Experimental investigation of the two-phase flow in a short horizontal microchannel with the height of 50 μm and width of 20 mm

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Abstract. The two-phase flow has been studied experimentally in a short horizontal microchannel with the height of 50 μm and width of 20 mm. The following regimes of two-phase flows have been registered: jet, bubble, stratified, annular, and churn. The regime map of two-phase flow has been plotted. This map has been compared with the regime map plotted for the channels of larger cross-section; it is shown that the height and width of a rectangular channel has a significant effect on the boundaries between flow regimes.

1 Introduction

Currently, there is rapid development of electronics of micro- and nanoscale, which promotes wide spread application of miniature heat exchangers. It is possible to use microburners, where liquid fuel combusts in minichannels [1]. Studies show that the heat exchange systems with the use of mini- and microchannels can take away the higher heat fluxes than the systems with a typical channel size larger than 1 mm or with freely falling films [2]. The surface-to-volume ratio of the flat channel increases with decreasing channel height. This feature provides high heat transfer rate in such systems.

The two-phase flows used in various systems in microelectronics, aerospace industry, transport, energy and other industries, has been actively studied in recent years. Many studies on the two-phase flow in mini- and microchannels have been published. The review of publications on two-phase flows in microchannels of different configurations is presented in [3, 4]. It is shown that many studies use round microchannels although the rectangular microchannels have more prospects for being used in the systems of thermal stabilization. In the rectangular microchannels, the flow pattern corresponds qualitatively to the regimes in tubes; despite the boundaries between the flows differ greatly. The mechanisms that influence formation of regimes in microchannels are described in [5, 6]. It is shown that the microchannel height has a significant influence on formation of the two-phase flow.

The goal of this study is investigation of characteristics of the two-phase flow and boundaries between the flow regimes in a short (with the length of 90 mm from the point of liquid inlet to the channel) rectangular microchannel with the height of 50 μm and width of

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20 mm. The results will be compared with the flow regimes in the microchannels of the larger cross-section.

2 Experimental setup and methods

The microchannel with the height of 50 mm and width of 20 mm is used as a working section. The bottom part of the working section is made of stainless steel plate, 160 mm long and 55 mm wide, processed by grinding, with a nozzle for liquid injection made at the angle of 11°. The microchannel is closed from the top by a quartz plate with previously applied antireflection coating. Between the glass and stainless steel plates, there are two constantan inserts of 50-µm height, defining the height of the channel. The contact angles have been measured before and after the experiment using the KRUSS DSA 100 installed on both surfaces. The microchannel height has been measured after the assembly at several points using the confocal technique. The average height of microchannel in the observation area is 48.7 ± 5.3 µm.

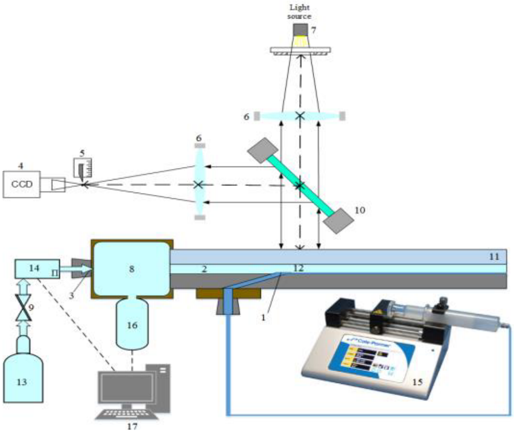

Fig. 1. Principle scheme of experimental setup: (1) liquid inlet to microchannel; (2) microchannel; (3) gas inlet to microchannel; (4) digital camera; (5) Schlieren-knife; (6) lenses; (7) light source; (8) gas chamber; (9) reducer; (10) beam splitter; (11) optical window; (12) observation area; (13) tank with gas; (14) regulator and sensor for flow rate measurements; (15) high precision syringe pump; (16) pressure sensor; (17) personal computer.

Gas mixture is fed to the central part of microchannel from tank (13). The gas flow rate is varied from 100 to 5000 ml/min and kept constant by the El-Flow flow controller of Bronkhorst Company (14). Gas is supplied to gas chamber (8), then it is fed to the microchannel through gas nozzle (2). The liquid flow rates are varied from 0.5 to 50 ml/min by high precision syringe pump Cole-Parmer EW-74905-54 (15). Liquid is introduced into the microchannel through liquid inlet (1). Superpure distilled deionized nano-filtered water, pre-cleared by Direct-Q® 3 UV installation, has been used as liquid. High-purity nitrogen has been used as gas. The distance between the gas and liquid nozzle is about 70 mm. The pressure in the gas chamber (8) is measured by the pressure sensor WIKA Type P-30 (16). The readings of this pressure sensor and current flow rate of gas are written in a file on a PC (17).

