Void fraction of nitrogen-water flow in flat microchannels

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Abstract. In this study, we investigated a behavior of time-averaged void fraction in five flat microchannels with cross sectional area of 0.05x10, 0.09x10, 0.15x10, 0.05x20 and 0.15x20 mm². The experiments have been conducted at fixed superficial velocity of liquid phase. The dependence between time-averaged void fraction and superficial gas velocity has been studied. It was shown, that this dependence may be approximate by power law with \( R^2=0.968 \). The dependence between time-averaged void fraction and homogeneous void fraction has been investigated. It was shown that the height of channel has not been affected by void fraction behavior, however the width of channel has influence: with an increasing of the channel width the dependence line shifts towards lager homogeneous fractions. However to take into account the influence of the channel width on surface area occupied by gas and to generalize data further investigations are required.

1. Introduction
Currently, microchannel based heat exchangers showed the effectiveness in comparison with conventional channels due to larger heat transfer surface area to volume ratio [1]. This feature leads to the use of microchannels in electronics cooling systems. Moreover, devices based on microchannels actively used in microfluidics for effective mixing and monodispersed droplets and bubbles generation [2]. The promising application of microchannels, especially in these fields causes an increase in the number of publications over the past two decades. Flat microchannels (rectangular channels with extremely high aspect ratio) have several benefits compared to channels of circular, rectangular and square geometry(shapes): less pressure drop with the same hydraulic diameter, larger surface area to volume ratio with the same hydraulic diameters. Furthermore, by now only several scientific groups have been studying flat microchannels [3,4].These features of the flat microchannels led to the prospects of their study and application in cooling systems for microelectronics, especially 3D microchips, since the characteristic dimensions of 3D microchips coincide with the characteristic dimensions of flat microchannels.

Void fraction is the important parameter affecting on heat transfer, pressure drop and flow patterns in microchannels. There are several void fraction measurement techniques summarized in [5]: mechanical (quick-closing valves, ultrasound, pressure drop), optical (light, laser, LIF [6], PIV [7]), ionizing radiation (gamma-ray radiation, X-ray radiation, neutron emission) and electrical (capacitive, resistive, capacitively coupled contactless conductivity detection, single- and multi-wire capacitance probes). In flat microchannels, the two-phase flow can be considered as flat to determine the void fraction, and therefore the optical technique is the simplest method for its determination. In this work, schlieren optical technique with MATLAB image processing has been applied to investigate void fraction in microchannels height from 50 to 150 micron and width from 10 to 20 mm.
2. Experimental setup and measurements technique

To study the two-phase flow in flat microchannels, the design of the test section was developed, where two spacers are clamped between stainless steel and glass plates, between which a microchannel was created. Using the thickness of these spacers, the thickness of the microchannel was set, and using the distance between them, the width of the microchannel can be varied. A nozzle was created in the bottom plate at an angle of ~ 30° for liquid injection. For each of the studied microchannels, the height was measured at several points using the confocal method. The confocal technique was described in [8]. The maximum deviation in the height of the microchannel does not exceed 5%.

The experimental setup is shown in figure 1. High-purity nitrogen was used as a gas. Gas was supplied from a cylinder (1); the flow rate is regulated using a high-precision Bronkhorst flow regulator (2). The gas then enters to the gas chamber (3), where its pressure was monitored using a BD Sensors pressure sensor (5). Milli-Q water was used as liquid. The liquid was fed into the microchannel using a Cole Parmer high-precision syringe pump (4). To study the gas-liquid interaction, the schlieren method was used, which is described in detail in [9]. Light from a point LED source passes through the lens (7) forming a parallel beam. Then the light passes through a beam splitter (8) and the upper plate of the microchannel made of glass (9), on which an antireflection coating was applied. After that, light was reflected from the interface, the light passes through a beam splitter (8) and a lens (10), falling into the camera. Thus, the camera captures an image of a two-phase flow, where the interface was clearly visible. The frame rate was 60 Hz. The resulting images are processed in MATLAB to determine the void fraction at various time intervals. Colorful images were obtained in various flow patterns: jet, stratified, bubble, churn and annular. There were detected next flow characteristics: films on the upper and bottom walls of microchannel, dry areas and liquid bridges. Time averaged void fraction was determined according to RGB-analysis with subsequent binarization to counting by the brightness threshold of the image. Dry areas, upper and bottom wall
liquid films were binarized by the same color, therefore the liquid films were neglected during the time-averaged void fraction calculation (figure 2b).

Void fraction calculation was performed as the ratio of the sum over all frames of binarized films and dried areas to the entire area of flow visualization. The minimum number of frames was 360. It is important to note, that the images should be of high quality, without noise and with a uniform background. Otherwise, additional background processing is required. The image processing technique for determining different flow characteristics is presented in detail in [3]. A similar technique is also used for pool boiling analysis [10].

The liquid film thicknesses were estimated based on the observed pattern of interference from the light source shown in (figure 3). Since the interference pattern is observed only if the optical path difference between the two waves does not exceed the coherence length, the film thickness can be estimated based on the coherence wavelength $\lambda_{coherence}$ for visible light in the following equations:

\[ \nu_1 = 4 \cdot 10^{14} \text{Hz} \,, \nu_2 = 7 \cdot 10^{14} \text{Hz} \,.
\]

\[ \tau_{coherence} = \frac{\pi}{2\pi \Delta \nu} = \frac{\pi}{2\pi (\nu_2 - \nu_1)} = \frac{1}{2 \cdot 4 \cdot 10^{14}} = 1.7 \cdot 10^{-15} \text{s} \quad (1) \]

\[ \lambda_{coherence} = c \tau_{coherence} = 3 \cdot 10^8 \cdot 1.7 \cdot 10^{-15} \approx 0.5 \mu\text{m} \quad (2) \]

Where, $\tau_{coherence}$ - characteristic coherence time, $\nu_1$ - minimal estimated frequency for visible light, $\nu_2$ - maximal estimated frequency for visible light.

