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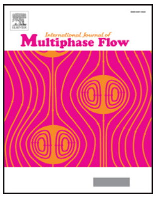

Two-phase flow patterns in short horizontal rectangular microchannels

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ABSTRACT

The two-phase flow in a short horizontal channel of a rectangular cross-section with the height of 100–500 μm and width of 9–40 mm was studied experimentally. The use of the Schliren and fluorescent methods made it possible to reveal the flow of liquid in the channel and to determine its characteristics quantitatively. The features of the churn, jet and drop flow patterns were studied in details. Two particular regimes that can be distinguished represent formation of immobile drops on the channel walls because of the liquid film or liquid bridges breakage and appearance of mobile drops due to the two-phase flow instabilities. It is found out that formation of various two-phase flow patterns and transitions between them are determined by instabilities of the liquid–gas flow in the side parts of a channel. Frontal instability has been observed during the liquid–gas interaction in the region of liquid output from the nozzle. It is shown that a change in the height and width of the horizontal channels has a substantial effect on the boundaries between the flow regimes. One of the results is that the region of the churn regime increases significantly with decreasing thickness of the channel.

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Introduction

Gas–liquid and vapor–liquid flows exist in various applications under the conditions of normal and reduced gravity. The tendency to minimization of devices in various fields of technology, including aerospace industry, electronics, transport, power engineering, and medicine accounts for a growing interest in hydrodynamics of gas–liquid flows and heat transfer in microsystems and microchannels.

At present, there is a revolutionary development in heat-exchanging systems with micro- and nanosizes, which have proved to be much more energy efficient than macrosystems with the channel sizes of 3–100 mm. With a decrease in the thicknesses of flat channels, the surface to volume ratio of the channel increases inversely proportional to its minimal transverse size (height). This causes high intensity of heat transfer in the microsystems. Such systems are receiving increasingly wider application in microelectronics, aerospace industry, transport, and power engineering.

The use of two-phase mechanical pumped loops offers a significant reduction in weight and size due to powerful heat transfer by latent heat. Many experiments on heat transfer in two-phase flows have been performed in the past using the channels with various geometry.

The number of publications concerning this theme is growing continuously. The reviews of investigations devoted to the two-phase flow regimes in channels of various geometries have been published: Bretherton (1961); Chinnov and Kabov (2006); Saisorn and Wongwises (2008); Shao et al. (2009); Rebrov (2010); Awad and Muzychka (2014); and Narcy and Colin (2015), etc.

The publications of Bretherton (1961) and Haverkamp et al. (2006) present the detailed review of articles devoted mainly to the flow in the circular micro-tubes. They consider the influence of channel dimensions, fluid properties, wettability, etc. on the two-phase flow regimes. The effect of geometry of different mixers was analyzed by Rebrov (2010). The works of Haverkamp et al. (2006) and Rebrov (2010) show that the regimes of gas–liquid flow in the microchannels depend significantly on the conditions of phase input to the channel. By Haverkamp et al. (2006), they used several initial regions. Gas moved along the microchannel, and liquid was supplied from its two sides. The angle of liquid supply was varied. Under different conditions of liquid supply, the boundaries of gas–liquid flow in the regime map are shifted. Although the qualitative character of the regime map is kept, the positions of boundaries of the two-phase flows are strongly influenced by the features of mixer and initial region geometry. All phase inputs can be divided into two fundamentally different groups: (1) the mixing input of different types, ensuring natural development of flow regimes (e.g., T –type mixer in the works

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Table 1
Two-phase flows in rectangular microchannels. *V* stands for a vertical channel; *H* for a horizontal channel; d_h - hydraulic diameter.

