Experimental study of gas-liquid flow in a rectangular microchannel using LIF method

G V Bartkus1,2 and V V Kuznetsov1,2
1 Kutateladze Institute of Thermophysics SB RAS, 1 Lavrentyev Ave., Novosibirsk, 630090, Russia
2 Novosibirsk State University, 2 Pirogov Str., Novosibirsk, 630090, Russia
E-mail: germanbartkus@gmail.com

Abstract. This paper aims at experimental study of gas-liquid flow in a horizontal rectangular hydrophilic microchannel with a cross-section of 200×400 μm. The ethanol and nitrogen are used as working liquids and gas accordingly in the microchannel with crossflow T-mixer at the channel inlet. Experimental data are obtained using high-speed visualization, laser flow scanning, and LIF method. The elongated bubble flow and transition flow are observed in the hydrophilic rectangular microchannel depending on gas and liquid flow rates. Using the LIF method, the non-uniform liquid film distribution is observed in the channel cross-section. The liquid film thickness is measured for elongated bubble flow and transition flow and compared with the Taylor law.

1. Introduction
Gas-liquid flow in microchannels is an important aspect of a wide range of applications. In microelectronics decreasing the component size and increasing the efficiency enhance the density of thermal energy inside the devices. Therefore, the microchannel heat sink is needed for the most efficient cooling of these devices. To cool such equipment, the microchannel cooling systems with a two-phase coolant are developed [1]. Microchannels are also used in bioengineering and pharmaceuticals [2] as well as in a fuel cell [3]. Explaining gas-liquid two-phase flow phenomena on the microscale helps to design more safe and productive systems based on microchannels. Knowledge about patterns of gas-liquid flow, pressure drop, and local flow characteristics is extremely important due to the influence of these characteristics on the intensity of heat and mass transfer [4, 5]. The hydrodynamics of gas-liquid and liquid-liquid flows in microchannels was studied in several works in which defined the main flow patterns, e.g. [4–7]. The present work aims at defining the main flow regimes for gas-liquid flow in the rectangular hydrophilic microchannel with cross-flow T-mixer and obtaining the flow local characteristics including the liquid film thickness, which are necessary for heat and mass transfer prediction.

2. Experimental equipment and methods
The experiments are performed using 95% ethanol and nitrogen gas in the horizontal hydrophilic microchannel with rectangular cross-sections of 200×400 μm. The experiment details are explained below. Figure 1 (a) illustrates the experimental setup scheme. Nitrogen, which is provided from a high-pressure tank (12) via the control valve (11) and gas flow controller (5) to the test section, was used in all experiments. Liquid flew from the tank (8) through the fluid flow controller (4) and further
into a mixer at the test section inlet, i.e. the microchannel (2). Before the mixer (see figure 1, b), the pressure transducer (3) was inserted into the gas branch to measure the test section inlet pressure for determining the real superficial gas velocity. The connectors (9, 10) allow removing the tank and pouring liquid very rapidly. The mass flow rates of gas and liquid were determined by using gas and liquid mass flow controllers (5, 4) by Bronkhorst, based on the thermal measuring principle. The gas controller was placed directly before the mixer and the pressure transducer to liquidate a large compressible gas volume, which could lead to fluctuations in the gas injection rate. The Bronkhorst power supplies (6, 7) were used for controllers. From the microchannel outlet, the gas-liquid mixture moved to the liquid tank (1), where the gas escaped to the atmosphere.

The microchannels consist of PDMS. A hydrophilic coating is applied by pumping through the microchannel an aqueous solution of polyvinyl alcohol after surface plasma activation. The contact angle is $11 \pm 4^\circ$.

![Figure 1](image1.png)

**Figure 1.** Schematic diagram of the experimental setup (a): 1 – liquid tank, 2 – microchannel, 3 – pressure transducer, 4, 5 – liquid and gas controllers, 6, 7 – power supplies, 8 – water tank, 9, 10 – connectors, 11 – control valve, 12 – high-pressure tank; (b) scheme of the microchannel with cross-flow T-mixer.

### 2.1. Laser-Induced Fluorescence method

The scheme of Laser-Induced Fluorescence (LIF) method is presented in figure 2. One of the method advantages is providing a high spatial resolution without making hydrodynamic disturbances.

![Figure 2](image2.png)

**Figure 2.** Schematic diagram of the Laser-Induced Fluorescence method.
Rhodamine 6G is added to the liquid as a fluorescent dye. Solid-state laser (532 nm) is used to light the liquid with the Rhodamine addition. The laser beam reflects from the mirror (17) in the experimental section, which is monitored using a high-speed camera. The fluorescent dye reemits another wavelength light due to the Stokes shift. The color filter (18) cuts the wavelength of laser and the camera registers the light emitted by liquid film. The light intensity in a photo image is directly proportional to the liquid film thickness, the Rhodamine concentration, and the laser radiation. Therefore, this method allows us to measure the liquid film thickness and obtain liquid distribution along the channel side.

