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INVESTIGATION INTO FLOW BOILING HEAT TRANSFER IN A MINICHANNEL WITH ENHANCED HEATING SURFACE

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Abstract: *The paper presents results of flow boiling in a minichannel of 1.0 mm depth. The heating element for the working fluid (FC-72) that flows along the minichannel is a single-sided enhanced alloy foil made from Haynes-230. Micro-recesses were formed on the selected area of the heating foil by laser technology. The observations of the flow structure were carried out through a piece of glass. Simultaneously, owing to the liquid crystal layer placed on the opposite side of the enhanced foil surface, it was possible to measure temperature distribution on the heating wall through another piece of glass. The experimental research has been focused on the transition from single phase forced convection to nucleate boiling, i.e. the zone of boiling incipience and further development of boiling. The objective of the paper is determining of the void fraction for some cross-sections of selected images for increasing heat fluxes supplied to the heating surface. The flow structure photos were processed in Corel graphics software and binarized. The analysis of phase volumes was developed in Techystem Globe software.*

1. INTRODUCTION

Boiling is a very efficient heat transfer process used in power engineering, chemical engineering and nuclear engineering. Mini heat exchangers are used in the interest of providing higher cooling capability for new technologies. It means a reduction of their size and cost, for an identical power. Owing to the change of state, which accompanies flow boiling in minichannels, it is possible to meet contradictory demands simultaneously, i.e. to obtain a heat flux as large as possible at small temperature difference between the heating surface and the saturated liquid and, at the same time, retain small dimensions of heat transfer systems.

The study presented here was conducted on a modernized experimental stand. The modernization of the previous stand described in [1-4,6,7] aimed to simplify and miniaturize the setup, update the data and image acquisition system, and expand the system to enable accurate deaeration. The new setup was adapted to environmental protection requirements and prepared for carrying out a wide spectrum of experiments. The main raw data available in minichannel boiling heat transfer experiment with the application of thermosensitive liquid crystal technique included the hue distribution along the heating foil and the volumetric heat flux generated inside the foil. The new setup also enabled simultaneous observation of two-phase flow structures being generated in flow boiling in minichannels.

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2. EXPERIMENTAL SET-UP

The essential part of the set-up is the test section with a vertical minichannel (Fig.1, #1), 1 mm deep, 40 mm wide and 360 mm long. The heating element for the working fluid (FC-72) flowing along the minichannel is approx. 0.1 mm Haynes-230 alloy foil (#2).

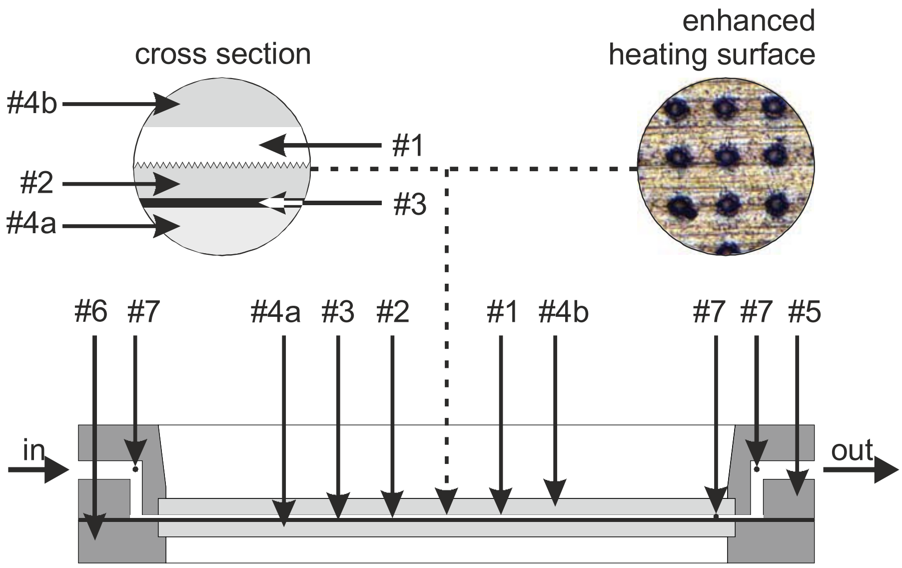


Figure 1: The schematic diagrams of the test section: #1-minichannel, #2-heating foil, #3-liquid crystal layer, #4a,b-glass sheet, #5-channel body, #6-front cover, #7-thermocouple

