Study of annular flow wave characteristics in a rectangular microchannel for gas-liquid flow with a viscous liquid

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Abstract. The wave characteristics of annular gas-liquid flow in a microchannel with a rectangular cross-section were experimentally studied. Viscous silicone oil PMS 200 and nitrogen were used as liquid and gas phases. To form the required flow regime, a side T-shaped mixer was located at the microchannel inlet. High-speed visualization allowed to register waves at the gas-liquid interface, located in the meniscus region on the microchannel short side for the wide range of superficial gas velocities. The binarization of the flow images and their subsequent processing were performed using the Python program, which made it possible to measure the liquid layer thickness and the wave amplitude depending on the gas superficial velocity. The dependences of the average liquid layer thickness and the amplitude of the waves on Regas were obtained and compared with the wave characteristics for the flow of ethanol-nitrogen mixture.

1 Introduction

The trend of system miniaturization in various modern technologies sets new standards for the use of multiphase flows in microchannels [1, 2]. The rectangular geometry of microchannels is currently widely used for technological applications: cooling systems [3, 4], chemical reactors [5], etc. However, there is lack of research aimed at a detailed study of the gas-liquid flow characteristics [6-8], which are determinant in such processes.

The annular flow regime in rectangular geometry microchannels, which is often used in many industrial applications, is characterized by non-uniform distribution of liquid along the channel perimeter with the formation of meniscus regions in the corners and a liquid film on the wide sides of the channel [8]. In the annular flow regime, large interfacial surface is realized with waves of various amplitudes and lengths, which significantly affects the intensity of heat and mass transfer processes [9, 10] and increases the efficiency.

This work is aimed at determining the average value of the liquid layer thickness and the average wave amplitude observed at the interface for various superficial velocities for the mixture flow of a viscous liquid PMS 200 and nitrogen, as well as comparing the data obtained for the case of a less viscous liquid - ethanol. This study can help to understand the previously unexplored process of liquid flow from the meniscus region into the liquid film, since the waves on the interfacial surface determine the transverse flows of the liquid and intensify the interfacial heat and mass transfer.

2 Experimental equipment and methods

The experiments were carried out for the mixture of viscous silicone oil PMS 200 (polymethylsiloxane) and gas nitrogen in a horizontal rectangular microchannel. Fig. 1(a) shows a diagram of the experimental setup. The flow rate of nitrogen supplied to the experimental section from the high pressure tank was regulated by a Bronkhorst EL-Flow gas flow controller. The HoneyWell sensor for measuring the pressure at the inlet, necessary to determine the normalized gas velocity, was located directly after the gas controller and before the mixer to reduce the volume of compressible gas. The liquid was supplied to the microchannel mixer using a syringe pump.

To form two-phase flow, the side T-shaped mixer was used, shown in Fig. 1 (b), where the arrows show phase connections. The channel length was 34 mm, a cross-section - 143 × 390 µm and microchannel was made of PDMS material. The PMS200 liquid wets the channel surface well and stratified flow was not observed in the experiments for the specified range of superficial velocities.

To visualize the gas-liquid flow regime and record its wave characteristics, an Optronis CR600x2 high-speed camera and a Mitutoyo Plan Apo 10X lens were used. Gas-liquid flow registering took place at a shooting rate of 2000 FPS at a distance of 28 mm from the side T-mixer. The camera and the LED-lamp were located on the opposite sides of the transparent microchannel, which made it possible to obtain contrast images with a high resolution of 2 µm/pixel. Subsequently, during processing, the images were binarized with registration.

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and measurement of the areas of the liquid layer thickness and the waves on the microchannel short side.

![Schematic diagrams of the experimental setup (a) and microchannel with T-shaped side mixer, sizes are shown in mm (b).](image)

Fig. 1. Schematic diagrams of the experimental setup (a) and microchannel with T-shaped side mixer, sizes are shown in mm (b).

