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Regimes of Two-Phase Flow in Short Rectangular Channel

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Abstract Experimental study of two-phase flow in the short rectangular horizontal channel with height 440 μm has been performed. Characteristics of liquid motion inside the channel have been registered and measured by the Laser Induced Fluorescence technique. New information has allowed determining more precisely the characteristics of churn regime and boundaries between different regimes of two-phase flow. It was shown that formation of some two-phase flow regimes and transitions between them are determined by instability of the flow in the lateral parts of the channel.

Keywords Regimes · Two-phase flow · Short rectangular channel

Introduction

Gas–liquid and vapor–liquid flows exist in a wide variety of applications in both normal gravity and reduced gravity environments. Recent years have seen considerable growth in the research of capillary hydrodynamics and heat transfer in microsystems, which is related to rapid progress in electronics and medicine and the development of miniature devices in various fields, in particular, aerospace, transport, and power engineering technologies. Thermal management systems on the satellites transfer heat from a source (electronic equipments) to a radiator panel. Different devices are used depending on the power to be transferred: heat pipes, loop heat pipes, capillary pumped loops, single-phase mechanical pumped loops. Future communication satellites will require heat removal capabilities larger than 10 kW.

The use of two-phase mechanical pumped loops offers a significant reduction in weight and size due to powerful heat transfer by latent heat. Quite significant number of experiments has been performed in the past on heat transfer in two-phase flows using channels with variable geometry. In the paper Kabov and Zaitsev (2009) the heat transfer to the thin liquid film which was moved by the action of gas flow was studied in the channel with height of 2 mm. Maximal value of heat flux achieved is equal to 250 W/cm^2. At the present time revolutionary development of micro and nano-size heat exchange systems takes place. That systems turn out to be more power efficient than the conventional systems with the channel size of 3–100 mm. But it is still unclear whether the separated flow regime with thin liquid film is stable in rectangular channels with the height less than 500 μm.

Two-phase flows in tubes with round cross sections have been studied in a broad range of diameters, including as small as 20 μm (Serizawa et al. 2002), while the flows in narrow vertical rectangular channels have

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been studied for gaps up to 300 μm (Xu et al. 1999). At the same time, horizontal rectangular channels with gaps below 2 mm are still insufficiently studied.

In cooling systems of microelectronics the length of two-phase flow in the channels should be less than 5–10 cm. In micro systems and Lab-on-Chip devices zone of two-phase flow could be several centimeters or millimeters. A review of investigations devoted to two-phase flow regimes in channels of various geometries has been published in Chinnov and Kabov (2006). Most of the published results refer to relatively long channels, where a two-phase flow length prior to entering the zone of investigation is two to three orders of magnitude greater than the channel height. Investigations of two-phase flow in short channels are limited.

Characteristics of two-phase flow of air–water mixture in a horizontal rectangular channel with the width of 65 mm, length of 170 mm and height (*h*) of 2 mm have been studied in Kabov et al. (2007b). The liquid film flows in the bottom part of the channel due to the shear stress on the gas–liquid interface. Liquid films with the smooth or wave surfaces and dry patches have been observed. Liquid film has two or three dimensional waves. The investigation of two-phase flow regimes in the short (length of 80 mm) rectangular horizontal channel in the wide range of gas and liquid flow rates has been made in Kabov et al. (2007a) and Chinnov and Kabov (2008) for the channel height equal to 1 and 0.3 mm.

Registration of two-phase flows has been performed by digital video and photo cameras using the Schliren technique based on light-ray reflection from gas–liquid boundary. New flow regimes (intermittent, jet and bubble-jet) which may be connected with new types of instability in two-phase flows inside the horizontal short rectangular channels with small height are detected. But the mechanism of instability was not found out because the technique which was used could not detect complex liquid motions inside the channel. The definition of boundaries between flow regimes has been made insufficiently accurate because information about liquid distribution inside the channel was absent.

The purpose of the present work is investigation of two-phase flow regimes and boundaries between them in the short (80 mm) horizontal rectangular channel with width of 30 mm and height of 440 μm using the new diagnostic technique. For experiments on board of the International Space Station, also, the short channels are preferable. The performed work is connected with the preparation of SAFIR experiment of the European Space Agency on the International Space Station.