On one side of this foil, micro-recesses were formed and distributed evenly on the selected area of the foil (40 x 40 mm), as shown in Fig. 2a. The micro-recesses, made with a laser device, are 10 μm in diameter and 3 μm deep evenly distributed every 100μm in both axes. The depth of the micro-recesses depends on the parameters of the laser energy settings. A 7μm high layer of melted metal, locally 5-10μm high, accumulates annularly around the micro-recesses. The photograph of the enhanced foil area with micro-recesses is shown in Fig. 2b, and Fig. 2c presents the 3D topography of this structure. More data on the enhanced structure can be found in [5] this collection of conference papers. It is possible to observe both surfaces of the minichannel through two openings covered with glass plates (see Fig. 1, #4). One plate (#4a) allows observing changes in the foil surface temperature. This observed side of the heating foil (between the foil and the glass) is covered with thermosensitive liquid crystal paint (#3). The opposite surface of the minichannel can be observed through another glass plate (#4b), which helps recognize the vapour-liquid two-phase flow patterns. K-type thermocouples (#7) are installed at the inlet and outlet of the minichannel and on the glass plate near the minichannel outlet.

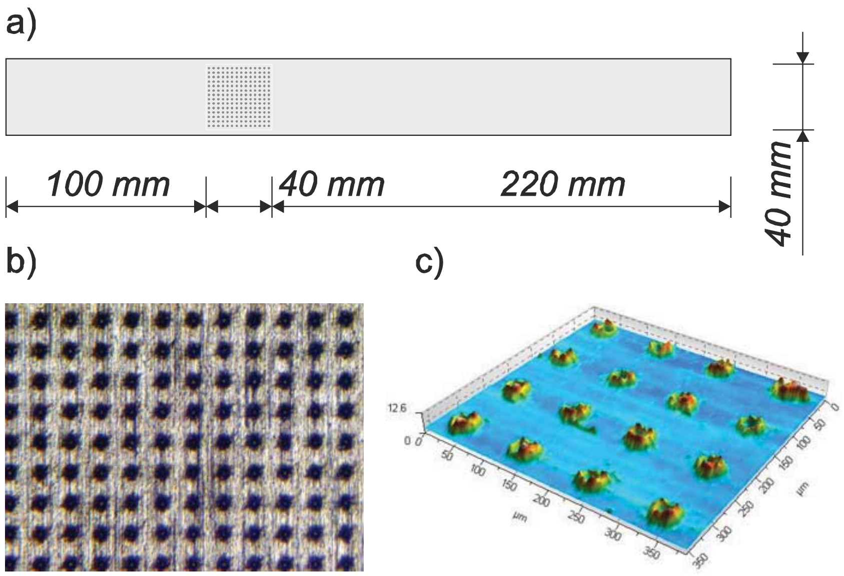


Figure 2: a) Heating foil with the selected enhanced area, b) a photo of the enhanced foil with micro-recesses, c) 3D topography of enhanced foil with micro-recesses

The main loop of the experimental stand (Fig. 3) with the test section (#1) consists of the following elements: #2-a rotary pump, #3-a compensating tank (pressure regulator), #4-a tube type heat exchanger, with water as the coolant, #5-a filter, #6-rotameters and #7-a deaerator. Two pressure converters are installed on the inlet and outlet of the minichannel (#8). The heating foil is provided with electric current by an inverter welder (#9) as a current regulated DC power supply (up to 300 A). Regulation and control of the system are provided by: #10-a shunt, #11-an ammeter, #12-a voltmeter.

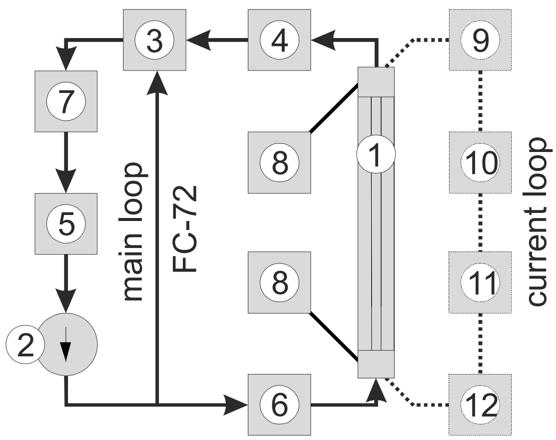


Figure. 3: The schematic diagrams of the main systems at the experimental stand: #1-test section, #2-rotary pump, #3-compensating tank/pressure regulator, #4-tube-type heat exchanger, #5-filter #6-rotameters, #7-deaerator, #8-pressure regulator, #9-inverter welder, #10-shunt, #11-ammeter, #12-voltmeter

The use of thermography has been made possible thanks to the color image acquisition system, Fig. 4. It consists of the following elements: lighting systems, two digital cameras, data acquisition system and a computer with the specialist software. The use of thermography has been made possible thanks to the color image acquisition system which includes the Canon G11 camera (#2) and fluorescent lamps emitting “cool white light” (#3). On the other side of the minichannel, the Canon Eos 550D digital SLR camera (#4) is used to observe flow structures. The lighting system uses 4 high power fluorescent lamps and 2 SLR camera flash lamps (#5). Measurement data is recorded with DaqBoard 2000 data acquisition station (#6) equipped with DASYLab software installed on a laptop (#7).