**Figure 2 (a).** Original image of two-phase flow. (Churn flow pattern, channel - 0.09x10 mm²). Designations: 1 – upper wall liquid film, 2 – liquid.

**Figure 2 (b).** Binarized image of two-phase flow for time-averaged void fraction. (Churn flow pattern, channel - 0.09x10 mm²).
3. Results and discussion

To investigate the influence of gas superficial velocity on time-averaged void fraction liquid superficial velocity was fixed. Figure 4 shows the dependence between time-averaged void fraction $\alpha$ and superficial gas velocity $U_{sg}$ in five microchannels at fixed superficial liquid velocity $U_{sl}$ equal to 0.33 m/s.

![Figure 4](image)

**Figure 4.** Time-averaged void fraction $\alpha$ versus gas superficial velocity $U_{sg}$ at fixed superficial velocity of liquid $U_{sl}=0.33$ m/s.

It was shown that with an increasing superficial velocity of gas, time-averaged void fraction increase as expected. The experimental points are best described by a power law with $R^2=0.968$.

Figure 5 shows the dependence between time-averaged void fraction $\alpha$ and homogeneous void fraction $\beta$ determined as a ratio between gas superficial velocity $U_{sg}$ to total superficial velocity of two-phase mixture $U_{sg}+U_{sl}$ in five microchannels at fixed superficial liquid velocity $U_{sl}$ equal to 0.33 m/s.

![Figure 5](image)
Figure 5. Time-averaged void fraction $\alpha$ versus homogeneous void fraction at fixed superficial velocity of liquid $U_{sl}=0.33$ m/s.

Figure 6. Time-averaged void fraction $\alpha$ versus homogeneous void fraction at fixed superficial velocity of liquid $U_{sl}=0.33$ m/s and fixed width of channel equal to 10 mm.

Figure 6 demonstrates time-averaged void fraction behavior at fixed width of channel equal to 10 mm. It was shown that the behavior of time averaged void fraction practically does not change during
an increasing of the height of channel. It is obviously according to void fraction definition:

\[ \varepsilon = \frac{V_{\text{gas}}}{V_{\text{channel}}} = \frac{S_{\text{gas}} h_{\text{gas}}}{S_{\text{channel}} h_{\text{channel}}} \]  

(3)

Where \( \varepsilon \) is void fraction, \( V_{\text{gas}} \) - volume occupied by gas phase, \( V_{\text{channel}} \) - observed channel volume, \( S_{\text{gas}} \) - observed gas area, \( S_{\text{channel}} \) - channel surface area, \( h_{\text{gas}} \) - height of gas, \( h_{\text{channel}} \) - height of channel. Neglecting the liquid film thickness \( h_{\text{gas}} \approx h_{\text{channel}} \). Hence:

\[ \varepsilon = \frac{S_{\text{gas}}}{S_{\text{channel}}} \]  

(4)

It is important to note, that equation 4 is valid only for flat channels, since in this approximation the visualized liquid film is assumed to be uniform along the channel width and the thickening of the film at the side walls (mostly, in annular flow) can be neglected due to the large aspect ratio.

Figure 7 demonstrates time-averaged void fraction behavior at fixed height of channel equal to 150 \( \mu \text{m} \). It is qualitatively shown that the width of channel affects on void fraction behavior. With an increasing of the width time-averaged void fraction decreased at the same homogeneous void fractions. This can be seen analytically also, that void fraction decrease with an increase of channel width:

\[ \varepsilon = \frac{S_{\text{gas}}}{S_{\text{channel}}} = \frac{S_{\text{gas}}}{WL} = \frac{f(W) L}{WL} \]  

(5)

where \( W \) - channel width, \( L \) - observed channel length.

**Figure 7.** Time-averaged void fraction \( \alpha \) versus homogeneous void fraction at fixed superficial velocity of liquid \( U_{\text{sl}} = 0.33 \text{ m/s} \) and fixed height of channel equal to 150 \( \mu \text{m} \).

However, the following issue remains unresolved: how the width of the channel \( W \) affects on the surface area occupied by gas \( S_{\text{gas}} \). To resolve this issue and generalize the data further investigations are required.

**Conclusion**
The experimental investigation of time-averaged void fraction in flat microchannels has been conducted. To investigate the influence of the gas phase, experiments have been performed at fixed
liquid superficial velocity. The dependence between time-averaged void fraction and gas superficial velocity has been investigated for all channels and it has been mentioned that experimental points are best approximated by a power law with $R^2=0.968$. The dependence between time-averaged void fraction and homogeneous void fraction has been studied. It has been shown experimentally and analytically that the height of the channel does not affect on time-averaged void fraction behavior. Experimentally shown, that the width of channel affects on void fraction behavior. With an increasing of the width time-averaged void fraction decreased at the same homogeneous void fractions. However, to resolve the issue about affecting the width on surface area occupied by gas and on the time-averaged void fraction respectively further investigations are required.

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