Experimental Setup and Technique of Measurement

Design of the test section and concept of experiment are shown in Fig. 1. The main part of the test section is a stainless steel plate with a length of 135 mm and a width of 60 mm mounted on a textolite base. The plate was covered with an optical glass lid. Flat spacers aligned in the flow direction create a 30-mm-wide channel. The high of the channel is 0.44 mm. The experimental setup includes two computer-controlled circuits, which maintain the uninterrupted flows of liquid and gas phases. The liquid is driven by a high-precision peristaltic pump and is injected into the gas flow via flat nozzle with an input gap height of 0.3 mm. The gas is supplied from a high-pressure vessel using a mass flow control and measurements device and is injected into the channel 30 mm before the liquid nozzle. For more details see paper Kabov et al. (2007a).

Laser induced fluorescence (LIF) technique based on the reemission of light by phosphor with spectral distribution which differs from the excited one has been used to investigate interaction between liquid and gas inside the channel. Basis of LIF technique and an example of its application for the measurements of the instant liquid film thickness distribution are given in Alekseenko et al. (2005). In the present study high-speed modification of LIF technique has been applied for study of the fast process of joint motion of gas and liquid in the mini-channel. Distilled water with dissolved in it in a small amount phosphor Rhodamine 6G has been used as a working liquid and Nitrogen as a working gas. The schematic of the technique is shown

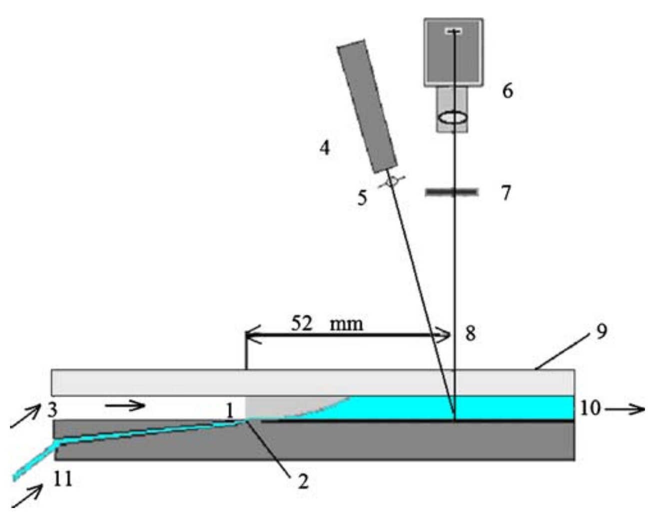


Fig. 1 Scheme of the test section. *1*—channel, *2*—nozzle for liquid, *3*—gas inlet, *4*—laser, *5*—cylindrical lens, *6*—digital camera, *7*—optical filter, *8*—field of view, *9*—glass cover, *10*—outlet of gas–liquid mixture, *11*—liquid inlet

in Fig. 1. For creation of supporting illumination the "Aries" series laser (4) with wavelength 532 nm and power of 50 mW is used. With the help of cylindrical lens (5) the laser beam is unwrapped into the line which is placed across the gas–liquid flow 52 mm away from the liquid entrance. The reemitted fluorescent light is registered by the high-speed (up to 2.1 kHz) digital camera VS-Ld-751 (6) with linear sensor SONY ILX-751A. Camera is equipped by the steep low-pass filter (7) which lets reemitted by phosphor light pass and cuts off laser emission. Local thickness of the liquid inside the channel is obtained using the local brightness of the image. Calibration of the measurement system has been performed under experimental conditions using the local intensity of the plane-parallel layer of the working liquid in the completely filled channel.

