EFFECT OF TUBE DIAMETER ON TWO-PHASE FLOW PATTERNS IN MINI TUBES

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The effect of tube diameter on two-phase flow patterns was investigated in circular tubes with inner diameters of 0.6, 1.2, 1.7, 2.6, and 3.4 mm using air and water. The gas and liquid superficial velocity ranges were 0.01–50 and 0.01–3 m/s, respectively. The gas and liquid flow rates were measured and the two-phase flow pattern images were recorded using high-speed CMOS camera. The flow patterns observed were dispersed bubbly, bubbly, slug, slug-annular, wavy-annular, stratified, and annular flows. These flow patterns were not observed in all the test diameters, but were found to be unique to particular tube diameters, confirming the effect of tube diameter on the flow pattern. The data obtained were compared to existing experimental data and flow regime transition maps which show generally reasonable overall agreement at the larger diameters, but significant differences were observed with the smaller diameter tubes.

On a analysé l'effet du diamètre des tubes dans des modèles d'écoulement biphasé dans des tubes circulaires avec des diamètres internes de 0,6, 1,2, 1,7, 2,6 et 3,4 mm en utilisant de l'air et de l'eau. Les écarts de vitesse superficielle de gaz et de liquide étaient de 0,01–50 m/s et 0,01–3 m/s respectivement. Les débits de gaz et de liquide ont été mesurés et les images des modèles d'écoulement biphasé ont été enregistrées à l'aide d'un appareil photo CMOS haute vitesse. Les modèles d'écoulement observés étaient l'écoulement à bulles, à bulles, en piston, en piston annulaire, ondulé annulaire, stratifié et annulaire. Ces modèles d'écoulement n'ont pas été observés dans tous les paramètres d'essai, mais on a constaté qu'ils étaient uniques aux diamètres de tubes particuliers, ce qui confirme l'effet du diamètre des tubes sur le modèle d'écoulement. Les données obtenues ont été comparées aux données expérimentales existantes et aux cartes de transition des régimes d'écoulement qui démontrent un accord global raisonnable de façon générale aux paramètres plus grands, mais des différences importantes ont été observées dans les tubes aux diamètres plus petits.

Keywords: two-phase flow, circular micro-tubes, flow patterns, flow maps, air–water system

INTRODUCTION

Gas–liquid two-phase flows in mini tubes frequently occur in many industrial applications such as electronic cooling, compact heat exchangers, compact refrigeration systems, and in micro-propulsion devices. Small diameter flow channels of the order of 1–2 mm are used in compact heat exchangers. These exchangers are used in aircraft, in air separation plants, chemical process industries, research nuclear reactors, and in chemical processing. They have remarkably high heat duties per unit volume. Heat transfer and pressure drop during two-phase flow cannot be predicted without knowledge of the flow patterns. Flow pattern recognition can be obtained by simple visual inspection of the flow in a transparent pipe, with a high-speed camera if the superficial velocities are of higher order, by measuring and quantifying the fluctuations of the flow parameters such as void fraction using capacitance probe or dynamic pressure which reflect the flow structure. The flow pattern identification from the signal fluctuations can be done by analysing the probability density function (PDF) or power spectral density function (PSD) of the time trace signal. Unlike larger diameter tubes, the flow regimes, patterns and pressure drop in narrow tubes are different, and the effects of channel diameter, roughness of the surface, inclination and fluid properties such as surface tension, viscosity on two-phase flow are important. In two-phase flow, the micro-scale size-effect starts becoming prominent at a much

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higher diameter of the order of 2 mm compared to 200 μm size in single-phase flow. This is because the fundamental length scale in single-phase flow is the mean-free path which is usually in microns (for gas flow), while in two-phase flow the fundamental length scale is the bubble diameter which is of the order of millimeters. Hence, the micro-scale size-effects are visible here in the millimeter range flow passages itself. Suo and Griffith (1964) studied the adiabatic flow of two phases in horizontal tubes of capillary diameter. The conditions under which the "long bubble flow" can exist and the correlations are valid were determined. Taitel and Dukler (1976) presented models for determining flow regime transitions in two-phase gas–liquid flow. A generalised flow regime map based on this theory was presented. Five basic flow regimes were considered, smooth stratified, intermittent (slug and plug), annular with dispersed liquid, and dispersed bubble. No distinction was made between slug, plug, or elongated bubble flows, all being considered different conditions of the intermittent flow regime. Barnea et al. (1983) did experiments on five glass pipes of 4, 6, 8.15, 9.85, and 12.3 mm with a length of 2.5 m and presented the flow-pattern transitions. The experimental results were compared with previously published models for horizontal and vertical flows valid for medium- and large-diameter pipes. Observed flow patterns for horizontal flows were stratified smooth, stratified wavy, elongated bubble, slug, annular, wavy-annular, dispersed bubble, and annular patterns. They also observed elongated bubble, slug, churn annular, and dispersed bubble for vertical upward flow. The theory for flow pattern transition by Taitel and Dukler (1976) was modified by Barnea et al. (1983) taking surface-tension effects into account. Damianides and Westwater (1988) presented flow maps for horizontal glass tubes of 1–5 mm diameter using 0.015–125.3 m/s (air) and 0.0024–5.72 m/s (water) with high-speed photography and fast response-pressure transducers. Bubble, annular, and intermittent flow patterns were observed. Coleman and Garimella (1999) conducted experiments on adiabatic flow of air–water mixtures in rectangular and circular tubes with hydraulic diameters ranging from 1.3 to 5.5 mm. Bubble–dispersed, elongated bubble, slug, stratified, wavy, annular–wavy, and annular flow patterns were identified. The results of their study showed that as the tube diameters were decreased, the transition between these flow regimes occurred at different combinations of superficial gas and liquid velocities. In addition, the aspect ratio, hydraulic diameter and surface tension were found to be important factors in determining the locations of flow-regime transitions. They finally concluded that the flow regime maps based on the data from larger diameter tubes may not be applicable for smaller diameter tubes. Triplett et al. (1999) observed flow patterns such as bubbly, churn, slug–annular, and annular by conducting experiments on circular and triangular channels with diameters 1.1, 1.45 mm and hydraulic diameters 1.09 and 1.45 mm, respectively. Xu et al. (1999) identified bubbly, slug, churn–turbulent, and annular patterns in vertical rectangular channels (260 mm in length and 12 mm in width) with narrow gaps of 0.3, 0.6, and 1 mm. Akbar et al. (2003) classified the flow regime maps into surface-dominated zone, inertia-dominated zone, and transition zone for hydraulic diameters which are closer to 1 mm. Kandlikar and Grande (2003) made the following classification based on the Knudsen number:

