Study of interface gas-liquid flow characteristics in a rectangular microchannel for wavy-annular flow

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Abstract. The aim of this work is an experimental study of a gas-liquid flow in a rectangular slit microchannel with a cross-section of $200 \times 2045$ µm. Ethanol/water (95/5) mixture and nitrogen are used as working liquid and gas, accordingly. The external T-mixer is used for obtaining of wavy-annular flow pattern. The experimental data on interfacial waves and their characteristics in the meniscus area on the short side of the microchannel are obtained using high-speed visualization for a wide range of gas and liquid superficial velocities. Images are processed using the Python libraries to define the average liquid layer thickness and maximum amplitude of waves. An increase of gas superficial velocity causes decreasing in the average liquid layer thickness and maximal amplitude of the liquid layer thickness. The waves on the liquid layer surface (maximal amplitude) can be three times larger than the average liquid layer thickness for presented liquid and gas velocities. With increasing gas superficial velocities more liquid displace from the meniscus area to the liquid film on the wide side of the microchannel.

1. Introduction
Today, there is a trend towards system miniaturization in different modern technologies. This growing tendency sets new application standards of two-phase flows in microchannels [1]. The rectangular geometry of microchannels with a high aspect ratio is more preferential now for cooling the equipment and in chemical engineering. At that, there are not so many works involved in the investigation of flow characteristics [2] in microchannels with large aspect ratios [3-5]. One of the most important and complex two-phase flow regimes in rectangular microchannels is annular flow, which is often used in many industrial applications. It is characterized by non-uniform liquid film distribution with forming area of the liquid menisci and liquid films [6]. Various scales in amplitude and wavelength of interfacial waves are usually present at the gas-liquid flow, which affects the heat and mass transfer [7]. The interfacial waves generation and dynamics mainly depend on the competition between Kelvin-Helmholtz instability and surface tension [8]. The present work is aimed at measuring liquid layer thickness, forming in the meniscus area in the rectangular microchannel, to define the average value of liquid layer thickness and maximal amplitude of waves on the liquid layer thickness for different gas and liquid superficial velocities, which will contribute to understanding the process of liquid transition from meniscus area to liquid film, which was not studied before.

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 $200 \times 2045$ µm. Figure 1 shows the schematic
diagram of the experimental setup. Nitrogen, which is 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 flow 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, for the presented gas superficial velocities, interfacial waves are observed at the long and short microchannel sides. The microchannel is assembled from glued glass and stainless plates. The mass flow rates of gas and liquid were determined by using gas and liquid mass flow controllers by Bronkhorst. Power supplies of the same company were used for controller management. The gas flow controller was placed directly in front of the mixer to reduce the compressible gas volume, which could lead to fluctuations in the gas injection rate. A pressure transducer was also inserted into the gas branch in front of the mixer 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.

![Schematic diagram of the experimental equipment for studying gas-liquid flow.](image)

3. Results

Experiments were carried out for wavy-annular flow regime, when liquid flows at the short sides of the microchannel (in the area of meniscus) and at the wide sides (thin liquid film) with waves on the interface, while gas flows in the center of the microchannel cross-section. Obtained images of wavy-annular gas-liquid flow were binarized using thresholding for accurate measuring of liquid layer thickness in the meniscus area. Image processing was done using Python libraries. Thresholding is used to create a binary image from a grayscale image. It is the simplest way to segment objects from a background. For pictures with a bimodal histogram, the minimum algorithm [9] takes a histogram of the image and smooths it repeatedly until obtaining only two peaks in the histogram. Figure 2 (a) shows the original image of gas-liquid wavy-annular flow, registered by the high-speed camera, at $J_{\text{gas}} = 5.97 \text{ m/s}$, $J_{\text{liq}} = 0.02 \text{ m/s}$, and corresponding histogram of pixel gray values for this image. As can be seen, the minimum algorithm can be implemented because the histogram distribution is bimodal. Figure 2 (b) shows the black and white image and the same histogram with a red line, which shows the threshold value of pixels obtained by the minimum algorithm. Using this threshold value, the original image in figure 2(a) was binarized and presented in figure 2(b).

Part of the flow image with a large amplitude wave is shown in figure 3 (a). Binarizing this image we obtained the accurate value of distance (liquid layer thickness) from the channel wall to meniscus, which is marked by the green line in figure 3(a), for one measuring. The thickness of the liquid meniscus is marked by the orange line. Obtaining values of liquid layer thickness along whole image
height for many images allowed calculating the average liquid layer thickness and defining the maximal amplitude of liquid layer thickness, marked by the dashed green line.

Figure 2. (a) Image of wavy-annular gas-liquid flow at \( J_{\text{gas}} = 5.97 \) m/s, \( J_{\text{liq}} = 0.02 \) m/s and corresponding histogram of pixel grey values for presented image. (b) Binarized image and histogram with a red line, which shows the threshold value of pixels by the minimum algorithm.

Figure 3. (a) Demonstration of liquid layer thickness and maximum wave amplitude. (b) Dependence of average liquid layer thickness and maximal amplitude on the gas superficial velocity for different liquid velocities.

Figure 3 (b) demonstrates the dependence of average liquid layer thickness and maximal amplitude on the gas superficial velocity for different liquid velocities. As can be seen, increasing gas superficial...
velocity caused decreasing in the average liquid layer thickness and maximal amplitude of the liquid layer thickness. The waves on the liquid layer surface (maximal amplitude) could be three times larger than the average liquid layer thickness. With gas superficial velocities growth more liquid displaces from the meniscus area to the liquid film on the microchannel wide side (2045 µm). The values of liquid layer thickness for different liquid superficial velocities and same gas velocities have close values at $J_{gas} < 6$ m/s and start to match at $J_{gas} > 12$ m/s. The same character is observed for values of maximal amplitude.

4. Conclusions
In this work, gas-liquid flow characteristics were studied using the high-speed visualization in the slit rectangular microchannel with a cross-section of $200 \times 2045$ µm for ethanol/water (95/5) mixture and nitrogen. For the wavy-annular flow, the average liquid layer thickness and maximal amplitude of waves were measured based on image processing. The dependences of average liquid layer thickness and maximal amplitude on the gas superficial velocity for different liquid velocities were obtained and analyzed. Gas superficial velocity growth caused a decrease in the average liquid layer thickness and also the maximal amplitude of the liquid layer. It was shown that the waves on the liquid layer surface (maximal amplitude) can be three times larger than the average liquid layer thickness for presented liquid and gas velocities. With increasing gas superficial velocities more liquid displace from the meniscus area to the liquid film on the microchannel wide side (2045 µm). The values of liquid thickness for different liquid superficial velocities and same gas velocities are close at $J_{gas} < 6$ m/s and start to match at $J_{gas} > 12$ m/s. The same pattern was observed for values of maximal amplitude. The obtained data will be useful for the design and optimizing of heat and mass transfer devices.

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