Liquid and gas interaction in the microchannel has been visualized in area (12) with the help of digital video and photo cameras by Schlieren photography technique. The Schlieren technique has been used to register and visualize surface deformations of the thin liquid film. Light from the source enters the microchannel with the gas-liquid flow through diffuser (7), lens (6), prism (10) and optical window (11). Light reflected from the gas-liquid interface is transmitted through beam splitter (10), lens (6) and camera lens filter (4). Knife (5) moved by a microscrew cuts the central part of the luminous flux. As a result, the camera captures a grayscale image, where a certain angle of the liquid-gas interface inclination corresponds to each gray level.

To visualize the two-phase flow, the high-speed camera FASTCAM-500M and digital camera Nikon D7000 in the Shlieren regime have been used. The detailed description of the Schlieren technique is presented in [7].

3 Experimental results and discussion.

The following regimes of two-phase flows have been registered in the channel of 50-µm height and 20-mm width during the experiment: jet, bubble, stratified, annular, and churn ones. The regime map is shown in Fig. 1. Inserts in this figure represent the characteristic patterns of the flow in the studied channel. Superficial velocities of liquid and gas, determined as the ratio of volumetric flow rate to cross-sectional area of the channel, have been used as the coordinates.

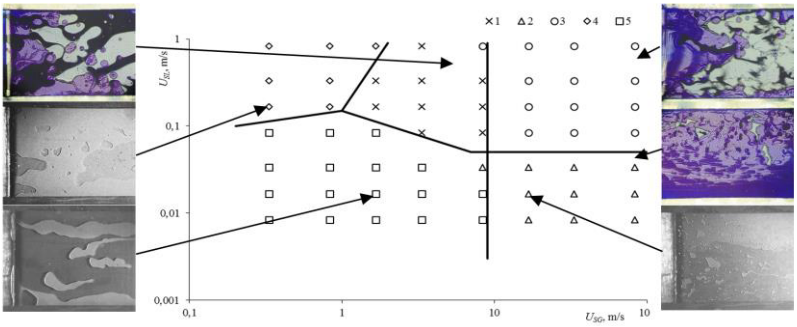

Fig. 2. The regime map of two-phase flows in microchannel with cross-section of 0.05×20 mm^2. Flow regimes: (1) churn; (2) stratified; (3) annular; (4) bubble; (5) jet.

At very low superficial liquid velocities, gas moves in the microchannel center, and the bulk of liquid moves at its periphery along the sidewalls and as jets in the center. With increasing superficial liquid velocity, it starts occupying a larger part of microchannel, and a gas flow moves in the center. There are no disturbances on the liquid surface. The stationary jet flow is observed at low superficial liquid and gas velocities, when the gas flow occupies less than a half microchannel width. The jet regime is specific for the flat mini- and microchannels. An increase in the superficial velocity of liquid increases pulsation frequency and amplitude, and leads to a loss of stability of the jet two-phase flow.

At high superficial velocities of liquid and low superficial velocities of gas, the amplitude of liquid perturbations in the lateral parts of microchannel reaches its half, forming the stable liquid bridges, and the bubble flow starts. Under this regime, liquid with many small gas bubbles moves along the channel. The size and number of bubbles change depending on the liquid and gas flow rates, but the bubble sizes are always much smaller than the channel width. There are also many small liquid droplets inside the bubbles. Formation of such droplets is caused by destruction of bridges or liquid films.

At low superficial liquid velocities and high superficial velocities of gas, the stratified regime is observed. Under this regime, a part of liquid moves along the bottom wall of the microchannel in the form of a film entrained by a gas flow. The upper wall of microchannel is dry. Gas under this regime occupies more than a half microchannel cross-section. The stratified regime is characteristic only of the non-circular microchannels because in the circular microchannels the film closes, forming the annular flow. The liquid droplets move along one of the microchannel sidewalls, leaving the traces on the liquid film. On the other side of microchannel, the film is not formed and droplets do not move. Two kinds of droplets can be distinguished: the large ones with the diameter of 1 to 3 mm, which represent the liquid bridges between the top and bottom walls of microchannel, and small droplets with the diameter less than millimeter on the microchannel wall or on the liquid film.

With increasing superficial liquid velocity, the film is formed on the upper wall of microchannel, and transition to the annular regime occurs. Under this regime, we can see the mobile liquid droplets that slide over the liquid films on the top and bottom walls of microchannel. The transition from the stratified to the annular flow is determined using the Schlieren technique. In the annular regime, liquid moves along the microchannel walls in the form of a film; in the central part, gas with droplets forms the flow core. Gas takes up much more volume than liquid. The liquid film is formed on the top wall of microchannel at a distance of several millimeters from the zone of liquid input to the microchannel. In previous experiments, in microchannels with the height of less than 200 μm, the film was formed on the top wall of microchannel directly near the liquid input into the microchannel due to front instability [5].