1. Conventional channels $D_h > 3$ mm
2. Minichannels 3 mm $\geq D_h \geq$ 200 μm
3. Micro-channels 200 μm $\geq D_h \geq$ 10 μm
4. Transitional channels 10 μm $\geq D_h \geq$ 0.1 μm
5. Transitional micro-channels 10 μm $\geq D_h \geq$ 1 μm
6. Transitional nano-channels 1 μm $\geq D_h \geq$ 0.1 μm
7. Molecular nano-channels 0.1 μm $\geq D_h$

Experiments were done by Chung and Kawaji (2004) with a mixture of nitrogen and water in circular channels of 530, 250, 100, and 50 μm diameter. Bubbly, slug, churn, slug–annular, and annular flows were observed for channels of hydraulic diameters 250 and 530 μm. Pehlivan et al. (2006) investigated the pressure drop and flow regimes in 3, 1, and 800 μm diameter tubes using air and water as two-phase fluids. They classified the flow regimes into inertia and surface-dominated zones. They observed bubbly, churn, intermittent, and annular flow pattern. Thome (2006) presented an overview of recent work on boiling and two-phase flow in mini- and micro-channels. Recently, Ide et al. (2007) presented the results of experiments on capillary tubes of inner diameters 1, 2.4, and 4.9 mm and in capillary rectangular channels with aspect ratios of 1–9. They observed bubble, intermittent, and annular-flow patterns. They reported that tube diameters have hardly any influence on flow patterns. A brief review of literature regarding two-phase gas–liquid adiabatic flow characteristics in mini- and micro-channels has been presented by Saisorn and Wongwises (2008); and Shao et al. (2009). Even though various experimental results have been reported on two-phase flow patterns in micro- and mini-channels, it can be concluded from the above; flow patterns in rectangular and triangular channels are very different from that in circular channels. Furthermore, in circular channels most of the studies do not cover the transition region of 2–0.5 mm, and, hence, more research needs to be done regarding the effect of tube diameter, roughness, physical property variations of fluids such as the viscosity, surface tension, thermal conductivity, etc. The main objective of the present study is to systematically investigate the various flow patterns in smaller diameter tubes by conducting experiments in circular narrow tubes in the range of 0.6–3.4 mm in diameter. This study also attempts to explain the effect of diameter on circular tube two-phase flow patterns by comparing with traditional as well as mini-channel flow maps available in literature.

EXPERIMENTS

The experimental set-up used in this study is designed for adiabatic co-current flow of air–water mixtures in round horizontal tubes. A schematic diagram of the experimental set-up is shown in Figure 1.

Distilled deionised water was pumped into the test loop by an 810LPH, 0.5HP water pump from an open tank. Air is blown at 1 bar. Both the liquid and gas streams flowed separately through a bank of Rota meters before entering the gas–liquid mixer. The gas–liquid mixer installed upstream of the test section or the observation zone ensures that the two phases get thoroughly mixed before entering the test section. The two-phase gas–liquid mixture then enters the test section.

A detailed description of gas–liquid mixer and the test section is shown in Figure 2. Air mixes with water through four holes each of 1 mm diameter in the mixing section. The test sections were made of Borosilicate smooth glass material with inner diameters of 0.623, 1.224, 1.732, 2.642, and 3.420 mm. The wall contact angle of water may be assumed to be 0°. Temperature of water stored in tank was at temperatures of 27–28°C. Each reading is taken only after 15 min even though the steady-state is reached earlier. Here, steady-state indicates that there should not be any change in flow patterns over a period of time with a fixed superficial velocity of water and air. The inner diameters of the tubes were measured

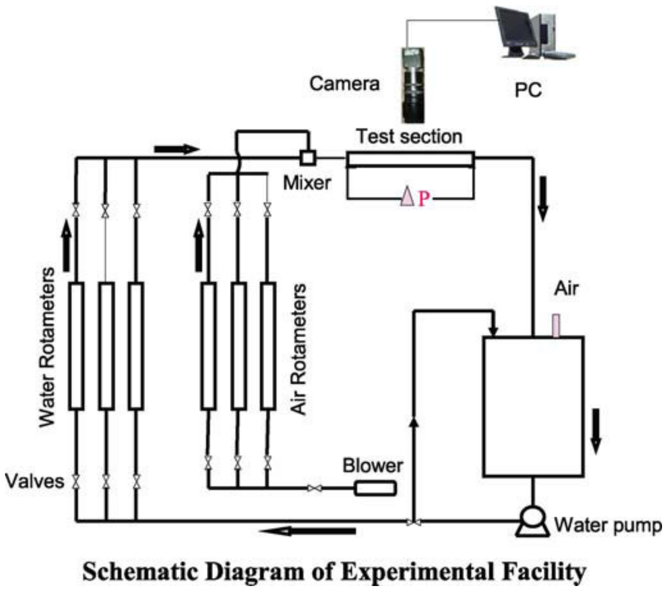


Figure 1. Schematic diagram of experimental facility.

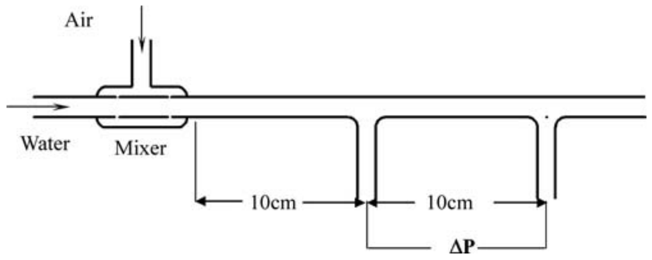


Figure 2. Mixer section along with test section.

