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Study of gas-water flow in horizontal rectangular channels*

E.A. Chinnov[1,2,3], F.V. Ron'shin[1,2], and O.A. Kabov[1,2]

[1]*Kutateladze Institute of Thermophysics SB RAS*, *Novosibirsk*, *Russia*

[2]*Novosibirsk State University*, *Novosibirsk*, *Russia*

[3]*Novosibirsk State University of Architecture and Civil Engineering*, *Novosibirsk*, *Russia*

E-mail: chinnov@itp.nsc.ru

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The two-phase flow in the narrow short horizontal rectangular channels 1 millimeter in height was studied experimentally. The features of formation of the two-phase flow were studied in detail. It is shown that with an increase in the channel width, the region of the churn and bubble regimes increases, compressing the area of the jet flow. The areas of the annular and stratified flow patterns vary insignificantly.

Key words: two-phase flow, flat channel.

Now there is revolutionary development of heat-exchanging systems of the micro- and nanoscale, which are much more energy efficient than the macro-systems with the channels of 3–100 mm. With a decrease in the flat channel thickness, the ratio of the channel surface to its volume increases inversely proportional to its minimum cross dimension, and this enhances heat transfer in microsystems. Such systems become increasingly common in microelectronics, aerospace industry, transport, and power engineering. The existing cooling systems do not meet modern requirements for heat removal from the high-heat sources in electronic and microelectronic equipment.

There are a significant number of studies on the two-phase flow. The publications on two-phase flow in channels of different configurations are reviewed in [1, 2]. It is shown that the majority of works study the long microchannels, however, the short channels are more promising for cooling the miniature devices with high heat release, such as microchips. In the heat exchangers based on short microchannels, relatively small pressure differences can be achieved. Despite the relevance of studying the two-phase flow in the short channels, the number of publications on this subject is very limited. The investigations of two-phase flow in the mini- and microchannels are not always univocal; they contain contradictions and different interpretations. The most works distinguish the following regimes of the two-phase flow:

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bubble, slug, and annular, available in all channels. At low superficial velocities of liquid and gas, the slug flow is observed. The slug regime is characterized by the large bullet-shape bubbles passing along the channel. The cross size of bubbles almost coincides with the channel diameter. With an increase in superficial velocity of liquid, the transition to the bubble regime occurs. In this regime, liquid containing many small gas bubbles moves along the channel. The size and number of bubbles change depending on the liquid and gas flow rates. At high superficial velocities of liquid and gas, the annular regime is observed. In the annular regime, the liquid moves over the channel walls as a film, and in the center, the gas with liquid droplets form the flow core.

The gas-liquid flows in the short horizontal minichannels with the thickness from 0.4 to 1 mm were studied in [3, 4]. New flow regimes (intermittent, jet, and bubble-jet ones) were revealed; these regimes can be associated with instability of the two-phase mixture flow in the horizontal rectangular channels of a small height. The structure of the two-phase flow in the channel of 200-μm height was analyzed in [5]. It is shown that the structure of the two-phase flow is affected by many parameters.

The boundaries between the regimes differ greatly depending on the experimental conditions. The conditions of the gas and liquid input are very important. The tubes can be connected with the help of a smooth mixer or they can be put perpendicularly to the channel by using a T-mixer. When comparing two mixers in [6] it was found that at transition from the T-mixer to the smooth mixer, the slug does not shift, the region of the jet regime reduces significantly, and the regions of slug-annular and churn regimes become narrower; but in general, the character of the regime map is kept. Such channel parameters as the shape and size of the channel also have a significant influence. The impact of forces on the two-phase flow changes with a change in the channel size. For the small channels, a decrease in their diameter promotes a shift of the boundaries between the intermittent and bubble, slug and slug-annular, slug-annular and dispersed flows towards higher superficial velocities of liquid and gas. However, a change in the channel size does not affect the boundary between the slug-annular and annular, annular and dispersed flows. There were also many studies in the channels of various shapes. Mainly the round, triangular, square, and rectangular channels were used. In the non-circular channels, the tendency of liquid accumulation in the corners was observed. This led to an increase in the area occupied by liquid at the edges of the channel, and reduction of the core area of the gas flow; therefore, the transition to the annular regime occurred earlier. The new regimes, not characteristic to the round channels of a small size, were distinguished, for example, the stratified regime. For the large channels (> 1 mm), their length has a significant effect also. With increasing length of the channel, the boundary between the bubble and slug regimes shifts towards the lower superficial gas velocity, whereas the boundary between the slug and annular flows shifts to the opposite direction. The effect of liquid parameters is also considerable. With an increase in liquid viscosity, the boundaries of the slug flow shift towards the higher superficial velocities of gas and liquid. By increasing the surface tension, the boundary of the bubble regime shifts toward the lower values of superficial gas velocity U_{SG}. The area of the jet-slug regime decreases significantly with increasing surface tension. The region of the churn regime shifts towards the higher values of U_{SG} with a decrease in the surface tension.

