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Two-Phase Flow in Short Rectangular Mini-Channel

Recent developments in electronics and medicine generate an interest in capillary hydrodynamics and heat transfer in Microsystems. Microsystems also are very important for aerospace industry. In the present paper we focus upon experiments in the short channel oriented horizontally with the width 40 mm, height 1 mm and length 80 mm. New flow regimes are observed and the two-phase flow pattern map is created. The obtained results are compared with the data available in the literature.

Introduction

The present work is connected scientifically with the basic research segments of the MAP "CBC" project (AO-2004-111, Convective Boiling and Condensation: local analysis and modeling of dynamics and transfers) of the European Space Agency and is a step in the preparation of the *SAFIR* (Single fin condensation: Film local measurements) experiment that has been selected by the European Space Agency to be designed and developed for a flight onboard the International Space Station.

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Gravity field plays a fundamental role in two-phase flows and surface tension effects can be isolated and better investigated in a low gravity environment. Some experimental procedures and measurement techniques have to be tested in on-ground conditions before design of an experimental setup for the International Space Station.

One of the recent reviews of publications on two-phase flow pattern maps for tubes and rectangular channels had been made in [1]. 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 investigated in [2]. Superficial gas velocity ($U_{SG}=Q_G/S$, Q_G – gas flow rate, m^3/s, *S*- area of cross section, m^2) changed from 0.8×10^{-2} to 1.5×10^{1} m/s and superficial liquid velocity ($U_{SL}=Q_L/S$, Q_L-liquid flow rate, m^3/s) changed from 4×10^{-4} to 2.4×10^{-2} m/s. The liquid pumped into the liquid nozzle of 200 μm height. The liquid film moved in the bottom part of the channel by the shear stress of gas. Liquid films with the smooth or wave surfaces and dry patches were observed. Liquid film had two or three dimensional waves. In [3] authors had investigated adiabatic two-phase flow in horizontal rectangular channel with cross section of 19.05×3.18 mm^2 and length of 1140 mm with mass velocity of water-air mixture varied from 50 to 2000 kg/m^{2}s.

There are no published experimental data for horizontal rectangular channels with h<2 mm. Long channels have been investigated systematically. Usual length of flow before the observation area was usually about 100 - 1000 equivalent diameters. In cooling systems of microelectronics the length should be less than 100 mm. In micro systems and Lab-on-Chip devices zone of two-phase flow could be several centimeters or millimeters. For experiments on board of space station, also, the short channels are preferable. The purpose of this work is investigation of two-phase flow regimes in the short (length of 80 mm) rectangular channel in the wide range of gas (nitrogen or air) and liquid (water) flow rates.

Experimental setup

Design of the test section and concept of experiment are shown in Figs 1 and 2. The basic element of the test section is a flat plate made of stainless steel having dimensions of 135×60×10 mm^3 in length, width and depth, respectively. This plate is placed on the support made of textolite. The plate is covered with a transparent, glass cover so that a channel of variable height can be created. Dimensions of the channel in the present experiment (height×width×length) are 1×40×80 mm^3. Distance from the gas nozzle to the liquid nozzle is 40 mm, which provides steady flow of gas at the moment it reaches the liquid. Controlled by peristaltic pump, distilled water is supplied from liquid container into buffer chamber and the nozzle of variable height. Dry nitrogen gas is supplied from a balloon. Gas flow rate is regulated through a computer by flow control and measurement gauge. The gas is evacuated to the atmosphere. Flow visualization by Schlieren technique [4] and video record is used. The bottom of the channel is covered by the black coating absorbing light. The heating element is not used in experiments.

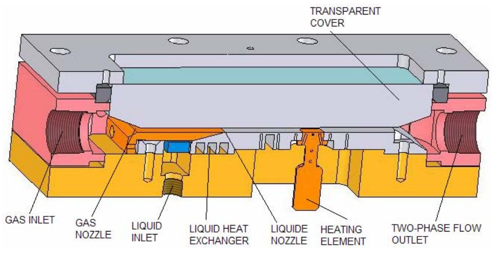


Fig. 1: Design of the test section.

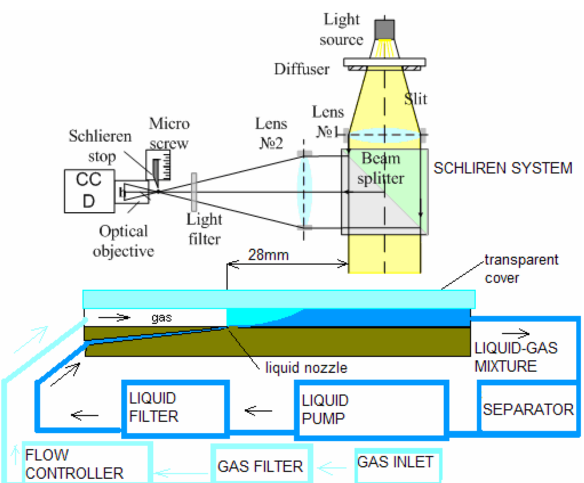


Fig. 2: Experimental set up and Schlieren technique.