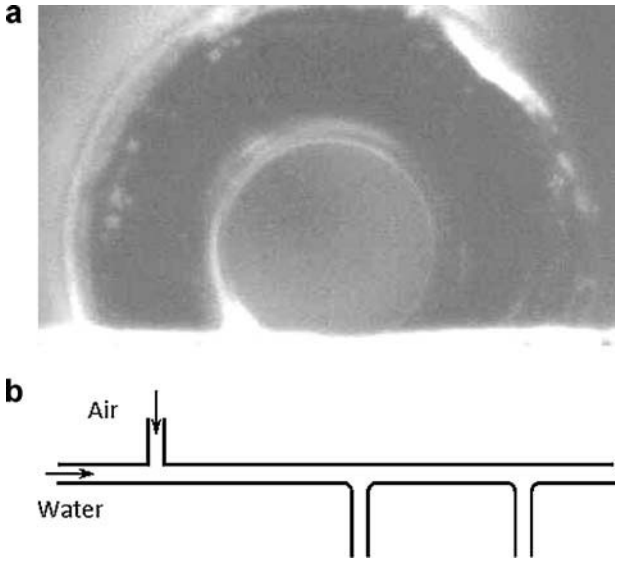


Figure 3. (a) Tube dia 2.6 mm. (b) Mixer section for 0.6 mm diameter tube.

using high-speed camera. Video graphs taken using Stream pix software was later converted into photographs and then analysed using Windig software to determine the tube diameter. A photograph taken is shown in Figure 3a. Points were marked at 10 different places on the photograph and diameter is measured on an average. Even a 5% error on the pipe diameter measurement gives an error of 30% on the friction factor as mentioned by Celata (2003).

Hereafter, the diameter of the tubes will be mentioned as 0.6, 1.2, 1.7, 2.6, and 3.4 mm only. A developing length of 10 cm length was provided between the mixer, and the test section (i.e., the observation zone) in order to avoid mixer effects on the flow patterns and their transitions. Following it is the test section which is 10 cm long and is provided with two pressure taps at the entrance and exit and is connected to differential pressure transducers to measure the pressure difference between test section inlet and outlet. Two transducers were used, one for low-pressure drops and the other for higher-pressure drops. The mixer section for the smallest diameter of 0.6 mm alone is different from the other tubes. Air is inserted in a perpendicular direction which mixes directly with water as shown in Figure 3b.

The flow visualisation system is equipped with a high-speed BASLER CMOS camera (Model No. A602f supported with IEEE 1394) with a zooming lens (Navitar Zoom 18–108 mmF/2.5). It has a maximum screen size resolution (pixel size) of 656 × 491 at 100 fps. This is adjustable depending upon the focusing area and frame speed. A screen resolution of 350 × 40 is used for visualising 0.6 mm tube with a frame speed of 1000 fps. The camera was mounted from the side of the test section. The test section is fixed on a wooden board. A floodlight of 500 W kept at a sufficient distance is used for viewing the flow patterns. Flow patterns were observed and the video graphs were recorded in a computer and subsequently analysed frame by frame with appropriate image processing software (StreamPix) to determine various flow regimes. The entire test loop was tested for leaks. Air pockets inside the test section and pressure taps were removed carefully before starting the experiments for each tube.

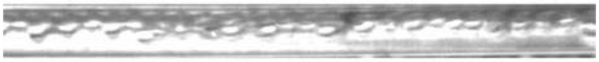
RESULTS

Flow Patterns

For 3.4 mm tubes, the superficial velocities varied from 0.03 to 1.84 m/s for liquid (U_l) and 0.15–6.12 m/s for air (U_g). Observed flow patterns were bubbly, dispersed bubbly, slug, slug-annular, and wavy-annular flow which is similar to that of large diameter tubes and are shown in Figure 4. (Flow directions in all the figures are from right to left.) Bubbly flow as shown in Figure 4a is characterised by spherical or non-spherical bubbles which may be of a size equivalent or less than that of the channel diameter. At high liquid and moderate gas velocities, spherical bubbles were observed as shown in Figure 4a and with further increase in gas velocity, the size of the bubble reduces, and the frequency with which the bubbles appear increases. In dispersed bubbly or churn flow pattern, as shown in Figure 4c, bubbles and smaller slugs appeared in dispersed form mostly occupying the top portion of the tube, and generally occur at high liquid and gas velocities. For low U_l and high U_g, slug type flow was observed as shown in Figure 4d. As noted by Triplett et al. (1999), increasing the mixture volumetric flux led to increase in the length of the slugs, eventually leading to merging of the slugs and the development of slug-annular flow pattern as shown in Figure 4f. In the slug-annular pattern, the liquid rises in the form of waves while in wavy-annular pattern gas in the core region causes the wavy pattern. In wavy-annular type flow slugs of sufficient velocity coalesce with each other and the gas trapped inside slugs develop a wavy pattern over the surface of the liquid as shown in Figure 4g. Coleman and Garimella (1999) have not made any a

Bubbly flow $U_g = 0.25$m/s, $U_l = 0.92$m/s

b

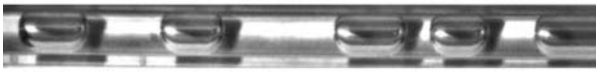


Bubble train

c

Dispersed bubbly $U_g = 2.29$m/s, $U_l = 1.22$m/s

d



Slug flow $U_g = 0.61$m/s, $U_l = 0.61$m/s

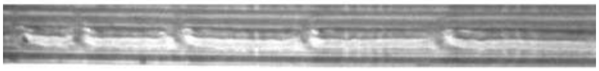
e

Slug train

f

Slug annular flow $U_g = 4.59$m/s $U_l = 0.24$m/s

g



Wavy annular flow $U_g = 3.67$m/s $U_l = 0.03$m/s

Figure 4. Photographs for 3.4 mm dia tube.

a

Bubbly flow $U_g = 0.785$m/s $U_l = 1.57$m/s

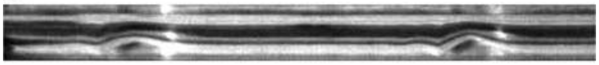
b

Dispersed bubbly flow $U_g = 7.85$m/s $U_l = 2.62$m/s

c

Slug flow $U_g = 1.31$m/s $U_l = 0.52$m/s

d



Slug annular flow $U_g = 7.85$m/s $U_l = 0.52$m/s

e

Wavy annular flow $U_g = 10.5$m/s $U_l = 0.42$m/s

f

Stratified smooth flow $U_g = 7.85$m/s $U_l = 0.02$m/s

g

Stratified wavy flow $U_g = 7.85$m/s $U_l = 0.04$m/s

Figure 5. Photographs for 2.6 mm dia tube.

