FEATURES OF TWO-PHASE FLOW REGIMES IN A HORIZONTAL RECTANGULAR MICROCHANNEL WITH THE HEIGHT OF 50 μm

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Two-phase flows of distilled deionized nanofiltered water and nitrogen gas in a microchannel with a height of 50 μm and a width of 20 mm have been investigated experimentally, in which the schlieren method was used to determine the main features of the two-phase flow in the microchannel. The two-phase flow regimes and the boundaries between them were investigated, and the following flow regimes were distinguished: bubble, churn, jet, stratified, and annular. The optical methods used allow detecting the liquid film on the lower and upper walls of the microchannel. The peculiarities of the two-phase flow were discovered in almost all flow regimes, such as the formation of droplets of various shapes and sizes as well as vertical liquid bridges. Several types of liquid bridges have been distinguished, such as movable and stationary vertical liquid bridges and horizontal bridges. Sessile liquid droplets with diameters of less than 1 mm located on the microchannel walls were also observed, and the main two-phase flow regimes and the boundaries between them have been detected. A comparison of regime maps for channels with different cross sections was carried out, and the height and width of the rectangular microchannel are shown to have a significant impact on the boundaries between the regimes.

KEY WORDS: microchannel, wide narrow channel, flow regime, two-phase flow

1. INTRODUCTION

Currently, the field of microelectronics is characterized by the rise of processor productivity due to an increasing number of transistors per unit area, which leads to increased heat flux from the processor. An effective solution would be to reduce the size of the liquid heat exchanger since the surface-to-volume ratio of the channel increases inversely proportional to its minimal transverse size (height). This feature causes a high heat transfer rate in such systems.

In order to improve and optimize the cooling system operation it is necessary to select the appropriate liquid and gas flow rates and the flow regime with the highest heat transfer coefficient. One of the first maps of flow regimes was the map for a water–air mixture in a 3.2-mm-diameter vertical tube (Hewitt, 1982). The following flow regimes were detected: slug, bubble, churn, and annular. Later, other studies showed that the position of the tube (with a diameter of 2.4 mm) is not essential for the two-phase flow of the water and air mixture, but that the diameter of the minichannel is more important (Fukano and Kariyasaki, 1993). Therefore, a reduction in the transverse dimensions (the transition from a minichannel to a microchannel) causes a decrease in the stratified regime area and an increase in the annular and churn regime areas.

The two-phase flow used in different systems in microelectronics and the aerospace, transport, and energy industries, among other industries, has been actively studied in recent years. A significant number of papers on two-phase flows in mini- and microchannels have been published. Overviews of the publications on two-phase flows in microchannels of various configurations are given in Chinnov and Kabov (2006), Shao et al. (2009), Rebrov (2010), and
Chinnov et al. (2015a). The results of investigations on two-phase flows in mini- and microchannels are sometimes ambiguous and contradictory and open to different interpretations. Most studies distinguish the following two-phase flow regimes: bubble, slug, and annular, which are present in all channels. New flow regimes or varieties of the known flow regimes have also been identified, namely, churn, jet, stratified, wavy, drop, etc. However, the boundaries between regimes differ significantly, depending on the experimental conditions. The process is affected significantly by conditions of the gas and liquid inlet in the channel and the channel parameters, such as size and shape. Many studies consider circular microchannels, although rectangular microchannels are more frequently used in thermal stabilization and cooling systems. In rectangular microchannels, the flow pattern differs substantially from the flow regime in pipes. The structure of two-phase flows in microchannels is not fully understood and requires detailed study.