Such factors, influencing the two-phase flow, as the geometry of the inlet section, channel diameter, cross-section shape, hydrophilicity of the channel wall surface, surface tension, and liquid viscosity were considered in [7]. It has been shown that the flows depend significantly on the conditions of phase input into the channel.

The review of main publications on the study of two-phase flow in rectangular minichannels is presented in [2]. According to analysis of publications, we can conclude that the number of publications on microchannels with the height of 1 mm or less and the width-to-height ratio over 10 is very limited, even though these channels are the most promising for cooling the super high-productive electronics, which requires removal of heat fluxes above 1000 W/cm^2.

The current work is aimed at the study of the two-phase flow regimes in a short (80 mm) horizontal microchannel with the width of 10–29 mm and height of 1mm.

Experimental setup and measurement method

The working section with the studied channel and layout of equipment for measurements are shown in Fig. 1. The setup includes the line of liquid circulation controlled by a PC. Gas was supplied from a vessel through the flow meters to the channel, and then it was evacuated into the atmosphere. The applied gas was saturated with liquid vapors before the inlet to the working section. Liquid was fed through flat nozzle *1* to studied channel *2* by means of high-precision peristaltic pump *7*. The nozzle was made in a stainless steel plate in the bottom part of the working section. Gas was fed to the central part of the channel through inlet hole *3* located at the distance of 40 mm from the liquid input, where the gas flow was stabilized. To change the channel height, the lateral inserts were used.

The interaction of the gas-liquid flows in region *13* was registered by the digital video and photo cameras. To study the interaction of liquid and gas in the channels, the method of laser-induced fluorescence [4, 8] was used; this method is based on re-radiation of absorbed light by a fluorophore with the spectral composition differing from exciting radiation. Distilled water with fluorophore Rhodamin 6G was used as the liquid, and nitrogen or air was used as the gas. To achieve reference radiation, laser *9* of Aries series with the power of 50 mW and wavelength of 532 nm was applied. A laser beam was expanded into a line by cylindrical lens *10*, this line passed across the gas-liquid flow at the distance of 52 mm from the point of liquid input into the channel, where the regime of the two-phase flow has been already stabilized. The re-radiated fluorescent light was registered by the digital camera VS-Ld-751 *11* equipped with a step light filter of low frequencies SONY ILX-751A *12*, which transmitted light, re-radiated by the fluorophore, and cut off laser radiation. This camera allows digitization of the received signal with a high sampling rate (up to 2.1 kHz). The measuring system was calibrated under the experimental conditions by the local intensity of luminescence of the plane-parallel layers of the working liquid in a fully filled channel. The channel from the top was closed by the optical glass lid.

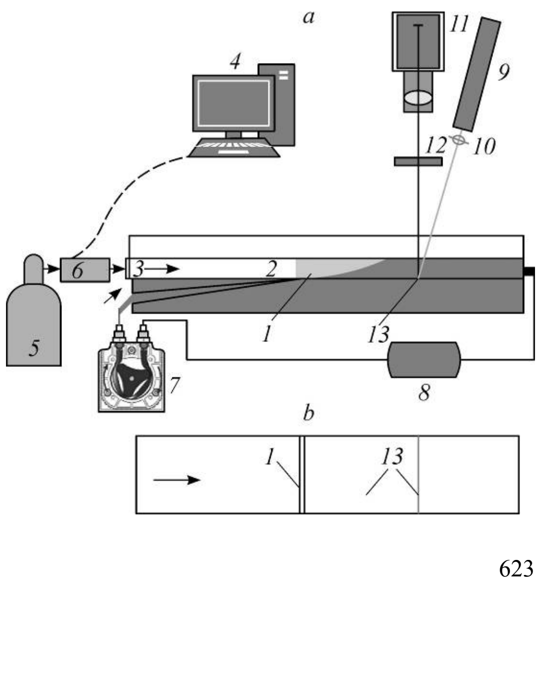

Fig. 1. Experimental setup.