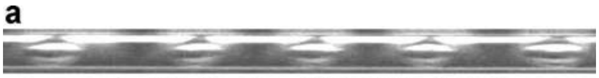
distinction between slug-annular and wavy-annular type flows. Wavy-annular flow pattern was observed by Barnea et al. (1983) in tubes of diameter 4–12 mm.

The superficial velocities from 0.01 to 3.4 m/s for liquids and 0.26–11 m/s for air were used in the 2.6 mm tube diameter. Flow patterns observed were bubbly, dispersed bubbly, slug, slug-annular, wavy-annular, and stratified-type flow. Stratified-wavy as well as stratified smooth-type flow as seen in Figure 5f and g were observed over a small region. As mentioned by Coleman and Garimella (1999), the stratified flow is characterised by complete separation of the liquid and gaseous phases. It can be stratified smooth in which the interface between two phases is without any fluctuation. Small interfacial waves are observed in the stratified wavy flow pattern. In the current experiments, both wavy and smooth stratified patterns were observed.

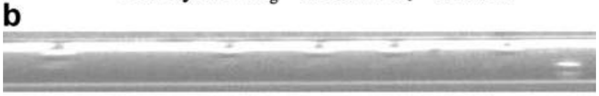
Flow patterns that were observed for 1.7 mm tube are shown in Figure 6a–e. The superficial velocities range from 0.03 to 3 m/s for liquids and 0.612–31 m/s for air. Flow patterns observed were bubbly, dispersed bubbly, slug, slug-annular, and annular-type flow. At higher gas mass flux, liquid is pushed towards the periphery of the tube as a thin film, while gas flows in the central core. This flow pattern is termed as annular flow as shown in Figure 6e which occurs at higher gaseous velocities. Stratified and wavy-annular flow was not observed. Surface-tension effects result in absence of stratified flow while decrease in tube diameter results in increase in acceleration of the fluid. The phases do not travel with the same velocity and coalescence of the slugs occur much faster than in larger tube diameters resulting in the absence of wavy-annular flow pattern in tube diameters <2 mm.

The superficial velocities for 1.2 mm diameter tube ranges from 0.025 to 2 m/s for liquids and 1.2–50 m/s for air. Flow patterns observed were bubbly, dispersed bubbly, slug, slug-annular, and annular-type flow and are shown in Figure 7a–f. Unlike larger diameter tubes, in 1.2 mm tubes slug flow is characterised by a long slug followed by a number of smaller slugs and spherical bubbles as seen in Figure 7b. It has been mentioned as creeping action by Damianides and Westwater (1988) which may be due to surface-tension effects as well as roughness of the test-section material having a significant part in flow patterns of capillary tubes. The trailing end of the slug breaks into smaller bubbles. This flow pattern is different from churn flow which occurs at higher liquid and gaseous velocities mentioned by Triplett et al. (1999) who has observed churn flow as a flow pattern with higher disruptions at the trailing end.

The superficial velocities for a 0.6 mm diameter tube ranges from 0.16 to 2 m/s for liquids and 2–50 m/s for air. Four distinct flow patterns were identified. Bubbly, dispersed bubbly, slug-annular, and slug flow patterns were observed depending upon various combinations of superficial liquid and gas velocities and are shown in Figure 8a–d. Slug-flow regime at lower superficial

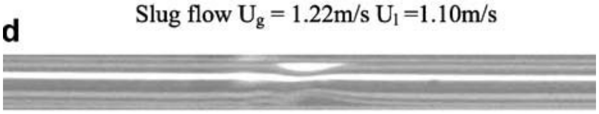


Bubbly flow $U_g = 1.22$m/s $U_l = 1.71$m/s

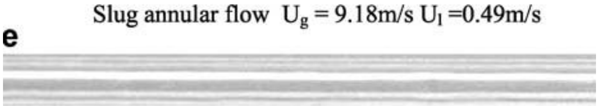


Dispersed bubbly flow $U_g = 9.18$m/s $U_l = 2.45$m/s

Slug flow $U_g = 1.22$m/s $U_l = 1.10$m/s



Slug annular flow $U_g = 9.18$m/s $U_l = 0.49$m/s



Annular flow $U_g = 24.5$m/s $U_l = 0.24$m/s

Figure 6. Photographs for 1.7 mm dia tube.

bubbly flow $U_g = 2.46$m/s $U_l = 0.98$m/s

Slug flow $U_g = 1.23$m/s $U_l = 0.24$m/s

Slug flow with tail ends breaking into small bubbles

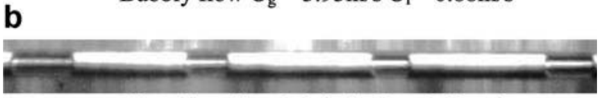
Dispersed bubbly flow $U_g = 6.15$m/s $U_l = 1.23$m/s

Slug annular flow $U_g = 9.83$m/s $U_l = 0.18$m/s

Annular flow $U_g = 30.7$m/s $U_l = 0.36$m/s

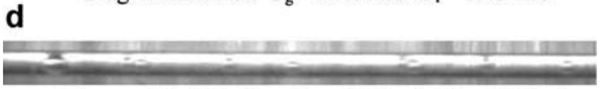
Figure 7. Photographs for 1.2 mm dia tube.

