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Two-Phase Flow in Short Horizontal Rectangular Microchannels with a Height of 300 μm

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Abstract—The two-phase flow in a narrow short horizontal channel with a rectangular cross section is studied experimentally. The channel has a width of 10, 20, or 30 mm and a height of 300 μm. The specifics of formation of such two-phase flows are investigated. It is demonstrated that the regions of bubble and churn flow regimes grow and constrain the region of jet flow as the channel gets wider. The boundaries of the regions of annular and stratified flow regimes remain almost unaltered.

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The current rapid progress in microelectronics facilitates the miniaturization of cooling systems. The available cooling systems do not meet current requirements concerning the removal of heat from high-heat sources in electronic and microelectronic equipment. As planar channels get thinner, the ratio of the surface area to the volume of a channel is increased in inverse proportion to its minimum crosswise size. This gives rise to an intense heat exchange in microsystems. Such systems turn out to be much more energy efficient than macrosystems with channel sizes in excess of 1 mm and are becoming more widespread both in microelectronics and in the aerospace industry, transport industry, and power engineering.

Published results of studies of two-phase flows in channels with various geometries were reviewed in [1, 2]. It was demonstrated that long microchannels (with their length being at least an order of magnitude larger than their maximum crosswise size, which, in the present case, is their width) were used in the majority of studies; however, short channels are more promising with regard to cooling tiny devices with a high heat output such as microchips. Fairly small pressure drops may be obtained in heat exchangers based on short microchannels. The initial section exerts a considerable influence on the two-phase flow structure in short channels, while the flow regime in long channels is affected only slightly by the initial section. Although the studies of two-phase flows in short channels are of immediate interest, the number of published papers on this subject is limited. The authors of [3, 4] investigated gas-liquid flows in short horizontal microchannels with a thickness of 0.4–1 mm. New flow regimes (intermittent, jet, and bubble-jet) were found. These regimes may be associated with instability of flow of a two-phase mixture in horizontal rectangular channels of a small height. The structure of a two-phase flow in a channel with a height of 200 μm was analyzed in [5]. A large number of parameters affect the structure of a two-phase flow. The influence of the following factors on the boundaries of a two-phase flow in microchannels was analyzed in [6]: the geometry of the initial sections, the diameter (crosswise size) of channels, the shape of channel sections, the hydrophilic properties of surfaces of channel walls, and the surface tension and viscosity coefficients of the liquid. It was shown that the flow regimes depend to a considerable extent on the conditions of injection of phases into the channel. The channel geometry, its width, and the ratio of its dimensions are all important factors.

It follows from the analysis of the published results that data on microchannels with a height of 300 μm and less are scarce. Still, such channels are the most promising ones with respect to the design of cooling systems for very-high-performance electronics that requires the removal of heat fluxes in excess of 1000 W/cm^2.

This Letter presents the results of studies of a two-phase flow in a rectangular microchannel with a length of 80 mm; a width of 10, 20, or 30 mm; and a height of 300 μm.

The experimental setup and the microchannel design were described in [5]. The Schlieren technique was used to record liquid films at the upper or lower channel walls and determine the two-phase flow regime [3]. Videos were recorded with their resolution ranging from 720 × 576 to 1920 × 1080 pixels and a frame rate of 25 fps. The frame width was generally larger than the channel width.

The major two-phase flow regimes were studied, the boundaries between them were determined, and the regime maps of the process were plotted for each

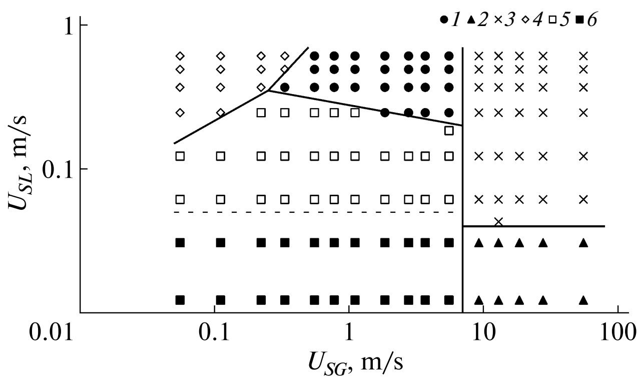

Fig. 1. Regime map of the two-phase flow in the channel with a section of a 0.3 × 30 mm. The flow regimes are as follows: (*1*) churn, (*2*) stratified, (*3*) annular, (*4*) bubble, (*5*) pulsating jet, and (*6*) stationary jet.