Analysis of research works shows 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 and the properties of the liquid, such as viscosity and surface tension. Haverkamp et al. (2006) analyzed the effect of the input phase on the two-phase flow structure and showed that the conditions for gas and liquid input significantly affect the boundaries of two-phase flow regimes in the microchannel. Comparisons of flow regimes in rectangular channels of different heights and widths are given by Chinnov et al. (2014a, 2015b, 2016). The height and width of the horizontal microchannel were found to greatly influence the boundaries between the flow regimes in the microchannel. Kabov et al. (2007) studied two-phase flow regimes in a rectangular microchannel with a height of 1 mm. It showed that the flow regimes in horizontal microchannels with a height of less than 1 mm differ substantially from the ones in the channels of larger height. Chinnov et al. (2015b, 2016) studied the mechanisms influencing the formation of the two-phase flow. Two new types of instability (frontal and lateral) were distinguished; they are responsible for the formation of flow regimes in a microchannel, depending on the channel dimensions and liquid and gas flow rates. It should be noted that with a decrease in the channel height, the surface characteristics such as roughness and wettability begin to significantly affect the two-phase flow regimes. Barajas and Panton (1993) studied the effect of contact angle on the two-phase flow structure in a circular channel with a diameter of 1.6 mm. A change in the wetting contact angle significantly changes the boundaries between regimes, and new regimes may appear, for example, when several liquid rivulets move along the channel. This is because an increase in the wetting contact angle impedes film formation on the channel walls. Serizawa et al. (2002) investigated the effect of surface treatment on the two-phase flow structure. In their study, more regular structures appeared in the smoother channel, and it was possible to observe liquid film instead of droplets in the slug regime in the channel under carefully treated clean surface conditions. This suggests that small defects change the channel wettability, affecting the spread and stabilization of the liquid film. With decreasing microchannel height, the wettability begins to have a significant effect on the two-phase flow regime (Choi et al., 2011b).

Due to the increased interest in micro- and nanosystems, the number of studies on two-phase flows in microchannels has increased. Recent studies of two-phase flows in rectangular microchannels with a height of less than 500 μm are given in Table 1. In the literature there is a tendency to miniaturized microchannels; however, the minimum characteristic size of the studied wide rectangular microchannels is 100 μm. This work investigates the characteristics of two-phase flows (in which the length from the liquid inlet to the microchannel is 90 mm) in a horizontal rectangular microchannel with a cross section of 0.05 × 20 mm² and compares the results with flow regimes in microchannels with larger cross sections.
TABLE 1: Two-phase flows in rectangular microchannels

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Channel Cross-Section Dimensions</th>
<th>Type of Two-Phase Mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Santos and Kawaji (2010)</td>
<td>$0.118 \times 0.119 \text{mm}^2$</td>
<td>Air–water</td>
</tr>
<tr>
<td>Choi et al. (2011a)</td>
<td>$0.5 \times 0.47 \text{mm}^2$, $0.5 \times 0.24 \text{mm}^2$</td>
<td>$\text{N}_2$–water</td>
</tr>
<tr>
<td>Chinnov and Kabov (2011)</td>
<td>$0.42 \times 40 \text{mm}^2$, $0.44 \times 30 \text{mm}^2$, $0.49 \times 20 \text{mm}^2$</td>
<td>$\text{N}_2$–water</td>
</tr>
<tr>
<td>Kuznetsov et al. (2012)</td>
<td>$0.217 \times 0.37 \text{mm}^2$</td>
<td>$\text{N}_2$–water</td>
</tr>
<tr>
<td>Kim et al. (2014)</td>
<td>$0.2 \times 0.2 \text{mm}^2$</td>
<td>Air–water</td>
</tr>
<tr>
<td>Patel and Garimella (2014)</td>
<td>$0.5 \times 0.5 \text{mm}^2$</td>
<td>Air–water</td>
</tr>
<tr>
<td>Holloway et al. (2014)</td>
<td>$0.184 \times 20 \text{mm}^2$</td>
<td>FC-72</td>
</tr>
<tr>
<td>Reeser et al. (2014)</td>
<td>$0.153 \times 0.305 \text{mm}^2$</td>
<td>Air–water, HFE-7200</td>
</tr>
<tr>
<td>Chinnov et al. (2015b)</td>
<td>$0.1 \times 20 \text{mm}^2$, $0.1 \times 30 \text{mm}^2$, $0.2 \times 34 \text{mm}^2$</td>
<td>$\text{N}_2$–water</td>
</tr>
<tr>
<td>Bar-Cohen and Holloway (2015)</td>
<td>$0.2 \times 10 \text{mm}^2$</td>
<td>FC-72</td>
</tr>
<tr>
<td>Chinnov et al. (2016)</td>
<td>$0.42 \times 9 \text{mm}^2$, $0.3 \times 10 \text{mm}^2$, $0.3 \times 20 \text{mm}^2$, $0.3 \times 30 \text{mm}^2$</td>
<td>$\text{N}_2$–water</td>
</tr>
</tbody>
</table>