Bubbly flow $U_g = 3.93$m/s $U_l = 0.88$m/s



Slug flow $U_g = 1.96$m/s $U_l = 0.68$ m/s

Slug annular flow $U_g = 24.6$ m/s $U_l = 0.16$ m/s



Dispersed bubbly flow $U_g = 24.6$ m/s $U_l = 1.38$ m/s

Figure 8. Photographs for 0.6 mm dia tube.

liquid and gas velocities occupy almost the entire visualisation area of test section. Annular flow regime was not observed for 0.6 mm tube even at higher-gas velocities such as 50 m/s, whereas Chung and Kawaji (2004) observed annular regime for 530 μm diameter circular tube at a gas velocity of 12.65 m/s and liquid velocity of 0.015 m/s. They observed annular flow pattern at very low liquid velocities. Annular flow was not observed for 100 and 50 μm diameter tubes in their experiments. According to Chung and Kawaji (2004), stronger surface-tension effects in a micro-channel allows the liquid film to bridge the gas core more easily than a mini-channel so that the formation of annular flow would be less probable. They have used nitrogen and water as two-phase fluids. In present experiments, even slug-annular flow pattern was observed over a limited scale since the entire liquid regime was almost laminar. The reason may also be due to the difference in the geometry of the mixer section for the 0.6 mm tube used in the present study.

An interesting feature in the case of larger tubes of diameter 3.4 and 2.6 mm is that the buoyancy effect is clearly visible in slug, bubbly, and slug-annular regime. Even plug and slug flow regime could be distinguished while such differences are nearly absent in smaller tubes of diameters <2 mm. Also bubbles and slugs were flowing without any coalescence as a train for a 3 mm diameter tube as shown in Figure 4b and e, even when adjacent bubbles or slugs are close to them confirming the homogeneous theory for certain combination of superficial liquid and gas velocities. According to the homogeneous theory both the fluids travel with almost same velocity. Slip ratio is equal to unity. If there are coalescence between bubbles, slugs, etc. then it means a fluid is accelerating or decelerating depending upon the other fluid velocity. In the case of bubble trains both the bubbles are very close to each other still they do not coalesce. It means that they are travelling with the same velocities confirming homogeneous theory.

Comparison of Flow Maps With Available Data

The flow-regime transition lines obtained with a 3.4 mm diameter tube is compared with that obtained with a 4 mm diameter tube by Damianides and Westwater (1988) and 4 mm diameter tube by Barnea et al. (1983) and are shown in Figure 9. The transition from slug flow to bubbly and dispersed bubbly flow of Damianides and Westwater (1988) agrees well with the present data. Barnea et al. (1983) had termed the plug region of Damianides and Westwater (1988) as elongated bubble. The term is appropriate since in milli- and micro-diameter tubes, the characteristic size of the bubble is quite often limited by the diameter of tube. The transition from slug to wavy-annular flow in the present study agrees well with that of Barnea et al. (1983). However, they have not distinguished between a slug-annular and wavy-annular flows which occur in larger tube diameters.

The flow patterns obtained in the 2.6 mm diameter tube are compared with that obtained in a 2.6 mm diameter tube by Coleman and Garimella (1999) in Figure 10. Bubbly and dispersed bubbly flow patterns were observed earlier while the dispersed

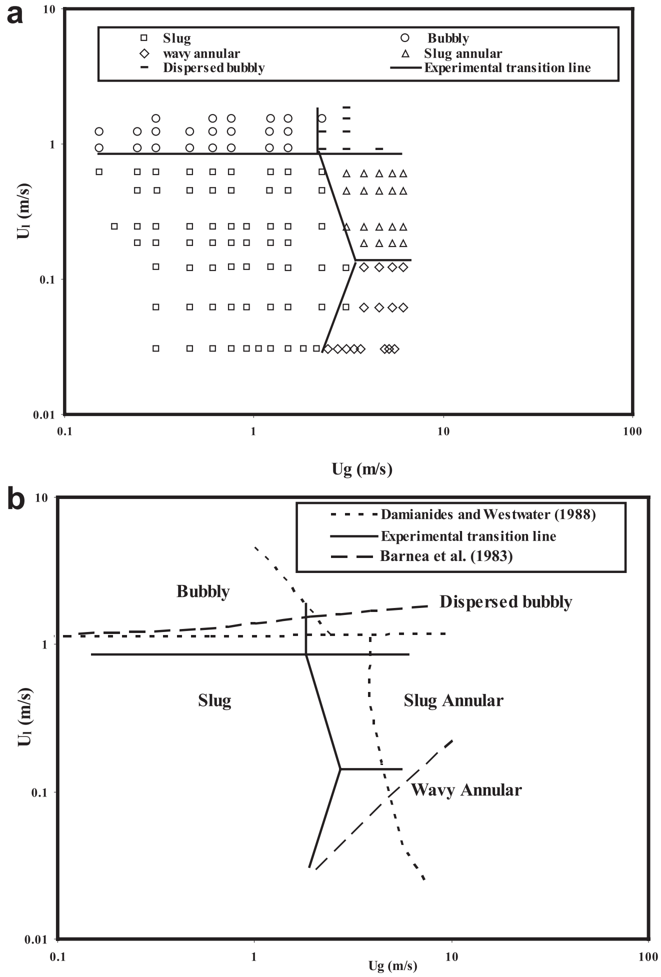


Figure 9. Flow regimes obtained in 3.4 mm tube: (a) Present data. (b) Comparison of present regimes with previous flow regime maps.

