Heat Mass Transfer (2017) 53:2799–2811
DOI 10.1007/s00231-017-2020-9

ORIGINAL

Experimental investigation of two-phase flow patterns in minichannels at horizontal orientation

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Received: 7 November 2016 / Accepted: 14 March 2017 / Published online: 27 March 2017

Abstract Two-phase flow is the simplest case of multiphase flow in which two phases are present for a pure component. The mini channel is considered as diameter below 3.0–0.2 mm and conventional channel is considered diameter above 3.0 mm. An experiment was conducted to study the adiabatic two-phase flow patterns in the circular test section with inner diameter of 1.1, 1.63, 2.0, 2.43 and 3.0 mm for horizontal orientation using air and water as a fluid. Different types of flow patterns found in the experiment. The parameters that affect most of these patterns and their transitions are channel size, phase superficial velocities (air and liquid) and surface tension. The superficial velocity of liquid and gas ranges from 0.01 to 66.70 and 0.01 to 3 m/s respectively. Two-phase flow pattern photos were recorded using a high speed CMOS camera. In this experiment different 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 3.0 mm. Similarly, wavy-annular flow pattern was not observed in 1.6 and 1.0 mm diameter tubes due to the surface-tension effect and decrease in tube diameter. Buoyancy effects were clearly visible in 2.43 and 3.0 mm diameter tubes flow pattern. It has also observed that as the test-section diameter decreases the transition lines shift towards the higher gas and liquid velocity. However, the result of flow pattern lines in the present study has good agreement with the some of the existing flow patterns maps.

1 Introduction

Two-phase flow is the simplest case of multiphase flow in which two phases are present in pure component. The flow within each phase or component will clearly depend on that geometric distribution. An appropriate starting point is a phenomenological description of the geometric distributions or flow patterns that are observed in common multiphase flows. This study describes the flow patterns observed in horizontal tubes and identifies a number of the instabilities that lead to transition from one flow pattern to another. A particular type of geometric distribution of the components is called a flow pattern or flow regime and many of the names given to these flow patterns (such as annular flow or bubbly flow) are now quite standard. Usually the flow patterns are recognized by visual inspection, though other means such as analysis of the spectral content of the unsteady pressures the volume fraction have been devised for those circumstances in which visual information is difficult to obtain [1]. Suo and Griffith [2] performed experiments in horizontal channels with 0.5 and 0.7 mm diameters, and could identify slug, slug–bubbly, and annular flow patterns. For transition from slug to slug-bubbly, no stratified flow observed in his experiment. He has correlated thickness of the liquid film around a bubble and found gas flow as long bubble. It also found surface tension force dominates over gravitational force. Taitel and Dukler [3] carried out the experimental investigation of two-phase flow patterns in mini channel for test section 1.1 and 1.45 mm. It's observed that the channel geometry has a small effect on flow patterns for circular channel, stratified flow was

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not observed. Barnea et al. [4] conduct the experiments and observed liquid velocity has a stronger influence on flow patterns rather than gas velocity. Also notify the transition model for larger diameter cannot predict transition boundaries in mini channels. Damianides and Westwater [5] done experiment on two-phase flow pattern using air and water as a fluid on glass tube 1–5 mm diameter. And observed Bubbly, annular and intermittent using air and water as a fluid. Fukano and Kariyasaki [6] observed they did not find separated flow in capillary tubes and predicted the critical pipe diameter between 5 and 9 mm. They did not observe stratified flow in small diameter pipes. It was noticed that channel orientation does not have any effect on current patterns and transition lines in diameter less than 4.9 mm. Coleman and Garimella [7] done experiment on adiabatic two phase flow on circular tubes with hydraulic diameter 1.3–5.5 mm. using air and water as fluid and observed bubbly, elongated bubble,wavy,stratified and annular flow. As the tube diameter decreases transition between flow regimes changed to higher superficial gas and liquid velocity. Triplett et al. [8] did systematic experimental investigation of two-phase flow patterns in micro channels of hydraulic diameters 1.09, 1.1, and 1.45 mm. Observed flow patterns such as bubbles, churn, slug–annular, and annular. He found that channel orientation does not have any effect of tube diameter. Yang and Shieh [9] found during the experimental investigation of two phase flow patterns for refrigerant R-134a and air–water in horizontal test sections for inside diameter 1.0–3.0 mm was performed. However, R-134a flow leads to a shift from slug to annular transition at lower values of gas velocity. The locations of bubble to plug and slug flow transition are also significantly affected by the working fluid properties. The effect of surface tension forces on micro- scale channels using air–water and the refrigerant R-134a, they found R-134a receives much lower surface tension as compared to air–water, with a circular tube of 1–3 mm diameter in horizontal orientation. Chen et al. [10] conducted experiments on circular glass tube of 1 and 1.5 mm diameter in horizontal and vertical configuration using nitrogen-water and observed bubbly, taylor, churn and annular flow regime. Akbar et al. [11] identified flow pattern zone as surface-dominated, inertia-dominated, and transition zone for hydraulic diameters which are more or less to 1 mm. Kandlikar and Grande [12] established the following, classification based on the Knudsen number:

1. Conventional channels Dh >3 mm.
2. Minichannels 3 mm ≥ Dh ≥ 200_m.
3. Micro-channels 200_m ≥ Dh ≥ 10_m.
4. Transitional channels 10_m ≥ Dh ≥ 0.1_m.
5. Transitional micro-channels 10_m ≥ Dh ≥ 1_m.
6. Transitional Nano-channels 1_m ≥ Dh ≥ 0.1_m.
7. Molecular Nano-channels 0.1_m ≥ Dh.

Pehlivan [13] classified the flow regimes into inertia and surface-dominated zones. They observed bubbly, churn, intermittent and annular flow pattern. Venkatesan and Das [14] investigated two-phase flow patterns inside circular mini channel using air–water mixtures and studied the effect of tube diameter on two-phase flow patterns in circular tubes with inner diameters of 0.6, 1.2, 1.7, 2.6 and 3.4 mm. The flow patterns observed were dispersed bubbly, bubbly, slug, slug-annular, wavy-annular, stratified, and annular flows. All these flow patterns were not observed in all the test sections, but some of the flow patterns were found similar to all test sections and it's confirming the effect of tube diameter on the flow pattern. Mehta and Banerjee [15] experimentally developed flow pattern maps for micro-scale channels and found that no theoretical models effectively predict the flow regime transition boundaries in the micro-scale channel. The aims of the present study are to study the experimental investigation of adiabatic two-phase flow patterns in mini channels and compare the experimental flow regime maps with existing flow regime maps and the effect of different parameter on flow patterns.

2 Experimental setup

The experimental setup is designed and fabricated by Autee et al. [16] to conduct experiments of two-phase flow with air–water mixture as shown in Fig. 1. The experimental setups consist of air and water circuits. Constant supply of air is controlled with the help of the bypass valve at 40 PSI measured by bourdon tube pressure gauge. Water is pumped using centrifugal pump from the storage tank of 200 L. Capacity. The flow rates of water and air are measured with rotameters ranges from 0.3 to 3 LMP and 10 to 100 LPM. To avoid the back pressure effect and proper mixing of fluids a specially designed acrylic mixing chamber is connected up in the lap with the test sections as shown in Fig. 2 The high speed camera is employed for recording of two-phase flow patterns. Differential pressure transducers are employed to measure the pressure drop across the test section and this data is acquired using the acquisition system connected to a PC.

2.1 Mixing chamber

Two-phase mixing chamber provides better uniformity of the flow stream. A detailed description of gas–liquid mixer and the test section is shown in Fig. 2.0. Mixing chamber is made of acrylic sheet. Air mixes with water through four holes each of 0.5 mm diameter done on DRO milling m/c. The air and water flows get mixed and flows smoothly in chamber without creating any back pressure effect on the measuring device (Fig. 3).