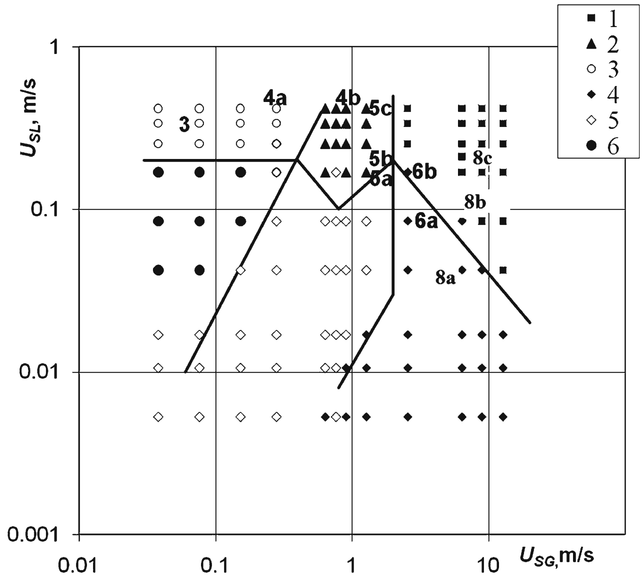


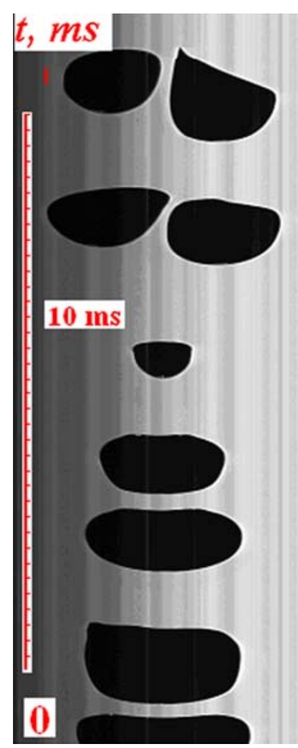
Fig. 2 Two-phase flow regimes map for horizontal channel (W × L × H) 30 × 80 × 0.44 mm^3. Experimental dates for flow regimes: *1*—annular, *2*—churn, *3*—bubbles, *4*—stratified, *5*—jet, *6*—slug

Results and Discussions

Superficial gas U_{SG} and liquid U_{SL} velocities defined as volumetric gas and liquid flow rates divided by the cross-section area of the channel are used traditionally as the basic experimental parameters. Using LIF technique the time-dependent cross distribution of the liquid inside the channel has been measured. Using these data, video and the Schliren visualization data the basic regimes of two-phase flow have been determined and the flow patterns map has been constructed (Fig. 2). The main flow regimes consist of: (1) annular flow (liquid film exists on top and bottom surfaces of the channel); (2) churn regime (the gas flows in a more chaotic manner through the liquid which is mainly displaced to the lateral channel walls); (3) bubbles flow regime (the size of the moving bubbles is much smaller than the width of the channel); (4) stratified regime (gas occupies the top of the channel); (5) jet regime (there is at least one liquid bridge in the jet and gas occupies a part of the channel width); (6) slug regime (the size of the moving bubbles is almost like the size of the channel).

Typical time-dependent images of intensity of phosphor fluorescent luminescence which is proportional to the thickness of the liquid are shown in Figs. 3, 4, 5, 6 and 8 (top view). Numbers in the two-phase flow regimes map (Fig. 2) coincide with the numbers of pictures with intensity of fluorescent luminescence. Time scale is also shown in Fig. 3. Image width is equal to the channel width. The bubbles flow regime is shown in Fig. 3. In the slug regime the bubble width is close to the channel width (see also bubble flow regime in Fig. 4a). Transition from jet regime to bubbles flow regime or to slug flow occurs when superficial liquid velocities are high and this transition is characterized by disintegration of single jet on the separated bubbles. As it can be seen in Fig. 3 in the bubbles flow regime the bubbles frequency is equal to 10–25 Hz and the passage time of the liquid bridge can be equal to 10 ms (minimal

Fig. 3 Image of fluorescent luminescence for U_{SG} = 0.076 m/s and U_{SL} = 0.25 m/s



