Experimental study of the gas-liquid flow characteristics in a rectangular channel with a large aspect ratio

G V Bartkus and V V Kuznetsov
Kutateladze Institute of Thermophysics SB RAS, 1 Lavrentieva Ave., Novosibirsk, 630090, Russia
E-mail: germanbartkus@gmail.com

Abstract. This paper experimental studies the gas-liquid flow in a rectangular slit microchannel with cross-section of 200 × 2045 μm. Ethanol and nitrogen are used as working liquids and gas, respectively. The microchannel with an internal symmetric hydraulic focusing mixer is used for the study of the flow pattern for elongated bubble and transition flows. For the study of the wave patterns in the liquid film, the microchannel with an external mixer is applied. Experimental data on flow patterns are obtained using high-speed visualization and laser-induced fluorescence (LIF) methods. Using method LIF for elongated bubble and transition flows the local film thickness is measured and compared with Taylor law. For microchannel with an external mixer, the local liquid film thickness is measured for a wavy film at high gas velocity, and the wave influence on local film distribution is discussed.

1. Introduction
Multiphase microsystems based on microchannels are used in many scenarios in different modern technologies. Their wide range of applications is due to their promising potential for chemical reactors, microchemical analysis, emulsion technology, mixing process, and medical applications [1]. Typical dimensions of the channels in these microsystems are in the range from hundreds of nanometers to hundreds of micrometers, which ensures the unique heat and mass transfer properties. Important parameters, which should be known for designing and optimizing the heat and mass transfer processes in microchannels, are the flow patterns [2], the pressure drop [3], the phase distribution, and the liquid film thickness [4]. The present work aims at measuring the local film thickness and liquid phase distribution in the channel cross-section for the elongated bubbles, the transition, and wavy-annular gas-liquid flows in the rectangular slit microchannel which have not been obtained earlier.

2. Experimental equipment and methods
Experiments are performed using 95% ethanol/water solution and nitrogen gas in the horizontal slit microchannel with rectangular cross-sections of 200 × 2045 μm. Figure 1 (a) shows the schematic diagram of the experimental setup. Nitrogen, provided to the test section from a high-pressure tank (12) via the control valve (11) and gas flow controller (5) was used in all experiments. Liquid flows from the tank (8) through the fluid flow controller (4) and further into the mixer placed at microchannel (2) inlet. The microchannel is assembled from glued glass and stainless plates with the length L of 6.5 cm. The interior symmetric hydraulic focusing mixer is placed at the inlet of the microchannel and it allows us to visualize the process of mixing [5]. This mixer contains a central channel with the same dimensions as a microchannel for the gas flow and two narrow channels on the
opposite sides of the gas channel for liquid injection. Before the mixer, a pressure transducer (3) is inserted into the gas branch to measure the inlet pressure needed for determining the superficial gas velocity. The connectors (9, 10) allow removing the tank and pouring liquid very rapidly. The mass flow rates of gas and liquid are determined by using gas and liquid mass flow controllers (5, 4) by Bronkhorst. The gas flow controller is placed directly before the mixer and the pressure transducer to reduce the compressible gas volume, which can lead to fluctuations in the gas injection rate. The Bronkhorst power supplies (6, 7) are used for controllers management. From the microchannel outlet, the gas-liquid mixture moves to the liquid tank (1), where the gas escapes to the atmosphere.

To study the wave patterns in the liquid film surface outlet, T-shape gas-liquid mixer was used. The gas-liquid mixture formed in this mixer entered the microchannel through the gas inlet; two liquid inlets were enclosed. At such gas-liquid flow formation, the liquid flew over the long side of the microchannel and did not contract menisci on its short sides for high gas superficial velocity.

![Figure 1](image_url).

The gas-liquid two-phase flow characteristics in the microchannel were photographed by high-speed video camera Optronis CR600x2 with frame rates of 500-2000 per second to visualize the flow regimes. The camera and LED lamp are located on different sides of the transparent microchannel.

