Experimental investigation of gas-liquid flow characteristics in slit rectangular and circular channels

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

Abstract. This paper aims at the experimental study of the flow characteristics of the ethanol-nitrogen mixture in vertical and horizontal channels. The 95% ethanol and nitrogen were used as working liquid and gas accordingly in slit rectangular microchannel with cross-section of 200 × 2000 μm and in a circular channel with ID=2.2 mm. The hydraulic focusing and T-shape mixers were used for gas-liquid flow formation. Experimental data were obtained using high-speed visualization, laser scanning, μLIF, and PLIF methods. Using method μLIF the non-uniform thickness of the liquid film was obtained at the cross-section of the rectangular microchannel. For the circular channel, the measurements of the local film thickness using the PLIF method confirmed accordance of the experimental data with Taylor law.

1. Introduction
The gas-liquid flow studies have advanced with the use of the microchannels in micro bioreactors, applications in bioengineering and pharmaceuticals [1], fuel cells [2], and microchannel heat sink as a suitable choice for electronic devices cooling [3]. The hydrodynamics of gas-liquid and liquid-liquid flows in microchannels was studied in several works in which the main flow patterns were defined, e.g. [4-6]. In the papers [7, 8], the flow local characteristics (such as liquid distribution in microchannel) were investigated. These characteristics are used for creating heat and mass transfer models, e.g. [9]. Study of gas-liquid flow characteristics in circular channels is necessary for understanding the processes emerged in pulsating heat pipes [10].

The aims of the present work are defining the main flow regimes for the gas-liquid flow of 95% ethanol-nitrogen mixture in the slit rectangular and circular channels and measuring the local liquid film thickness, which is necessary for heat and mass transfer prediction.

2. Experimental equipment and methods
Experiments were conducted for 95% ethanol-nitrogen mixture in the horizontal rectangular microchannel with a cross-section of 200 × 2000 μm. Figure 1 (a) shows the experimental setup scheme. Nitrogen is provided from a high-pressure tank (12) via the control valve (11) and gas flow controller (5) to the test section. The 95% ethanol flows from the tank (8) through the fluid flow controller (4) and further into the focusing mixer at the inlet of the test section (2). Before the mixer, a pressure transducer (3) was inserted into the gas line of the mixer to measure inlet pressure for determining 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. The gas controller was placed directly before the mixer and the pressure transducer was installed to eliminate a large compressible gas volume, which could lead to fluctuations of 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 microchannel consist of glued glass and stainless plates with length \( L = 6.5 \text{ cm} \). The interior focusing mixer shown in figure 1 (b) is placed at the inlet of the microchannel and it allows us to visualize the mixing process.

The same experimental setup was used for the study of the gas-liquid upward flow in a vertical circular glass tube with ID=2.2 mm. For this case, external T-mixer was used for the formation of the ethanol-nitrogen mixture at the bottom of the test section.

2.1. Micro Laser Induced Fluorescence method (µLIF)

Figure 2 (a) illustrates the scheme of Laser Induced Fluorescence (µLIF) method. One of the LIF method advantages is providing a high spatial resolution without making hydrodynamic disturbances. Rhodamine 6G was added to the liquid as a fluorescent dye. The solid-state laser with the wavelength 532 nm was used to stimulate the liquid with the Rhodamine addition. The laser beam is reflected from the mirror (13) on the experimental section. The fluorescent dye reemits the light in another wavelength. The color filter (14) cuts the wavelength of laser and camera registers light from the liquid film. The light intensity degree in the photo 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.

2.2. Planar Laser Induced Fluorescence method (PLIF)

Figure 2 (b) shows a schematic diagram of the PLIF technique for studying the upward ethanol-nitrogen flow in a circular channel with ID=2.2 mm. Rhodamine 6G was also added to the liquid as a fluorescent dye. In method PLIF camera registers the fluorescence at the angle of 90° to the direction of the laser beam. It allows us to visualize liquid distribution inside the channel for obtaining liquid film thickness between the channel wall and liquid-gas surface. The feature of the present study is the absence of a special box with liquid for correction of channel curvature during the measurements.
3. Results

3.1. Slit rectangular channel
Using the high-speed video recording it was obtained that two main flow regimes are formed in the slit microchannel (200x2000 μm) depending on the gas and liquid superficial velocities: the elongated bubble flow and transition flow. The flow pattern map presented in figure 3 was plotted in the coordinates of gas and liquid superficial velocities. The solid line in figure 3 shows experimentally obtained transition from elongated bubble flow to transition flow.

