn flows).

An interesting observation related to bubble-to-slug transition in this work as well as in all previous large diameter vertical work is that all the models prediction are closer to experimental results at higher liquid velocities only and deviates at the low liquid velocities [4, 5, 9, 10, 11, 14]. This trend suggest that while constant critical void fraction approach is able to predict closer behaviour, the approach is limited to higher liquid velocities only, and at lower liquid superficial velocity some other mechanism related to diameter individually or combine with critical void fraction approach seems to be responsible for this transition. This observation is consistent with the experimental results of Omebere-Iyari *et al.* [10] for pipe size of 189mm and of Omebere-Iyari *et al.* [11] for pipe size of 194mm where similar trends as observed in this work were found for the Taitel *et al.* [30] model.

The experimental result and the performances of the slug to churn flow transition models [29, 30, 32, 33, 34, 38] are depicted in Figure 9. The experimental result indicates a gradual shift from agitated bubbly to churn flow. The trends predicted by Taitel *et al.* [30], McQuillan and Whalley [32] and Brauner and Barnea [33] are all in contradiction to the experimental trends. It is to be noted that Taitel *et al.*, [30] and McQuillan and Whalley [32] transition curves terminate at slug to bubble transition boundary. Although the general trend of current experimental boundary is consistent to Mishima and Ishii [29] and Tengesdal *et al.* [38] slug-churn transition, experimental boundary appears at lower gas superficial velocities than predicted by above models. This means that both the models predict a higher slug to churn transition upon increase in diameter. It is to be noted that the our experimental observation is also supported by the work of Ohnuki and Akimoto [4] with 200mm vertical pipe experiments, who found that this transition occurred earlier than predicted with Mishima and Ishii [29].

It is clear from above analysis that none of the flow regime transition models are adequate for predicting the flow regimes in large diameter vertical pipes as a whole.

4. Comparison with other experimental studies conducted in large diameter vertical pipe:

It is observed that the dispersed bubbly flow in present work almost lie at the similar location where undisturbed bubbly flow was observed by Ohnuki and Akimoto [4]. Similar observations are also made for the churn/froth flow. However the differences arises in the region where current work show bubbly and agitated bubbly flow, the previous work [4] refer the flow patterns in this range as agitated bubbly, churn bubbly and churn slug. It is emphasised that the previous work is based on visual observation and looking into detail it seems very likely that this discrepancy is due to semantic rather than actual flow behaviour as the visual observation tends to be subjective. It is also very likely that this detail classification arises due to the fact that their agitated bubbly/churn bubbly to churn slug transition was well separated by Mishima and Ishii [29] bubble to slug transition model. However similar to current work their slug to churn transition was observed earlier than predicted by Mishima and Ishii [29] slug to churn transition model.

Similar to above, Shoukri *et al*. [5] reported three flow patterns namely bubbly, churn and annular flow in 200mm diameter vertical pipe experiments. The flow patterns were determined by high speed camera as well as signals of optical probes. It is to be noted that they did not classify the bubbly and dispersed bubbly flow and also regarded the current agitated bubbly and churn/froth flow as only churn flow. Looking at their work without the detail classification of bubbly/dispersed bubbly flow and agitated bubbly and churn/froth flow a satisfactory agreement exist. However unlike the current results of flow map comparison, they reported a reasonable conformity with Taitel *et al*. [30] and Mishima and Ishii [29] model with their experimental work.

Omebere-Iyari *et al.* [10] employed nitrogen-naphtha as working fluid at high pressure condition of 20 and 90 bars while Omebere-Iyari *et al.* [11] work is based on 194mm diameter 46.4 bar saturated steam-water vertical upflow experiments. A direct comparison of these work is not possible as the physical properties especially gas density, viscosity, surface tension are affected by operating pressure and which further affect the two phase flow behaviour especially the flow pattern transitions e.g. the effect of increased gas density is to move the flow pattern transitions to higher gas superficial velocity [42]. Thus the higher pressure are likely to reduce the gas phase coalescence rate and increase the breakup rates so the smaller bubbles are formed that increases the overall void fraction and thus delay the transition from bubbly flow.