2. EXPERIMENTAL SETUP AND METHODS

The scheme of the experimental setup is shown in Fig. 1. The gas mixture was supplied to the central part of the microchannel from the tank (no. 13). The gas flow rate was adjusted from 100 to 5000 ml/min and kept constant with the aid of an El-Flow flow controller (Bronkhorst, AK Ruurlo, The Netherlands) with 0.5% precision (no. 14). Gas was introduced into the gas chamber (no. 8) and entered the microchannel through a gas nozzle (no. 2). The liquid flow rate varied from 0.5 to 50 ml/min using a Cole-Parmer EW-74905-54 high-precision syringe pump with 0.355% accuracy (no. 15). The liquid was supplied to the microchannel through the liquid inlet (no. 1). The liquid used was ultra-pure distilled deionized nanofiltered water, which was pre-cleared with a Direct-Q 3 UV unit. The measured electrical conductivity of water after cleaning was 0.05 μS/cm at 25°C. The gas used was high-purity nitrogen. The distance between the gas and liquid nozzles was about 70 mm. Pressure in the gas chamber (no. 8) was measured by a WIKA Type P-30 pressure sensor (no. 16). The data for the pressure sensor and the current gas flow rate were written to a file on a personal computer (no. 17).

The interaction between the gas and liquid in the microchannel was visualized in the area (no. 12) using digital video cameras in the schlieren photography mode. The schlieren method was used to register and visualize surface deformations in the thin liquid film. The light from the source entered the microchannel with the gas–liquid flow through a diffuser (no. 7), lens (no. 6), beam splitter (no. 10), and optical glass (no. 11). The light reflected from the gas–liquid interface passed through a beam splitter (no. 10), lens (no. 6), and camera lens filter (no. 4). The schlieren knife-edge shifted by a micro-screw (no. 5) highlighted the central part of the light flux. As a result, the camera captured a grayscale image, where each gray level corresponds to a certain angle of inclination of the liquid–gas interface.

The test section (see Fig. 2) consisted of two parallel plates with a length of 160 mm and a width of 55 mm (top, glass; bottom, stainless steel); the distance between them was set by two 50-μm-thick constantan spacers. In the lower plate (at an angle of 11°), there was a nozzle through which liquid was fed by the high-precision syringe pump in the space between the plates. The microchannel dimensions were the following: length = 160 mm, width = 20 mm, and height = 50 μm.

The test section was assembled as follows: the stainless steel plates, glass, and nozzle for the liquid were set with constantan spacers; U-shaped holders made of brass were used to clamp the constantan spacers; the test section was sealed with a silicone sealant; and the width of the microchannel was changed by various spacers that set the microchannel height and width. After assembling the work area, the microchannel height was measured at several
FIG. 1: Schematic diagram of the experimental setup (1 – liquid input into the microchannel; 2 – microchannel; 3 – gas input into the microchannel; 4 – digital cameras; 5 – schlieren knife edge; 6 – lenses; 7 – light source; 8 – gas chamber; 9 – reducer; 10 – beam splitter; 11 – optical glass; 12 – observation area; 13 – gas tank; 14 – regulator and sensor for flow measurement; 15 – high-precision syringe pump; 16 – pressure sensor; 17 – personal computer)

FIG. 2: Test section (1 – gas input into the microchannel; 2 – liquid input into the microchannel; 3 – two-phase mixture output)
points by a confocal method using the DT IFC2451 (Micro-Epsilon, Ortenburg, Germany) confocal setup. The essence of the confocal method is that the sensor projects a polychromatic (white) light on the surface of the test sample. Inside the sensor, there are lenses that focus each wavelength of light at a certain distance with a controlled chromatic aberration. After reflection from the studied surface, the sensor receives light, which is transmitted to the controller. This is followed by spectral analysis, and then using the data from the controller the distance to objects reflecting the light is calculated. The measurement results are shown in Fig. 3. The average value of the microchannel height was 48.9 ± 18.9 μm. The average value of the microchannel height in the observation area was 48.7 ± 5.3 μm.

The glass was pre-deposited by antireflective coating [glass K8 with a four-layer deposition of HfO2 (thin layer) + SiO2 (thin layer) + HfO2 (thick layer) + SiO2 (thick layer)]. The stainless steel plate was pre-treated by polishing with an abrasive P400 (according to ISO 6344) with a grain size of 28–40 μm. The roughness value was Ra = 0.47 μm.