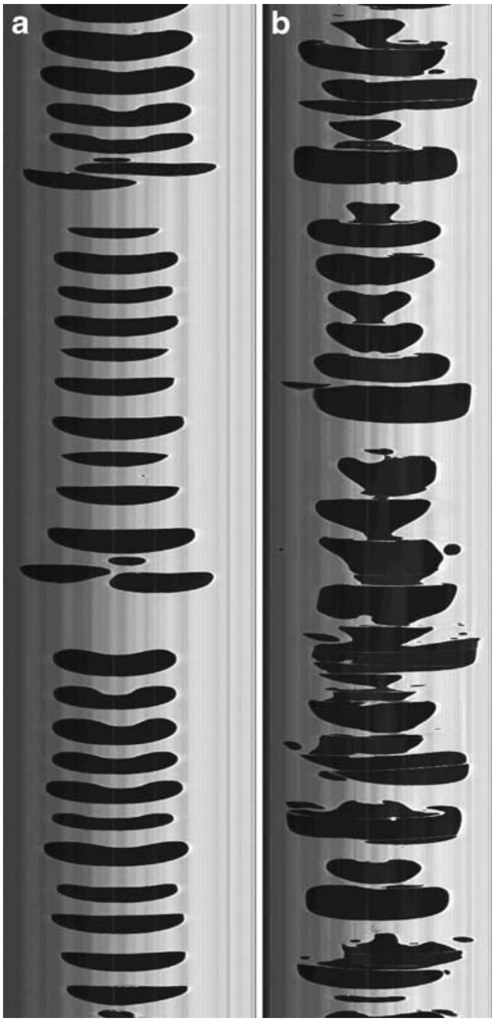


Fig. 4 Distribution of liquid in the channel as a function of time. **a**—Bubble regime $U_{SG} = 0.28$ m/s, $U_{SL} = 0.42$ m/s, **b**—churn regime $U_{SG} = 0.76$ m/s, $U_{SL} = 0.42$ m/s

scale mark on the line). Jet pulsation frequency is less then 10 Hz as a rule.

Stationary jet flow regime is observed when the superficial gas and liquid velocities are small. The same result has been obtained also in the work Kabov et al. (2007a). Increase of the superficial liquid velocity leads to the loss of stability of two-phase flow. Growing of pulsations of the gas jet similar to those shown in Kabov et al. (2007a) and Chinnov and Kabov (2008) has been observed. On the initial stage of the perturbation development after the long enough waiting time (about 5–10 s) the collapse of the jet flow is occurred (the liquid from the lateral parts is joined). After that the jet abruptly, with period of about 0.4 s, is widened and narrowed several times. Then the full decay of oscillations is going on. In the case of jet flow in the channel no more than one liquid bridge can be existed simultaneously. The transition to the slug regime is occurred with appearance of the second bridge.

With increasing of the superficial velocity of the liquid phase, the jet regime becomes less and less stable. At higher superficial velocities of liquid and medium superficial velocities of gas, the flow loses stability, and the gas stream begins to expand and contract at a rather high frequency (up to 100 Hz), Fig. 5a. The instability is manifested by the decay of a single stream and/or the interaction of several gas streams, which results in the mixing of gas and liquid. This corresponds to the onset of a churn flow regime (see Figs. 4b, 5b, c). In horizontal channels with height more than 1 mm this regime was not observed (Kabov et al. 2007a). Contrary this was the main flow regime in a 0.3-mm-thick horizontal micro-channel (Chinnov and Kabov 2008) and in a vertical rectangular channel (Xu et al. 1999). The clear definition of the churn flow regime and of the boundaries of this flow regime is absent in the literature. Data obtained by LIF technique allows

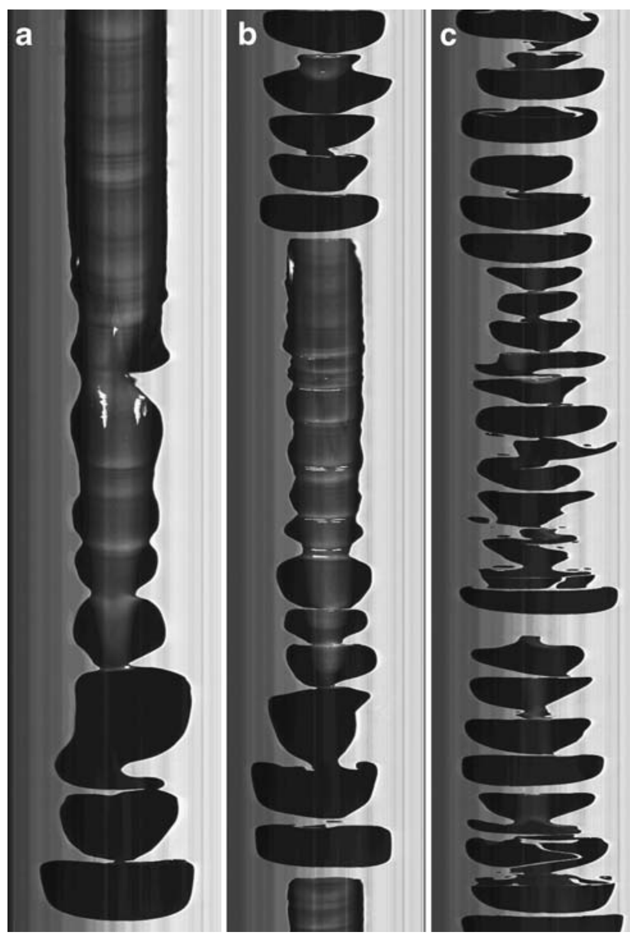


Fig. 5 Distribution of liquid in the channel as a function of time. Churn regime: **a**—$U_{SG} = 1.27$ m/s, $U_{SL} = 0.17$ m/s, **b**—$U_{SG} = 1.27$ m/s, $U_{SL} = 0.25$ m/s, **c**—$U_{SG} = 1.27$ m/s, $U_{SL} = 0.42$ m/s

