Features of two-phase flow patterns in horizontal rectangular microchannels of height 50 μm

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Abstract. The horizontal microchannel with the height of 50 micrometres and width of 40 mm of a rectangular cross-section has been used to study two-phase flow. The classical patterns of two-phase flow in the channel (bubble, stratified, churn, jet, and annular) have been detected. Experimental information allows us to define the characteristics of the regimes and to determine precisely the boundaries between the patterns of the two-phase flows.

1 Introduction

There is a revolutionary development in pharmacy lab-on-chip systems where micro- and nanochannels more efficient than free-flowing liquid macrosystems [1] or ones with characteristic channels height larger than 1 mm [2]. The surface to volume ratio of the channel increases inversely proportional to its minimal transverse size with a decrease in the thicknesses of flat channels. Such systems are receiving increasingly wider application in pharmacy, microelectronics, aerospace industry, transport, and power engineering.

The reviews of the studies on two-phase flows in channels with different geometries can be found in [3-5]. In most publications relatively long channels are considered. In such channels the conditions of liquid and gas entry to the channel do not have a significant effect on the structure of two-phase flow. The length of the channels is two or more orders of magnitude higher than their transverse dimension in such systems. The short channels have broader prospects for using in technical applications, such as, biochips and cooling devices for microelectronics. Sufficiently small pressure drops can be achieved in the heat exchangers based on short microchannels. The number of publications on this subject is very limited. The gas-liquid flows in the short horizontal mini- and microchannels have been studied in [6-10]. It is shown that there are many factors affecting on the structure of the two-phase flow.

One way to solve the problems of microelectronic cooling is the use of short microchannels with a two-phase heat-transfer agent, where there is intense evaporation in the zone of active heat release with high velocities of subcooling gas-liquid flow under the conditions of relatively small pressure. The aim of this study is to investigate the regimes of two-phase patterns and boundaries between them in the short (length of 90 mm) horizontal channel with the height of 50 μm and width of 40 mm using the modern techniques.

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2 Experimental setup and methods of measurement

The experimental setup includes two computer-controlled circuits, which maintain the flow of liquid and gas phases. Figure 2 presents the schematic diagram of experimental setup with microchannel (2) and shows the arrangement of instruments for the applied measurement techniques.

The main part of the test section is a stainless steel plate with the length of 160 mm and width of 55 mm. The plate is covered with an optical glass. The height of the microchannel is 50 microns. The microchannel is created by placing two parallel constantan strips with height 50 μm , width 7.5 mm and length 160 mm between a stainless steel plate and glass window so the rectangular microchannel with the size of 50 $\mu\text{m} \times 40 \text{ mm} \times 90 \text{ mm}$ is created.

The liquid is driven by a high precision syringe pump and injected into the microchannel by liquid nozzle (1). The gas have been supplied into the microchannel throw the gas nozzle (2) from the gas chamber (8). The distance between gas and liquid nozzle is about 70 mm. The liquid–gas interaction in the channel have been visualised in region (12) by the digital video and photo cameras in the Schlieren photography mode using the light beam reflected from the gas–liquid interface. The Schlieren method have been used to register deformation and visualize the liquid film surface. Light from a source (7) through a diffuser, a lens (6), a prism (10) and an optical glass cover (11) penetrates into the channel with the gas-liquid flow. Light, reflected from the gas-liquid interface was transmitted through separation prism (10), lens (6) and filter to camera objective (4). A knife (5), moved by a microscrew, cut the central part of the light beam. As a result, the video camera recorded the intensity of light reflected from the surface separating gas and liquid depending on the angle of this surface inclination from the axis of reference radiation.

Figure 1. Schematic diagram of the experimental arrangement: (1) flat nozzle for the injection of liquid; (2) microchannel; (3) gas inlet; (4) digital camera; (5) optical knife; (6) lenses; (7) light source; (8) gas chamber; (9) pressure valve; (10) beam splitter; (11) optical window; (12) area of measurement; (13) gas balloon; (14) flow control and measurement gauge; (15) syringe liquid pump.

3 Experimental results and discussion

The basic two-phase flow patterns have been studied experimentally; the boundaries between various patterns have been detected. The map of flow regimes of the process has been created. Figure 2 shows the map of two-phase flow patterns in the 40-mm-wide horizontal channels with the height of 50 μm . The superficial velocities of gas U_{SG} and liquid U_{SL} (determined as the volume flow rates of gas or liquid divided by the cross-sectional area of the channel) have been used as the coordinates in this

figure. The solid lines in the figure show the boundaries of the flow patterns for this channel. The following flow patterns have been determined: bubble, jet, stratified, churn, and annular ones.

Figure 2. Map of the flow patterns of the two-phase flow in the channel with a cross section of 0.05×40 mm². Flow patterns: 1 – churn, 2 – stratified, 3 – annular, 4 – bubble, 5 – jet.

The bubble flow regime is observed in the range of high superficial velocities of liquid and low velocities of gas. The main part of the channel is occupied by liquid, where the gas bubbles move (Fig. 3a). The gas bubbles with the diameter from 1 to 10 mm have been observed. Sometimes bubbles coalesce, forming large bubbles. The liquid moves near the side walls of the channel. The rate of nucleation increases and the bubble sizes remain approximately the same with an increase in the gas velocity. For high superficial velocities of liquid at an increase in the superficial velocity of gas, the bubbles coalesce and bridges between the bubbles are broken, forming the churn flow regime. For the low superficial velocities of liquid at an increase in the superficial velocity of gas, the bubbles coalesce, forming a gas jet and the flow turns to the jet one.