At superficial velocities of liquid from 0.1 to 1 m/s and superficial gas velocities from 1 to 10 m/s, the churn flow is observed. This regime is characterized by the features of the jet and bubble flows. This regime is characteristic of the vertical channels, and it occurs in the wide horizontal microchannels. The broken bridges are typical of this regime. The churn flow is caused by development of jet flow instability and increasing pulsation frequency of liquid, moving near the sidewalls of microchannel under the influence of the gas flow. Both the gas flow (with discontinuity) and gas bubbles can be observed under this regime. The churn flow is considered in detail in [8].

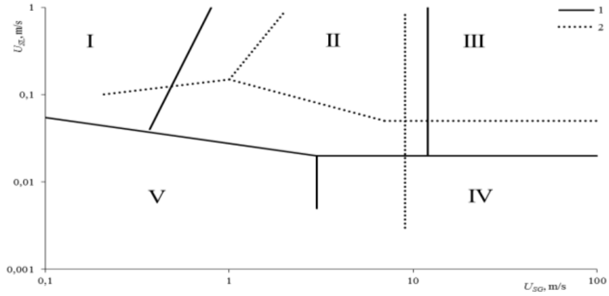

Fig. 3. The effect of microchannel width on the boundaries between the flows for the channels with different cross-sections. Flow regimes: I – bubble, II – churn, III – annular, IV – stratified, V – jet; channel cross-sections: 0.05×40 mm^2 (1), 0.05×20 mm^2 (2).

A comparative regime map plotted for microchannels with cross-section of 0.05×20 mm^2 and 0.05×40 mm^2 is shown in Fig. 3. It is seen that with an increase in the microchannel width, the zones of the churn and bubble flow increase (the boundary between the churn and jet flow moves towards the lower superficial liquid velocities), compressing significantly the zone of the jet flow. The boundary between the bubble and churn regimes moves towards the lower superficial gas velocities, narrowing the area of the bubble flow. The boundary between the jet and stratified flows moves towards the lower superficial velocities of gas with an increase in the microchannel width, and the region of stratified flow increases. The boundary between the annular and stratified regimes shifts toward the lower superficial velocities of liquid.

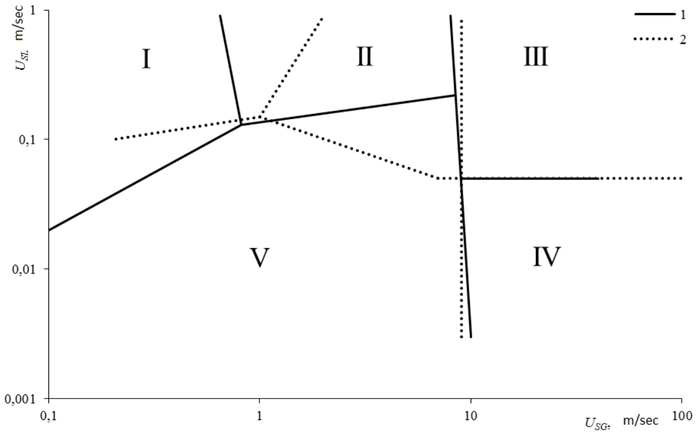

Fig. 4. The effect of microchannel height on the boundaries between the flows for the channels with different cross-sections. Flow regimes: I – bubble, II – churn, III – annular, IV – stratified, V – jet; channel cross-sections: 0.1×20 mm^2 (1), 0.05×20 mm^2 (2).

A comparative regime map plotted for microchannels with cross-section of 0.1×20 mm^2 and 0.05×20 mm^2 is shown in Fig. 4. It is seen that with an increase in the microchannel height, the boundary between the churn and jet flows moves towards the higher superficial velocities of liquid, and the boundary between the churn and bubble flows shifts towards the lower superficial velocities of gas. With an increase in the microchannel height, the boundary between the bubble and jet flows also moves towards the lower superficial velocities of liquid, narrowing the region of the jet flow. The regions of the stratified and annular flow regimes are not affected by the microchannel height.

In conclusion, it should be noted that in the channel of rectangular cross-section of 50×20 mm^2, the main regimes of the two-phase flow have been registered and the boundaries between them have been determined. The regime maps plotted for the channels with different cross-sections have been compared. It is shown that the height and width of the rectangular microchannel have a significant effect on the boundaries between the regimes.

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