a — scheme of setup, *b* – working section with studied channel; *1* — flat nozzle for liquid supply, *2*— channel, *3* — gas input into the channel, *4* — PC, *5* — gas vessel, *6* — flow meters, *7* — high-precision peristaltic pump, *8* — vessel with liquid, *9* — laser, *10* — cylindrical lens, *11* — digital camera with linear transducer, *12* — light filter, *13* — zone of measurements.

New information, which allowed studying the characteristics of the churn and stratified patterns and the boundary between the two-phase flow regimes, was obtained by the fluorescence method used to record the changes in the liquid flow in the channel with time. The studies were performed in the channels with the height of 1 mm and width of 10 mm, 19 mm, and 29 mm.

Results

The main regimes of the two-phase flow were studied experimentally, the boundaries between them were determined, and the regime map of the studied process for the studied channel with the height of 1 mm was plotted (Fig. 2). Superficial velocities of gas U_{SG} and liquid U_{SL}, determined as the volumetric gas or liquid flow rate divided by the channel cross section, are used as the coordinates in the figure. The boundaries of the flow regimes for the channel with cross section 1×10 mm are shown by the solid lines. The following main flow regimes are distinguished: bubble, slug, jet, stratified, churn, and annular.

Liquid flowed out of nozzle *1* (Fig. 1) and moved to the lateral parts of the channel under the action of capillary forces. Only for low superficial velocities of gas and relatively high superficial velocities of liquid, the bubbles were formed near the liquid input into the channel.

At very low superficial velocities of liquid, gas moved in the central part of the channel, while the bulk of liquid moved along its periphery along lateral walls. Disturbances on the surface of the liquid were not observed. The stationary jet regime was observed at low superficial velocities of liquid and gas, when the gas flow occupied no more than a half of the channel cross section. The jet regime is specific for the flat minichannels. Increasing the superficial liquid velocity led to an increase in the frequency and amplitude of pulsations and stability loss of the jet regime of the two-phase flow. At low superficial gas velocities, the amplitude of liquid perturbation in the lateral parts of the channel reached its half, stable liquid bridges were formed, and bubble or slug flow regime began. At U_{SG} = 0.05 m/s, U_{SL} = 0.02 m/s, the stable liquid bridges appear. The transition to the slug flow occurs.

The slug regime was observed at low superficial velocities of liquid and gas. The slug regime is characterized by the large bullet-shape bubbles passing along the channel. The diameter of bubbles was about the channel width. At U_{SL} = 0.11 m/s; U_{SG} = 0.05 m/s,

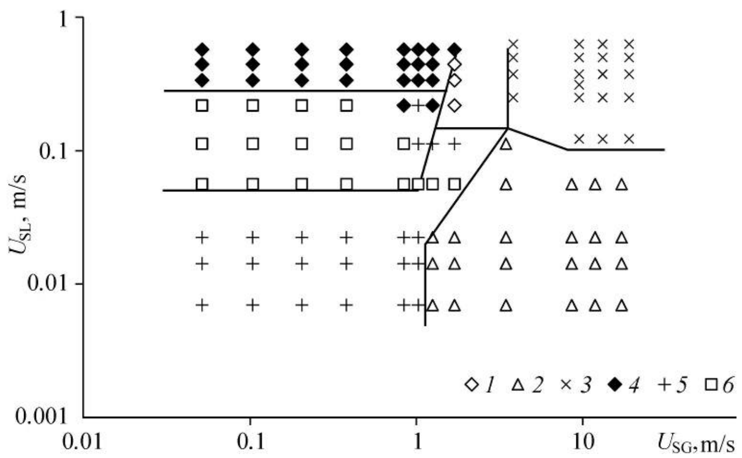

Fig. 2. Regime map of the two-phase flow in the channel with cross section of 1×10 mm.
Flow regimes: *1* — churn, *2* — stratified, *3* — annular, *4* — bubble, *5* — jet, *6* — slug.