This is what has been observed in both set of experiments (at 20 and 90 bar) by Omebere-Iyari *et al.* [10], where bubbly flow is seen till the critical void fraction of 0.68 which is contrary constant value of 0.25 predicted by Taitel *et al*. [30] and a value of 0.3 by Mishima and Ishii [29]. Although annular flow was not encountered in current work and as well as in Ombere-Iyari *et al.* [11] work but semi-annular and annular flow is seen by Omebere-Iyari *et al.* [10] in the region predicted as slug to churn transition by most of the models. Also no slug or churn flow is observed in their work [10], the only intermittent character flow observed was at very low liquid and gas flowrates.

Omebere-Iyari *et al.* [11] observed bubbly and churn turbulent flow in the range where current work shows the bubbly and agitated bubbly. While an agreement exist for bubbly flow region, the discrepancies arise for the flow designated as churn turbulent flow. It is perceived that their churn turbulent flow observed is similar to the agitated bubbly flow in current study and their transition from bubble to churn turbulent are not much different from our observation of bubbly to agitated bubbly flow results. It is to be noted that in current work churn/froth flow occurs at $j_g >$ 1.5m/s with probability mass function plots indicating a negatively skewed distribution with distinct peak associated with churn/froth flows. Whereas the churn turbulent flow in former case [11] is more Gaussian type distribution similar to those observed in our agitated bubbly flow with mostly positively skewed distribution. It may be that the definition of churn turbulent flow used by them is taken from the two phase flow in bubble columns where flow regime (in column diameter D > 100mm) are based on two types namely; homogenous flow (also referred as bubbly flow) and heterogeneous flow (also called churn turbulent) [43]. However it also reminded that even in bubble column application, the two flow regimes are separated by a region considered as transition regime. This transition zone is considered to be the region where visible bubble coalescence, breakup and minor oscillations exist, which might be considered synonymous with agitated bubbly flow encountered in this work. Nevertheless both the above mentioned work [10, 11] although performed at the high pressures when compared to Taitel *et al.* [30] flow transition models yielded similar trends to the ones obtained in this work for bubble to slug transition i.e. an earlier transition indicated by the model then observed in large diameter vertical upflow experiments; also the deviation is smaller at higher liquid flow rates than at lower rates.

5. Conclusions

1. Two phase air-water flow experiments were performed in 250mm nominal diameter vertical pipe to study flow patterns and flow pattern transitions. The flow pattern of each flow condition was determined visually as well as by statistically interpreting the pressure drop signals.
2. Four flow patterns were visually identified in the current experimental range namely; dispersed bubbly, bubbly, agitated bubbly and churn/froth flow. Unfortunately existing setup did not allow experiments in annular flow regime.
3. The time-varying sectional void fraction signals were analyzed by probability mass function plots in a manner to similar researchers [21, 22, 23, 24, 35]. The plots provided good indication of the prevailing flow regimes.
4. In is observed that in contrast to the slug flow in smaller diameter pipes ($D <$ 100mm); agitated bubby flow is found to dominate this (slug flow) region in our experiments. Thus this work reports the absence of conventional slug flow consisting of smooth bullet shaped Taylor bubble and pure liquid slug in large

diameter vertical riser neither the bimodal peak associated with it in probability mass function distribution [21, 22, 35].

5. A host of statistical parameters extracted from the time-varying void fraction signals were used to identify the observed flow pattern transitions. Based on the observed changes of standard deviation of void fraction fluctuations, the flow regime transition from bubbly-to-agitated bubbly and from agitated bubbly-to-churn/froth flow were identified.
6. After identifying the above features unique to large diameter vertical two phase flow a flow pattern map was developed and compared with various existing vertical flow pattern map/models. It was found that there are appreciable discrepancies in various flow regime transition boundaries due to the diameter effect.
7. Dispersed bubbly flow is found to occur at much lower water superficial velocities than predicted by various bubbly-to-dispersed bubbly flow transition models.
8. The bubbles-to-slug transition models of various existing vertical flow pattern maps are unable to predict the bubbly-to-agitated bubbly transition. Although a closer trend is observed at higher liquid velocities by all the models, the trend deviate in the low water velocities range. This signifies that constant critical void fraction criteria used in bubble-to-slug flow models of Mishima and Ishii [29] and Taitel *et al.* [30] is not valid in general.
9. Transition to churn/froth flow in experiments occurs at lower values of air superficial velocity than observed with slug-to-churn transition models based on conventional pipe sizes.