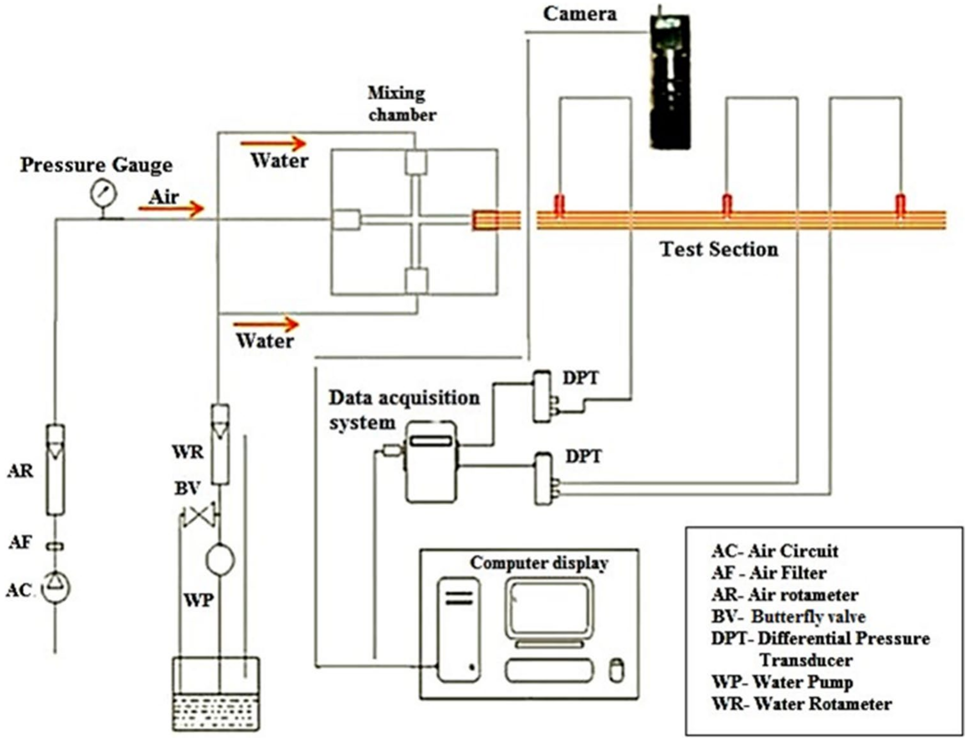

Fig. 1 Schematic diagram of experimental set-up

3 Result

The investigations were taken out to examine the current flow pattern in mini channels ranges from 1.1 to 3.0 mm diameter circular tubes. Detailed investigation of observed flow pattern carried out in this study as discussed in the next parts.

3.1 Flow patterns for test section 1.1 mm

An experiment was conducted to investigate two-phase flow patterns for the test section of 1.1 mm diameter and total length 650 mm. The superficial velocities of water and air vary from 2.19–14.0 and 1.7–66.70 m/s respectively. Five different two-phase flow patterns were identified, such as bubbly, dispersed bubbly, slug, slug annular and annular flow as shown in Fig. 4. Bubbly flow can be categorized by the occurrence of small spherical–bubbles. The shape of the bubbles suggests the dominance of the surface tension force, in the dispersed bubbly flow increasing the gas velocity and reducing the liquid velocity the spherical bubbles discrete in small bubbles. The combination of small spherical bubble observed. In the slug flow characterized by a long slug followed by a number of smaller slugs and longer slug as seen in Fig. 4c, It has been mentioned as creeping action by Damianides and Westwater [5] and roughness of the test-section material having a upmost part in flow patterns of capillary tubes. When the gas velocity is increased under the slug flow condition, waves are formed and a small wave shown in the Fig. 4d. Further increasing the gas velocity it has found that continuous liquid along walls and gas in core as shown in Fig. 4e.

3.2 Flow regime maps for test section 1.1 mm

The visualized flow pattern data are plotted as shown in Fig. 5a. With gas and liquid superficial velocities as coordinates. Different transition lines are identified and traced on the map at low air and high liquid velocities, bubbly flow are observed. Bubbly flow changes to dispersed bubbly by increase in air velocity. At low air and liquid slug flow is observed. Slug flow changes to annular flow with increase in air velocity. It has found that major area of the flow pattern map is occupied by slug and bubbly flow regimes. This is known as surface tension dominated regime. The transition from slug to annular flow is sharp.

3.3 Comparison of experimental flow regimes with existing flow regime maps for test section 1.1 mm

The flow regime map developed based on the experimental study is compared with the maps with some of the available existing literature. The flow-regime transition lines obtained with a 1.1 mm diameter tube is compared with that obtained with Coleman and Garimella [7] of tube diameter 1.09 mm and Venkatesan and Das [14] of tube

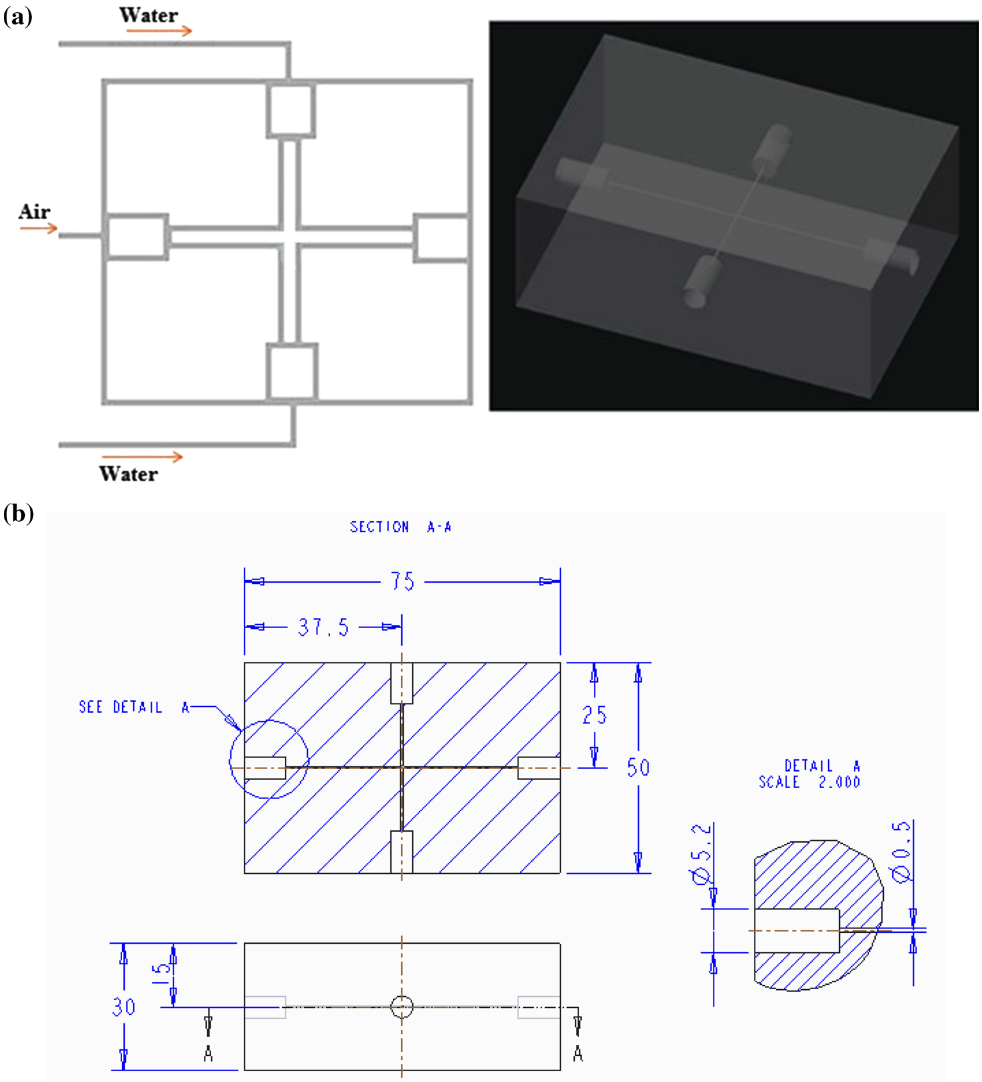

Fig. 2 **a** 3D model of mixing chamber. **b** Systematic drawing of mixing chamber