### 3 Results

The experiments were carried out for the annular flow regime for the range of superficial gas and liquid velocities $J_{\text{gas}} = 24.3 - 93.8$ m/s, $J_{\text{liq}} = 0.01$ m/s, where $J_{\text{gas}}$ and $J_{\text{liq}}$ were determined as the volume flow rate divided by the microchannel cross section. Examples of flow images are shown in Fig. 2(a) and Fig. 5(a) for various superficial gas velocities. For the annular flow regime, the liquid is distributed continuously over the entire perimeter of the microchannel, closing and forming areas of a thin film on the wide sides and menisci on the microchannel short sides, while the gas flows in the center of the channel. For low gas velocities, waves were observed only on the microchannel short sides. An increase in the superficial gas velocity leads to decline in the amplitude of the waves on the menisci and the liquid layer thickness. The liquid from the meniscus flowed into the film on the wide side of the microchannel and perturbation waves were formed in the form of a “ring”, occupying the entire perimeter of the channel and moving along the length of the channel.

For the obtained images of gas-liquid flow, the binarization procedure was performed, which is an effective and widely implemented way to separate objects in the image from the background, in order to accurately determine the boundaries of the liquid layer thickness and wave amplitude. Image processing was done using the Python program. For images with a bimodal histogram, the minimum algorithm [11] builds a histogram of pixel grey values on the image (from 0 to 255) and smooths it many times until there are two peaks remains on the histogram. Minimum value on the histogram between peaks will be the threshold, which is determined automatically by the program. Pixel intensity values above this value are displayed in white in the image, the rest in black. Fig. 2(b) shows an example of a pixel grayscale histogram for the flow image in Fig. 2(a). As you can see, the minimum algorithm can be implemented, since the initial distribution of the histogram is bimodal.

The red line on the histogram shows the threshold value determined for this image. Using the threshold value, the original image in Fig. 2(a) was converted to binary form and presented in Fig. 2(c). Image binarization simplifies and automates the measuring process of the liquid layer thickness $L$ and wave amplitude $A$.

![Image of annular flow of PMS200-nitrogen mixture in a rectangular microchannel for superficial velocities $J_{\text{liq}} = 0.01$ m/s and $J_{\text{gas}} = 76.4$ m/s (a). Histogram of pixel greyscale values for annular flow image the Fig. 2(a)). The red line shows the threshold value of the pixel. (b) Binarized image corresponding to the Fig. 2(a) for the annular flow regime for superficial velocities $J_{\text{liq}} = 0.01$ m/s, $J_{\text{gas}} = 76.4$ m/s (c).](image)

Fig. 2. Image of annular flow of PMS200-nitrogen mixture in a rectangular microchannel for superficial velocities $J_{\text{liq}} = 0.01$ m/s and $J_{\text{gas}} = 76.4$ m/s (a). Histogram of pixel greyscale values for annular flow image the Fig. 2(a)). The red line shows the threshold value of the pixel. (b) Binarized image corresponding to the Fig. 2(a) for the annular flow regime for superficial velocities $J_{\text{liq}} = 0.01$ m/s, $J_{\text{gas}} = 76.4$ m/s (c).

Fig. 3 represents the values measured during image processing: the liquid layer thickness (L), marked by a green line, was determined as the average value within one image and was equal to the distance from the channel wall to the boundary of the liquid meniscus; the wave amplitude (A), marked by a dashed orange line, was determined for the wave on the microchannel short side as the distance from the liquid layer to the meniscus. Subsequently, the average dimensionless values $<L>/W$ and $<A>/W$ were used below, where $W$ is the microchannel width.
Fig. 3. Designation of measured characteristics: liquid layer thickness (L), wave amplitude (A), liquid meniscus width - on the original (a) and binarized (b) images for the annular flow regime PMS200-N2 for $J_{\text{liq}} = 0.01 \text{ m/s}$, $J_{\text{gas}} = 24.3 \text{ m/s}$.

Fig. 4 shows the dependence of pressure inlet on the $Re_{\text{gas}}$ for ethanol-nitrogen and PMS200-nitrogen mixtures for close superficial velocities. The use of viscous liquid made it possible to make the annular flow stable even at a liquid low flow rate in comparison with the flow of ethanol-nitrogen and the pressure increases significantly, at the same time.