10. A satisfactory agreement was obtained with other large diameter studies with inconsistencies mainly attributable to confusion in the identification of flow patterns.

Acknowledgments:

This work has been partially supported by BP Exploration. The Authors wishes to thanks for their support. The first author also wishes to express sincere gratitude for the financial support provided by the Process and Systems Engineering Group, Cranfield University.

References

[1] **Cheng, H., Hills, J. H. and Azzopardi, B. J. (1998)**. "A study to bubble-to-slug transitions in the vertical gas-liquid flow in columns of different diameter". *International Journal of Multiphase flow*, Volume 24(3), pp 431-452.

[2] **Hibiki, T. and Ishii, M. (2003).** "One dimensional drift flux model for two phase flow in large diameter pipe". *International Journal of Heat and Mass transfer*, Volume 46(7), pp 1173-1790.

[3] **Hirao, Y., Kawanishi, A., Tsuge, A. and Kohriyama, T. (1986).** "Experimental study on drift flux correlation formulas for two phase flow in large diameter tubes". *Proceedings of 2nd International Topical Meeting on Nuclear Power Plant Thermal Hydraulic and Operations Conference*. Tokyo, Japan. April 15-17, 1986.

[4] **Ohnuki, A. and Akimoto, H. (2000)**. "Experimental study on transitions of flow pattern and phase distribution in upward air-water two phase flow along a large vertical pipe". *International Journal of Multiphase flow*, Volume 26(3), pp 367-386.

[5] **Shoukri, M., Stankovic, B., Hassan, I., Dimmick, J. (2000).** "Effect of pipe diameter on flow pattern transitions and void fraction of air-water flow in vertical pipes". *Proceedings of ICONE-8, 8th International Conference on Nuclear Engineering.* Baltimore, MD, USA. April 2-6, 2000.

[6] **Prasser, H-M., Boettger, A., Beyer, M., Carl, H., Lucas, D., Schaffrath, A., Schűtz, P., Weiss, F-P., and Zschau, J. (2002).** "TOPFLOW tests on the structure of the gas-liquid Interface in a large vertical pipe". *Forschungszentrum Rossendorf Annual Report-2002*, FZR-380.

[7] **Sun, X., Smith, T. R., Kim, S., Ishii, M. and Uhle, J. (2002).** "Interfacial area of bubble flow in a relatively large diameter pipe". *Experimental Thermal and Fluid Science*. Volume 27, pp 97-109.

[8] **Oddie, G., Shi, H., Durlofsky, L. J., Aziz, K., Pfeffer, B. and Holmes, J. A. (2003).** "Experimental study of two and three phase flows in large diameter inclined pipes". *International Journal of Multiphase Flow,* Volume 29(4), pp 527-720.

[9] **Shen, X., Saito, Y., Mishima, K., and Nakamura, H. (2006).** "A study on the characteristics of upward air–water two-phase flow in a large diameter pipe", *Experimental Thermal and Fluid Science*, Volume 31, pp. 21-36.

[10] **Omebere-Iyari, N. K., Azzopardi, B. J. and Ladam, Y. (2007).** "Two-phase flow patterns in large diameter vertical pipes at high pressures", *The AIChE Journal*, Volume 53(10), pp. 2493-2504

[11] Omebere-Iyari, N. K., Azzopardi, B. J., Lucas, D., Beyer, M. and Prasser, H-M. (2008) "The characteristics of gas/liquid flow in large risers at high pressures", *International Journal of Multiphase Flow*, Volume 34(5), pp 461-476.