Before the experiment, we measured the wetting contact angles of the stainless steel and glass plates by the sessile drop method using a KRÜSS DSA 100 analyzer (KRÜSS GmbH, Hamburg, Germany). The advancing contact angle was measured as follows: a droplet with a diameter of less than 1 mm was placed on the test surface, which then spread on the surface due to liquid pumping through a needle. At a certain drop size the contact angle became constant, and which point measurements were performed. During the measurements of the receding angle, the droplet size decreased as the surface dried: a large drop (approximately 3 mm in diameter) was placed on the surface and then slowly decreased as it was sucked through the needle. The measuring results are shown in Fig. 4. Before the experiment on the glass, the advancing contact angle was 45.8° ± 2.1°, and the receding contact angle was 24.6° ± 0.7°. On the stainless steel plate, the advancing contact angle was 92.5° ± 2.7°, and the receding contact angle was 22.0 ± 0.4°. After the experiment on glass, the advancing contact angle was 71.9° ± 5.1°, and the receding contact angle was 28.7° ± 2.2°. On the stainless steel plate, the advancing contact angle was 78.8° ± 1.1°, and the receding contact angle was 45.4° ± 2.2°.

To visualize the two-phase flow, a Fastvideo-500M (KRÜSS GmbH, Hamburg, Germany) high-speed camera and a Nikon D7000 (Nikon Co., Ltd., Ayutthaya, Thailand) digital camera were used in the schlieren photography mode. Calibration of the methodology was carried out as follows. First, the microchannel was supplied only with gas, and the image was recorded when all of the microchannel walls had dried [see Fig. 5(a)]. Then, the microchannel was supplied with liquid and a small flow of gas to prevent the liquid from getting into the gas chamber. In this pattern, there is a clear difference between the microchannel area filled with liquid (no. 4) and the unwetted area on the upper and lower walls of the microchannel (no. 3), as shown in Fig. 5(b). This area is located on the edges of the microchannel and is a few millimeters in width. Next, the microchannel was fed a large gas flow and a small flow of liquid for the film to start forming on the lower wall of the microchannel [see Fig. 5(c)]. In this pattern, the motion of the thin liquid film on the lower wall of the microchannel (no. 5) is observed. The film on the lower wall of the microchannel (no. 5) is significantly lighter than the unwetted area in the microchannel (no. 3). Movable vertical liquid bridges between the

![FIG. 3: Characteristic size of the microchannel and the area of observations](image-url)
upper and lower walls of the channel (4) and surges of liquid on the upper wall of the microchannel (no. 6) were also formed. The next step was visualization of the film on the upper wall of the microchannel, where the microchannel was supplied large flows of gas and liquid [see Fig. 5(d)]. Near the liquid nozzle, the film was formed on the lower wall of the microchannel (no. 5). The film on the upper wall of the microchannel (no. 6) formed at a distance of several millimeters from the liquid inlet in the channel. It is also possible to observe the vertical motion of liquid bridges in such a regime (no. 4). The film on the lower wall of the microchannel always exists when there is a film on the upper wall of the microchannel. This is due to the configuration of the input section. Thus, the basic types of gas–liquid flows in a microchannel have been distinguished. It should be noted that this method allows detecting the main characteristics of the two-phase flow in the microchannel: liquid bridges between the upper and lower walls and the film on the upper and lower walls.

3. EXPERIMENTAL RESULTS

As a result of the experiment, the following five main regimes of two-phase flows have been registered, namely: jet, bubble, stratified, annular, and churn. Figure 6 shows the regime map created from the results. The coordinates used were the superficial velocities of liquid and gas, determined as the ratio of the volumetric flow to the cross-sectional area of the channel.
FIG. 5: Calibration of schlieren method using the Nikon D7000 digital camera; (a) gas flow in the microchannel; (b) liquid flow in the microchannel; (c) the formation of the film on the lower wall of the microchannel; (d) the formation of the film on the upper wall of the microchannel (1 – gas input into the microchannel; 2 – slit in the lower wall of the microchannel for liquid input; 3 – unwetted area on the upper and lower walls of the microchannel; 4 – microchannel area filled by liquid; 5 – film on the lower wall of the microchannel; 6 – film on the upper wall of the microchannel; white arrows, direction of gas motion; black arrows, direction of liquid motion)

