Experimental study of wavy-annular flow in a rectangular microchannel using LIF method

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

Abstract. This article aims at studying gas-liquid flow in a rectangular microchannel with a high aspect ratio (200 × 2045 μm). Liquid and gas phases were 95% ethanol and nitrogen mixture. Experimental flow characteristics are obtained using high-speed visualization and laser-induced fluorescence (LIF) methods. Using the LIF method for wavy-annular flow, the average film thickness, liquid film distribution, and liquid film width were measured. The dependences of the liquid film width and the average film thickness on gas superficial velocity are presented in graphical form and analyzed. An increase in gas superficial velocity causes growth of the liquid film width and thickness of the liquid film, which indicates the process of liquid transfer from the menisci area to the liquid film. For different liquid velocities and the same gas superficial velocities, close values of averaged liquid film thickness were observed for flow with 2D waves and 3D waves on liquid film.

1. Introduction
Nowadays the trend of multiphase microsystems based on microchannels [1, 2] is rapidly developing. This technology is already used in cooling equipment and chemical engineering. Annular flow is often utilized in many industrial applications, based on microchannels, and knowledge about important characteristics of flow should be known for designing safe and effective heat and mass transfer devices. The pressure drop [3] and the cross-sectional fluid distribution [4] are examples of these characteristics, and not so many studies are directed to their investigation in microchannels with large aspect ratios, which can provide the maximal contact surface of heat removal [5, 6]. The present study aims to measure the local and averaged film thickness, liquid phase distribution, and liquid film width for wavy-annular gas-liquid flow in the rectangular slit microchannel.

2. Experimental equipment and methods
Experiments were performed using ethanol/water (95/5) mixture 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, which was provided to the test section from a high-pressure tank via the control valve and Bronkhorst gas flow controller to the test section, was used as a gas phase. Ethanol/water (95/5) mixture flows from the tank through the fluid controller and further into the external mixer placed in front of the microchannel. The external T-shape mixer was used for forming a two-phase flow. In such a way of the gas-liquid flow formation, interfacial waves were observed at the long and short microchannel sides at the presented gas superficial velocities. The mass flow rates of gas and liquid were determined using gas and liquid mass flow controllers by
Bronkhorst. The gas flow controller was placed in front of the mixer for reducing the compressible gas volume, which could lead to fluctuations in the gas injection rate. In front of the mixer, a pressure transducer was inserted into the gas branch to measure the inlet pressure needed for determining the superficial gas velocity. From the microchannel outlet, the gas-liquid mixture moved to the liquid tank (waste), where the gas escaped to the atmosphere.

The gas-liquid two-phase flow characteristics were registered by high-speed camera Optronis CR600x2 with a frequency of 500-1250 FPS to visualize the flow regime. The camera and LED lamp were located on different sides of the transparent glass 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 with a wavelength of 532 nm was used to stimulate the fluorescence. The laser beam was reflected from the optical prism in the experimental section. The Rhodamine 6G reemits another wavelength light due to the Stokes shift. The color filter cuts the wavelength of laser radiation and the camera registers the fluorescence from the liquid film. The light intensity degree on the image is directly proportional to the liquid thickness, the dye concentration, and the laser intensity. Based on LIF calibration this method allows measuring liquid thickness distribution and obtaining the area of the liquid film that existed along the channel’s wide side. The applicability of the LIF method was shown for elongated bubble and transition flows [7], and good agreement was obtained with the LFD method measurements [8] and Taylor's law [9], which makes it possible to use this method for annular flow [10, 11].

3. Results

Visualization and LIF measurements were made for wavy-annular flow regime when liquid flows in menisci at the short sides of the rectangular microchannel and the liquid film on the wide sides with waves on an interface. Gas flows in the center of the microchannel cross-section. The waves on the surface of the liquid film and in the meniscus area are successfully registered using the LIF method.

The variations of the local liquid film thickness distribution, obtained by the LIF method, for half cross-section of the microchannel, as well as corresponding images of flow regimes, obtained by high-speed visualization, are shown in figure 2 (a). The distributions are presented for wavy-annular flow without waves on the liquid film, marked by blue markers \(J_{\text{liq}} = 0.02 \text{ m/s} \ J_{\text{gas}} = 5.96 \text{ m/s}\) and with 3D waves on liquid film, marked by orange markers \(J_{\text{liq}} = 0.02 \text{ m/s} \ J_{\text{gas}} = 29.84 \text{ m/s}\). The direction of flow is shown on images by white arrows and places of LIF measuring labeled by dashed lines of corresponding colors. The width of liquid film and the local liquid film thickness \(\delta\), which were measured in the experiments, are also designated in figure 2(a). As can be seen, gas superficial
velocity increase causes the growth of the liquid film width and thickness of the liquid film, which indicates the process of liquid transfer from the menisci area to the liquid film on the microchannel wide sides. Figure 2(b) demonstrates the dependence of liquid film width occupation, normalized by microchannel wide side width, equal to 2045 μm, on gas superficial velocity. An increase in liquid superficial velocity of the flow without waves on liquid film leads to a decrease of liquid film occupation because a significant portion of liquid flows in the meniscus. Further growth in gas superficial velocity makes the liquid film occupation values closer for different liquid velocities.