Results

The flow pattern map is shown in Fig. 3. The main flow regimes consist of: 1) *bubbles* flow regime (the size of the moving bubbles is much smaller than the width of the channel); 2) *slug* regime (the size of the moving bubbles is almost like the size of the channel); 3) *intermittent jet* regime (there is at least one liquid bridge in the gas jet); 4) *jet* (gas jet occupies a part of the channel width); 5) *stratified* regime (gas flow occupies the top of the channel); 6) *annular* flow (liquid film exists on top and bottom surfaces of the channel); 7) *annular-droplet* or disperse regime (liquid film disappears from the top wall and the part of the bottom wall, there are liquid jets and drops).

In *bubbles* regime liquid separates each bubble from top and bottom walls of the channel**.** Figure 4a shows structure of the liquid film on the top wall. Spots (black points) and waves are visible. The former most probably are the dry patches. With increasing superficial liquid velocity the speed of bubbles increases and dry patches practically disappear. The wetting effect by changing transparent cover (plexiglass instead of the optical glass) results in some specific bubbles regimes. Bubbles move in array and sometimes may adhere to the wall in the places where dry patches exist. As the result bubbles may stop or generate stable gas jets. Gas jet and intermittent jet regimes may be present in the area of bubbles regime (Fig. 3).

In the *slug* regime there are waves and dry patches in the liquid film moving between the bubble and the upper glass wall similarly to the bubbles regime (Fig. 4b). Data rectangular channel with cross section of 19.05×3.18 mm^2 are presented also in Fig. 3. Slug regime is one of the most important regimes for two-phase flow. This regime degenerates in the short channel with a small height. In this regime bubbles have cross size almost like the channel width. And bubble length also may be comparable with length of the channel. So, one slug only may move in such a short channel.When number of liquid bridges separating air areas decreases to one, slug regime transforms to *intermittent jet* regime.

The *jet* regime is one of the most important regimes in short channels and may consist of several sub regimes. *Stationary jet* regime is typical for relatively small gas and liquid superficial velocities. Increasing of gas and liquid superficial velocities leads to *pulsating jet* regime. Gas jet is expanded and shrunken periodically, Fig.5. With further increasing of the superficial liquid velocity the jet regime becomes unstable, Fig. 6. Liquid flow perturbations arise on the lateral side of the channel. And as a result large volumes of liquid penetrate to a central part of the channel. When the liquid superficial velocity is very high, the flow regime becomes stable. Gas swirl appears in the center of the channel, Fig. 7. Small air jets may separate from the swirl. This flow may be characterized as a transition to *churn regime*.

A wavy liquid film flow takes place on the bottom wall of the channel in *stratified* regime. The upper wall of the channel is dry. It should be noted that unlike the results of [2] smooth stratified regime is not observed in this narrow channel. Liquid near lateral walls of the channel fills all height of the channel. If liquid near a lateral wall is unstable transition to *annular* regime may be observed. Liquid from the lateral walls moves on the upper wall of the channel. Surface area wetted by the water on the upper wall of the channel increases when the gas superficial velocity increases, Fig. 8.