In the range of low superficial velocities of liquid and gas from $U_{SL} = 0.008$ m/s, $U_{SG} = 0.1$ m/s to $U_{SL} = 0.04$ m/s, $U_{SG} = 2$ m/s, the jet flow pattern with many small drops is observed. This regime is characteristic for the channels with the height below 200 μ m. The gas-liquid jet with predominance of gas moves along the channel. The feature of this regime in comparison with the higher channels is the presence of many drops in the gas jet. Two particular regimes that can be distinguished represent formation of immobile drops on the channel wall due to liquid film or bridge breakage and appearance of mobile drops because of the two-phase flow instability. The characteristic drop diameter in this flow is observed from several microns to several millimetres. If the upper part of the channel is dry, the drops do not move and exist long until their washing by a continuous liquid flow.

The churn flow pattern is observed at high superficial liquid velocities. The churn flow occupies a considerable part in the map. This pattern is considered in detail in the paper [10]. A transition from the bubble (with continuous liquid regions) to the churn regime is determined by the appearance of breaks in the liquid. On the contrary, a transition from the jet to the churn flow pattern is manifested by formation of filled stable regions, the number of which is greater than one. The churn flow pattern relates to development of instability in the jet flow pattern, which leads to increasing frequency of gas interaction with liquid supplied from the lateral walls of the channel. The continuous liquid bridges disappear at transition to the annular flow. The destruction of bridges contributes to the appearance of stationary droplets on the walls of the channel which exist until washing by a continuous liquid flow.

In the range of low superficial liquid velocities, the transition from the jet to the stratified flow pattern occurs at an increase in the superficial gas velocity. In this flow, a part of liquid moves along the bottom wall of the channel in the form of a film entrained by the gas flow. Under the stratified flow pattern, gas occupies almost the entire width of the channel. Liquid fills its full height only in a narrow area along the lateral walls of the channel.

The transition to the annular pattern occurs with an increasing superficial velocity of liquid. In the annular flow pattern, liquid moves along the channel walls as a film, and gas with droplets forms the flow core in the central part of the channel. As compares to the stratified flow, under the annular flow regime the film in the upper part of the channel occupies a larger area. In the side parts, there are the

contacts with the lower film, resulting in formation of the annular flow. The transition from the stratified flow pattern to the annular one is manifested by a significant increase in the area of the film at the top of the channel. The film on the upper channel wall is formed immediately after the liquid input to the channel (as it occurs in the channel height below of 0.1 mm, [7]).

Figure 3. (a) The photo of the bubble flow at $U_{SL} = 0.17$ m/s, $U_{SG} = 0.17$ m/s obtained by shadow technique: (1) gas input to the channel, (2) slot in the lower channel wall for liquid input to the channel, (3) gas bubbles, (4) liquid; (b) the photo of the mobile drops in the annular pattern obtained by schlieren technique: (1) the liquid film on the upper channel wall, (2) mobile drops.

The feature of the channels height below of 200 μm in comparison with the higher channels is the presence of many drops in the gas jet. Drops appear for almost all two-phase flow patterns in the channel height of 50 μm . Two particular regimes that can be distinguished represent the formation of immobile drops on the channel wall due to liquid film or bridge breakage and appearance of mobile drops because of the two-phase flow instability. The second case is illustrated by the Schlieren image Figure 3b, where the dark regions correspond to liquid filling the channel from the top to the bottom and the bright regions represent the liquid on the inner surface of the top cover. After the ejection of liquid towards the center (caused by perturbation, [8]) and its subsequent return, a fraction of ejected liquid separated in the form of a drop. The diameters of these drops exceed the channel thickness and are typically from 50 μm to several millimetres, while their shapes are nearly circular due to the action of capillary forces.

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References

1. E. A. Chinnov, *Journal of Heat Transfer* **138**, 9 (2016).
2. V. V. Zamashchikov, A. A. Korzhavin, E. A. Chinnov, *Combust. Explos. Shock Waves* **50**, 381 (2014).
3. N. Shao, A. Gavrilidis, P. Angeli, *Chemical Engineering Science* **64**, 2749 (2009).
4. E. V. Rebrov, *Theor. Found. Chem. Eng.* **44**, 355 (2010).
5. E. A. Chinnov, O. A. Kabov, *High Temp.* **44**, 773 (2006).
6. O. A. Kabov, E. A. Chinnov, V. Cheverda, *Microgravity sci. technol.* **XIX**-3/4, 44 (2007).
7. E. A. Chinnov, O. A. Kabov, *Doklady Physics* **57**, 42 (2012).
8. E. A. Chinnov, F. V. Ron'shin, O. A. Kabov, *Int. J. Multiphase Flow* **80**, 57 (2016).
9. V. Haverkamp, V. Hessel, H. Löwe et al., *Chem. Eng. Technol.* **29**, 1015 (2006).
10. E. A. Chinnov, F. V. Ron'shin, V. V. Guzanov, D. M. Markovich, O. A. Kabov, *High Temp.* **52**, 681 (2014).