FIG. 6: Map of two-phase flow regimes in a microchannel with a cross section of $0.05 \times 20 \text{ mm}^2$ (flow regimes: 1 – churn; 2 – stratified; 3 – annular; 4 – bubble; 5 – jet)
3.1 Jet Regime

At very small superficial velocities of liquid, the gas moves in the central part of the microchannel, and the bulk of the liquid moves at its periphery along the side walls and as jets in the center of the microchannel. In microchannels with a height of more than 100 μm, the liquid moves only along the lateral walls of the microchannel (Chinnov et al., 2015b, 2016). With an increase in the liquid superficial velocity, the liquid occupies a much larger part of the microchannel, and the gas jet moves along the center. Disturbances on the liquid surface are not observed. The stationary jet regime is observed at small superficial velocities of liquid and gas, when the gas flow occupies not more than half the width of the microchannel. Chinnov et al. (2014b) presented a detailed investigation of the jet regime, in which two sub-regimes were identified: stationary and pulsating jets. Under the stationary regime, liquid moves along the channel sides, and the rest space is occupied by gas. Under this regime, the upper wall of the channel is not wetted. Pulsations of liquid are not observed in this flow regime. With increasing superficial liquid velocity, liquid moving along the channel sides occupies a larger volume and the dry area decreases. Under the pulsating jet regime, liquid moving along the side walls of the channel occupies the main part of the channel. In the region of liquid input, gas occupies the channel center. At a certain moment, liquid is discharged from the sides and forms a film on the upper wall of the channel. Then, the film moves along the channel, entrained by gas, and after a certain period of time this process is repeated, forming a pulsating jet. The jet regime is specific to flat mini- and microchannels. The increase in superficial liquid velocity leads to an increase in the frequency and amplitude of pulsations and the loss of stability in the jet regime of the two-phase flow. At low superficial gas velocities, the amplitude of liquid perturbations in the lateral parts of the microchannel reaches its half, stable liquid bridges are formed, and the bubble flow regime is achieved.

Figure 7(a) presents the jet regime at $U_{SG} = 0.333$ m/s and $U_{SL} = 0.017$ m/s. The liquid occupies a much larger volume than the gas. In such a regime in a microchannel, there is gas jet motion in the center of the microchannel and along one of the walls of the microchannel. This asymmetry may be caused by nonuniformity of the input area. In channels of larger height, the liquid is distributed along the side walls, which is conditioned by the influence of capillary forces. In the studied microchannel, liquid does not always spread along the walls, which may be caused by a significant microchannel height-to-width ratio (more than two orders of magnitude). With an increase in the superficial gas velocity to $U_{SG} = 1.667$ m/s, the volume occupied by the liquid is significantly reduced. In the microchannel, several liquid jets move. In addition, in the microchannel motion of the vertical liquid bridges between the upper and lower walls of the microchannel is observed. With a further increase in the superficial velocities of gas and liquid, the

FIG. 7: Photograph of the jet regime using the Fastvideo-500M camera in the microchannel with a cross section of 0.05 × 20 mm² at (a) $U_{SG} = 0.333$ m/s, $U_{SL} = 0.017$ m/s and (b) $U_{SG} = 3.333$ m/s, $U_{SL} = 0.033$ m/s, top view (1 – gas input into the microchannel; 2 – slit in the lower wall of the microchannel for liquid input; 3 – unwetted area on the upper wall of the microchannel; 4 – liquid; white arrows, direction of gas motion; black arrows, direction of liquid motion)
intensity of the formation of vertical liquid bridges increases and the flow pattern becomes more complex. Figure 7(b) presents the jet regime at $U_{SG} = 3.333 \text{ m/s}$ and $U_{SL} = 0.033 \text{ m/s}$. It is evident that at such superficial gas and liquid velocities the liquid jet is broken, and there is motion of liquid jets and liquid bridges with a characteristic size of several millimeters. There is also the formation of sessile droplets, which is caused by the destruction of the liquid film and vertical liquid bridges. After passage of the liquid, a thin liquid film remains on the microchannel walls. This pattern is the boundary between the jet and churn regimes.

