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Abstract

An experimental investigation of typical flow patterns in adiabatic gas–liquid mixture (air-water) generated in a micro T-junction varying the superficial velocity of the fluids is presented. The micro Tjunction is made as intersection of two glass microchannels with a rectangular cross-section having a width of 300 lm and a height of 256 lm. The air–water mixture is obtained by means of an injection of air in perpendicular direction with respect to a straight stream of water. The air flow is broken in slugs having geometrical characteristics depending on the superficial velocity ratio imposed. Changing the air and water superficial velocity from 0.005 m/s up to a maximum value of 0.15 m/s, different kinds of intermittent slugs have been observed. In this way, a flow pattern map has been generated in order to reword the main characteristics of the intermittent slug flow generated after the T-junction as a function of the superficial air–water velocity ratio. In order to build the flow pattern map, 256 experimental runs characterized by different values of superficial velocity have been made. Different kinds of Taylor bubble flows have been observed during this experimental campaign: for a fixed low value of the air flow rate, by increasing the water flow rate it has been evidenced how the formation of the bubbles becomes faster and the length of the single

bubble becomes shorter. A detailed discussion of the impact of the superficial air to water velocity ratio on the observed flow patterns is given.

1. Introduction

Microfluidic systems have experienced during recent years a strong development due to their increasing market penetration in many fields. Electro-osmotic pumping system, diffusive separation system, micromixers, DNA amplifiers and chemical microreactors are just few examples of the current applications of microfluidic systems [1-2]. An interesting research topic in microfluidic is the investigation of two-phase flows in microdevices, *i.e.*, systems where the simultaneous presence of gas/vapour and liquid phase occurs. The main feature of two-phase flows is the presence of an interface which separates the phases. When the characteristic dimensions of the channels are decreased the influence of the surface forces becomes predominant on the volume forces and, in addition, inertial forces become negligible with respect to capillary forces; this fact determines a significant change in the evolution of the typical flow patterns of two-phase flows in microchannels compared to conventional channels. Two-phase flows have been extensively investigated in conventional channels and reword results have been reported in the literature [3] in terms of flow pattern evolution as a function of superficial velocities of the phases for channels having a diameter larger than 3 mm. On the contrary, the analysis of two-phase flows in microsystems is so far limited to simple geometries and to a limited range of superficial velocities. Useful review about systems and techniques utilized for the analysis of two-phase flows in micro systems has been made by Shao et al. [4]. In their work they have made an overview of the main results published in literature about two-phase flow behaviour in micro systems, covering the years between 1964 and 2008 and the main results, obtained in terms of flow patterns in microchannels with different geometries, have been summarized by means of specific flow pattern maps.

Air-water mixtures in microchannels have been investigated by Kawaji et al [5]. In that work, the test section was made up by circular microchannels of fused silica with an inner diameter of 100 μm. The cocurrent flows of deionized water and nitrogen were pre-mixed in a cross junction before reaching the detection section. Cubaud and Ho [6] studied the mixing of air and water in a square microchannel, made by glass and silicon, with a cross shaped junction. The water flowed in the straight direction and perpendicularly have been injected two streams of air. Haverkamp et al. [7] have made an analysis of the mixing of nitrogen and water in rectangular stainless steel microchannels with diameters of 150 μm and 294.5 μm both for cross shaped junctions and smooth junctions. Sairson and Wongwises [8] have published a work on the effects of channel diameter on flow pattern, void fraction and pressure drop of two-phase air-water in circular micro channels. In this work three different circular microchannels of fused silica with diameters of 0.53, 0.22 and 0.15 mm have been considered. The mixing chambers were designed to introduce the air-water mixture smoothly along the channel. In the same year, Santos and Kawaji [9], have made a numerical modelling and experimental investigations of air-water slug formation in a square micro T-junction of fused silica by determining when the Taylor regime breaks into a bubbly flow. Arias and González-Cinca [10], have made an experimental analysis of the transition from Taylor to bubble regime in a flow generated by a circular T-junction in a microchannel of 1 mm of diameter.

The analysis of the scientific literature puts in evidence that all the experimental works devoted to the analysis of the two-phase behavior of air-water mixtures in a micro T-junction up to now have typically investigated values of superficial velocity, both for air and water, ranging between 0.1 m/s and 100 m/s. No investigations have been reported for lower values of superficial velocity.