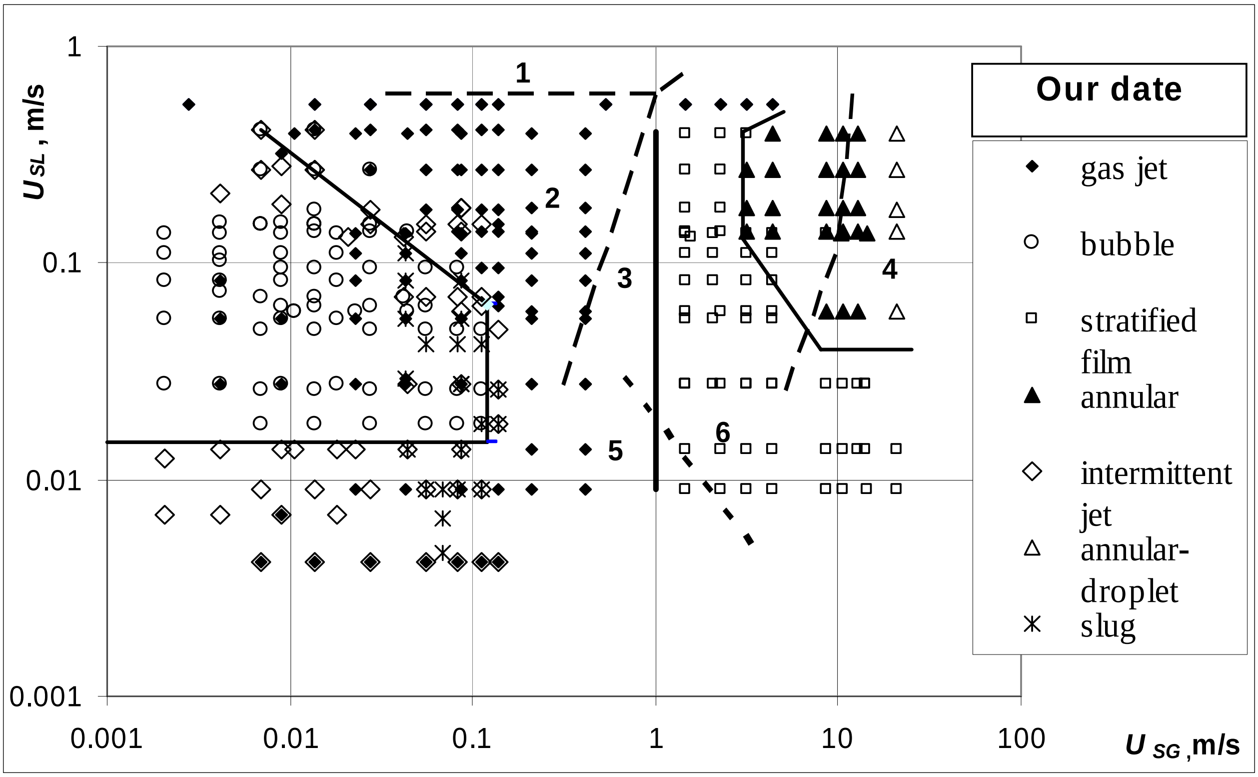
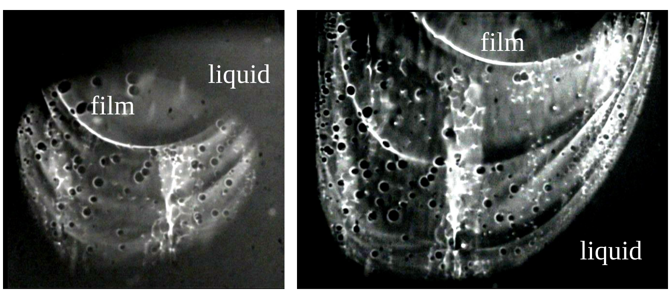


Fig. 3: Two-phase flow pattern map in rectangular channel, width of 40 mm, length of 80 mm and height of 1 mm. Comparison our experimental data (solid lines) with other data for horizontal rectangular channels. Channel 3.18 x19.05 mm^2 (dashed lines) [3] regimes: 1 – small bubbles, 2 – large bubbles or plug, 3 – slug, 4 – annular. Channel 2x65 mm^2 (dotted line) [2] regimes: 5 –smooth separated, 6 –stratified wavy film.



a – bubbles regime U_{SL}=0.06 m/s, U_{SG}=0.023 m/s.

b – slug regime U_{SL}=0.11 m/s, U_{SG}=0.043 m/s.

Fig. 4: Schlieren photos.

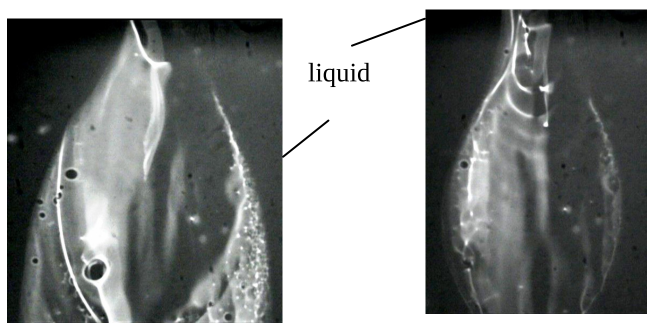


Fig. 5: Pulsing jet U_{SL}=0.14 m/s, U_{SG}=0.21 m/s.

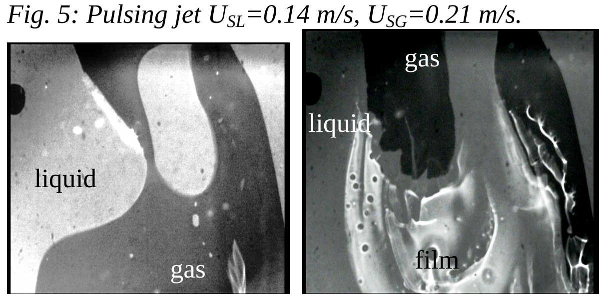


Fig. 6: Unstable jet regime U_{SL}=0.11 m/s, U_{SG}=0.42 m/s.