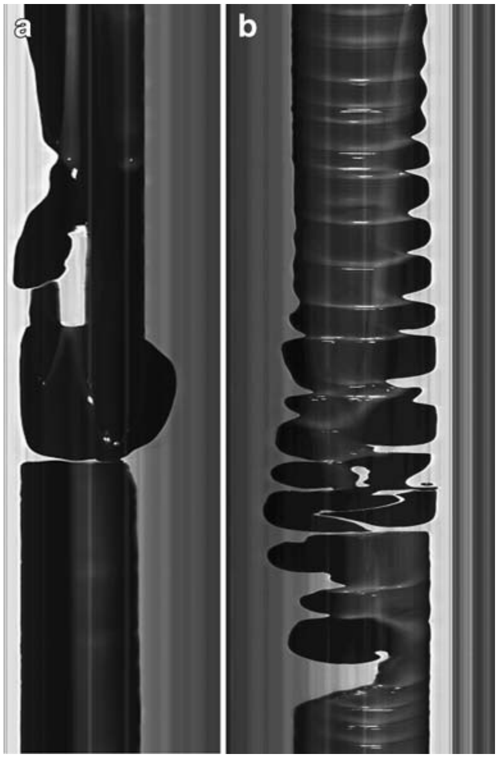


Fig. 6 Distribution of liquid in the channel as a function of time. Transition to annular regime: **a**—stratified regime U_{SG} = 2.55 m/s, U_{SL} = 0.082 m/s, **b**—annular regime U_{SG} = 2.55 m/s, U_{SL} = 0.17 m/s

defining the churn regime as alternation of continuous and disrupting liquid bridges. Transition from the bubble flow regime (continuous liquid bridges, Fig. 4a) to the churn flow regime is accompanied by appearance of the liquid bridges rupture. In this case churn flow is formed by breakdown of the gas bubbles in the same manner as in Chinnov and Kabov (2008).

Quite the reverse transition from the jet flow regime to the churn flow regime is accompanied by appearance of some liquid bridges (continuous or discontinuous). Number of liquid bridges in the channel should exceed one. On the boundary of the churn regime, Fig. 5, number of continuous liquid bridges is equal to one to two per second. With increasing of superficial gas velocity number of continuous liquid bridges increases up to two to four per second and when the superficial gas velocity is maximal number of such bridges achieves six to eight per second. In the last case the churn flow regime formation is caused by the development of the instability of the jet flow regime, i.e. increasing of the frequency of interaction of the liquid waves coming from the lateral parts of the channel. With transition to the annular flow regime continuous liquid bridges disappear (compare Figs. 5b and 6b).

Some features of transition from the stratified flow regime to the annular flow regime in the area close to the churn and jet flow regimes are shown in Fig. 6. Even in the stratified flow regime some rare disturbances could lead to the separation of the portion of liquid and to the movement of this portion to the central part of the channel, Fig. 6a. But the stable liquid bridges are not formed. As it could be seen from the video registration of the process the liquid on the top wall of the channel is absent. This fact allows getting the distribution of the liquid film thickness on the bottom part of the channel. The liquid thickness distribution H in the channel reconstructed using the phosphor illumination intensity is shown in Fig. 7a. One can see from the instantaneous distribution of fluid in the channel (Fig. 7b) that the liquid can fill the whole channel height also locally in the center part of the channel. In the area of the gas–liquid boundary the reconstructed liquid thickness can be slightly higher than the channel height