Laser-Induced Fluorescence (LIF) method scheme is presented in figure 1 (b). A fluorescent dye Rhodamine 6G was added to the liquid. The solid-state laser (532 nm) was used to stimulate the fluorescence. The laser beam reflected from the mirror (17) in the experimental section. The fluorescent dye reemitted another wavelength light due to the Stokes shift. The color filter (18) cut the wavelength of laser and camera register fluorescence from the liquid film. The light intensity degree on the image was directly proportional to the liquid thickness, the Rhodamine concentration, and the laser radiation. Therefore, this method allowed us to measure the liquid film thickness and obtain liquid distribution along the channel side.

3. Results

3.1. LIF measurements for elongated bubbles and transition gas-liquid flows

For the formation of the elongated bubble and the transition flows the interior hydraulic focusing mixer is used. For this case of gas-liquid flow formation, the liquid initially is held near the short sides of the microchannel due to capillary forces and then occupies the channel cross-section due to
instability of the gas-liquid interface. Figure 2 shows the liquid film thickness averaged along the long side of the microchannel depending on the gas superficial velocity. The average liquid film is calculated as a sum of liquid film thicknesses along the long side of the microchannel (from one liquid meniscus to another one) divided on the width of the liquid film. As can be seen, the average thickness of the liquid film is close to Taylor law \([7-8]\) prediction for superficial velocities smaller than 0.5 m/s. For higher velocity more liquid flows in the meniscus and the average film thickness stops to increase when increasing the gas velocity.

**Figure 2.** Dependence of average film thickness on superficial gas velocity for \(J_{\text{liq}} = 0.066 \text{ m/s}\) (elongated bubble flow, \(J_{\text{gas}} < 0.15 \text{ m/s}\); transition flow, \(J_{\text{gas}} > 0.15 \text{ m/s}\)), the graph inside presents the example of liquid film distribution for the elongated bubble flow.

3.2. LIF measurements for wavy annular gas-liquid flow

For obtaining liquid film flow with waves on the long side of the microchannel the external mixer is used. Images of flow with waves of different sizes on the long side of the microchannel are shown in figure 3 (a-d) depending on the gas flow rate. As can be seen, increasing gas superficial velocity causes a decrease in the wavelength and the waves become three-dimensional if gas superficial velocity exceeds 17.9 m/s. Simultaneously with the waves on the liquid film surface, the large amplitude waves are observed in the meniscus area.

Figure 3 (e) demonstrates variation of the local liquid film thickness in time for annular gas-liquid flow with waves. The liquid mainly flows in the film on the long side of the microchannel and the interaction of the waves causes a strong influence on the shape of the liquid surface in comparison with elongated bubble flow without waves, presented in figure 2. The waves on the surface of the liquid film are successfully registered using the LIF method, and the height of waves may be twice larger than the liquid film thickness.

**Conclusions**

In this work, gas-liquid flow characteristics have been studied by LIF and high-speed visualization methods in slit rectangular microchannel with cross-section of 200x2045 \(\mu\text{m}\) for 95% ethanol-nitrogen flow. For the elongated bubbles and transition flows, when most of the liquid flows in the menisci, the average film thickness has been measured and compared with Taylor law. For wavy annular gas-liquid flow, when most of the liquid flows in the film on the long side of the microchannel, liquid waves have been registered and liquid film distribution has been obtained. Waves’ height may be two times larger than the liquid film thickness.
Figure 3. Images of adiabatic flow of ethanol-nitrogen mixture in microchannel of 200x2045 μm for superficial velocities \( J_{\text{lig}} = 0.02 \text{ m/s} \), (a) \( J_{\text{gas}} = 11.94 \text{ m/s} \), (b) \( J_{\text{gas}} = 17.91 \text{ m/s} \), (c) \( J_{\text{gas}} = 29.67 \text{ m/s} \), (d) \( J_{\text{gas}} = 59.40 \text{ m/s} \) (e). Distribution of liquid film thickness along the long side of the microchannel for the flow of ethanol-nitrogen mixture at superficial velocities of \( J_{\text{lig}} = 0.022 \text{ m/s} \), \( J_{\text{gas}} = 29.02 \text{ m/s} \).

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