Two-phase flow regimes in a horizontal microchannel with the height of 50 µm and width of 10 mm

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Abstract. Two-phase flows of distilled deionized nanofiltered water and nitrogen gas in a microchannel with a height of 50 µm and a width of 10 mm have been investigated experimentally. The schlieren method has been used to determine main features of the two-phase flow in the microchannel. This method allows detecting the liquid film on the lower and upper walls of the microchannel as well as droplets of various shapes and sizes or vertical liquid bridges. Two-phase flow regimes have been observed, and their boundaries precisely determined using post-processing of the recordings. The following flow regimes have been distinguished: bubble, churn, jet, stratified and annular. Comparison of regime maps for channels of different widths has been carried out, and this parameter showed to have a significant impact on the boundaries between the regimes in microchannels of a height of less than 100 µm.

Introduction

The last decades have seen the miniaturization of devices in various fields of engineering, for example: in the space and chemical industries, in hydrogen and nuclear power, in treating materials, and in medicine. It is well-known that the existing cooling systems do not meet the modern requirements for heat removal from these highly heat-intense sources, and it seems probable that the next generation of heat exchangers will be based on flows in mini and micro channels. The studies show that such systems are more energy efficient than macrosystem with free-flow of liquid [1,2]. Indeed, as the thickness of the channel decreases, the ratio of the channel surface to its volume increases inversely proportional to its minimal cross dimension, which leads to heat exchanges of dramatic intensity.

The logical consequence of this need of a new technological solution is the recent interest on two-phase flows in these kind of conditions, as many studies have been published on this matter over the last years. Overviews of the publications on two-phase flows in micro channels of various configurations are given in [3-5]. Even if the results of investigations on two-phase flows in mini- and micro channels can be sometimes ambiguous, contradictory and open to different interpretations, some breakthrough have been made on the subject. It is now established that the two-phase flow structure is mainly influenced by the following parameters: the channel geometry and the dimensions as well as
the parameters of the input section [6,7] and the properties of the liquid, such as viscosity and surface tension.

Research originally gave priority to circular flows, to get insights on these new phenomena’s characteristics, but as rectangular shapes tend to be more convenient to design heat exchangers, studies have recently focused on two-phase flows within rectangular channels. However, only one study has investigated flows’ behaviours in wide rectangular channels with a height of less than 100 µm and was carried by Ronshin et al. [8] on a 50 µm × 20 mm channel. The present study comes in its wake, as flows in a 50 µm × 10 mm channel have been investigated using the same methods to better understand the behaviours previously witnessed.

Experimental setup

As stated above, the purpose of this study is the experimental investigation of two phase flows of distilled deionized water and nitrogen gas in a microchannel with the height of 50 µm and a width of 10 mm. This paper focuses mainly on two-phase flows regimes and on the boundaries between them.

The test section, figure 1, consists of two parallel plates with a length of 160 mm and a width of 55 mm (the top plate being made of antireflecting glass and the bottom one of stainless steel); the distance between them is set by two constant spacers with a thickness of 50 µm. The liquid nozzle is placed in the lower plate at an angle of 11°. The microchannel dimensions are: length: 160 mm, width: 10 mm, height: 50 microns. Nitrogen of high purity is supplied into the central part of the microchannel from the tank. Its flow rate is adjusted from 20 to 1000 ml/min and kept constant with the aid of the flow controller with a precision of 0.5 %. It enters the gas chamber before going in the microchannel through a gas nozzle. The liquid flow rate varies from 0.5 to 50 ml/min using a high-precision (with an accuracy of 0.355 %) syringe pump. The liquid, extra-pure deionized nanofiltered water, is supplied into the microchannel through the liquid inlet after being pre-cleaned. Its measured electrical conductivity after cleaning is 0.05 µS/cm at 25°C. The distance between the gas and liquid nozzles is about 70 mm. The pressure in the gas chamber is measured by a pressure sensor. The data it provides and the current gas flow rate are recorded on a file on a personal computer.