diameter 1.2 mm as shown in Fig. 5b. The transition from slug to slug-annular flow and from slug-annular to annular flow observed in the present study agrees reasonably well with Coleman and Garimella [7] and Venkatesan and Das [14]. Bubbly flow pattern observed late compared with the transition from slug to bubbly flow reported by Venkatesan and Das [14] but very much agree with Coleman and Garimella [7]. While the transition from slug to bubbly flow, slug-annular to dispersed bubbly flow and slug to slug-annular flow pattern shows very good agreement with that reported by Coleman and Garimella [7].

3.4 Flow patterns for test section 1.63 mm

Two-phase flow patterns for the internal test section of 1.6 mm diameter and total length was 195 mm. The superficial velocities range from 0.998 to 4.97 m/s of liquids and 1.6 to 39.9 m/s for air used in the 1.6 mm test section. Four different flow patterns were identified, namely, bubbly, dispersed bubbly, slug, and annular flow as shown in Fig. 6. The bubbly flow obtained in the form of spherical bubble which occurs at higher gaseous velocities as shown in Fig. 6a, the observed bubble is larger in size as compared to bubble observed in 1.1 mm test section. The spherical shape of the bubbles indicates the domination of the surface tension force, as the channel diameter decreases. In dispersed bubbly flow, further increasing the gas velocity and reducing the liquid velocity the spherical bubbles discrete in small bubbles (Fig. 6b).

A number of smaller slugs observed in the present study at the lower range of liquid and gas velocity compared to slug for 1.1 mm test section as shown in Fig. 6c. At higher gas mass flux, liquid is pushed towards the periphery of the tube as a thin film, and gas flows in the central core. This flow pattern is termed as annular flow.

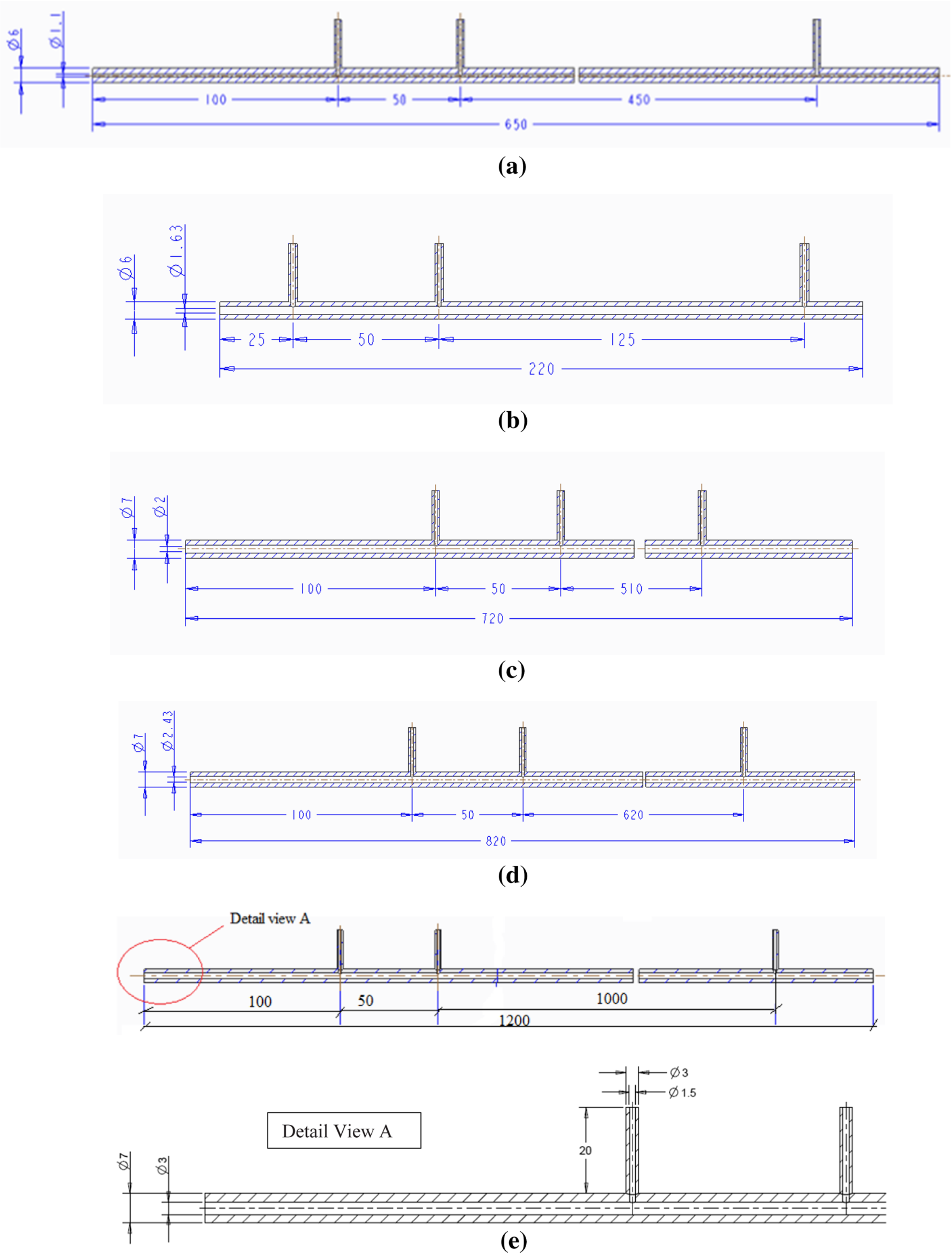

Fig. 3 Schematic diagram of test section. **a** Schematic drawing of test section of dia 1.1 mm. **b** Schematic drawing of test section of dia 1.63 mm. **c** Schematic drawing of test section of dia 2.0 mm. **d** Schematic drawing of test section of dia. 2.43 mm. **e** Schematic drawing of test section of dia. 3.0 mm. **f** Test section of 1.1 mm diameter. **g** Test section of 1.6 mm diameter. **h** Test section 2.0 mm diameter. **i** Test section 2.6 mm diameter. **j** Test section 3.0 mm diameter. **k** Photographic view of test section with mixing chamber