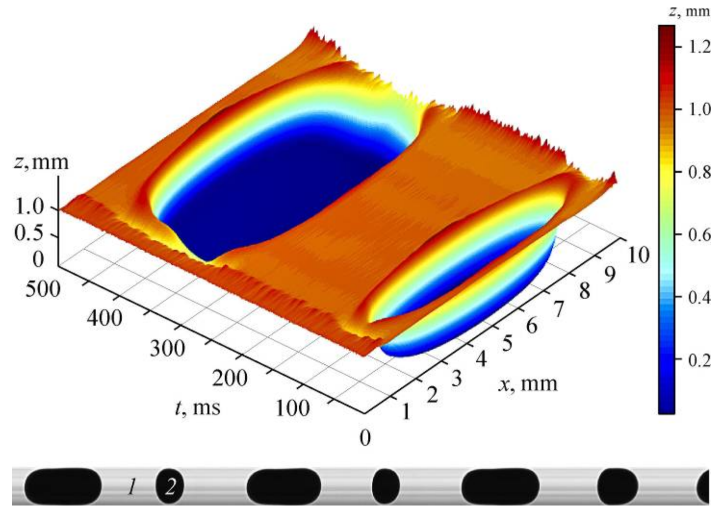

Fig. 3. Distribution of liquid in the channel for U_{SG} = 0.05 m/s, U_{SL} = 0.11 m/s.
1 — liquid, *2* — gas bubbles.

the motion of the pairs of large and small bubbles with frequency ν = 1.5 Hz was observed (Fig. 3).

With an increase in superficial velocity of liquid the transition to the bubble flow occurs. In this regime, liquid comprising many small gas bubbles moves along the channel. The size and number of bubbles vary depending on liquid and gas flow rates, but the sizes of the bubble are always much smaller than the channel width. With an increase in superficial liquid and gas velocity, the bubble frequency increases. Distribution of liquid at U_{SL} = 0.56 m/s, U_{SG} = = 1.02 m/s is shown in Fig. 4*a*. Under these conditions, 27 bubbles during 2 seconds were observed. With an increase in superficial velocity of gas up to до U_{SG} = 1.7 m/s, the number of bridges increases up to 32 in 2 s (Fig. 4*b*). The frequencies characteristic to the bubble regime are presented in Table 1.

Table 1

Characteristic frequencies for bubble regime

U_{SL}, m/s	0.56	0.56
U_{SG}, m/s	1.02	1.7
ν, Hz	13.5	16

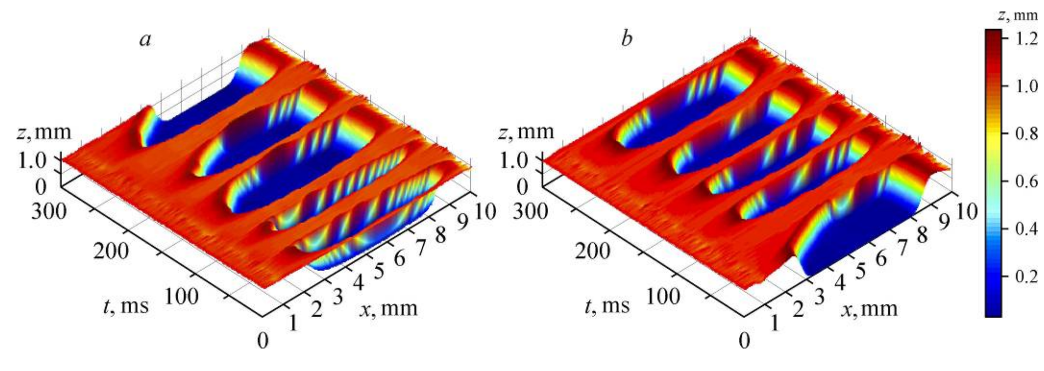

Fig. 4. Distribution of liquid in the channel for the bubble flow.
a — U_{SG} = 1.02 m/s, U_{SL} = 0.56 m/s, *b* — U_{SG} = 1.7 m/s, U_{SL} = 0.56 m/s.