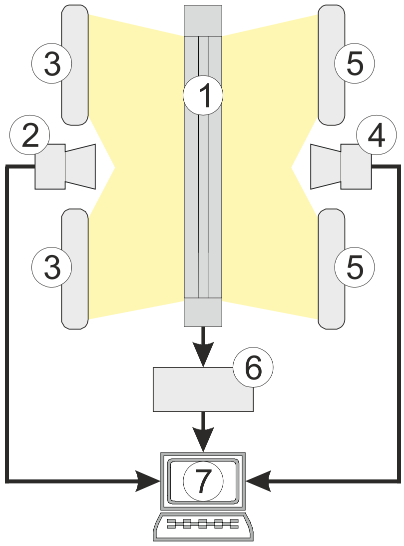


Figure 4: The diagram of the experimental data and image acquisition system: #1-test section, #2-digital camera, #3,5-lighting system, #4-digital SLR camera, #6-data acquisition station, #7-laptop

3. EXPERIMENTAL METHODOLOGY

The calibration procedure has to precede the boiling heat transfer investigation. Its aim is to assign corresponding temperature values to the hues observed on the surface covered with liquid crystals. During the calibration process, the water of the pre-set temperature is fed to the minichannel in the closed cycle in the supplementary degassed system with the heater equipped with autotransformer. The surface colour description for the determined temperature is performed similarly to the way described in [1], but instead of HSI hue, the colour description was used as its number. Custom-made software, developed in Delphi ver. 5.0 is used for this application.

After the calibration process, the main closed flow loop with FC-72 is actuated once the fluid is degassed. At the beginning, when the liquid flows along the minichannel, an increase in the electric power supplied to the heating foil (Fig. 5, images from #1 up to #22) causes flow boiling incipience (BI). Owing to the liquid crystal layer located on the heating wall contacting the glass, it is possible to observe a "boiling front" and measure temperature distribution on the heating wall. Flow structure observation is carried out simultaneously at the opposite side of the minichannel. The "boiling front" is identified as a sudden drop in the temperature of the heating surface following its rise, at constant capacity of the internal heat source [1-7]. It moves upstream together with an increase in the heat flux. The abrupt decrease in heating surface temperature results from the vapor bubbles spontaneous formation in the wall adjacent layer. They function as internal heat sinks, absorbing significant amount of energy transferred to the liquid. When the heat flux is being increased further, black hue is replaced with a new hue sequence in the upper part of images. This occurs when developed nucleate boiling is in progress in the minichannel. Then the current supplied to the foil is gradually reduced (Fig. 5, images from #23 up to #33) following the occurrence of blue hue on the foil surface. Mild hue changes, in the direction opposite to the spectrum sequence are observed to accompany the decrease in the current supplied to the foil. As a result, heat transfer returns to forced single phase convection.

4. ANALYSIS OF THE EXPERIMENTAL DATA

The analysis was based on the images obtained by means of the thermosensitive liquid crystals technology with a digital camera and on the corresponding photos of two-phase flow structures with an SLR camera.

The local heat transfer coefficient is determined with the use of the two-dimensional model of heat transfer through foil and glass [5]. Similarly to heating surface temperature measurement errors discussed in [1], the mean temperature measured using liquid crystal thermography error is estimated to be 0.9 K. A detailed discussion of heat flux and heat transfer coefficient errors can be found in [1].