The calibration of the method was carried out for completely flooded microchannel with a gap of 200 μm, using the concentration of Rhodamine 6G equal to 0, 1, 2, 5, and 10 mg/l at a given intensity of the laser radiation. The signal from the matrix of the high-speed camera was processed and the intensity of fluorescence was determined depending on dye concentration. Approximating this dependence for the dye concentration from 1 to 10 mg/l, we obtained the calibration dependence of fluorescence intensity on dye content. According to these data, the dependence of the fluorescence intensity on the thickness of a liquid layer δ was obtained. The effect of the laser flashes number on the intensity of fluorescence was obtained and sequential illumination using two flashes at 30 mg/l concentration was selected, which provided the necessary sensitivity of the measuring system. This value of dye concentration was lower than the concentration of Rhodamine equal to 62.5 mg/l, at which the linear relationship still existed [8].

3. Results

3.1. Maps of flow patterns

Figure 3 shows the map of flow patterns for ethanol/nitrogen flow in the microchannel with the crossflow T-mixer. Using the high-speed visualization, it has been obtained that two main flow regimes are formed in hydrophilic microchannel depending on the gas and liquid superficial velocities: the periodic elongated bubble flow and the transition flow. Based on experimental observations, the map of flow patterns, presented in figure 3, is plotted in the coordinates of gas and liquid superficial velocities. The green line in figure 3 shows the observed transition from elongated bubble flow to transition flow characterized by the rapid growth of the standard deviation in light intensity during flow laser scanning.

![Figure 3](image_url)

**Figure 3.** Map of flow patterns for ethanol/nitrogen mixture in a microchannel with crossflow T-mixer.
3.2. Liquid film thickness
A key characteristic for describing the flow of a two-phase mixture in a microchannel is the distribution of liquid film thickness in the channel cross-section. Using the LIF method, the liquid film distribution along the long side of the channel is obtained for the flow of ethanol/nitrogen mixture. Figure 4 (a) shows the distribution of the liquid film thickness along the single bubble for periodic elongated bubble flow. It has been revealed that the film thickness in the central section of the bubble decreases along the bubble for the elongated bubble flow due to the action of capillary forces. The measured liquid film thickness in the central section of the bubble is found to exceed the calculation according to Taylor law [9-10], created for the circular channels and usable only for estimation.

![Figure 4. Local film thickness along the bubble for ethanol/nitrogen flow with \( J_{\text{lig}}=0.2 \) m/s, \( J_{\text{gas}}=0.38 \) m/s in comparison with Taylor law (a), and distribution of liquid film thickness in a bubble cross-section for transition flow at \( J_{\text{lig}}=0.2 \) m/s, \( J_{\text{gas}}=3.63 \) m/s (b).](image)

For transition flow, it is obtained that the thickness of a liquid film in the central section of a microchannel increases immediately after perturbation wave passing on the meniscus, figure 4 (b), and the liquid distribution along the long side of the channel is non-uniform due to the action of capillary forces. The color lines in figure 4 (b) show the variation of the form of the liquid surface in time.

Conclusions
In this work, gas-liquid flow characteristics have been studied by LIF and high-speed visualization methods in the horizontal hydrophilic microchannel with cross-section of 200x400 \( \mu \)m and crossflow mixer for 95% ethanol-nitrogen flow. The elongated bubbles and transition flows are the main regimes for the given range of superficial velocities; the map of flow patterns has been plotted. For the obtained regimes, the local film thickness and liquid distribution have been measured along the microchannel long side, and data have been compared with Taylor law.

Acknowledgment
The reported study was funded by the Russian Science Foundation grant №16-19-10519-C.
References

[1] Tuckerman D B, Pease R F W 1981 IEEE Electron device letters 5 126–9
[2] Hibara A, Nonaka M, Hisamoto H, Uchiyama K, Kikatautani Y, Tokeshi M and Kitamori T 2002 Analytical Chemistry 74 1724–8
[3] Tonkovich A Y, Ziika J L, LaMont M J, Wang Y, Wegeng R S 1999 Chem. Eng. Sci. 54 2947–51
[4] Kuznetsov V V, Shamirzaev A S, Kozulin I A, Kozlov S P 2013 Heat Tran. Eng 34 235–45
[5] Ronshin F V, Dementyev Y A, Chinnov E A, Cheverda V V, Kabov O A 2019 Microgravity Science and Technology 31 693–707
[6] Bartkus G 2017 Experimental study of gas-liquid flow local characteristics in rectangular microchannel MATEC Web of Conferences 115 05015
[7] Kovalev A V, Yagodnitsyna A A, Bilsky A V 2018 Chem. Eng. Journal 352 120–32
[8] Minakov A, Yagodnitsyna A, Lobasov A, Rudyak V, Bilsky A 2013 La Houille Blanche 5 12–21
[9] Taylor G I 1961 Journal of Fluid Mechanics 10 161–5
[10] Aussillous P and Quéré D 2000 Physics of fluids 12 2367–71