The experimental work described in this paper wants to fill this gap by analyzing the flow patterns generated in a micro T-junction for values of the superficial velocity less than 0.1 m/s. In Figure 1 is reported the flow pattern map proposed by Chung and Kawaji [11] and Hassan et. al. [12] for the analysis of the two-phase flow at the exit of a T-junction. The shaded area in this map highlights the operative conditions covered by the present work. The aim of the experimental campaign described in this paper is to enlarge the investigation field of Santos and Kawaji [9] for micro T-junctions covering superficial velocities between 0.01 m/s and 0.16 m/s both for water and air by analyzing in detail the main features of the Taylor slug regime and of Taylor annular regime generated in a rectangular glass microchannel where air and water were mixed adiabatically by means of a micro T-junction. An experimental campaign of 256 experimental runs have been made in order to study the transition from slug to annular Taylor regime. For a fixed value of the superficial velocity of air and water, the value of the static air pressure before the T-junction as well as the frontal and backside velocity of the bubble have been experimentally evaluated and linked to the observed flow pattern.

2. The experimental apparatus and procedure

In Figure 2 the sketch of the test rig used in this work is given. The investigation of the evolution of flow patterns through the microchannel is based on the use of an inverted microscope (*Nikon Eclipse T2000*) (1 in Figure 2) illuminated by means of a Mercury lamp (2). An air immersion lens (3) with a numerical aperture NA = 0.25 and magnification M = 10 is used. The microscope is connected to high speed camera (*Olympus I-speed*) (4) by means of which the evolution of the morphology of the air bubbles generated by the T-junction as a function of the imposed flow rate of air and water is studied by recording 1500 frame per second. A LCD monitor (5) directly connected to the high speed camera enables the real-time visualization of the flow conditions through the microchannel. The T-junction (6) used in these tests is a commercial glass microjunction (*Translume*) made as an intersection of two straight glass microchannels with a declared rectangular cross-section with a width of 300 μm and height of 256 μm. Both microchannels are made by laser etching on a substrate of high quality fused silica and then bonded with the same material. The relative roughness of the inner walls is declared to be <0.1% by the manufacturer. Previous analyses [13,14] conducted by analysing, with the help of micro Particle Image Velocimetry (μPIV), the dynamic behaviour of single phase liquid flows (water) through the T-junction have demonstrated that the shape of the cross section is generally no perfectly rectangular but presents a nearly trapezoidal shape with the greater base located on the upper part of the channel with an apex angle of 88°. The hydraulic diameter linked to the cross-section (D_h) is estimated to be equal to 281 μm.

The air-water mixture is obtained by means of an injection of air (7) in perpendicular direction with respect to a straight stream of water (8) (see Figure 3) with the help of two syringe pumps (*Harvard PHD4400* (8b), *Cole-Parmer Hills* (7b)). A differential gauge pressure (*Validyne DP15*) (9), connected by means of a signal amplifier (10) to the multimeter (*Agilent 34401A*) (11) is used in order to measure the value of the air pressure before the T-junction. The trend of the measured pressure is recorded on the PC (12) by means of a LabView code.

The flow rate of air and water through the inlet branches of the T-junction are imposed by means of the syringe pumps. Both the fluids are contained into two glass commercial syringes (*Hamilton GasTight 1010 TLL, 10ml*) compatible with the respective syringe pumps. The flow rates chosen for the experimental campaign are in the range from 6.4 ml/h up to 48 ml/h.

In Table 1 the typical values of uncertainty of the instruments used in the described test rig are summarized.

Before starting each experimental run, in order to avoid any pressure fluctuation during the charge phase of the system, any liquid droplet present in the air supply branch was removed: in fact, due to the imposed pressure larger than the atmospheric value, when steady-state conditions are reached, the liquid contained in the microchannel and along the branch of water supply tends to rise into the connection of the air supply if the air reservoir is disconnected from the system. In each experimental run, the volumetric flow rates of water and air were set by means of the programmable syringe pumps. Due to the compressibility of air it is not trivial to reach steady state conditions along the air branch; in each test, the water pump first and the air pump after were started and during all the experimental runs the value of the air pressure was constantly monitored. The outflow of the two-phase mixture has been kept constant at a pressure over the atmospheric value by keeping the outlet section immersed in 2 cm of deionized water. With this arrangement the pressure rebound caused by the out flow has been drastically reduced. The image acquisition was started only when steady-state flow regime conditions were reached. The establishment of a steady-state flow conditions was highlighted by the stabilization of the air pressure value that, after reaching the peak value when the generation of Taylor bubbles took place, maintains itself at a constant value depending on the imposed flow parameters.