3.2 Bubble Regime

With an increase in the superficial velocity of the liquid, compared with the case described in the previous section, stable horizontal bridges of liquid begin to form between the side walls of the microchannel, i.e., there is a transition from the jet flow regime to the bubble regime. In this regime, liquid containing many small gas bubbles moves along the channel. The size and the number of bubbles change depending on the gas and liquid flow rates, but the dimensions of bubbles always remain much smaller than the width of the channel. With an increase in the superficial velocities of liquid and gas, the frequency of bubbles increases. At $U_{SG} = 0.333 \text{ m/s}$ and $U_{SL} = 0.167 \text{ m/s}$ [see Fig. 8(a)], both small and large gas bubbles move in the channel, with a characteristic size that is much smaller than the width of the channel but on the order of the channel width. In addition, there is a significant amount of sessile drops of liquid inside the bubbles. The formation of such drops is caused by the destruction of the bridges or liquid film. With an increase in the superficial velocities of gas and liquid to $U_{SG} = 0.833 \text{ m/s}$ and $U_{SL} = 0.333 \text{ m/s}$ [see Fig. 8(b)], the frequency of bubble generation increases. The bubbles move along the left and right walls of the microchannel, and in the middle stationary small bubbles are observed.

3.3 Stratified Regime

The stratified regime is observed at small superficial liquid velocities and large superficial gas velocities (Fig. 6). In this regime, the liquid moves along the lower wall of the microchannel in the form of a film entrained by the gas flow. The upper wall of the microchannel remains dry. The gas in this regime occupies more than half of the microchannel cross section. The stratified regime is characteristic only in the non-circular microchannels because in round microchannels the film closes, forming an annular regime (Chinnov et al., 2015a). Figure 9(a) presents the stratified regime at $U_{SG} = 16.667 \text{ m/s}$ and $U_{SL} = 0.017 \text{ m/s}$. Gas moves in the center of the microchannel, occupying

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**FIG. 8:** Photograph of the bubble regime using the Fastvideo-500M camera in the microchannel with a cross section of $0.05 \times 20 \text{ mm}^2$ at (a) $U_{SG} = 0.333 \text{ m/s}, U_{SL} = 0.167 \text{ m/s}$ and (b) $U_{SG} = 0.833 \text{ m/s}, U_{SL} = 0.333 \text{ m/s}$, top view (1 – gas input into the microchannel; 2 – slit in the lower wall of the microchannel for liquid input; 3 – moving gas bubbles; 4 – liquid; 5 – stationary gas bubbles; white arrows, direction of gas motion; black arrows, direction of liquid motion)
FIG. 9: Photographs of the stratified regime in the microchannel with a cross section of $0.05 \times 20 \text{ mm}^2$ made (a) using the Fastvideo-500M camera at $U_{SG} = 16.667 \text{ m/s}$, $U_{SL} = 0.017 \text{ m/s}$ and (b) using the Nikon D7000 camera in the schlieren photography mode at $U_{SG} = 83.333 \text{ m/s}$, $U_{SL} = 0.033 \text{ m/s}$, top view (1 – gas input into the microchannel; 2 – slit in the lower wall of the microchannel for liquid input; 3 – moving vertical liquid bridges; 4 – film on the lower wall of the channel; 5 – unwetted area on the lower wall of the microchannel; 6 – stationary vertical liquid bridges; 7 – liquid film on the upper channel wall; white arrows, direction of gas motion; black arrows, direction of liquid motion)

a larger part of its cross section. Along one of the sidewalls of the microchannel, vertical liquid bridges move (no. 3) on the film (no. 4), leaving traces on the liquid films. At another side wall of the microchannel the film is not formed, and the vertical bridges almost do not move (no. 6). Such asymmetry can be caused by the inhomogeneity of the input section. The characteristic size of the liquid bridges between the upper and lower walls of the microchannel is from 1 to 3 mm. Sessile drops with a characteristic size of less than 1 mm form on the unwetted walls of the microchannel. Liquid bridges between the upper and lower walls of the channel form near the liquid nozzle, and the destruction of liquid bridges or liquid film causes the formation of the sessile drops. With an increase in the superficial velocity of gas and liquid to $U_{SG} = 83.333 \text{ m/s}$ and $U_{SL} = 0.033 \text{ m/s}$ [see Fig. 9(b)], fewer drops and bridges are formed. On the lower wall of the microchannel, there is a moving liquid film (no. 4), on which vertical liquid bridges sometimes move, leaving behind traces (no. 3). In general, stationary vertical bridges of liquid are not observed in this regime.