The dependences of pressure inlet on $Re_{\text{gas}}$ for different liquids are shown in Fig. 4. Experiments were performed for close superficial velocities ($J_{\text{liq}} = 0.013 \text{ m/s}$, $J_{\text{gas}} = 24.3-76.4 \text{ m/s}$), which were used for the PMS200-nitrogen flow. For the flow of ethanol-nitrogen mixture, a stratified flow was observed in the indicated velocity range and a comparison of the wave characteristics is shown in Fig. 5 (a-b). It can be seen that with an increase in viscosity by more than two orders of magnitude, an annular flow was observed at the same superficial velocities, where a stratified flow was observed for a less viscous liquid (ethanol) and the flow in microchannel was determined by the T-shaped mixer geometry. The raise in viscosity led to growth of the wave amplitude and the liquid layer thickness by more than 1.5 times.

Additionally, experiments were carried out for the flow of a 90% (m) ethanol-nitrogen mixture in order to compare the effect of viscosity on the wave characteristics of the flow. Table 1 summarises physical properties of different used liquids. Both liquids wet the PDMS surface well, have close surface tension and different kinematic viscosity coefficients. During the flow formation of the PMS200-nitrogen mixture in the T-shaped mixer, the stratified flow regime was not realized, which was observed for the ethanol-nitrogen flow at close superficial gas and liquid velocities.

<table>
<thead>
<tr>
<th>$\rho$ [kg/m$^3$]</th>
<th>$\sigma$ [H/m]</th>
<th>$\nu$ [m$^2$/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMS 200</td>
<td>968</td>
<td>0.021</td>
</tr>
<tr>
<td>90% (m) ethanol</td>
<td>818</td>
<td>0.023</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.13 $\times$ 10^{-6}</td>
</tr>
</tbody>
</table>

Experiments for an ethanol-nitrogen mixture were performed for close superficial velocities ($J_{\text{liq}} = 0.013 \text{ m/s}$, $J_{\text{gas}} = 24.3-76.4 \text{ m/s}$), which were used for the PMS200-nitrogen flow. For the flow of ethanol-nitrogen mixture, a stratified flow was observed in the indicated velocity range and a comparison of the wave characteristics is shown in Fig. 5 (a-b). It can be seen that with an increase in viscosity by more than two orders of magnitude, an annular flow was observed at the same superficial velocities, where a stratified flow was observed for a less viscous liquid (ethanol) and the flow in microchannel was determined by the T-shaped mixer geometry. The raise in viscosity led to growth of the wave amplitude and the liquid layer thickness by more than 1.5 times.

Fig. 5. Dependences of dimensionless averages liquid layer thickness $<L>/W$ (a) and $<A>/W$ wave amplitudes (b), marked with the standard deviation, on $Re_{\text{gas}}$ for different liquids.
4 Conclusions

This paper presents the experimental results of wave characteristics for gas-liquid flow in a rectangular microchannel with a cross section 143×390 μm for the annular flow of PMS200- nitrogen mixture. The side T-shaped mixer was used for flow formation.

For the annular flow regime, high-speed visualization was performed and histograms of pixel grey value for images were plotted. Based on the histograms, the flow images were binarized to determine the wave characteristics: liquid layer thickness L and the wave amplitude A for various gas flow rates. Comparison of wave characteristics for the flow of 90% ethanol-nitrogen mixture for close gas and liquid superficial velocities was also made in order to compare the effect of viscosity.

The dependences of the dimensionless averages of the liquid layer thickness <L>/W and the wave amplitude <A>/W on the Re_gas number were obtained. Re_gas raise caused a decrease in the liquid layer and the wave amplitude for both mixtures (PMS200-nitrogen, 90% ethanol-nitrogen). The value of the dimensionless average wave amplitude <A>/W varied in the range of 0.05–0.15 for the PMS200-nitrogen mixture. For Re_gas>800 the dimensionless average liquid layer thickness ceased to decrease and reached the minimum value <L>/W=0.035. The <A>/W could exceed by a factor of 2 the value of <L>/W for the presented liquid and gas flow rates for the PMS200-nitrogen mixture. As the superficial gas velocity increased, more liquid was displaced from the meniscus region into the liquid film on the wide sides of the microchannel (390 μm).

An increase in viscosity by more than two orders (PMS200-nitrogen flow) led to the increase in the wave amplitude and the liquid layer thickness by more than 1.5 times. At the same superficial velocities for a less viscous liquid (90% ethanol), a stratified flow was observed and the flow was determined by the geometry of the mixer.

The obtained data will be useful for designing and optimizing heat and mass transfer devices.

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