**Figure 2.** Schematic diagram of μLIF (a) and PLIF (b) experimental methods.
Figure 4 shows the distribution of the liquid film thickness in channel cross-section along the long side for the horizontal microchannel. The measurements were carried out for the elongated bubble flow (figure 4 (a)) and the transition flow (figure 4 (b)). As it is shown, the liquid film thickness is non-uniform due to the determining influence of capillary forces. It was found that the film thickness along the central line of the bubble is not varied for the elongated bubble flow and does not change with distance from the bubble head (figure 4 (a)). For transition flow, it was observed that the liquid film along the central line of the bubble increases immediately after perturbation wave passing on the meniscus interphase, and then decreases until new wave passing (figure 4 (b)).

It has been obtained that the measured thickness of the liquid film is substantially less than in the calculation based on the model of a uniform film formed behind the liquid plug. This shows the possibility of a significant intensification of the heat exchange during evaporation in relation to circular channels.

Figure 3. Map of flow patterns.

Figure 4. Distribution of liquid film thickness along the microchannel long side in different places for superficial velocities: (a) $J_{\text{lig}}=0.041$ m/s, $J_{\text{gas}}=0.084$ m/s, (b) $J_{\text{lig}}=0.041$ m/s, $J_{\text{gas}}=0.83$ m/s.
3.2. Circular channel

Using the high-speed video recording two main flow regimes were observed in the circular channel (ID=2.2 mm): the elongated bubble flow and the transition flow, respectively. The liquid film thickness for elongated bubble flow was measured using PLIF. Due to the absence of a special box with liquid for correction of channel curvature and due to the effect of total reflection in PLIF imaging [11] the value of the liquid film was overestimated. The correction on measured liquid thickness was done using the value of thickness calculated from Taylor law [12, 13] for the same Ca numbers (Ca=µUbub/σ). It was obtained that the ratio between measured and calculated values does not change considerably in the elongated bubble flow for all studied Ca numbers. Figure 5 shows the comparison between the corrected dimensionless film thickness (purple dots) and the dimensionless film thickness calculated using Taylor law (green line with dots). The corrected values with the same correction factor are in good agreement with Taylor law and using this correction factor allows measuring the liquid film thickness by PLIF method with accuracy of up to 10% without correction box. Also, the average value of the correction factor is in a good agreement with data from [11].

![Figure 5. Comparison of corrected experimental data with Taylor law.](image)

Conclusions

The flow pattern map for the slit horizontal microchannel with cross-section of 200 × 2000 μm was presented. The elongated bubble flow and transition flow regimes are formed in this microchannel in given range of gas and liquid superficial velocities. Using µLIF method the non-uniform liquid film thickness was obtained at the microchannel cross section for two regimes. The thickness is substantially less than in the calculation based on the model of a uniform film formed behind the liquid plug. This fact shows the possibility of a significant intensification of the heat exchange during evaporation in relation to circular channels.

For the vertical circular channel with ID=2.2 mm the elongated bubble flow and the transition flow were observed using the high-speed video recording. Liquid film thicknesses was measured for Ca<0.01 by method PLIF. This measurements confirmed accordance of the experimental data with Taylor law.

Acknowledgment

The reported study was funded in the framework of the state task to IT SB RAS AAAA-A17-117022850026-8 (part 3.2) and funded by RFBR, project number 18-08-01282 (part 3.1).
References

[1] Hibara A, Nonaka M, Hisamoto H, Uchiyama K, Kikatautani Y, Tokeshi M and Kitamori T 2002 Analytic. Chem. 74 1724–8
[2] Trabold T A 2004 Proc. of 2nd Int. Conf. on Microchannels and Minichannels (Rochester, New York, USA) ASME 119–27
[3] Tuckerman D B, Pease R F W 1981 IEEE Electron device letters 5 126–29
[4] Kuznetsov V V, Kozulin I A, Shamirzaev A S 2012 Proc. of 6th European Thermal Sciences Conf. Journal of Physics: Conference Series 395 012093
[5] Kovalev A V, Yagodnitsyna A A, Bilsky A V 2018 Chem. Eng. Journal 352 120–32
[6] Ronshin F and Chinnov E 2019 Exp. Thermal . Fluid Sc. 103 262–73
[7] Bartkus G V and Kuznetsov V V 2018 Dynamics of Multiphase Media 1939 020001
[8] Kozulin I A, Kuznetsov V V 2011 J. of App. Mech. and Tech. Phys 52 956–64
[9] Kuznetsov V V, Shamirzaev A S 2016 Heat. Tran. Eng 37 1105–13
[10] Mangini D, Marengo M, Araneo L, Mameli M, Fioriti D and Filippeschi S 2018 Experimental Thermal and Fluid Science 97 304–12
[11] Häber T, Gebretsadik M, Bockhorn H and Zarzalis N 2015 Int. J. Multiphase Flow 76 64–72
[12] Taylor G I 1961 J. Fluid Mech. 10 pp 161–5
[13] Aussillous P and Quéré D 2000 Physics of fluids 12 2367–71