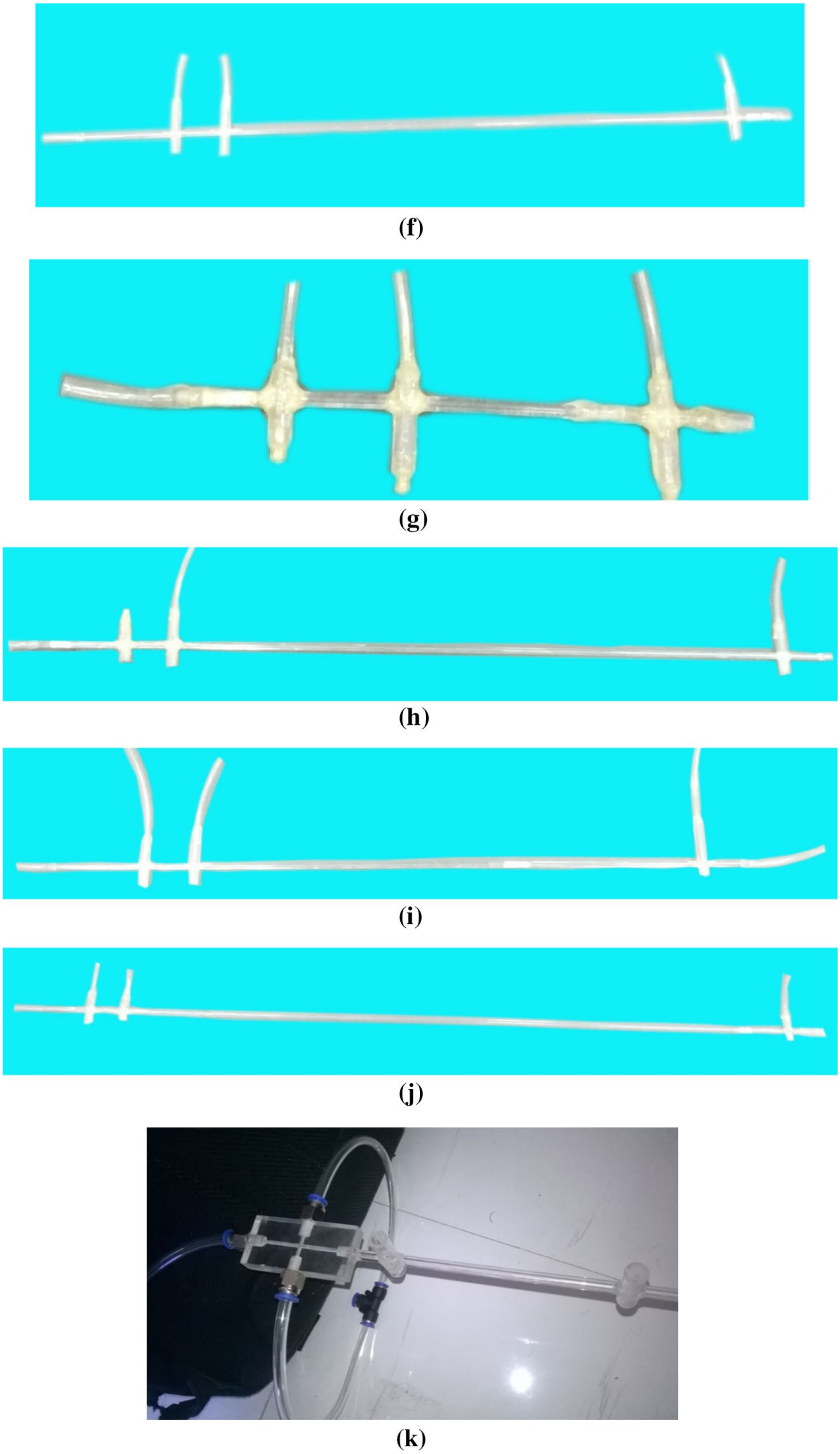

Fig. 3 continued

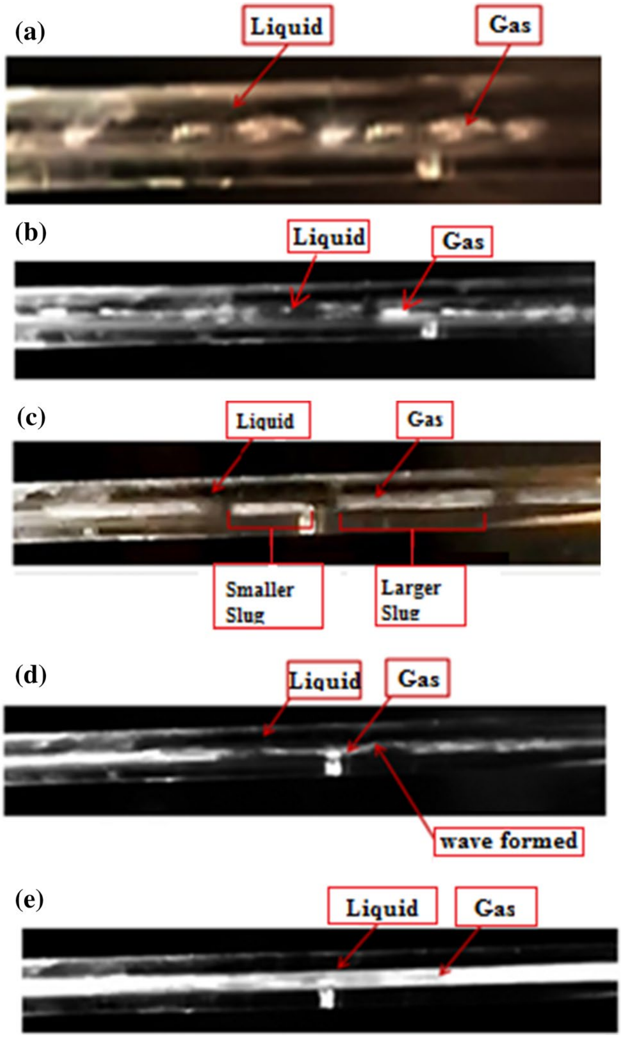

Fig. 4 Photographs for 1.1 mm dia tube. **a** Bubbly flow Ug = 3.51 m/s; Ul = 7.02 m/s. **b** Dispersed bubbly flow Ug = 14.0 m/s; Ul = 6.58 m/s. **c** Slug flow Ug = 1.75 m/s; Ul = 2.19 m/s. **d** Slug annular Ug = 17.5 m/s; Ul = 2.19 m/s. **e** Annular flow Ug = 43.8 m/s; Ul = 2.19 m/s

3.5 Flow regime maps for test section 1.63 mm

The slug flow regime in present study shown in Fig. 7a exists over a wide range of liquid and gas velocities. Bubbly flow observed earlier compare to test section of 1.1 mm. Bubbly flow changes to dispersed bubbly by increases in air velocity. Slug flow changes to annular flow with increase air velocity. Due to increasing the gas velocity under the slug flow condition waves are formed and it’s very difficult to distinguish slug annular and wavy annular. Stratified and wavy annular flow was not observed due to the Surface-tension effects and decrease in tube diameter results.

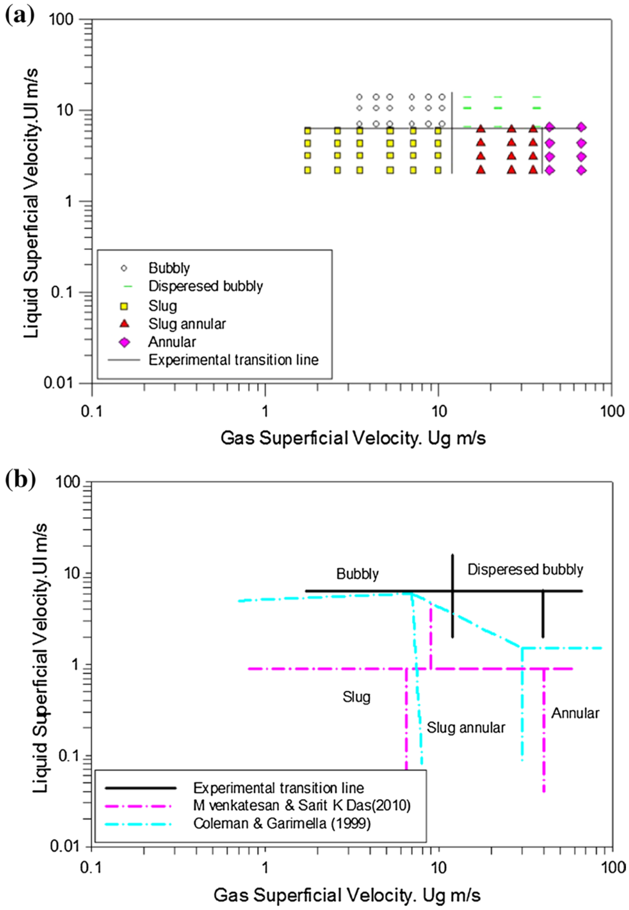

Fig. 5 Flow regimes obtained in 1.1 mm tube: **a** experimental data. **b** Comparison of experimental flow regimes with existing flow regime maps