3.4 Annular Regime

With an increase in the superficial liquid velocity, compared with the case described in the previous section, the film is formed on the upper wall of the microchannel, and the transition to the annular regime occurs. In this regime, we observe movable vertical liquid bridges gliding on liquid films on the upper and lower walls of the microchannel. The transition from the stratified regime to the annular flow regime is determined using the schlieren method. In the annular flow regime, the liquid moves along the walls of the microchannel in the form of a film, and in the central part the gas, together with the vertical liquid bridges, forms the core of the flow. The gas occupies a much larger volume than the liquid. The formation of a liquid film on the upper wall of the microchannel occurs at a distance of several millimeters from the liquid input into the microchannel. In previous experiments, in microchannels with a height of less than 200 \text{ mm}, the formation of the film on the upper wall of the microchannel occurred directly near the area of liquid input into the microchannel due to the influence of frontal instability (Chinnov et al., 2016). Figure 10 shows a schlieren photograph of the annular regime at $U_{SG} = 83.333 \text{ m/s}$ and $U_{SL} = 0.667 \text{ m/s}$. It can be seen that in this regime, the main part is occupied by the gas core with liquid bridges of complex form, and the film on the upper wall is formed first near the lateral parts of the microchannel and then in the central part of the microchannel. It is possible to detect the film on the lower (no. 4) and upper (no. 5) walls of the microchannel. It can be seen that the film on the
Features of Two-Phase Flow Regimes in Microchannels

3.5 Churn Regime

The churn regime is observed at superficial liquid velocities from 0.1 to 1 m/s and superficial gas velocities from 1 to 10 m/s. This regime is characterized by features of both jet and bubble regimes. This regime is characteristic of vertical channels (Xu et al., 1999) and is observed in wide horizontal microchannels (Kabov et al., 2007). A characteristic feature of this regime is the presence of horizontal ruptured liquid bridges. The existence of the churn regime is due to the development of instability in the jet regime and an increase in the pulsation frequency of liquid moving in the microchannel side walls under the action of the gas flow. Figure 11 presents schlieren photographs of the churn regime at $U_{SG} = 6.667$ m/s and $U_{SL} = 0.333$ m/s, depending on time. The flow structure in this regime is chaotic, and the features of both bubble and jet regimes are observed. At the liquid inlet, there is formation of the liquid film on the lower wall of the microchannel (no. 4) and areas where the liquid fills the entire height of the channel (no. 3). At a distance of several few millimeters from the liquid nozzle, the formation of the film on the upper wall of the microchannel (no. 5) is observed. Directly at the liquid nozzle (no. 1), horizontal liquid bridges are formed. It is also clear that in some places on the upper liquid film ruptures appear. The main feature of the churn regime is the existence of continuous and ruptured horizontal liquid bridges between the side parts of the channel. With lapse of time, these bridges may both destroy and form. The churn regime occupies a large area on the map of flow regimes (Fig. 6). On the contrary, the transition from the jet regime to the churn regime is accompanied by the appearance of continuous filled horizontal liquid bridges that are stable and whose number in the microchannel exceeds unity. In the transition to the annular flow regime, the continuous filled liquid bridges disappear.

4. COMPARISON OF FLOW REGIME MAPS

Figure 12 presents a comparative regime map for microchannels with cross sections of 0.05 × 20 and 0.05 × 40 mm$^2$ (Ron’shin et al., 2016). Each of the boundaries in the map represents the transition zone from one flow regime to another one. It is seen that with increasing width of the microchannel the area of churn and bubble flow regimes
FIG. 11: Schlieren photograph of the churn regime using the Nikon D7000 camera in the microchannel with a cross section of $0.05 \times 20 \text{ mm}^2$ at $U_{SG} = 6.667 \text{ m/s}$ and $U_{SL} = 0.333 \text{ m/s}$ depending on time, top view (1 – gas input into the microchannel; 2 – slit in the lower wall of the microchannel for liquid input; 3 – microchannel areas, completely filled with liquid; 4 – film on the lower wall of the microchannel; 5 – film on the upper wall of the microchannel; white arrows, direction of gas motion; black arrows, direction of liquid motion)