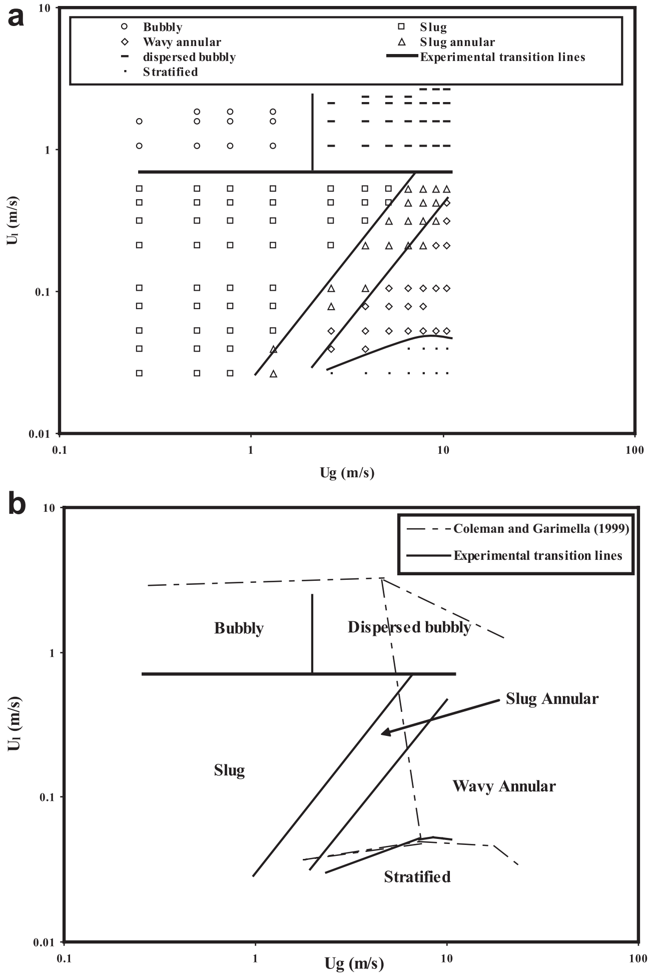


Figure 10. Flow regimes obtained in 2.6 mm tube: (a) Present data. (b) Comparison of present regimes with previous flow regime maps.

bubbly flow occurred over a wider range in the present study compared to that obtained by Coleman and Garimella (1999). They did not distinguish between slug-annular and wavy-annular flow. However, the transition from slug to wavy-annular flow agrees reasonably well with the results of the present study and the transition from slug/wavy-annular to stratified flow agrees very well.

Figure 11 shows the flow-regime map obtained with a 1.7 mm tube compared with data obtained on a 2 mm tube by Damianides and Westwater (1988) and on a 1.75 mm diameter tube and this has been by Coleman and Garimella (1999). The slug regime in the present study exists over a wider range of liquid and gas velocities compared to the data of Damianides and Westwater (1988); and Coleman and Garimella (1999). Slugs could be seen without tail ends breaking. Bubbly flow occurred earlier compared to the transition from slug to bubble flow observed by Coleman and Garimella (1999). The transition from slug to slug-annular flow obtained in the present study agrees well with that of Coleman and Garimella (1999) (slug to wavy-annular line), while transition from slug-annular to annular pattern agrees reasonably well with that of wavy-annular to annular pattern of Coleman and Garimella (1999). In present experiments, the slug-annular flow regime observed is within the Coleman and Garimella's (1999) wavy-annular flow regime. It may be reemphasised here that Coleman and Garimella (1999); and Damianides and Westwater (1988) flow maps does not report on churn flow and slug-annular flow regimes.

The flow pattern observed with 1.2 mm tube diameter in the present study were compared with the flow transitions on a 1.09 mm diameter tube obtained by Triplett et al. (1999) and on a 1 mm tube by Damianides and Westwater (1988) and are shown in Figure 12. The transition from slug to slug-annular flow and from slug-annular to annular flow observed in the present study agrees reasonably well with that obtained by Triplett et al. (1999); and Damianides and Westwater (1988) (pseudo slug to annular transition line). Bubbly flow pattern was observed much earlier when compared with the transition from slug to bubbly flow reported by Triplett et al. (1999), while the transition from slug to bubbly flow, slug to slug-annular and slug-annular to dispersed bubbly flow pattern show very good agreement with that reported by Damianides and Westwater (1988). The occurrence of bubbly flow earlier may be due to higher surface roughness of the glass tube which results in higher shear.

Figure 13 shows the flow regimes obtained on a 0.6 mm diameter tube and compared with a 530 μm diameter tube of Chung and Kawaji (2004). Smaller bubbles and bubble size of the order of the tube diameter which were spherical were observed in the churn flow regime as mentioned by Chung and Kawaji (2004). Transition from slug to slug-annular regime of Chung and Kawaji (2004) agrees reasonably well with the present study. Annular