3.6 Comparison of experimental flow regimes with existing flow regime maps for test section 1.63 mm

The flow patterns obtained in the 1.63 mm diameter tube are compared with the Coleman and Garimella [7] of tube diameter 1.75 mm and Venkatesan and Das [14] of tube diameter 1.7 mm as shown in Fig. 7b. Bubbly and dispersed bubbly in present study agree very well with Coleman and Garimella [7] and Venkatesan and Das [14]. Slug flow agrees with Venkatesan and Das [14]. Annular flow in present study agrees with Venkatesan and Das [14] are shown in the Fig. 7b.

3.7 Flow patterns for test section 2.0 mm

Two-phase flow patterns for the internal diameter of 2.0 mm of total length 710 mm. The superficial velocities range from 0.60 to 4.80 m/s of liquids and 1.06 to 21.20 m/s for air. Four different two-phase flow

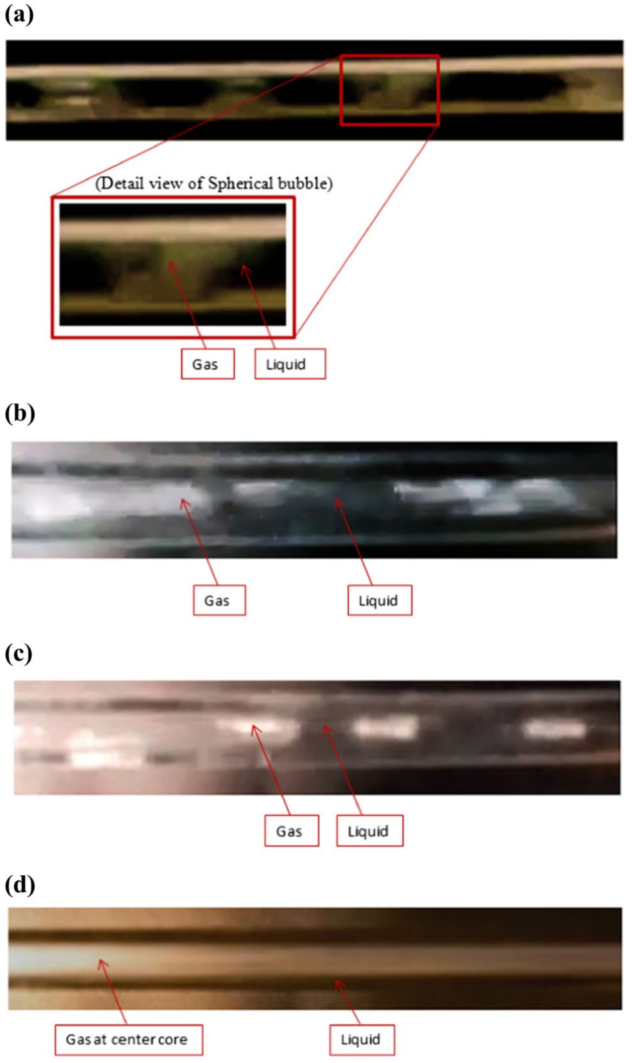

Fig. 6 Photographs for 1.6 mm dia tube. **a** Bubbly flow Ug = 1.6 m/s; Ul = 3.32 m/s. **b** Dispersed bubbly flow Ug = 12.4 m/s; Ul = 3.32 m/s. **c** Slug flow Ug = 1.6 m/s; Ul = 0.99 m/s. **d** Annular flow Ug = 24.0 m/s; Ul = 0.99 m/s

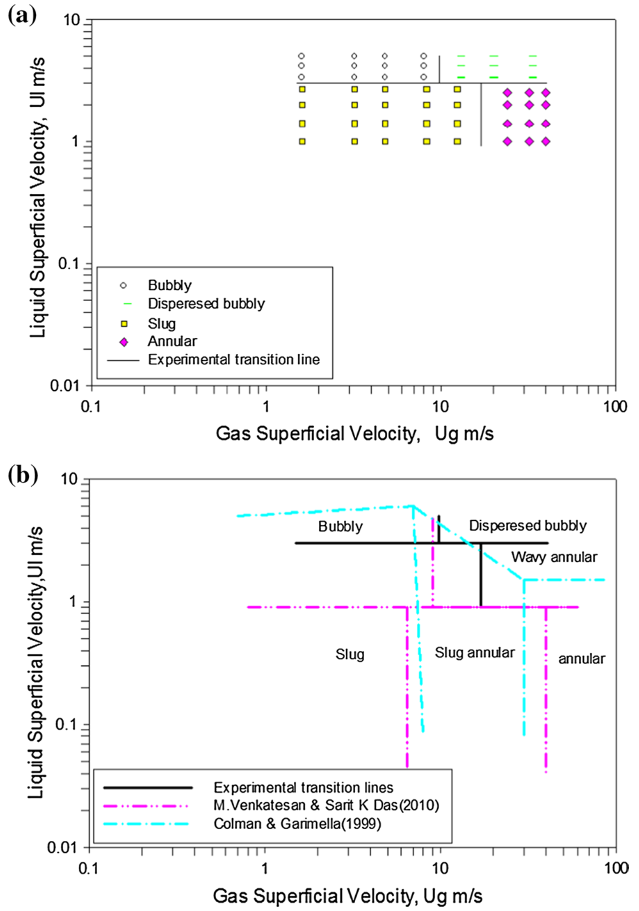

Fig. 7 Flow regimes obtained in 1.63 mm tube: **a** experimental data. **b** Comparison of experimental flow regimes with existing flow regime maps

patterns were identified, these such as bubbly, dispersed bubbly, slug and slug annular flow as shown in Fig. 8. Bubbly flow is characterized by a number of smaller bubbles in continuous form and the area occupied by bubble is almost the diameter of tube as shown in Fig. 8a.

Dispersed bubbly observed at higher superficial gas velocity and lower liquid velocity. Slug flow observed at moderate superficial gas and liquid velocity the phases do not travel with the same velocity and coalescence of the slugs occurs. Slug flow found in the longer in length as shown in Fig. 8c. At higher gas velocity and lower liquid velocity after slug flow Wave is formed and slug is mixed to next slug and a small wave as shown in the Fig. 8d.

3.8 Flow regime maps for test section 2.0 mm

Different transition lines are identified and traced on the map Fig. 9a. The bubbly flow regime in present study exists over a wide range of liquid and gas velocities. Bubbly flow changes to dispersed bubbly by increases in air velocity. Slug flow found in smaller region compared to test section 1.63 mm. As the diameter increases the coalescence slug occur an in much faster in larger tube diameter resulting in the absence of wavy annular flow. Increasing the gas velocity under the slug flow condition waves are formed and it's very difficult to distinguish slug annular and wavy annular. Stratified and wavy annular flow was not observed due to the surface-tension effects and decrease in tube diameter results.