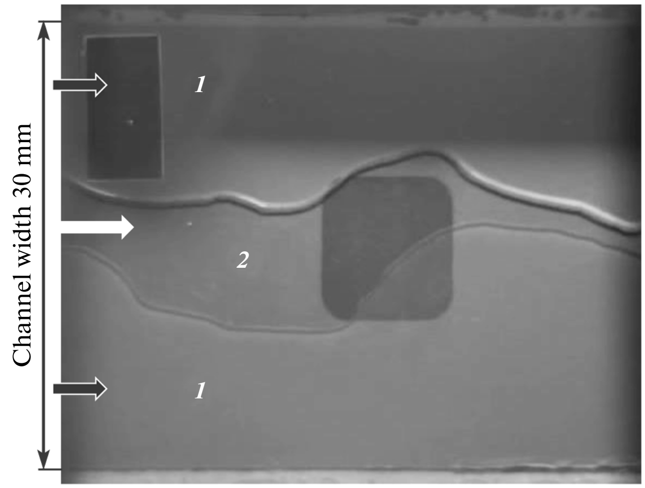

Fig. 2. Schlieren image of the jet regime in the channel with a section of a 0.3 × 30 mm at U_{SG} = 0.22 m/s and U_{SL} = 0.12 m/s (top view). Indicated are (*1*) the liquid and (*2*) the unwetted area at the upper channel wall. Black arrows point in the direction of liquid flow, and the white one points in the direction of gas flow.

channel. Figure 1 shows the regime map of the two-phase flow in the channel with a width of 30 mm. Superficial gas U_{SG} and liquid U_{SL} velocities were used as coordinates. These velocities were defined as the ratio of the volumetric gas or liquid flow rate to the cross-section area of the channel. The following major flow regimes were identified: bubble, jet, stratified, churn, and annular flows. Two subregimes (stationary and pulsating) were singled out for the jet regime.

When the superficial liquid velocities were very low, the gas flowed along the central part of the channel, while the liquid flowed mainly at its periphery along the side walls (Fig. 2). No disturbances were observed at the liquid surface. The stationary jet regime was established at low superficial liquid and gas velocities when the gas flow occupied no more than a half of the channel section. The upper channel wall was not wetted in this regime. When the superficial liquid velocity was raised, the liquid flowing along the side regions of the channel filled a greater volume, while the dried region shrank in size. At sufficiently high superficial liquid velocities (U_{SL} > 0.05 m/s), a film was formed at the upper channel wall due to the ejection of liquid from the channel sides, and the pulsating jet regime was established. The liquid flowing along the sides of the channel occupied the majority of it in this regime. The center of the channel in the region of liquid inlet was occupied by gas. At a certain point in time, the liquid was ejected from the sides and formed a film at the upper channel wall. The film was then entrained by the gas flow and moved along the channel. This process was repeated after a little while, and a pulsating jet was formed. The jet regime is specific for planar short minichannels. Further increases in the superficial liquid velocity resulted in an increase in the frequency and amplitude of pulsations and led to the loss of stability of the jet regime of two-phase flow. When the superficial gas velocities were low, the amplitude of liquid disturbances in the side regions of the channel reached a half of its size, stable liquid bridges were formed, and slug or bubble flow regimes were established.

In the bubble flow regime, the liquid containing many small gas bubbles flowed along the channel. The size and number of these bubbles depended on the liquid and gas flow rates, but their crosswise size was significantly smaller than the channel width. The rate of motion of bubbles was increased with increasing superficial liquid and gas velocities. As the superficial gas velocity was increased further, the liquid bridges that separated the bubbles from each other started to break up, and the transition to the churn flow regime occurred. This regime is typical for vertical channels [7] (where it is induced by gravity) and is also observed in wide horizontal microchannels with a height lower than 1 mm. The churn flow regime occupies a large part of the map and was analyzed in detail in [5]. The transition from the bubble (continuous filled liquid bridges) regime to the churn one was accompanied by the rupture of liquid bridges. The transition from the jet regime to the churn one was, by contrast, accompanied by the emergence of continuous filled bridges. These bridges were stable, and there were more than one of them in the channel. The churn regime emerged due to the instability of the jet regime and an increase in the frequency of surges of the liquid flowing at the side walls of the channel under the influence of the gas stream.