At low superficial liquid velocities and high superficial gas velocity, the stratified regime was observed. In this regime, a part of the liquid moved along the bottom wall of the channel in the form of a film entrained by the gas flow. The upper wall of the canal was dry. Gas in this regime occupies more than a half of channel cross section. The stratified regime is characteristic only for the non-round microchannels because in the round channels the film closes forming the annular flow. The stratified flow at U_{SG} = 17 m/s, U_{SL} = 0.02 m/s is shown in Fig. 5*a*. In the stratified regime, gas occupied almost the entire width of the channel; only a narrow area near the lateral walls of the channel liquid completely filled its height. In the region of the stratified flow of liquid the first periodic perturbations occurred at U_{SL} = 0.02 m/s, U_{SG} = 3.42 m/s (Fig. 5*b*). It is seen that gas moves in the channel center, occupying most part of its cross section. Under the influence of the gas flow, liquid is distributed as a smooth film on the bottom wall of the channel. The main part of liquid accumulates near the lateral walls of the channel due to the capillary forces. On one of the lateral walls, the wave motion of liquid is observed. With a further increase in the superficial gas velocity, the frequency of periodic disturbance increases (Figs. 5*c*, 5*d*). An increase in the superficial liquid velocity leads to the loss of stability of the two-phase flow in this regime.

The frequencies of characteristic pulsations are shown in Table 2 depending on the superficial velocities of liquid and gas. At U_{SG} = 1.7 m/s, U_{SL} = 0.02 m/s, there were no pulsations. With an increase in superficial velocity of gas up to 3.42 m/s, the first periodic perturbations occurred near the channel walls. It is obvious that with an increase in superficial velocity of liquid, the frequency of lateral pulsations increases significantly; with an increase in superficial velocity of gas, the frequency of lateral pulsations increases slightly.

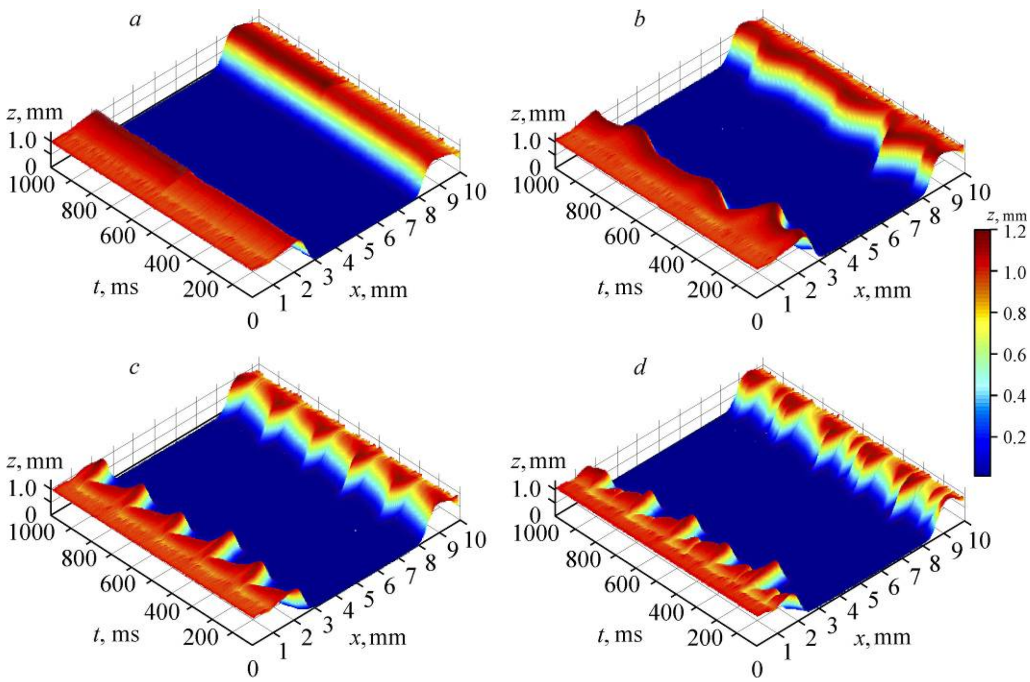

Fig. 5. Distribution of liquid in the channel at different superficial velocities of liquid and gas.
a — U_{SG} = 1.7 m/s, U_{SL} = 0.02 m/s, *b* — U_{SG} = 3.42 m/s, U_{SL} = 0.02 m/s, *c* — U_{SG} = 8.51 m/s, U_{SL} = 0.02 m/s, *d* — U_{SG} = 11.91 m/s, U_{SL} = 0.02 m/s.