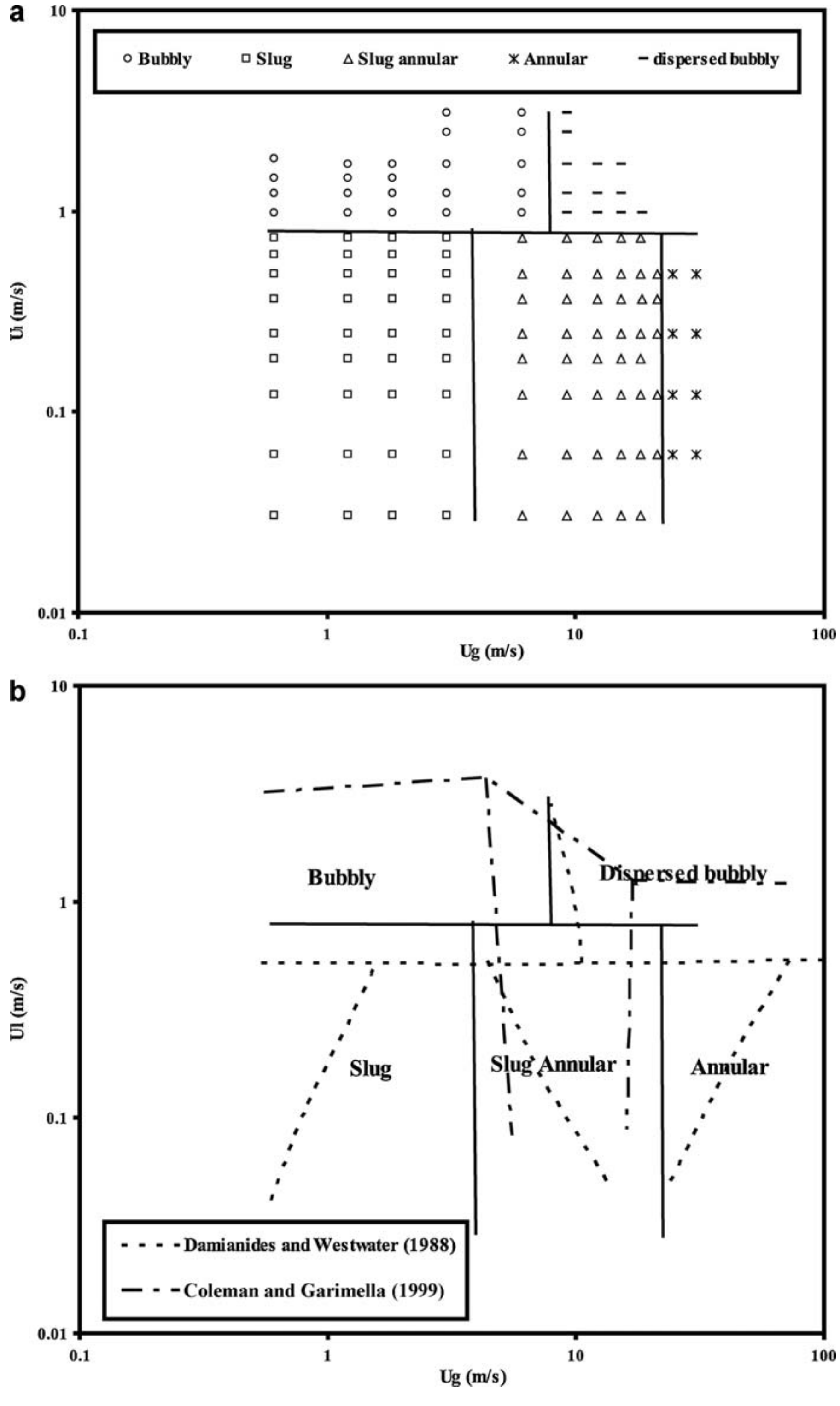


Figure 11. Flow regimes obtained in 1.7 mm tube: (a) Present data. (b) Comparison of present regimes with previous flow regime maps.

flow was not observed in the present study even at the highest gas velocities of more than 50 m/s.

Figure 14 shows experimental flow maps for all five tubes considered. To have a common nomenclature for the definition of the basic flow patterns, intermittent is used to denote slug, slug-annular, and wavy-annular flow, while dispersed includes bubbly as well as dispersed bubbly flow. The results are compared with the flow regime map of 5 mm tube diameter of Damianides and Westwater (1988). As observed by Damianides and Westwater (1988), smaller tubes require much larger gas flow to change from intermittent to annular flow. However, for tube diameter 0.6 mm, annular flow was not observed even at higher gas flow rates. Much of the difference in flow patterns is observed in intermittent regime.

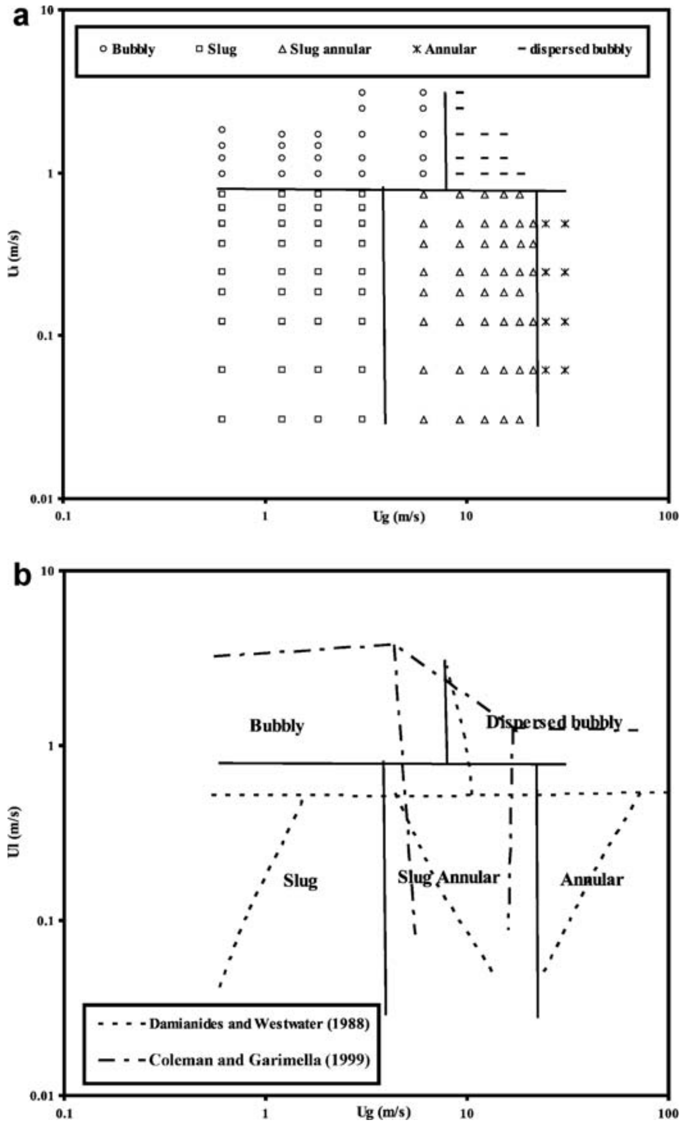


Figure 12. Flow regimes obtained in 1.2 mm tube: (a) Present data. (b) Comparison of present regimes with previous flow regime maps.