**Figure 2.** (a) Local liquid film thickness distribution for wavy-annular flow for \( J_{\text{liq}} = 0.02 \) m/s \( J_{\text{gas}} = 5.96 \) m/s (blue line) and \( J_{\text{liq}} = 0.02 \) m/s \( J_{\text{gas}} = 29.84 \) m/s (orange line). (b) Dependence of liquid film side occupation, normalized on microchannel wide side of 2045 μm, on gas superficial velocity.

Figure 3 shows the dependence of average liquid film thickness on the gas superficial velocity for different liquid velocities. The average liquid film is calculated as a sum of liquid film thicknesses along the liquid film width divided by the width [7]. As can be seen, for superficial gas velocity 6 m/s, when waves are observed just on the microchannel short sides, the average thickness of the liquid film is proportional to the liquid superficial velocity. For higher gas velocities, when 2D waves on the liquid film were registered, the average liquid film is significantly larger in comparison with the flow without waves on liquid film. This is due to the ejection of fluid from the menisci area to the liquid film, which is demonstrated in figure 2. For different liquid velocities, close values of averaged liquid film thickness are shown for the same gas superficial velocities. Further gas superficial velocity increase leads to forming 3D waves on liquid film and reducing average liquid film thickness because of forming waves of smaller wavelengths and amplitudes. During the transition to the annular flow
with 2D waves, the average film thickness ceases to increase in a rectangular microchannel. A similar effect was also observed for film thickness, measured by the LFD method [8] in the circular channel for the ethanol-air mixture.

![Figure 3](image-url)  
 Figure 3. Average liquid film thickness versus the gas superficial velocity for different liquid velocities with image examples of flow regime.

### 4. Conclusions

In this work, gas-liquid flow characteristics were studied by the LIF and high-speed visualization methods in the slit rectangular microchannel with a cross-section of \(200 \times 2045\ \mu m\). Ethanol/water (95/5) mixture was used as liquid, nitrogen – as a gas. The width of liquid film and the local liquid film thickness \(\delta\) were measured in the experiments and analyzed. An increase in gas superficial velocity caused the growth of the liquid film width and thickness of the liquid film, which indicates the process of liquid transfer from the meniscus area to the liquid film. The graphical dependence of liquid film width occupation on gas superficial velocity was plotted. The growth of gas superficial velocity makes the liquid film occupation values closer for different liquid velocities. For different liquid velocities and the same gas superficial velocities, close values of averaged liquid film thickness were observed for flow with 2D waves and 3D waves on liquid film.

### Acknowledgment

The reported study was funded in the framework of the state task IT SB RAS 121031800215-4.

### References

[1] Naqiuddin N H, Saw L H, Yew M C, Yusof F, Ng T C, Yew M K 2018 *Renewable and Sustainable Energy Reviews* **82** 901-914

[2] Yue J, Chen G, Yuan Q, Luo L, Gonthier Y 2007 *Chemical Engineering Science* **62** 2096-2108

[3] Kawahara A, Chung P Y, Kawaji M 2002 *Int. J. Multiph. Flow* **28** 1411-1435

[4] Xue T, Yang L, Ge P, Qu L 2015 *Optik* **126** 2674-2678

[5] Bartkus G V, Kuznetsov V V 2021 *Journal of Engineering Thermophysics* **30** 14-18

[6] Kuznetsov V V, Shamirzaev A S 2016 *Heat Transf. Eng.* **37** 1105–1113

[7] Bartkus G V, Kuznetsov V V 2020 *Journal of Physics: Conference Series* **1677** 012049

[8] Han Y, Shikazono N 2009 *International Journal of Heat and Fluid Flow* **30** 842-853

[9] Aussilous P, Quéré D 2000 *Physics of fluids* **12** 2367–71

[10] Alekseenko S, Cherdantsev A, Cherdantsev M, Isaenkov S, Kharlamov S, Markovich D 2012 *Experiments in fluids* **53** 77-89

[11] Chinnov E A, Ronshin F V, Kabov O A 2016 *International Journal of Multiphase Flow* **80** 57-68