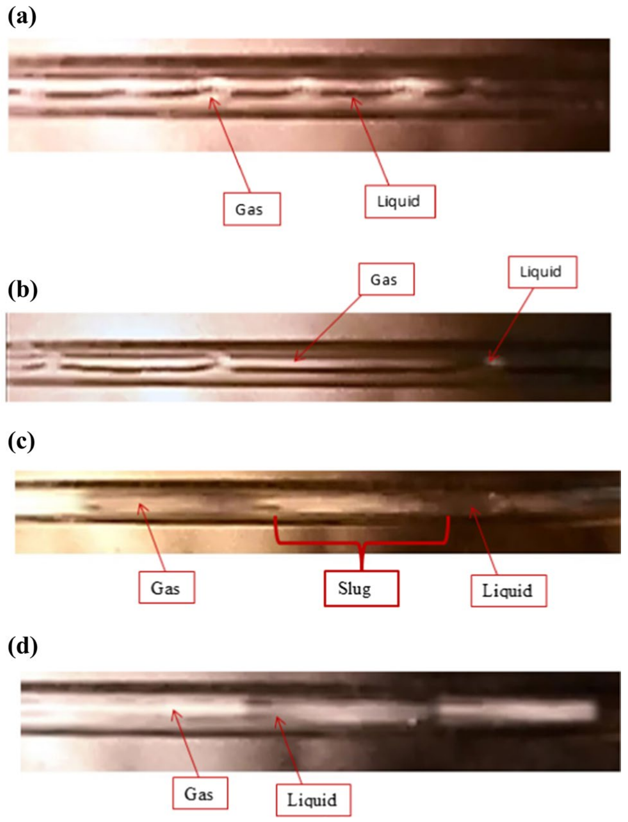

Fig. 8 Photographs for 2.0 mm dia tube. **a** Bubbly flow U_g = 1.06 m/s; U_l = 2.65 m/s. **b** Dispersed bubbly flow Ug = 10.60 m/s; Ul = 1.99 m/s. **c** Slug flow Ug = 2.12 m/s; Ul = 1.60 m/s. **d** Slug annular flow U_g = 10.6 m/s; U_l = 0.66 m/s

3.9 Comparison of experimental flow regimes with existing flow regime maps for test section 2.0 mm

Figure 9b shows the flow-regime map obtained with a 2.0 mm tube compared Coleman and Garimella [7] of tube diameter 1.75 mm and Venkatesan and Das [14] of tube diameter 1.7 mm. as shown in Fig. 9. Bubbly and dispersed bubbly in present study agree very well with Coleman and Garimella [7] and Venkatesan and Das [14]. Slug flow agrees with Coleman and Garimella [7]. Slug annular flow in present study agrees with Venkatesan and Das [14]. The transition from slug to slug-annular flow obtained in the present study agrees well with that of Coleman and Garimella [7] (slug to wavy-annular line) and Venkatesan and Das [14].

3.10 Flow patterns for test section 2.43 mm

Two-phase flow patterns for the internal test section of 2.43 mm diameter and total length was 820 mm. The superficial velocities vary from 0.3 to 3.9 m/s for liquids and 0.94–15.70 m/s for air were used in the 2.43 mm test section.

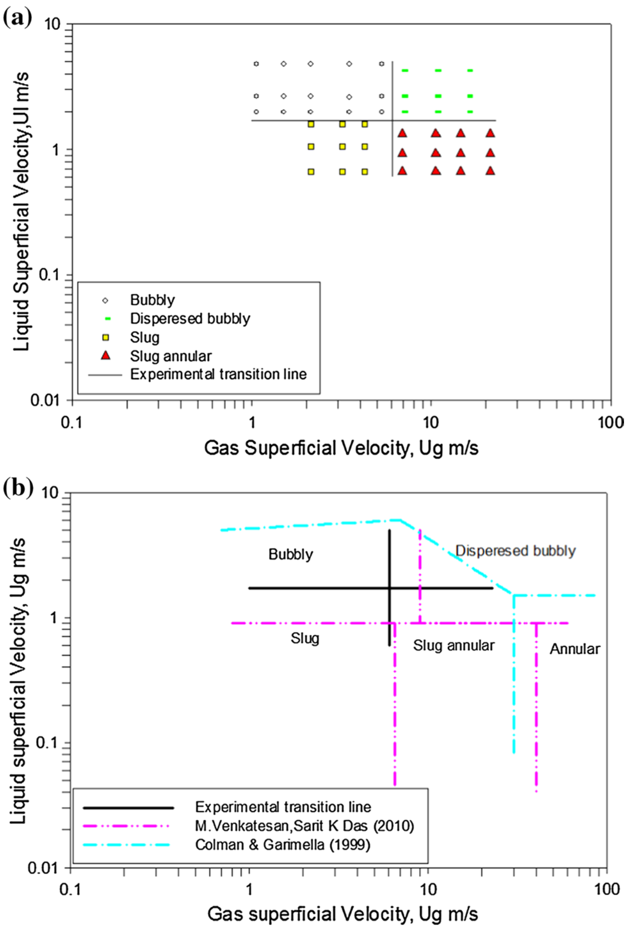

Fig. 9 Flow regimes obtained in 2.0 mm tube: **a** Experimental data. **b** Comparison of experimental flow regimes with existing flow regime maps

Four different two-phase flow patterns were identified, namely, bubbly, dispersed bubbly, slug, and wavy annular flow as shown in Fig. 10. In bubbly flow coalescence between bubbles clearly visible due to buoyancy effect as shown in Fig. 10a. Dispersed bubbly flow observed at higher Superficial gas velocity and lower liquid velocity as shown in Fig. 10b, the coalescence between bubbles is still observed due to buoyancy effect. Slug flow at moderate superficial gas and liquid velocity a small but continuous slug flow observed as shown in Fig. 10c. In the wavy annular flow when the gas velocity is increased under the slug flow condition wave are formed on the liquid-gas interface these wave travel in the direction flow.

3.11 Flow regime maps for test section 2.43 mm

In Fig. 11a. Bubbly flow observed at low gas and liquid velocity. Dispersed bubbly flow observed at higher gas

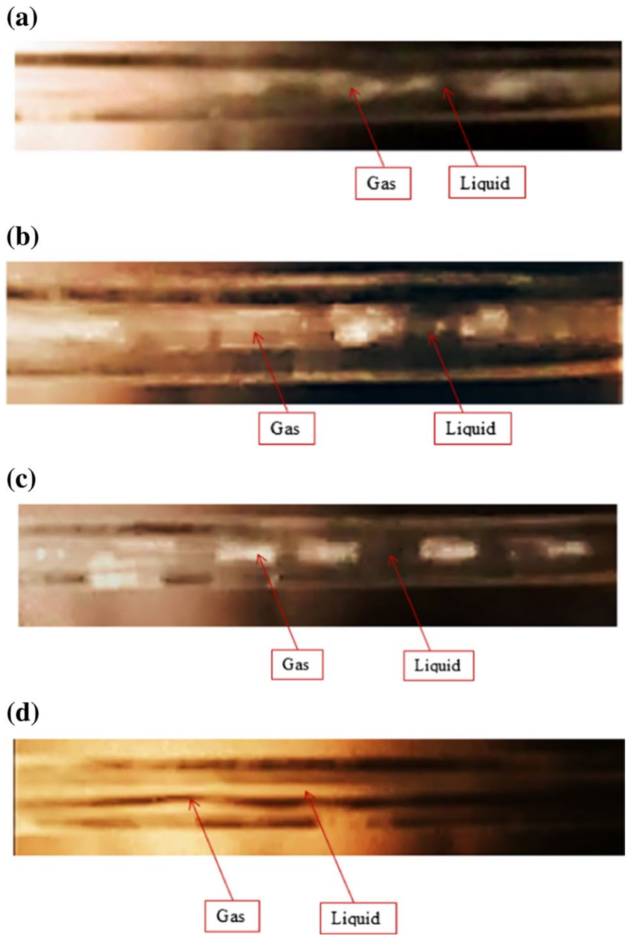

Fig. 10 Photographs for 2.43 mm dia tube. **a** Bubbly flow Ug = 0.94 m/s; Ul = 1.57 m/s. **b** Dispersed bubbly flow Ug = 9.42 m/s; $U_l = 2.35$ m/s. **c** Slug flow $U_g = 1.57$ m/s; $U_l = 0.62$ m/s. **d** Wavy annular flow $U_g = 9.42$ m/s; $U_l = 0.39$ m/s

