Application of the laser-induced fluorescence to study local characteristics of a gas-liquid flow in rectangular microchannel

G V Bartkus¹² and V V Kuznetsov¹²
¹Novosibirsk State University, 2 Pirogova Str., Novosibirsk, 630090, Russia
²Kutateladze Institute of Thermophysics SB RAS, 1 Lavrentieva Ave., Novosibirsk, 630090, Russia

E-mail: germanbartkus@gmail.com

Abstract. The Laser-Induced Fluorescence (LIF) method was used to characterize liquid phase distribution in rectangular slit microchannel with cross-section 200×1205 μm for horizontal gas-liquid flow. Ethanol and nitrogen were used as working liquid and gas accordingly. The feature of this study is an application of hydraulic focusing cross-junction mixer for obtaining elongated bubble and transition flows in the microchannel with a high aspect ratio. Using LIF measurements for elongated bubble and transition flows the liquid film distributions were obtained for different distances from the bubble top and average liquid film thickness was compared with the prediction according to Taylor’s law.

1. Introduction
The device miniaturization trend set new standards for micro-scale application of two-phase flows and new opportunities for technological implementation arose. So gas-liquid and liquid-liquid flows in microchannels are utilized for microchannel cooling systems with a two-phase coolant [1], in bioengineering [2] and a fuel cell [3]. Knowledge about multiphase flow characteristics helps to explain flow phenomena for design more safe and productive systems. Flow patterns, pressure drop, gas-liquid phase distribution, wave dynamics and liquid film thickness are extremely important parameters due to their direct influence on the intensity of heat and mass transfer [4, 5]. For studying these characteristics contactless Laser-Induced Fluorescence method is often applied due to high spatial and temporal resolution [6]. The hydrodynamics of gas-liquid and liquid-liquid flows in microchannels was studied in several works using the LIF method [7–10]. The present work aims to define gas-liquid phase distribution in the rectangular microchannel with a cross-junction mixer and to measure average liquid film thickness, which are necessary for heat and mass transfer prediction, and to compare experimental data with well-known correlation.

2. Experimental setup and method
Experiments were performed using 95% ethanol solution as liquid and nitrogen as gas in the horizontal microchannel with rectangular cross-section 200×1205 μm. Figure 1(a) shows the schematic diagram of the experimental setup. Nitrogen is provided to the test section from a high-pressure vessel via the control valve and gas flow controller. Liquid flows from the tank through the fluid flow controller and further into the cross-junction mixer. Figure 1(b) shows the scheme of the microchannel with the cross-junction mixer. This mixer contains a central channel with the same dimensions as the microchannel for

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gas flow and two narrow channels on the opposite sides for liquid injection. Liquid and gas inlets, the outlet, and the region of mixing are marked by blue and green circles consequently. The microchannel is assembled from glued glass and stainless plates with a length L = 6.5 cm. Before the mixer, a pressure sensor was inserted into the gas branch to measure the inlet pressure needs for determining the superficial gas velocity. The mass flow rates of gas and liquid were determined by using gas and liquid mass flow controllers by Bronkhorst. The gas flow controller was placed directly before the mixer and the pressure sensor to reduce the compressible gas volume, which could lead to fluctuations in the gas injection rate. From the microchannel outlet, the gas-liquid mixture moved to the liquid tank, where the gas escapes to the atmosphere.

![Diagram](image)

**Figure 1.** Schematic diagram of the experimental facility for ethanol-nitrogen flow (a), scheme of the microchannel with the cross-junction mixer (top view) (b).

Laser-Induced Fluorescence (LIF) method scheme is presented in figure 2. A fluorescent dye Rhodamine 6G was added to the liquid and fluorescence was stimulated by the solid-state laser (532 nm). The laser beam reflected from the optical prism to the visualization area and the fluorescent dye reemits another wavelength light due to the Stokes shift. The orange color filter before the camera cuts the laser wavelength and the camera register only the fluorescence from the liquid film. The level of light intensity on the image is directly proportional to the thickness of a liquid layer, the Rhodamine concentration, and the laser radiation intensity. Therefore, this method allows us to measure the liquid film thickness and obtain liquid distribution along the channel side.
3. Results

LIF measurements were made for elongated bubble and transition flows (unstable elongated bubble flow) of the ethanol-nitrogen mixture. Figure 3 demonstrates the liquid distributions for a single bubble. Curves on the graph correspond to distributions at different places away from the bubble top and marked with different colors. The orange line on the image shows the place of measuring corresponds to liquid distribution by orange markers. As seen the liquid film in the rectangular microchannel consists of a thin liquid film at the channel wall and liquid-filled channel corners-menisci. It was obtained that the maximum thickness in the center of the liquid film is decreasing lengthwise the bubble due to the action of the capillary forces and the area of the liquid film is increasing from the bubble top (distribution marked by black markers) to the end (distribution by blue markers).

Figure 3. Distribution of liquid film thickness along microchannel long side for ethanol-nitrogen flow at superficial velocities $J_{\text{lig}} = 0.056$ m/s, $J_{\text{gas}} = 0.07$ m/s. The orange line on the image shows the place of LIF measuring across bubble and liquid distribution marked by orange markers corresponds to it.

Results of experimentally measured average liquid film thicknesses are plotted in comparison with Taylor’s law in figure 4. Taylor’s law is a convenient empirical equation obtained by Aussillous and

![Figure 2](image_url)  
**Figure 2.** Schematic diagram of the Laser-Induced Fluorescence method.
Quere [11] for Taylor’s data [12] of thicknesses at the circular channel for air-viscous liquid flow. It was correlated as a function of dimensionless capillary number $Ca$ and presented in equation (1)

$$\frac{\delta}{D_h} = \frac{0.67Ca^{2/3}}{1 + 3.35Ca^{2/3}},$$

where $\delta$ – liquid film thickness, $D_h$ – hydraulic diameter, $Ca = \mu U / \sigma$, $\mu$ – viscosity, $U$ – bubble velocity, $\sigma$ – surface tension.

The average liquid film is calculated as a sum of thicknesses along the long side of the microchannel divided on the width of the liquid film (from left minimum thickness to right one). The data for one capillary number corresponds to the average measured film thickness for different distances from the top of the bubble. Comparison with average film thickness is appropriate due to non-uniform liquid film thickness in rectangular microchannel unlike the distribution of liquid for a circular channel. As can be seen, the measured average thickness of the liquid film is higher than the calculated value by Taylor’s law [11] for $Ca < 0.02$, but for $Ca > 0.05$, which corresponds to transition flow, good data agreement is observed. Taylor’s law does not fully predict film thickness for the rectangular microchannel. The average film thickness is also decreasing from the bubble top to the end.

\[ J_{liq} = 0.056 \text{ m/s} \]
\[ J_{liq} = 0.11 \text{ m/s} \]

4. Conclusions
Gas-liquid flow characteristics were studied by the LIF method in the slit rectangular microchannel with cross-section $200 \times 1205 \mu m$ for 95% ethanol-nitrogen mixture. Non-uniform liquid film distribution was obtained in the rectangular microchannel cross-section. For the elongated bubble and transition flows, when most of the liquid flow in the menisci, the average film thickness was calculated and compared with Taylor’s law for the same capillary numbers. The value of average measured film thickness is larger than the prediction by Taylor’s law for $Ca < 0.02$. For $Ca > 0.05$ good data agreement was observed. It was shown that the thickness in the center of liquid film and average thickness are decreasing along the bubble direction due to the action of the capillary forces.

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