When the superficial gas velocity was increased, the transition to the annular flow regime occurred and continuous filled liquid bridges disappeared. This transition was initiated by an increase in the frequency of lateral surges that induced the formation of a liquid film at the upper channel wall. In the annular flow regime, the liquid flowed in the form of a film along the channel walls, and the flow core was formed in the central region by the gas together with droplets. The volume occupied by gas in this regime was significantly larger than that occupied by liquid.

When the superficial liquid velocity was reduced, no film was formed at the upper channel wall and transition to a separated flow regime occurred. In this regime, a portion of liquid flowed in the form of a film, which was entrained by the gas stream, along the lower channel wall. The upper channel wall was dried. The gas occupied more than a half of the channel section in this regime. The separated regime is often observed only in microchannels of a nonround shape, since the film in round tubes with small diameters is closed into a complete circle and thus establishes annular flow [8]. The gas occupied almost the entire channel width in the separated regime, and the liquid filled the entire channel height only in narrow regions at the sides of the channel. The gas flowing in the center of the channel occupied the majority of its section in this regime. Under the influence of the gas stream, the liquid flowed in the form of a smooth film along the lower channel wall and the side walls.

Figure 3 presents a comparison of the regime maps of channels with a section of 0.3 × 10, 0.3 × 20, 0.3 × 30, and 0.3 × 40 mm. It can be seen that the region of churn and bubble regimes became larger (its boundaries were shifted toward lower superficial liquid velocities) as the channel width was increased. The region of the jet flow regime shrank in size in the process. The instability of the two-phase flow to disturbances in the region of liquid inlet was enhanced as the channel got wider. If a channel is wide, a significant portion of liquid may enter it not only along its sides, but also in its central part. This facilitated gas–liquid flow mixing, and the transition from the jet regime to the churn one occurred at lower superficial liquid velocities. The boundary between the pulsating jet regime and the stationary jet one was not altered in any channel. The regions of annular and separated flow regimes were altered insignificantly.

It should be noted in conclusion that the specific features of the jet regime in channels with a rectangular cross section and a height of 300 μm were revealed, and two subregimes (stationary and pulsating) of the jet regime were identified. The regime maps for channels with a height of 300 μm and a width of 10, 20, or 30 mm were compared, and it was found that the channel width exerted a considerable influence on the boundaries between regimes. The regions of bubble and churn regimes became larger and constrained the region of jet flow as the channel became wider. The boundaries of the regions of annular and separated flows remained almost unaltered.

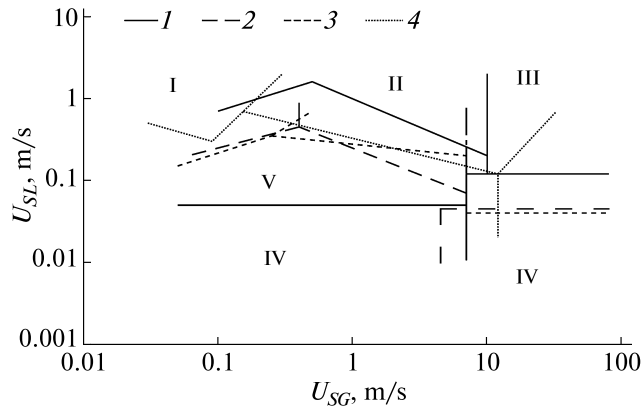

Fig. 3. Comparison of regime maps for channels with the following sections: (*1*) 0.3 ×10, (*2*) 0.3 × 20, (*3*) 0.3 × 30, and (*4*) 0.3 × 40 mm. The flow regimes are as follows: (I) bubble, (II) churn, (III) annular, (IV) stratified, (V) pulsating jet, and (VI) stationary jet.

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