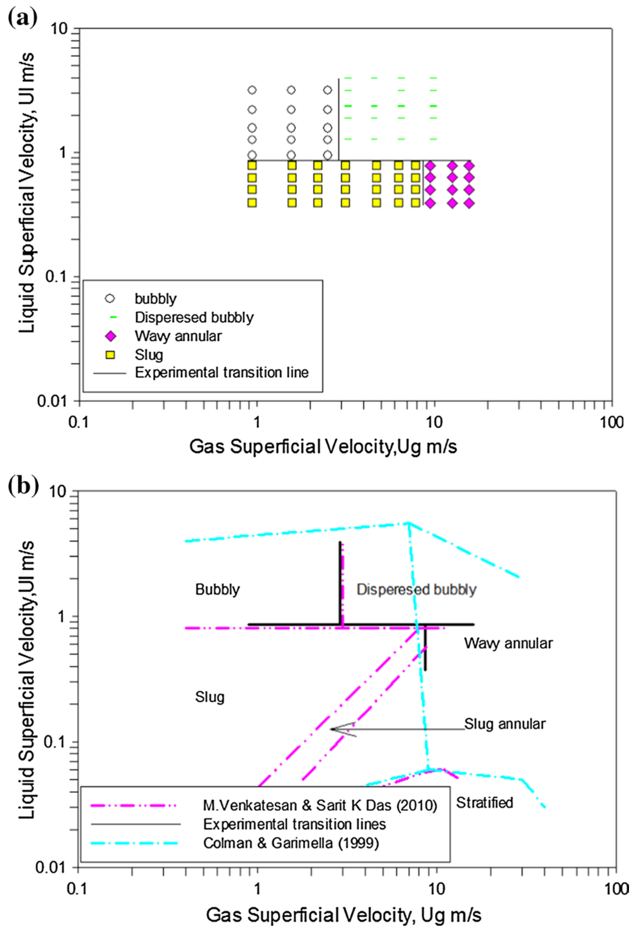

Fig. 11 Flow regimes obtained in 2.43 mm tube: **a** Experimental data. **b** Comparison of experimental flow regimes with existing flow regime maps

and lower liquid velocity. Slug flow observed over large region of moderate gas and liquid velocity. At higher gas velocity and lower liquid velocity wavy annular flow was observed over small region. Small interfacial waves are observed in wavy annular flow pattern.

3.12 Comparison of experimental flow regimes with existing flow regime maps for test section 2.43 mm

Figure 11b shows the flow-regime map obtained with a 2.43 mm tube compared with Coleman and Garimella [7] and Venkatesan and Das [14]. Present study agrees reasonably well with Venkatesan and Das [14]. Slug annular flow not found in the present study because it's very difficult to distinguish between slug-annular and wavy-annular flow and it's agreed with Coleman and Garimella [7] as shown in Fig. 11. Stratified flow is not found due to the low range of liquid and gas velocity not attempted. 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 flow agrees very well.

3.13 Flow patterns for test section 3.0 mm

Two-phase flow patterns for the internal test section of 3.0 mm diameter and total length was 1150 mm. The superficial velocities from 0.29 to 3.07 m/s for liquid (Ul) and 0.47–9.43 m/s for air (Ug). Five different two-phase flow patterns were identified, i.e., bubbly, dispersed bubbly, slug, slug-annular and wavy annular flow as shown in Fig. 12. Bubbly flow as shown in Fig. 12a is characterized 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. Further increasing in gas velocity, the size of the bubble reduces, and the frequency with which the bubbles appear increases. For low U_l and high U_g, slug type flow was observed as shown in Fig. 12c. In the slug-annular flow pattern shown in Fig. 12d. The liquid increases in the form of waves while in wavy-annular pattern gas in the core region causes the wavy pattern. Coleman and Garimella [7] have not made any distinction between slug-annular and wavy-annular type flows patterns. Flow observed by Venkatesan and Das [14] and Barnea et al. [4] in tubes of diameter 3.5 mm and 4–12 mm respectively.

3.14 Flow regime maps for test section 3.0 mm

As shown in Fig. 13a. Bubbly flow observed at low gas and liquid velocity over a wide range. Dispersed bubbly observed at higher gas and lower liquid velocity. Slug flow observed over large region of moderate gas and liquid velocity. At higher gas velocity and lower liquid velocity slug annular flow was observed over small region.

3.15 Comparison of experimental flow regime maps with existing flow regime maps for test section 3.0 mm

The flow-regime transition lines obtained with a 3.0 mm diameter tube is compared with Damianides and Westwater [5] of tube diameter 4.0 mm and Barnea et al. [4] of tube diameter 3.7 mm and Venkatesan and Das [14] of tube diameter 3.4 mm as shown in Fig. 13b. The transition from slug flow to bubbly and dispersed bubbly flow of Venkatesan and Das [14] and Damianides and Westwater [5] agrees well with the present data. Barnea et al. [4] had categorized the plug zone of Damianides and Westwater [5] as elongated bubbly.

The term is appropriate since in mille and micro-diameter Tubes, the distinctive size of the bubble are quite often limited by the diameter of tube. The transition from slug to Slug-annular flow in the present study agrees well with that of Damianides and Westwater [5]. However, Slug annular to wavy annular not found in the present data due to the limitations of the experimental set up but it shows in the Venkatesan and Das [14] and Damianides and Westwater [5]. Barnea et al. [4] they have not distinguished between slug-annular and wavy-annular flows for larger tube diameters.

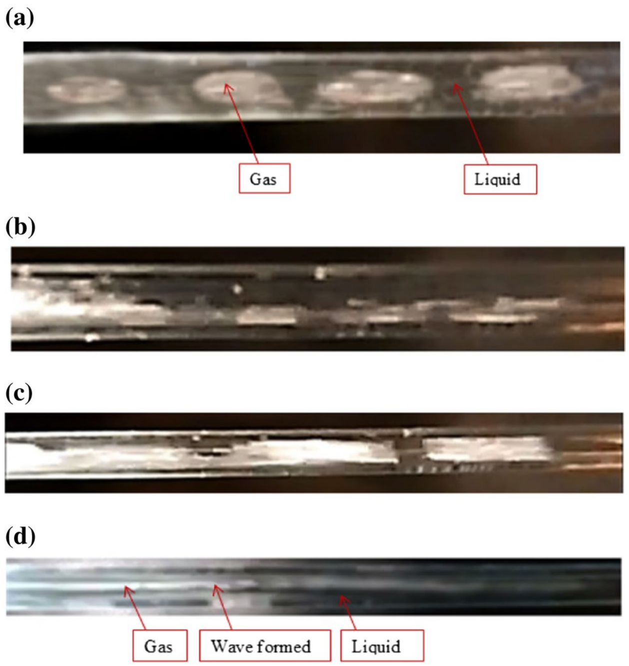

Fig. 12 Photographs for 3.0 mm dia tube. **a** Bubbly flow Ug = 0.47 m/s U_l = 0.70 m/s. **b** Dispersed bubbly flow Ug = 3.77 m/s Ul = 1.89 m/s. **c** Slug flow Ug = 0.47 m/s Ul = 0.47 m/s. **d** Slug annular flow U_g = 5.90 m/s U_l = 0.29 m/s