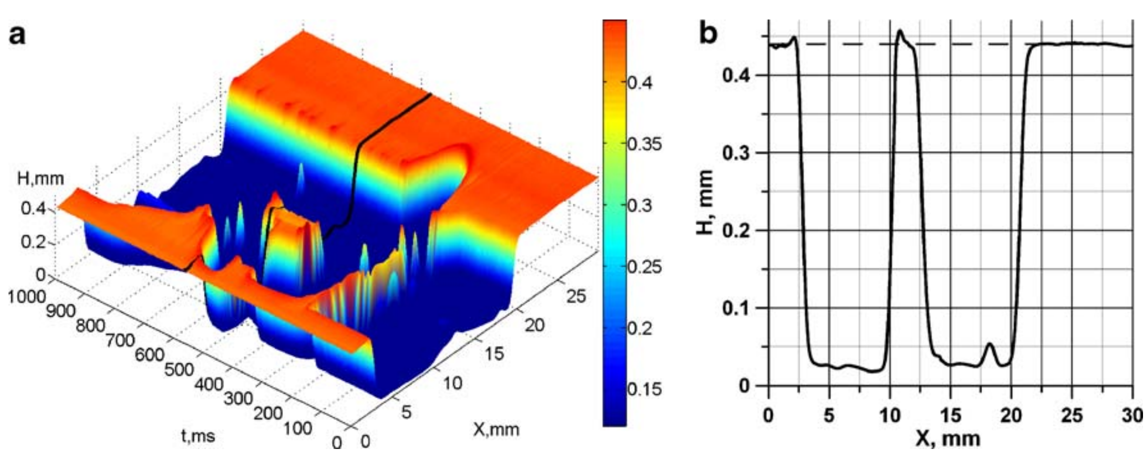


Fig. 7 Transition from stratified film flow regime to annular regime U_{SG} = 2.55 m/s, U_{SL} = 0.082 m/s. **a**—variation of the thickness of the liquid over time in the cross-section of the channel. **b**—instantaneous distribution of fluid in the channel at time t = 560 ms

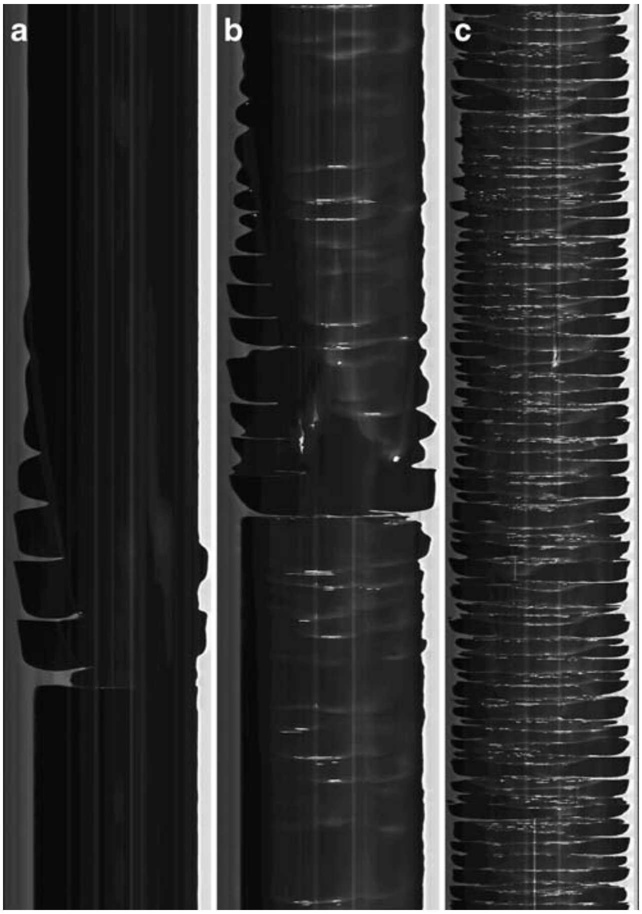


Fig. 8 Distribution of liquid in the channel as a function of time. Transition to annular regime: **a**—stratified regime $U_{SG} = 6.4$ m/s, $U_{SL} = 0.042$ m/s, **b**—annular regime $U_{SG} = 6.4$ m/s, $U_{SL} =$ 0,084 m/s, **c**—annular regime $U_{SG} = 8.9$ m/s, $U_{SL} = 0.17$ m/s

(dashed line in the Fig. 7b) because of some optical distortions. The possible error of the liquid thickness definition is not more than 40 μm that is less than 10% of the channel height. The width of the gas motion area is slightly bigger in the stratified flow regime than the half of the channel width. The boundary between the jet and the stratified flow regimes corresponds to the situation when the areas occupied by the gas and the liquid across the width of the channel are equal.