Reference	Type of two-phase mixture	Dimensions of channel cross-section	Orientation
Beinusov et al. (1978)	Air–water	0.2×124 mm^2, 0.25×124 mm^2, 0.5×124 mm^2	V
Lowry and Kawaji (1988)	Air–water	80×0.5 mm^2	V
Bonjour and Lallemand (1998)	R-113	0.5×2 mm^2	V
Xu et al. (1999)	Air–water	0.3×12 mm^2 and 0.6×12 mm^2	V
Coleman and Garimella (1999)	Air–water	circular and rectangular, $d_h = 1.3$, 1.75, 2.6, 5.5 mm	H
Bi and Zhao (2001)	Air–water	0.75×1.5 mm^2	H
Hibiki and Mishima (2001)	Air–water	0.3×17 mm^2	V
Kawaji and Chung (2003)	N_2-water	0.096×0.096 mm^2	H
Cubaud and Ho (2004)	Air-water	square, $d_h = 200$ and 525 μm	H
Waelchli and von Rohr (2006)	N_2-water, ethanol, glycerol (10%) and glycerol (20%)	rectangular, $d_h = 187.5$–218 μm	H
Cubaud et al. (2006)	Air-water, water with surfactant	square, $d_h = 525$ μm	H
Haverkamp et al. (2006)	Air-water, isopropanol	rectangular, stainless steel ($d_h = 150$ μm and 294.5 μm); borosilicate glass ($d_h = 66.67$ μm)	H
Xiong and Chung (2007)	N_2-water	0.213×0.206 mm^2, 0.419×0.406 mm^2 and 0.630×0.615 mm^2	H
Yu et al. (2007)	Air- silicone oil	0.125×0.125 mm^2 and 0.125×0.25 mm^2	H
Kabov et al. (2007a)	N_2-water	1×40 mm^2	H
Yue et al. (2008)	CO_2-water	rectangular, $d_h = 200$ μm, 400 μm and 667 μm	H
Pohorecki et al. (2008)	N_2-water, ethanol	Rectangular and square; $d_h = 843$ μm	H
Chinnov and Kabov (2008)	N_2-water	0.3×40 mm^2	H
Chinnov et al. (2009)	N_2-water	0.44×30 mm^2	H
Santos and Kawaji (2010)	Air-water	0.118×0.119 mm^2,	H
Choi et al. (2011)	N_2-water	0.5×0.47 mm^2, 0.6×0.41 mm^2, 0.5×0.24 mm^2	H
Kozulin and Kuznetsov (2011)	N_2-water	0.67×2 mm^2	V
Kuznetsov et al. (2012)	N_2-water	0.217×0.37 mm^2	H
Kuznetsov et al. (2013)	N_2-water	0.72×1.5 mm^2	V, H
Houshmand et al. (2014)	N_2-water	1.5×0.225 mm^2	H
Kim et al. (2014)	Ar-water	0.2×0.2 mm^2	H
Patel and Garimella (2014)	Air-water	0.5×0.5 mm^2	H
Holloway et al. (2014)	FC-72	0.184×20 mm^2	H
Chinnov et al. (2014)	N_2-water	0.2×34 mm^2	H
Reeser et al. (2014)	Air-water, HFE-7200	0.153×0.305 mm^2	H

of Haverkamp et al., 2006 and Rebrov, 2010); (2) the structured input, which ensured the smooth supply of liquid, without any stages and edges. (e.g., the smooth mixer in the works of Haverkamp et al., 2006 and Rebrov, 2010). For the first case, there are many publications. In the present work the second case was investigated, whose importance increases due to the rapid development of mini-systems with relatively short channels. For such systems in some cases, the initially set regime will be kept along the whole flow (see for example Kabov et al., 2007b; Kabov et al. 2011).

The boundaries of two-phase flow regimes are affected significantly by their geometry. The rectangular channels are more preferable for practical applications in the systems of microelectronic and other equipment cooling. These channels can ensure the maximal contact surface of heat removal. The main characteristics of the experiments on the study of two-phase flow in the rectangular channels with the transverse size less than 1 mm are presented in Table 1.

Most of the published results refer to relatively long channels, where the two-phase flow length before entering the zone of investigation is two to three orders of magnitude greater than the channel height. Investigations of the two-phase flow in the short channels are limited.

One of the ways to solve the problems of microelectronic cooling can be the use of short microchannels with a two-phase heat-transfer agent, which ensures intense evaporation in the zone of active heat release with high velocities of subcooling gas-liquid flow under the conditions of relatively small pressure.

Characteristics of the two-phase flow of the 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 by 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. The liquid film with the smooth or wavelike surfaces and dry patches have been observed. The liquid film had two- or three-dimensional waves.

Holloway et al. (2014) studied the adiabatic two-phase flow of fluid FC-72 in a short horizontal microchannel. The microgap channel was 35 mm long, 20 mm wide, and has the milled gap depth of 184 μm.

The two-phase flow regimes in the short (length of 80 mm) rectangular horizontal channels in the wide range of gas and liquid flow rates were studied by Kabov et al. (2007a); Chinnov et al. (2009); and Chinnov et al. (2014) for the channel height of 1 and 0.2 mm. The two-phase flows were registered by the digital video and photo cameras using the Schliren and fluorescent techniques. New flow patterns (intermittent, jet, bubble-jet and churn) which may be connected with the new types of instability in the two-phase flows inside the horizontal short rectangular channels with small height were detected. Despite the relevance of studies of the two-phase flows in short channels, the number of publications on this topic is limited.

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 the width of 9 to 40 mm and height of 100 to 500 μm using the modern diagnostic techniques.

Experimental setup and technique of measurement

The design of the test section and concept of experiment are shown in Figs. 1 and 2. The main part of the test section is a stainless steel plate with the length of 135 mm and width of 60 mm mounted on a textolite base. The plate was covered with an optical glass lid. The experimental setup included two computer-controlled circuits, which maintained the flow of liquid and gas phases. Fig. 1 presents the schematic diagram of experimental setup with channel (*2*) and shows the arrangement of instruments for the applied measurement techniques. The liquid was driven by a high precision peristaltic pump and introduced into the gas flow via flat nozzle (*1*). The nozzle was made in the stainless steel plate and its output gap was positioned in the downstream part of the working section. The gas was

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