Table 2

Characteristics frequencies for the stratified regime

U_{SL}, m/s	0.02	0.02	0.02	0.02	0.05	0.05
U_{SG}, m/s	1.7	3.42	8.51	11.91	8.51	11.91
ν, Hz	-	2	2.5	3	7	7.5

Table 3

Characteristics frequencies for the annular regime

U_{SL}, m/s	0.11	0.23	0.23	0.56	0.56
U_{SG}, m/s	8.51	3.42	11.91	3.42	8.51
ν, Hz	14	14	32	18.5	34

With increasing superficial velocity of liquid, the transition to the annular regime occurred. The reason for this transition was an increase in frequency of lateral pulsations, as a result, the liquid film appeared also on the upper channel wall. The transition from the stratified to the annular flow regime was determined using the Schlieren method. In the annular flow regime, the liquid moves along the channel walls as a film, in the central part gas with the droplets forms the flow core. The gas occupies much more volume than liquid. The spikes near the lateral walls of the channel occur also. The frequencies of spikes for different superficial velocities of liquid and gas are shown in Table 3. It is seen that with increasing superficial velocity of liquid and gas, the spike frequency increases significantly.

At high superficial liquid velocities, the churn regime was observed. This regime is characteristic to the vertical channels [2], where it occurs due to gravity, and it is also observed in the wide horizontal microchannels, where it is caused by the capillary forces. The broken bridges are characterized to this regime. The existence of the churn flow is discussed in detail in [5], it is caused by the development of instability of the jet regime and increasing frequency of pulsations of liquid moving along the lateral walls of the channel under the influence of the gas flow. The churn flow occupies a large area on the map (Fig. 2). The transition from the bubble (continuous liquid-filled bridges) to the churn flow was accompanied by formation of breaks in the bridges. Vice versa, the transition from the jet to the churn flow was accompanied by formation of continuous filled bridges, which were stable, and their number in the channel exceeded one. The churn flow is caused by development of jet flow instability and increasing frequency of interaction of liquid from the lateral walls of the channel. At transition to the annular regime, the continuous filled bridges of liquid disappear. The churn flow at $U_{SG} = 1.7$ m/s, $U_{SL} = 0.23$ m/s is shown in Fig. 6, where the broken and continuous liquid bridges can be seen. The formation frequency of continuous or broken bridges was 11.5 Hz.

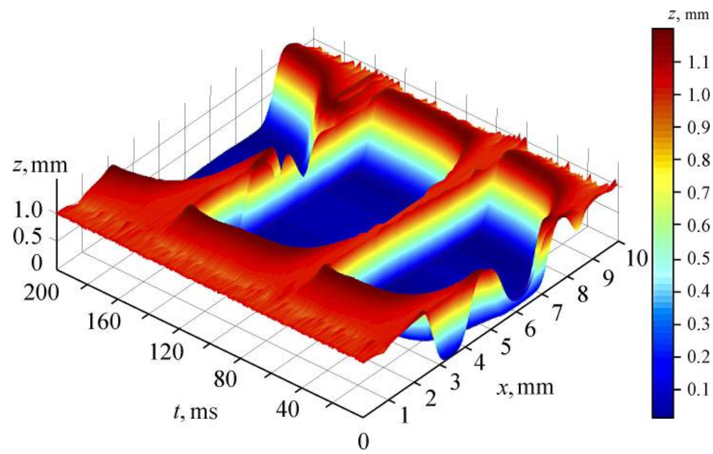

Fig. 6. Distribution of liquid in the channel at $U_{SG} = 1.7$ m/s, $U_{SL} = 0.23$ m/s.

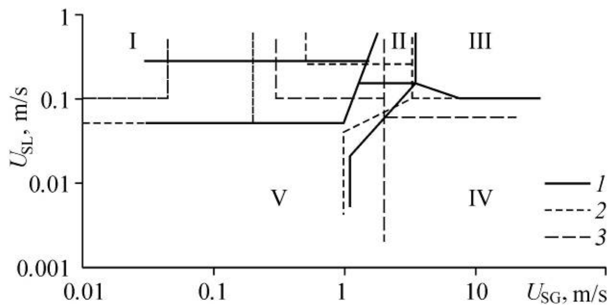

Fig. 7. The effect of channel width on the regime boundaries for the channels with different cross sections.