Unperturbed 8 seconds of images at 1500 fps have been acquired and post-processed both for the analysis of the detachment position of the bubbles close to the centre of the T-junction (see Figure 3) and for the analysis of the flow pattern of the air-water mixture at 20 mm of distance from the centre of the T-junction in the direction of the outflow (Figure 4). The described procedure has been repeated for every experimental run.

Each run has been characterized by the values of the gas and liquid superficial flow velocity defined as follows:

$$U_{GS} = \frac{\dot{V}_{air}}{A_{ch}}; \qquad U_{LS} = \frac{\dot{V}_{w}}{A_{ch}} \tag{1}$$

where A_{ch} is the cross sectional area of the microchannel and $\dot{V}_{air}$ and $\dot{V}_{w}$ are the imposed volumetric flow rate of air and water respectively.

3. Post processing analysis

Figure 4 shows a typical raw image of a air bubble at 20 mm of distance from the centre of the T-junction in the direction of the outflow. The air bubble is axisymmetric and its contour appears shaded and for this reason its volume cannot be defined precisely. The procedure of bubble size detection has been based on a home-made Matlab Image Toolbox script. First, the borders of the channel have been manually detected, then the axis of the bubble was detected. Second, a low-pass filter has been combined with a high-pass filter in order to select the intensity values of the primary image within an imposed range. Then, the gray-scale image obtained by the filtering procedure described above has been converted to binary by a threshold procedure. The output binary image has values of 1 (white) for all pixels in the input image with luminance greater than a particular threshold and 0 (black) for all other pixels. The image obtained was segmented, with white predominance in place of the bubble and many black holes within. A method of filling the holes with four-connected background neighbours for each pixel has been applied. As a result, white bubble contours have been obtained. This was not the real bubble, since the shadow has been clipped. The shadow layer has been estimated by a gray-gradient technique, then the shadow layer to the bubble has been added, as it is shown in Figure 5. The bubble area and bubble velocity have been then obtained by means of the analysis of the evolution in time of the bubble contour within the channel. Bubble velocity (W_b) has been calculated by dividing the space between the positions of the nose of the bubble recorded in two consequently images by the time interval between the images (in this case the time interval is linked to the image per second recorded by the speed camera: $\Delta\tau$=1/1500=0.667 ms).

By post-processing the images of the bubbles it is possible to estimate the average bubble length (L_b) and the average liquid plug length (L_w).

In the frame #1 a reference line is fixed in correspondence of the initial position of the bubble nose. The number of the acquired frames, after frame #1, where the gas slug crosses the reference line until the back meniscus is beyond the reference line is counted (n_b). In this way the time needed by the air bubble to cross completely the reference line can be considered equal to ($n_b\Delta\tau$).

The same procedure can be followed in order to assign to the liquid slug a length; in this case the number of images in which the liquid slug crosses the reference line is counted (n_w).

The length of the air bubble (L_b) and of the liquid slug (L_w) can be obtained by multiplying the time ($n_b\Delta\tau$) or ($n_w\Delta\tau$) by the velocity of the bubble (W_b) or of the liquid slug (W_w).

This procedure is followed by analysing automatically the whole set of frames acquired in which N_b air bubbles and N_w liquid slugs are recognized. The length associated to the air bubbles as well to the liquid slug is obtained as average value by considering the set of bubbles and liquid slugs recorded:

$$
\begin{aligned}
L_b &= \frac{1}{N_b}\sum_{i=1,N} W_{b,i} n_{b,i} \Delta\tau \\
L_w &= \frac{1}{N_w}\sum_{i=1,N} W_{w,i} n_{w,i} \Delta\tau
\end{aligned}
\qquad (2)
$$

It is possible to demonstrate that this methodology for the estimation of the length of the air bubbles and of the liquid slugs introduces a maximum error on the length estimation in the worst case equal to the single displacement (i.e. $W_b\Delta\tau$ or $W_w\Delta\tau$). In the case of the air bubbles, this error can be neglected for Taylor-Annular and Long Taylor regimes where the bubble length is very large. In these cases errors less than 1% (Taylor-Annular) and 2.3% (Long Taylor) can be obtained in the range of superficial velocity covered in this experimental campaign. On the contrary, the inaccuracy on the bubble length becomes relevant as the bubbles became shorter and faster (up to 30%).