[12] **Schlegel, J.P., Sawant, P., Paranjape, S., Ozar, B., Hibiki, T., Ishii, M. (2009).** "Void fraction and flow regime in adiabatic upward two-phase flow in large diameter vertical pipes", *Nuclear Engineering and Design*, Volume 239(12), pp. 2864-287.

[13] **Hashemi, A., Kim, J. H., and Sursock, J. P.** (1986) "Effect of diameter and geometry on two phase flow regimes and carry over in model PWR hot leg". *Proceedings of 8th International Heat Transfer Conference*. San Francisco, CA, USA. August 17-22, 1986.

[14] **Ohnuki, A. and Akimoto,** H. (1996). "An experimental study on developing air-water two phase flow along a large vertical pipe: effect of air injection method. *International Journal of Multiphase flow*, Volume 22(6), pp. 1143-1154.

[15] **Shipley, D. G.** (1984) "Shorter Communications: two phase flow in large diameter pipes". *Chemical Engineering Science*, Volume 39(1), pp. 163-165.

[16] **Ali, S. F. (2009).** Two Phase Flow in Large Diameter Vertical Riser. *PhD Thesis*, Cranfield University, Bedfordshire, UK.

[17] **Ali, S. F. and Yeung, H., (2008a)**. "*Hydrodynamic behaviour in large diameter vertical riser: experimental and simulation studies*". *In proceedings of 11th International Conference on Multiphase Flow in Industrial Plant*. Palermo, Italy: 7-10 September 2008.

[18] **Ali, S. F. and Yeung, H., (2010).** "*Experimental Investigation and Numerical Simulation of Two Phase Flow in Large Diameter Horizontal Flowline-Vertical Riser*". Petroleum Science and Technology, Volume 28, pp 1079-1095.

[19] **Ali, S. F. and Yeung, H., (2008b).** "*Performance assessment of void fraction correlations in large diameter vertical pipe upflow*". *In proceedings of 11th International Conference on Multiphase Flow in Industrial Plant*. Palermo, Italy, 7-10 September 2008.

[20] **Qazi, N. and Yeung, H. (2006)**. *"Remote access and monitoring of two phase flow rig using Web/WAP protocol"*, National Instruments: LabVIEW in the Curriculum Paper Contest, pp. 80-85.

[21] **Tutu, N. K. (1984)**. "Pressure drop fluctuations and bubble-slug transition in a vertical two phase air-water flow", *International Journal of Multiphase flow*, Volume 10(2), pp21l-216.

[22] **Matsui, G. (1984).** "Identification of flow regimes in vertical gas-liquid flow using differential pressure fluctuations", *International Journal of Multiphase flow*, Volume 10(6), pp 711-720.

[23] **M. Anunziato and G. Girardi. (1984).** *"*Flow pattern identification by pressure drop and void fraction fluctuations analysis in vertical two phase flow*"*, In European Two-Phase Flow Group Meeting, Rome. June, 19 - 21 1984.

[24] **Matsui, G. (1986).** "Automatic identification of flow regimes in vertical two-phase flow using differential pressure fluctuations". *Nuclear Engineering and Design*, Volume 95, pp 221-231.

[25] **Blaney, S. and Yeung, H. (2008).** "Investigation of the exploitation of a fast-sampling single gamma densitometer & pattern recognition to resolve the superficial phase velocities & liquid phase water cut of vertically upward multiphase flows". *Flow Measurement and Instrumentation*, Volume 19, pp 57-66.

[26] **Friedel, L. (1979).** "Improved Friction Pressure Drop Correlations for Horizontal and Vertical Two Phase Pipe Flow," *European Two Phase Flow Group Meeting,* Ispra, Italy.

[27] **Lombardi, C., and Carsana, C. G. (1992).** "Dimensionless Pressure Drop Correlation for Two-Phase Mixtures Flowing Upflow in Vertical Ducts Covering Wide Parameter Ranges". *Heat and Technology*, Volume 10 (1-2), pp. 125-141.