In the annular flow regime the frequency of the waves (liquid throwing from the lateral parts of the channel to the center) is increased (Fig. 6b). Also the separation of the part of the liquid from the lateral streams may occur. But in this case liquid film is always presented on the upper wall of the channel. In the region of the high superficial gas velocities the transition from the stratified to the annular flow regimes is occurred with increasing of the superficial liquid velocity. In the case of stratified flow regime, Fig. 8a, a part of the liquid is moved on the bottom wall of the channel in the form of film entrained by the gas flow. Gas occupies significantly more than the half of the channel width. In the stratified flow regime the first disturbances appear after the long enough waiting time.

Figure 9a shows variation of the thickness of the liquid over time in the cross-section of the channel which is reconstructed using the image shown in Fig. 8a. Before appearance of the disturbance the growth of liquid layer on the one sidewall is occurred. The mean time of disturbance development is equal to 0.7 s, waiting time is equal to 5.3 s and period between damped liquid peaks is equal to 91 ms. On the opposite channel sidewall some deformations on the gas-liquid interface

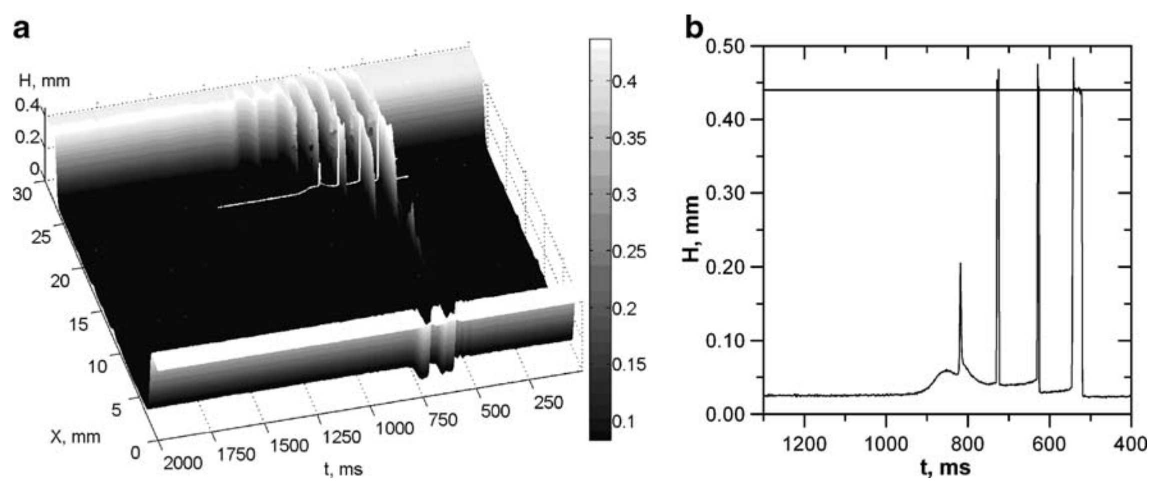


Fig. 9 Variation of the thickness of the liquid over time, $U_{SL} = 6.4$ m/s, $U_{SG} = 0.042$ m/s: **a**—in the cross-section of the channel, **b**—in the section X = 23.6 mm

also have been detected in this moment. The maximal disturbance amplitude is equal to 11.7 mm and practically reaches the middle of the channel. Figure 9b shows the distribution of the liquid over time in the channel along the line shown in Fig. 9a. In the section placed 6.4 mm away from the left sidewall of the channel four disturbances are registered and the last one is not filled the whole channel height. With increasing of the superficial liquid velocity, the stratified flow regime transforms into the annular flow regime because of increasing of the wave frequency and liquid emission from the side parts of the channel to the upper wall of the channel, Fig. 8b. The annular flow regime in this measurement point occurs when frequency of the liquid emission is equal to 20–30 Hz. With the further increase of the superficial gas and liquid velocities the pulsation frequency in the annular flow regime increases up to 100 Hz, Fig. 8c.

Conclusions

A study of two-phase flow regimes in short (length 80 mm) narrow rectangular horizontal channel (width 30 mm and height 440 μm) has been performed. Laser Induced Fluorescence technique has been used for registration of time-dependent liquid flow inside the channel. The new information allows to define characteristics of the churn flow regime and to specify more precisely the boundaries between the various regimes of two-phase flows. It was shown that the instability of liquid flow near the sidewalls influents essentially on the transition between several regimes of two-phase flow in the short rectangular channel.

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