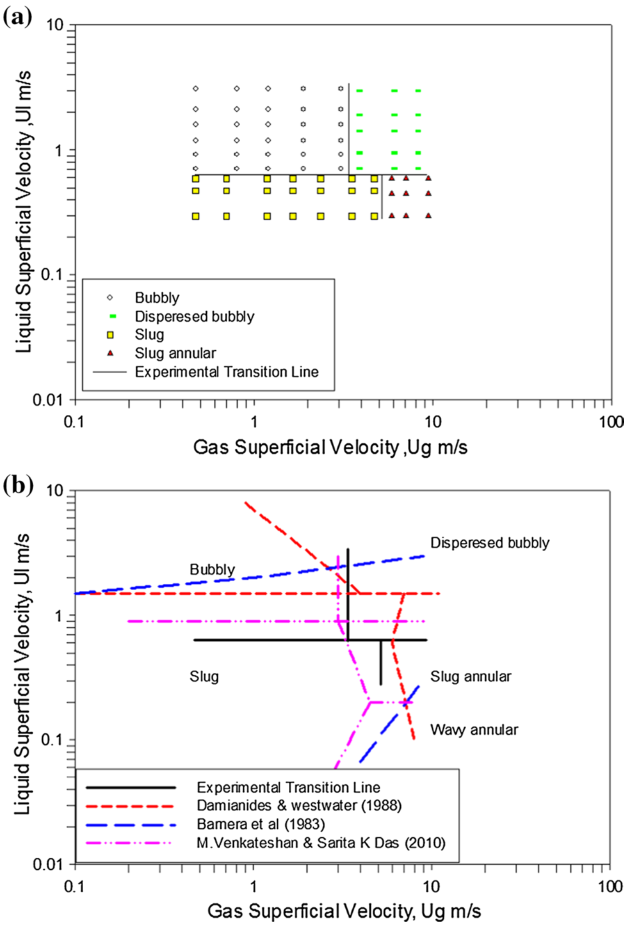

Fig. 13 Flow regimes obtained in 3.0 mm tube: **a** experimental data. **b** Comparison of experimental flow regimes with existing flow regime maps

3.16 Effect of tube diameter on two-phase flow regimes in mini-channels

Different flow regimes were identified for different tube diameters that confirmed the diameter effect on flow patterns in two-phase flows. Wavy-annular flow pattern was not observed in 3.0, 2.0, 1.63 and 1.1 mm diameter tubes due to 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. Slug annular flow not found in 2.43, and 1.6 mm diameter. According to [8] Triplett slug-annular flow is an intermediate between slug flow and annular flow. 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. A stable slug is formed only when there is a sufficient liquid below the wave to maintain such a slug. Stratified flow was not observed for tube diameters 1.1–3.0 mm due at very low range of gas and liquid velocities two-phases are separated, due to experimental limitations low ranges of gas and liquid could not attend. Annular flow not found in 3.0, 2.43, and 2.0 mm diameter.

3.17 Effect of tube diameter on two-phase flow regime transitions

When the channel diameter decreases from 3 to 1.1 mm, the bubbly and slug transition boundary shifts towards higher gas and liquid side as shown in Fig. 14. The annular flow regime moves to higher gas velocities as the channel size reduces from 3 to 1 mm. This is because, as the liquid film gets thinner in smaller micro channels, the increasing shear stress is likely to cause more fluctuations in the gas liquid interface. The bubbly to dispersed bubbly transition lines moves to higher gas and liquid velocities as the channel size reduces.

4 Conclusions

Experiments is conducted to study and investigate the adiabatic air–water two-phase flow patterns in mini channels for horizontal orientation for different test section of diameter 1.1, 1.63, 2.0, 2.43 and 3.0 mm. The superficial velocity varies from 0.2 to 14.0 m/s for liquid and 0.4–66.70 m/s for air. The two-phase flow was visualized through a high-speed CMOS camera and flow regime maps are presented for different tube diameters. The available experimental facility is modified as per the requirement of present experimentation. Different flow patterns were identified for diameter ranges 1.1–3.0 mm. However the effect of tube diameter on two-phase flow patterns was observed. Stratified flow not observed in all test section. For diameter 2.63 mm, bubbly flow observed at low gas and liquid velocity. Dispersed bubbly observed at higher gas and lower liquid velocity. Slug flow observed over large region of moderate gas and liquid velocity bubbly, dispersed bubbly and slug flow observed for all test section. Similarly slug annular flow observed for test section 1.1, 2.0 and 3.0 mm. Slug annular flow not observed for test section 1.63 and 2.43 mm due to increasing the gas velocity under the slug flow condition waves are formed and it’s very difficult to distinguish slug annular and wavy annular. For diameter 1.1, 1.63 and 2.0 mm wavy annular flow not observed due to the surface-tension effects and decrease in tube diameter results. For tube diameter 2.0 mm the phases do not travel with the same superficial velocity and amalgamation of the slugs occur much faster rather than in larger tube diameters resulting in the absence of wavy-annular and annular flow pattern in tube diameters less than 2 mm. Annular flow not found for the test section 1.63, 2.0, 2.43 and 3.0 mm diameter, due to the surface-tension effects and decrease in tube diameter. For tube diameter 3.0 mm Buoyancy effect is clearly visible in bubbly and slug flow. Dispersed bubbly flow occurred over a wider range in present study and agree reasonably well with Venkatesan and Das [14]. Slug annular flow not found in the present study because it’s very difficult to distinguish between slug-annular and wavy-annular flow and it’s agreed with Coleman and Garimella [7]. The transition from slug to wavy-annular flow agrees with the results of the existing study of Venkatesan and Das [14]. Bubbly and slug transition boundary shifts towards lower superficial velocity of gas and liquid as the channel diameter decreases from 3 to 1.1 mm. The annular flow regime moves to higher superficial gas velocities as the

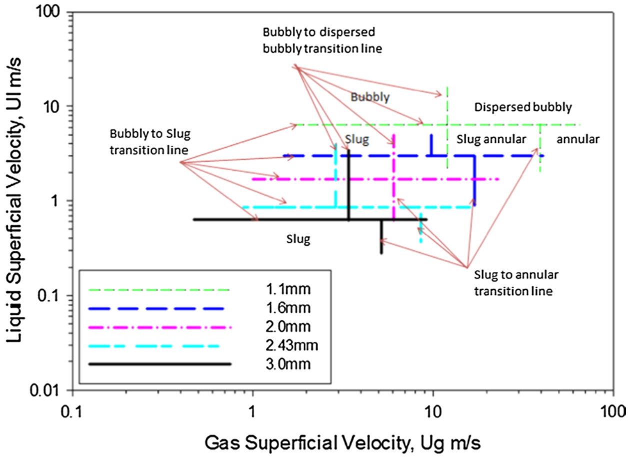

Fig. 14 Experimentally observed flow regimes transition lines

channel size decreased from 3 to 1 mm. This is because, as the liquid film gets thinner in smaller micro channels, the increasing shear stress causes more fluctuations in the gas and liquid interface. The bubbly to dispersed bubbly transition lines moves to higher superficial velocity of gas and liquid as the channel size reduces.

Acknowledgements The authors would like to express their appreciation to the Marathwada Institute of Technology, Aurangabad for providing lab facility for this study.

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