**Figure 1.** The scheme of the experimental setup
Interactions of gas and liquid in the microchannel are visualized in the observation area using digital video cameras according to the requirements of the schlieren method [9], figure 2, an experimental process used for registration and visualization of surface deformations of a thin liquid film which works as follows: the light enters the micro channel hosting the gas-liquid flow through a diffuser (1), lens (2), a beam splitter (3) and an optical glass (4). The reflection of the gas-liquid interface passes through a beam splitter (3), a lens (5) and a camera lens filter (6). The schlieren knife-edge (7), shifted by a micro-screw, highlights the central part of the light flux. As a result, the camera captures a grayscale image, where each grey level corresponds to a certain angle of inclination of the liquid-gas interface.

**Figure 2.** The scheme of the schlieren method

To allow us to perform our experiments in the best conditions possible, the glass has been pre-deposited with an antireflective coating and the stainless-steel plate has been pre-treated by polishing with an abrasive P400 with a grain size of 28 to 40 µm. After assembling, the microchannel height has been measured at several points using a confocal method. The wetting contact angles of the stainless steel and glass plates have been measured using the sessile drop method using the KRUSS DSA 100 installation. The advancing contact angle on the glass is 62.8±0.1°, and the receding contact angle is 27.6±0.7°. On a stainless steel plate the advancing contact angle is 90.1±0.1°, and the receding contact angle is 15.7±0.7°. The difference between our advancing and receding angles is our contact angle hysteresis, which characterize the liquid flow in our channel.

**Experimental results**

Our experiments allow us to distinguish the main regimes of the two-phase flow, which are the jet, bubble, stratified, churn and annular ones; and to draw its regime map, using the Reynolds number of liquid and gas as coordinates, figure 4.

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Re_L = \frac{U_{SL} \cdot d_h}{\nu_L}; \quad Re_G = \frac{U_{SG} \cdot d_h}{\nu_G},
\]
where $U_{SL} = Q_L / S$ – superficial liquid velocity; $U_{SG} = Q_G / S$ – superficial gas velocity; $Q_L$ – liquid flow rate; $Q_G$ – gas flow rate; $S$ – channel cross-sectional area; $d_h$ – hydraulic diameter; $\nu_L$ – liquid kinematic viscosity; $\nu_G$ – gas kinematic viscosity.

![Figure 3](image)

**Figure 3.** Map of two-phase flow regimes in the microchannel with a cross-section of $0.05 \times 10 \text{ mm}^2$.

The flow regimes: (1) bubble; (2) churn; (3) annular; (4) stratified; (5) jet

### 1.1. Jet regime

Jet regime corresponds to small superficial velocities of liquid and gas. In these conditions, we observed that the gas moves into the central part of the micro channel while most of the liquid moves alongside walls and as jets near the channel’s center, as opposed to the jet regime in micro channels with a height of more than $100 \mu m$ where the liquid moves only along the channel’s sidewalls [10,11].

The major characteristics of the jet regime (as detailed in [11]), which is specific to flat mini and micro channels, are: It can be observed at small superficial velocities of gas and liquid, when the gas flow does not occupy more than half the channel’s width. There are no disturbances on the liquid surface. An increase of the liquid superficial velocity makes it occupy a much larger part of the channel (as expected), while the gas flow gets confined to the channel’s center.

Two types of jet regimes can exist in microchannels [10]: the stationary and the pulsating jet regimes. The first one complies with the definition given above, where liquid superficial velocity is very low and liquid moves along the sidewalls, the upper wall stays dry and there are no pulsations. The second one corresponds to higher liquid flows where the liquid, still moving along the sidewalls, occupies most of the channel. At a certain moment, when the liquid load on the side reaches a critical amount, the water moves towards the channel’s center to form a film on the upper wall before being dragged by the gas flow. After some time, the process is repeated, and the pulsating jet regime is reached.

As opposed to channel height of $300 \mu m$ [10], we didn’t witness the pulsating jet regime during our experiments. We did observe that an increase in superficial liquid velocity leads to a loss of stability in the two-phase flow, which is in keeping with previous studies on the matter. Eventually, at low superficial gas velocities, keeping increasing the liquid superficial velocity will result in the formation of stable liquid bridges and in the reach of the bubble regime.
1.2. Bubble regime
As stated in the previous section, increasing liquid superficial velocity at low gas superficial velocity will eventually lead to the formation of stable horizontal bridges between the channel’s sidewalls, which constitutes the transition between the jet and bubble regimes. In these conditions, the liquid contains many small bubbles of gas and occupies all the available space of the channel. The size and the frequency of the formation of the bubbles increase with the liquid and gas flow rates, but the bubbles’ characteristic sizes remain marginal compared to the channel’s dimensions.