Following the methodology suggested by Santos and Kawaji [9], the analysis of the acquired images described before is useful in order to obtain an experimental evaluation of the time-averaged volumetric void fraction (α) associated to the flow pattern generated at the exit of the T-junction.

The experimental time-averaged volumetric void fraction α have been compared in Figure 6 with the homogeneous void fraction β defined as follows:

$$\beta = \frac{U_{GS}}{U_{GS} + U_{LS}} \tag{3}$$

The data in Figure 6 show a linear correlation between the time-averaged volumetric void fraction and the homogeneous void fraction based on the measured values of the superficial velocity of air and water. These results confirm the observations of Chung and Kawaji [11] and Saisorn and Wongwises [8] on microchannels having similar inner dimensions. The result depicted in Figure 6 demonstrates that in this case it is possible to characterize the flow pattern of the air-water mixture by using α or β indifferently.

4. Results and discussion

In Figure 7 the flow pattern map proposed for T-junction by Chung and Kawaji [11] and Hassan et. al. [12] is used in order to analyze the flow pattern evidenced experimentally by the two-phase flow originated at the exit of the micro T-junction, 20 mm far from the centre of the T-junction where the air flow meets the water flow. Each point in Figure 7 represents an experimental point obtained by imposing different values of the superficial velocity of air (U_{GS}) and water (U_{LS}) at the inlets. The points reported in Figure 7 are 256.

For the experimental runs indicated by means of a point surrounded by a circular marker in Figure 7, the average bubble velocity (W_b), the average bubble length (L_b) and the average value of the void fraction (α) as well as the homogeneous void fraction (β) are reported in Table 2, as a function of the superficial velocity U_{GS} and U_{LS}. In Table 2 in correspondence of each experimental run a flow pattern is also indicated.

In general, two types of flow patterns have been detected after the T-junction: slug Taylor regime and Taylor-Annular regime. The comparison between the data obtained in this work and the results found in the literature by using T-junctions [11, 12] shows a good agreement in terms of transition between the slug Taylor regime and Taylor-Annular regime which is generally obtained when U_{LS} is decreased for large values of U_{GS}. Anyway, as evidenced by the data in Table 2, the slug Taylor regime is strongly influenced by U_{LS}. The experimental results quoted in Table 2 show that Taylor-Annular regime is characterized by a void fraction α greater than 0.9 (β>0.87) and the dimensionless bubble length L_b/D_h, obtained by scaling the bubble length on the hydraulic diameter of the microchannel, is generally larger than 20. The experimental results suggest to divide the Taylor slug regime into three different regions depending on the void fraction value (α) and on the dimensionless bubble length (L_b/D_h). When α ranges between 0.81 and 0.9 ($0.78<\beta<0.87$), L_b/D_h ranges between 7 and 20 and the Taylor regime is characterized by long air bubbles (for this reason this flow pattern is named “Long Taylor”). For α ranging between 0.7 and 0.82 ($0.65<\beta<0.78$) air bubbles become shorter and L_b/D_h ranges between 3.5 and 7: this flow pattern has been named “Middle Taylor”. For α less than 0.7 ($\beta<0.65$) the air bubble becomes shorter and shorter with L_b/D_h lower than 3.5; this flow regime has been named “Short Taylor”. The four different flow regimes have been evidenced in Figure 7 by using different symbols.

Figure 8 shows examples of the typical bubbles at the exit of the T-junction which correspond to the four flow patterns individuated. The typical shape of the air bubble in the Taylor Annular flow pattern is characterized by a large length and by the presence of a typical ring of water which surrounds the bubble close to its tail (visible in the second image starting from the left in Figure 8a). On the contrary, Long Taylor (Figure 8b), Middle Taylor (Figure 8c) and Short Taylor (Figure 8d) air bubbles differ only for their length. Short Taylor bubbles are generally contained in a single frame.

In Table 3 the suggested boundaries of each flow regime in terms of dimensionless bubble length, void fraction (α and β) and superficial velocity are given.

In Table 4 the measured values of the pressure at the inlet air branch, 10 cm before the T-junction have been reported as a function of U_{GS} and U_{LS}. The experimental tests covered by the data reported in Table 4 are individuated in Figure 7 by a squared symbol.