[28] **Hewitt, G. F. and Roberts, D. N. (1969).** "Studies of two-phase patterns by simultaneous X-ray & flash photography". Atomic Energy Research Establishment Report -M 2159, Harwell, England. (Cited in: Omebere-Iyari, N. K., Azzopardi, B. J. and Ladam, Y. (2007) *"Two-phase flow patterns in large diameter vertical pipes at high pressures"*, The AIChE Journal, Volume 53(10), pp. 2493-2504)

[29] **Mishima, K. and Ishii, M. (1984)**. "Flow regime transitions criteria for upward two phase flow in vertical tubes". *International Journal of Heat and Mass transfer*, Volume 27 (5), pp 723-737.

[30] **Taitel, Y., Barnea, D. and Dukler, A. E. (1980).** "Modelling flow pattern transitions for steady upward gas-liquid flow in vertical tubes". AIChE Journal, Volume 26(3), pp. 345-354.

[31] **Weisman, J. and Kang, S. Y. (1981).** "Flow pattern transitions in vertical and upwardly inclined lines", *International Journal of Multiphase Flow*, Volume 7(3), pp 271-291.

[32] **McQuillan, K. W. and Whalley, P. B. (1985).** "Flow patterns in vertical two phase flow". *International Journal of Multiphase Flow*, Volume 11, pp 161-175.

[33] **Brauner, N. and Barnea, D. (1986).** "Slug/Churn Transition Upward Gas-Liquid Flow", *Chemical Engineering Science*, Volume 41, pp 159-163.

[34] **Barnea, D. (1987).** "A unified model for predicting flow pattern transitions for the whole range of pipe inclinations. *International Journal of Multiphase flow*, Volume 13(1), pp 1-12.

[35] **Costigan, G. and Whalley P. B. (1997).** "Slug flow regime identification from dynamic void fraction measurements in vertical air-water flows". *International Journal of Multiphase flow*, Volume 23(2), pp 263-282.

[36] **Vince, M. A. and Lahey Jr., R. T. (1982).** "On the development of an objective flow regime indicator", *International Journal of Multiphase Flow*, Volume 8(2), pp 93-124.

[37] **Chen, X. T., Cai, X. D. and Brill, J. P. (1997).** "A general model for transition to dispersed bubble flow". *Chemical Engineering Science,* Volume 52(23), pp 4373-4380.

[38] **Tengesdal, J. O., Sarica, C., and Kaya, A. S. (1999).** "Flow-pattern transition and hydrodynamic modelling of churn flow", *SPE Journal*, Volume (4), pp. 342-348. SPE-57756.

[39] **Song, C. H., No, H. C., and Chung, M. K. (1995).** "Investigation of bubble flow developments and its transition based on the instability of void fraction waves", *International Journal of Multiphase Flow*, Volume 21(3), pp 381-404.

[40] **Cheng, H., Hills, J. H. and Azzopardi, B. J. (1998).** "A study to bubble-to-slug transitions in the vertical gas-liquid flow in columns of different diameter". *International Journal of Multiphase flow*, Volume 24(3), pp 431-452.

[41] **Guet, S., Ooms, G., Oliemans, R. V. A. and Mudde, R. F. (2003).** "Bubble injector effect on the gaslift efficiency". *The AIChE Journal*, Volume 49(9), pp 2242-2252.

[42] **Krishna, R, Wilkinson, P. M., Van Dierendonck, L. L. (1991).** "A model for gas holdup in bubble columns incorporating the influence of gas density on flow regime transitions", *Chemical Engineering Science*, Volume 46(10), pp 2491-2496.

[43] **Shah, Y. T., Kelkar, B. G., Godbole, S. P., Deckwer, W. D. (1982).** "Design parameters estimations for bubble columns reactors", *The AIChE Journal*, Volume 28, pp 353-379.

Appendix

Notation

D *Pipe diameter (m)*

j_a *Air superficial velocity (m/s)*

j_w *Water superficial velocity (m/s)*

Greek Symbols

α *Void fraction*

α_c *Critical void fraction,* $\alpha_c=0.25$ *or* $\alpha_c=0.30$

Acronyms

PMF Probability mass function

UK United Kingdom

PVC Polyvinyl Chloride

Subscripts

a *air*

w *water*