1.3. Stratified regime
As shown on the regime map, the stratified regime can be observed at low superficial liquid velocities and at high superficial gas velocities. It is characterized by the presence of a liquid film in the bottom of the channel, dragged by the gas flow. As the gas occupies most of the channel’s section, the upper wall remains dry. This regime can only be observed in flat microchannels, as in circular ones the liquid film closes to reach the annular regime [4].

1.4. Annular regime
If we come back to the regime described above and increase the superficial liquid velocity, a liquid film forms on the channel’s upper wall: this is the transition from the stratified to the annular regime, determined using the schlieren method. In these conditions, moving vertical liquid bridges glide on the liquid films occupying the upper and lower walls of the microchannel. These films contain most of the liquid flow, and form several millimeters downstream the liquid nozzle, as opposed to flows in channels of a height of more than 50 µm where their formation occurs at the nozzle due to frontal instability [10]. The core of the two-phase flow is constituted of the gas flow, which fills most of the available space, partitioned by the moving liquid bridges.

Figure 4 is showing the schlieren photograph of the annular regime at $U_{SG} = 11.7$ m/s and $U_{SL} = 0.233$ m/s. Most of the channel is occupied by the core of gas and complex vertical liquid bridges, and the liquid film on the upper wall first forms on the channel’s center (at the vertical from the liquid film on the lower wall) before spreading to its sides. The use of the schlieren technique enabled us to distinguish this film from the liquid film on the lower wall of the channel.

![Figure 4. Schlieren photo of the annular regime at $U_{SG} = 11.7$ m/s and $U_{SL} = 0.233$ m/s](image)

1.5. Churn regime
This particular regime is observed at superficial liquid velocities superior to 2 m/s and at superficial gas velocities going from 2 to 7 m/s, and is characteristic of vertical channels [12] and of wide horizontal microchannels [13]. It regroups features of both jet and bubble regimes, and is characterized by the presence of fractured horizontal liquid bridges. Its appearance is due to development of
instabilities in the jet regime, and in the gas induced increase of the pulsation frequency of the liquid moving along the sidewalls.

The flow structure in this regime is chaotic: at the liquid inlet, there is formation of the liquid film on the channel’s lower wall, and in some areas the liquid fills its entire height. A few millimeters downstream the nozzle, we generally observe the formation of the film on the upper wall of the microchannel, and we can witness some ruptures in this entity. However directly at the liquid nozzle, horizontal continuous and/or ruptured liquid bridges are continually formed, and will crumble in the channel over time.

This regime occupies a large area on the map of flow regimes. While the transition from the jet to the churn regime is accompanied by the appearance of numerous continuous and stable horizontal liquid bridges, the transition from the churn to the annular flow regime is accompanied by the disappearance of these bridges.

**Conclusions**

By comparing regime maps it appears that, in keeping with the previous studies carried by Ronshin et al. [8] (with the 0.05×20 mm² and 0.05×40 mm² cross sections), decreasing the micro channel’s width causes the churn flow regime’s area to shrink at the benefit of all other regime flow areas.

Indeed, even though the hydraulic diameter changes insignificantly, we can affirm now that changing the channel’s width has a significant effect on the two-phase flow regimes. This is because in wide micro channels, liquid jets forming near the liquid nozzle develop not only along the side walls, but also in the center of the conduct: their interaction results in the appearance of the churn regime. Thus, decreasing the channel’s width reduces the number of such jets, which logically brings the constriction of this regime’s region.

More specifically, we observed that due to pressure change (coming with the width reduction): The transition between the bubble and the churn regimes moves toward higher superficial velocities of gas. The crossover from the jet to the churn regime moves towards higher liquid superficial velocities. The border between the jet and the stratified areas moves toward lower gas superficial velocity. The transition from the stratified to the annular regime moves toward higher liquid superficial velocities. The transition from the churn to the annular regime happens at lower gas superficial velocities.

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