The value of the pressure indicated in Table 4 is the value recorded at the air branch supply when the system reaches steady-state conditions, as explained before. It is evident that pressure monotonically increases when U_{GS} and U_{LS} are increased and its value ranges from 1.3 bar up to 2 bar for the larger values of U_{GS} and U_{LS} considered in these tests.

In Figure 9 the trend of the average bubble velocity W_b as a function of the sum of the superficial flow velocity of the liquid and the gas is shown. The data indicates that the average velocity of the air bubble increases with the increasing of the sum of the liquid and gas superficial velocity. This result is in good agreement with the observations made by Santos and Kawaji [9] by testing larger values of superficial velocity.

In Figure 10 the average value of the air bubble length is reported as a function of the liquid superficial flow velocity; the data depicted in Figure 10 demonstrate that the bubble length decreases in a logarithmic way with the increasing of the liquid superficial flow velocity and in these experimental tests it reaches a nearly stable value of around 390 μm (L_b/D_h=1.4) when the Short Taylor flow regime is reached.

In Figure 11 the same conclusion can be obtained in terms of time-averaged volumetric void fraction α: it is evident that α decreases linearly with the increasing of the superficial liquid velocity. On the contrary, the average value of the void fraction is weakly dependent on the air superficial flow velocity for 0.03 m/s < U_{GS} < 0.148 m/s. The same conclusion can be made on β.

Finally in Figure 12 the same plot proposed by Santos and Kawaji [9] in order to investigate the dependence of the static pressure along the air branch by the imposed air and liquid superficial flow velocity is shown. The results obtained in this work are in qualitative agreement with the observations of Santos and Kawaji [9]: it is possible to establish a correlation between the gas inlet pressure scaled on the gas superficial velocity and the ratio between the gas superficial velocity and the liquid superficial velocity. The data of Figure 12 highlight that the gas static pressure established along the air inlet branch of the T-junction when the steady-state condition is reached increases when the liquid superficial velocity is larger than the gas superficial velocity ($U_{GS}/U_{LS}<1$).

5. Conclusions

In this paper an experimental investigation of the flow patterns generated by an adiabatic mixing of air/water flows into a micro T-junction is presented. T-junction has been obtained by crossing two trapezoidal glass microchannels with a hydraulic diameter of 281 μm. Imposed values of the superficial velocity of air and water lower than 0.16 m/s have been considered in order to extend the database of available experimental results quoted in the open literature. The experimental results presented in this paper have evidenced that for low values of superficial velocity, at the exit of the T-junction only Taylor slug and Taylor Annular regimes can be generally established. Starting from the dimensions of the air bubbles generated at the outlet of the T-junction it is possible to divide the Taylor regime into three different regimes:

- Long Taylor regime, characterized by long air bubbles with a length which can be larger than 20 times the hydraulic diameter of the outlet microchannel; the void fraction ranges between $0.81 < \alpha < 0.9$ ($0.78 < \beta < 0.87$),
- Middle Taylor regime, where the void fraction ranges between $0.7 < \alpha < 0.82$ ($0.65 < \beta < 0.78$) and the bubble length is larger than 7 times the hydraulic diameter of the outlet microchannel
- Short Taylor regime, characterized by very short air bubbles at the outlet of the T-junction where the void fraction α is less than 0.7 ($\beta<0.65$) and the minimum bubble length is of the order of the hydraulic diameter of the outlet microchannel of the T-junction.

The experimental results have evidenced that the average length of the air bubbles at the outlet of the T-junction as well as the void fraction are strongly dependent on the value of the liquid superficial velocity; when the liquid superficial velocity decreases the length of the air bubbles increases and the slug regime becomes an annular regime.

The trends of void fraction and pressure as a function of the imposed superficial flow velocity confirm qualitatively the results obtained by other authors by analysing T-junctions with imposed inlet flow velocities larger than 0.2 m/s.

6. Nomenclature

D_h hydraulic diameter of channel, (μm)

f average frequency of the image acquisition (Hz)

L average length, (μm)

p pressure, (bar)

U superficial velocity, (m/s)

$\dot{V}$ volumetric flow rate, (m^3/s)

W average velocity, (m/s)

Greek symbols

α void fraction

$\Delta\tau$ time delay between two images, (ms)

Subscripts

air air

b bubble value

GS gas supply value

LS liquid supply value

w water

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