Flow regimes: I — bubble, II — churn, III — annular, IV — stratified, V — jet; channel cross sections: 1×10 mm (*1*), 1×19 mm (*2*), 1×29 mm (*3*).

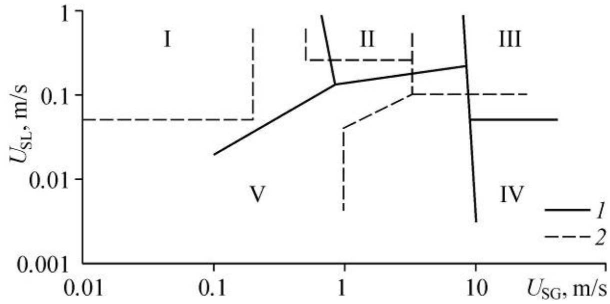

Fig. 8. The effect of channel height on regime boundaries for the channels with different cross sections.

Flow regimes: I — bubble, II — churn, III — annular, IV — stratified, V — jet; channel cross sections: 0.1×20 mm (*1*), 1×19 mm (*2*).

The results of processing of all experimental results are presented in Figs. 7 and 8. The comparative regime map is shown in Fig. 7 for the channels with cross sections of 1×10 mm, 1×19 mm, and 1×29 mm. It is obvious that with an increase in the channel width, the areas of the churn and bubble regimes increase (they shift towards the higher superficial velocities of liquid), contracting the region of the jet flow. The areas of the annular and stratified regimes change insignificantly.

The comparative regime map is shown in Fig. 8 for the channels with cross sections of 0.1×20 mm and 1×19 mm. According to Fig. 8, with an increase in the channel height, the area of the stratified regime increases, and the region of the churn flow decreases considerably. At an increase in the channel height, the area of the jet flow changes its position. The area of the annular regime does not change with an increase in the channel height. With increasing channel height, the intensity of droplet formation decreases.

Conclusion

Application of the fluorescence method allowed us to register and determine quantitatively the main characteristics (dependence of liquid distribution in the channel vs. time, repetition rates of bubble and liquid pulsations, pulsation amplitude) of the two-phase flow in the short rectangular horizontal channels 1 mm height. The basic regimes of the two-phase flow were distinguished: bubble, slug, stratified, churn, and annular. The boundaries between the regimes and frequencies of characteristic pulsations were determined. It is shown that a change in the height and width of the horizontal channel has a significant effect on the boundaries between the regimes.

References

1. **E.A. Chinnov and O.A. Kabov,** Two-phase flows in pipes and capillary channels, High Temperature, 2006, Vol. 44, No. 5, P. 773−791.
2. **E.A. Chinnov, F.V. Ron'shin, and O.A. Kabov,** Regimes of two-phase flow in micro- and minichannels (review), Thermophysics and Aeromechanics, 2015, Vol. 22, No. 3, P. 265−284.
3. **O.A. Kabov, E.A. Chinnov, and V.V. Cheverda,** Two-phase flow in short rectangular mini channel, Microgravity Science and Technology, 2007, Vol. 19, No. 3/4, P. 44−47.
4. **E.A. Chinnov, V.V. Guzanov, V.V. Cheverda, D.M. Markovich, and O.A. Kabov,** Regimes of two-phase flow in short rectangular channel, Microgravity Science and Technology, 2009. Vol. 21, No. 1, P. 199−205.
5. **E.A. Chinnov, F.V. Ron'shin, V.V. Guzanov, D.M. Markovich, and O.A. Kabov,** Two-phase flow in a horizontal rectangular microchannel, High Temperature, 2014, Vol. 52, No. 5, P. 681−687.
6. **V. Haverkamp, V. Hessel, H. Löwe,** Hydrodynamics and mixer-induced bubble formation in microbubble columns with single and multiple channels, Chem. Engng Technol., 2006, Vol. 29, No. 9, P. 1015−1026.
7. **E.V. Rebrov,** Two-phase flow regimes in microchannels, Theor. Found. Chem. Engng, 2010, Vol. 44, No. 4, P. 355−364.
8. **S.V. Alekseenko, V.A. Antipin, V.V. Guzanov, S.M. Kharlamov, and D.M. Markovich,** Three-dimensional solitary waves on falling liquid film at low Reynolds numbers, Phys. Fluids, 2005, Vol. 17, P. 121704-1−121704-4.