increases. The boundary between the churn and the jet regimes is shifted toward the lower superficial velocity of liquid, significantly contracting the region of the jet flow regime. The boundary between the bubble and the churn regimes is shifted toward the lower superficial velocity of the gas, causing significant contraction of the region of the bubble regime. The boundary between the jet and the stratified regimes is shifted to lower superficial gas velocities with increasing width of the microchannel, and the region of the stratified regime increases. The boundary between the annular and stratified regimes is shifted toward the lower superficial velocity of liquid. Despite the fact that the hydraulic diameter changes insignificantly, the change in the width of the microchannel has a significant effect on the two-phase flow regimes. This is because liquid jets in wide microchannels form near the liquid nozzle not only along the side walls but also in the center of the microchannel. The formation of the churn regime is due to the interaction of these jets. The number of such jets increases with an increase in the width of the microchannel, and this may cause expansion in the region of the churn regime.

Figure 13 presents a comparative regime map of microchannels with the following cross sections: $0.05 \times 20 \text{ mm}^2$ and $0.1 \times 20 \text{ mm}^2$ (Chinnov et al., 2015b) and $0.3 \times 20 \text{ mm}^2$ (Chinnov et al., 2015c). The width of the channels in all three experiments was the same and the height varied from 50 to 300 $\mu$m. Figure 13 shows that an increase in the height of the microchannel causes the boundary between the churn and jet regimes to shift toward higher superficial liquid
FIG. 12: Effect of the microchannel width on the regime boundaries for channels with a height of 50 μm in different flow regimes [I, bubble; II, churn; III, annular; IV, stratified; V, jet; at channel cross sections of 0.05 × 40 mm² (Ron’shin et al., 2016) (1 – solid lines) and 0.05 × 20 mm² (2 – dotted lines); liquid is distilled water (Milli-Q) and gas is nitrogen]

FIG. 13: Influence of the microchannel height on the regime boundaries for channels with in different flow regimes [I, bubble; II, churn; III, annular; IV, stratified; V, jet; at channel cross sections of 0.05 × 20 mm² (1 – solid lines), 0.1 × 20 mm² (Chinnov et al., 2015b) (2 – dotted lines), and 0.3 × 20 mm² (Chinnov et al., 2015c) (3 – dashed-dotted lines); liquid is distilled water (Milli-Q) and gas is nitrogen]

velocities and the boundary between the churn and bubble regimes to shift toward lower superficial gas velocities. The minimum area of the bubble regime was detected in a microchannel with a cross section of 0.3 × 20 mm². In general, regions of stratified and annular regimes are not affected by the height of the microchannel.

5. CONCLUSIONS

In conclusion, it should be noted that main characteristics of the two-phase flow in the horizontal channel with a rectangular cross section of 0.05 × 20 mm² have been determined for a wide range of gas and liquid flow rates by using the schlieren method. The authors were able to detect liquid film on the lower and upper walls of a microchannel.
The peculiarities of the two-phase flow, such as the formation of droplets and vertical liquid bridges, were discovered in almost all flow regimes. Several types of liquid bridges were distinguished: movable and stationary vertical liquid bridges as well as horizontal bridges. In addition, it was possible to register sessile liquid droplets with a diameter of less than 1 mm located on the walls of the microchannel. The main two-phase flow regimes and the boundaries between them have been determined. A map of the flow regimes in the channel with a cross section of 0.05 × 20 mm² was created. A comparison of regime maps for channels of different cross sections was realized. It was shown that the height and width of the rectangular microchannel has a significant impact on the boundaries between the regimes. In particular, when increasing the microchannel height, the boundary between the churn and jet regimes shifts toward higher superficial liquid velocities and the boundary between the churn and bubble regimes shifts toward lower superficial gas velocities. In general, the regions of stratified and annular regimes are not affected by the microchannel height.

With an increase in the microchannel width, the area of the churn and bubble regimes increases, significantly contracting the region of the jet flow regime. The boundary between the bubble and churn regimes shifts toward the lower superficial gas velocities, causing contraction in the region of the bubble flow regime. The boundary between the jet and stratified regimes shifts toward the lower superficial liquid velocities with an increase in the microchannel width, and the area of the stratified region increases. The boundary between the annular and stratified regimes shifts toward the lower superficial liquid velocities. Despite the fact that the map of regimes does not change significantly with decreasing channel height, new features in the patterns of two-phase flows appear. The thickness of the liquid film also decreases, which can lead to heat transfer intensification in such systems.

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REFERENCES