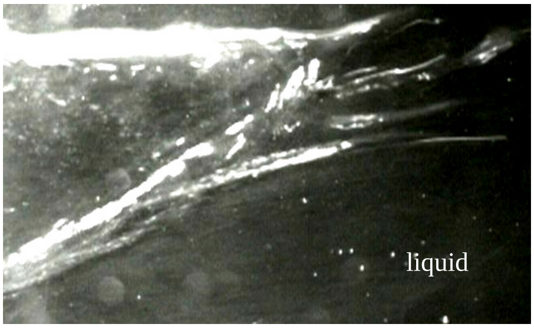
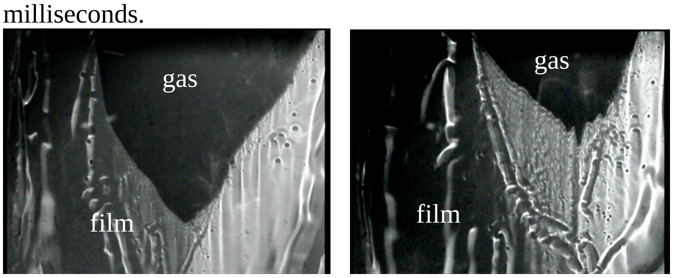
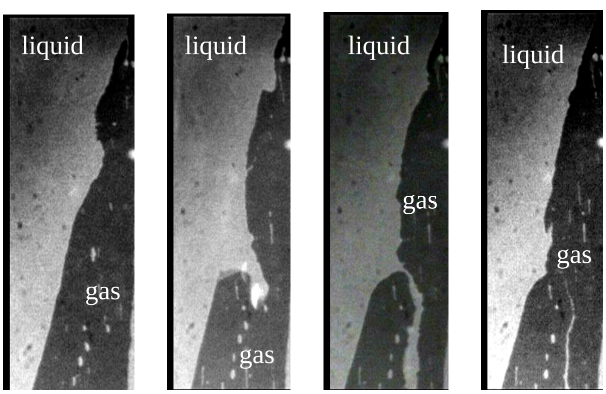


Fig. 7: Gas swirl U_{SL}=0.54 m/s, U_{SG}=0.14 m/s.

In *annular-droplet* regime liquid drops arise. The mechanism of gas and liquid interaction is changed. A movement of a large volume of liquid to the upper wall of the channel is terminated. The upper wall of the channel is almost dry. Liquid jets and drops are ejected to the dry central area of the channel from the liquid flows along the lateral walls, Fig. 9. In the picture liquid film on the upper wall is visible on the left part of the photograph. Finger-shaped jets are ejected periodically from the liquid film. Large number of liquid drops arises in the channel. The numbers in Fig. 9 show time in milliseconds.



U_{SL}=0.06m/s, U_{SG}=10.6m/s. U_{SL}=0.06 m/s, U_{SG}=12.7 m/s.
Fig. 8: Annular regime.



0 120 240 360 ms
Fig. 9: Annular-droplet regime U_{SL}=0.14 m/s, U_{SG}=20.8 m/s.

Discussion

The two-phase flow pattern map developed for the small rectangular horizontal channel with gap of 1 mm is compared with maps available in the literature for a large size of the channel, Fig. 3. Experimental data of [3] for the channel with cross section of 3.18×19.05 mm^2 (dashed lines) are presented for the superficial liquid velocity more than 0.025 m/s. For the channel with cross section of 2×65 mm^2 (dotted line, [2]) experimental data are available for the superficial liquid velocity less than 0.025 m/s. As a result stratified smooth and stratified wavy film flow regimes are not observed for the channel with gap of 3.18 mm.

Comparison shows that there is a satisfactory agreement for annular regime. A good agreement with data [2] for stratified wavy film flow regime takes place also. Gas jet regime arises according to our data and slug regime strongly transforms in comparison with [3]. Stratified smooth and small bubbles regimes disappear in the channel with cross section of 1×40 mm^2 according to our observations. This result is similar one obtained in [5] for horizontal tubes with a small diameter where stratified smooth regime disappears at D<2 mm.

Conclusions

A study of two-phase flow regimes in narrow rectangular horizontal channel is performed. The obtained data are compared with the previous experimental data [2, 3, 5]. Flow regimes in the present horizontal rectangular channel having gap of 1 mm are quite different from the classical two-phase flow regimes for horizontal channels with $h \geq 2$ mm.

The new gas jet regime is found. This regime, most probably, arises in the result of channel length decreasing and includes several sub-regimes: stable gas jet, intermittent jet, pulsing jet, unstable jet, gas swirl.

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