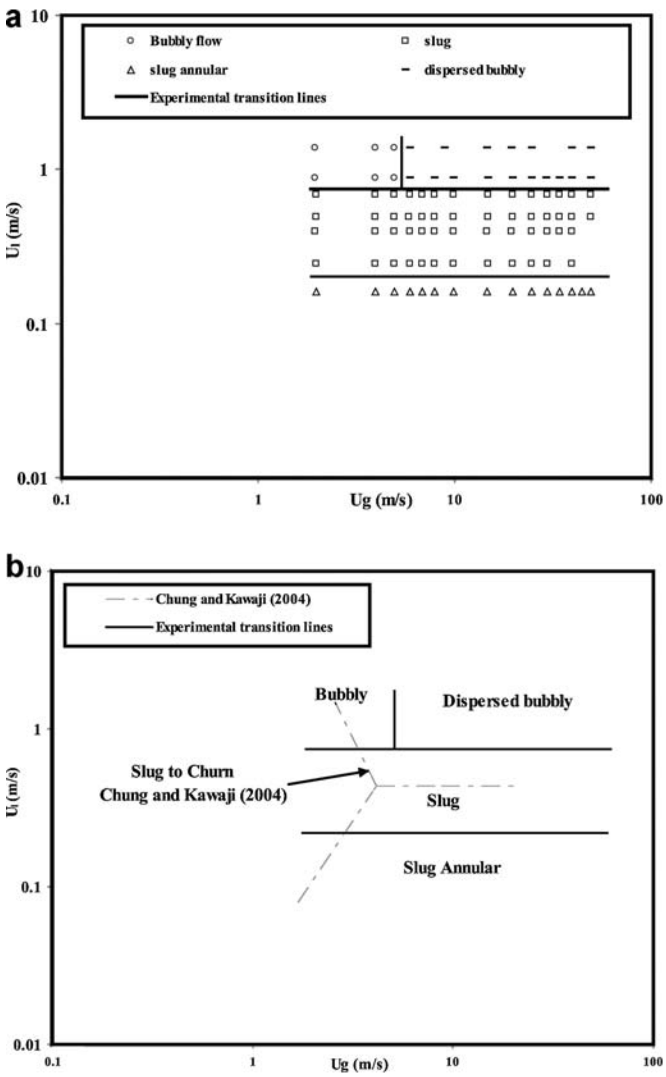


Figure 13. Flow regimes obtained in 0.6 mm tube: (a) Present data. (b) Comparison of present regimes with previous flow regime maps.

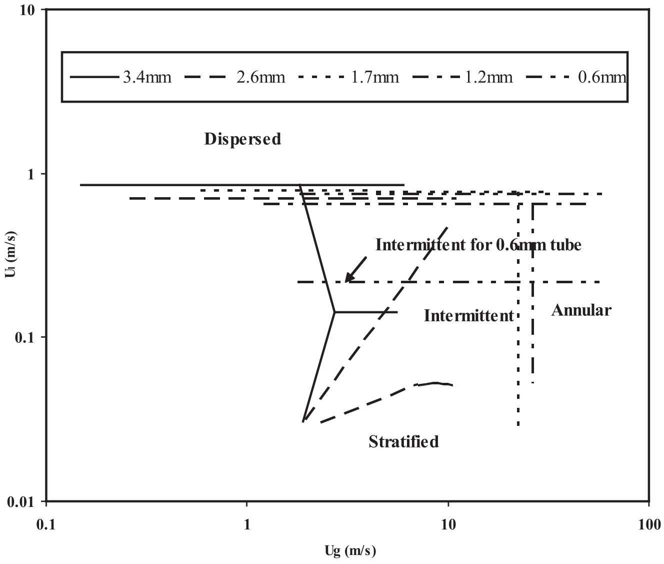


Figure 14. Comparison of flow regimes obtained in various tubes.

DISCUSSION

The flow regime identification by Taitel and Dukler (1976) starts with a stratified flow pattern. With increase in liquid flow rate, the level of liquid in the tube rises and a liquid wave is formed. Depending upon tube dimensions the wave formed by the liquid tends to block the flow. If the gas flow rate is sufficiently low, then the occurrence of slug or plug flow occurs. In plug flow, the effect of gravity is clearly visible and the wave occupies almost the top of the tube. This is the first case of transition of stratified to intermittent flow pattern. Plug and slug patterns are included in intermittent flow pattern according to Taitel and Dukler (1976). With further increase in gaseous flow rate, the liquid in the wave is separated and forms an annulus which is termed as annular flow. Annular flow exists when the superficial gas velocity is sufficiently high. It is a continuous gas core uninterrupted by a liquid slug. This is the second case of transition of stratified to annular flow pattern. According to Taitel and Dukler (1976), due to the formation of a wave in the liquid surface, there is a increase in acceleration of the gas phase with decrease in pressure due to Bernoulli effect. This makes the wave to grow. It can be seen by flow visualisation that over a range of combination of superficial liquid and gaseous velocities, the ratio between lengths of gas slug to liquid slug remains almost constant over the entire length of tube. In the present case of small diameter tubes, gas trapped inside slugs gets compressed with coalescence of adjacent slugs even though they do not merge together since the slugs are travelling with more or less the same velocity. The small increase in such velocities results in compression of gas resulting in a gas slug having a fold pattern resulting in a wavy-annular flow pattern. However, with further decrease in tube diameter merging of slugs occurs in an accelerated manner which results in the absence of wavy-annular flow pattern and there is a direct transition of slug-annular to annular flow pattern. According to Triplett slug-annular flow is an intermediate between slug flow and annular flow. A stable slug is formed only when there is a sufficient liquid below the wave to maintain such a slug. When this level is not sufficient annular flow takes place. Intermittent flow is developed when equilibrium liquid level in the pipe is above the pipe centre line. The present flow maps indicate that even with higher superficial gaseous velocities the equilibrium liquid level may be higher which results in absence of annular flow pattern in 0.6 mm tube. Also in smaller tube diameters the gravity force has a less effect which results in absence of plug flow with tube diameters less than 2 mm making buoyancy forces to be less significant. These results definitely have a significant effect in nucleate boiling mechanism in flow boiling characteristics which need to be further investigated. The present investigation clearly demonstrates how the change of flow pattern and associated phenomena are influenced by decreasing tube dimension. These results show that there is an unmistakable effect of tube size on flow patterns in milli- and micro-channels which can influence frictional and thermal characteristics of two-phase flow.

CONCLUSIONS

Two-phase flow patterns inside circular mini-tubes were experimentally studied using air–water mixtures. The different tube diameters used were 0.6, 1.2, 1.7, 2.6, and 3.4 mm. Superficial gas and liquid velocity ranges were 0.01–50 and 0.01–3 m/s, respectively. The two-phase flow was visualised through a high-speed CMOS camera and flow regime maps are presented for different tube diameters.

Unique flow patterns were identified for different tube diameters that confirm the diameter effect on flow patterns in two-phase flows. Stratified flow was not observed for tube diameters less than 2 mm. Similarly, wavy-annular flow pattern was not observed in 1.7, 1.2, and 0.6 mm diameter tubes. Annular flow pattern was not observed in the 0.6 mm diameter tube even at high-gas velocities. In the 1.2 mm diameter tube, slug flow is characterised by breaking of the longer slugs followed by shorter slugs and smaller bubbles which were not observed in other diameter tubes. Buoyancy effects were clearly visible in 2.6 and 3 mm diameter tubes. The present experimental data were also compared with similar literature data of Triplett et al. (1999); Coleman and Garimella (1999); Barnea et al. (1983); and Damianides and Westwater (1988) with generally good agreement in most regimes but with significant differences at lower tube diameters.

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