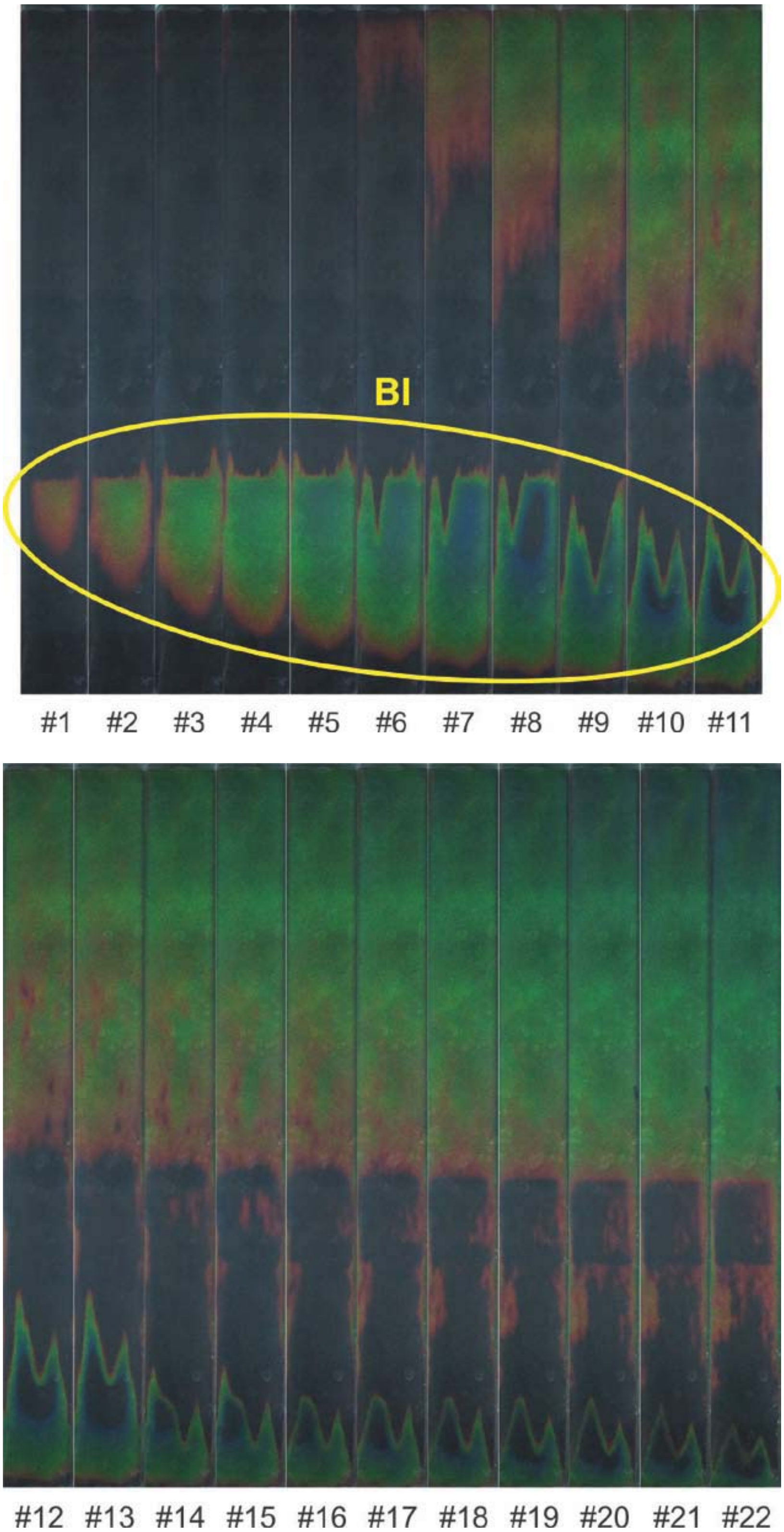
For the selected settings: #4, #13 and #22 (see Fig. 5) void fraction calculations were conducted. The flow structure photos were processed in Corel graphics software. After the photos had been binarized, which helped determine the boundary between the liquid and the vapour, the analysis of phase volumes was developed in Techystem Globe software. The software made it possible to obtain volumes of two phases in the select cross-section for the chosen area.

Three images from one series are selected for increasing heat fluxes supplied to the heating surface. For three cross-sections marked as I, II, III of each image (5 x 40 mm) the void fraction is determined. Cross-sections are placed at the distance of 90 mm (I), 270 mm (II) and 336 (III) from the inlet to the minichannel. They are marked with white horizontal lines on to the real two-dimensional image of the surface temperature distribution. Vertically arranged enlarged cross-sections of two-phase flow structure images and binarized cross-sections (black and white images) adopted for analysis in Techsystem Globe are also shown. Figure 6. presents the following: selected colour heating foil images (a), the corresponding two-phase flow structure images (b), enlarged cross-sections of colour heat images (c), enlarged cross-sections of two-phase flow structure images - real (d) and binarized (e).

The void fraction was determined according to the following formula:

$$\varphi = \frac{V_v}{V_l + V_v} = \frac{A_v \cdot \delta_{ch}}{(A_l + A_v) \cdot \delta_{ch}} = \frac{A_v}{A_l + A_v} \tag{1}$$

Liquid and vapour cross-section areas were obtained from phase image analysis performed by means of Techsystems Globe software. The results were presented as void fraction dependence along the minichannel length, in the Fig. 7.


BI
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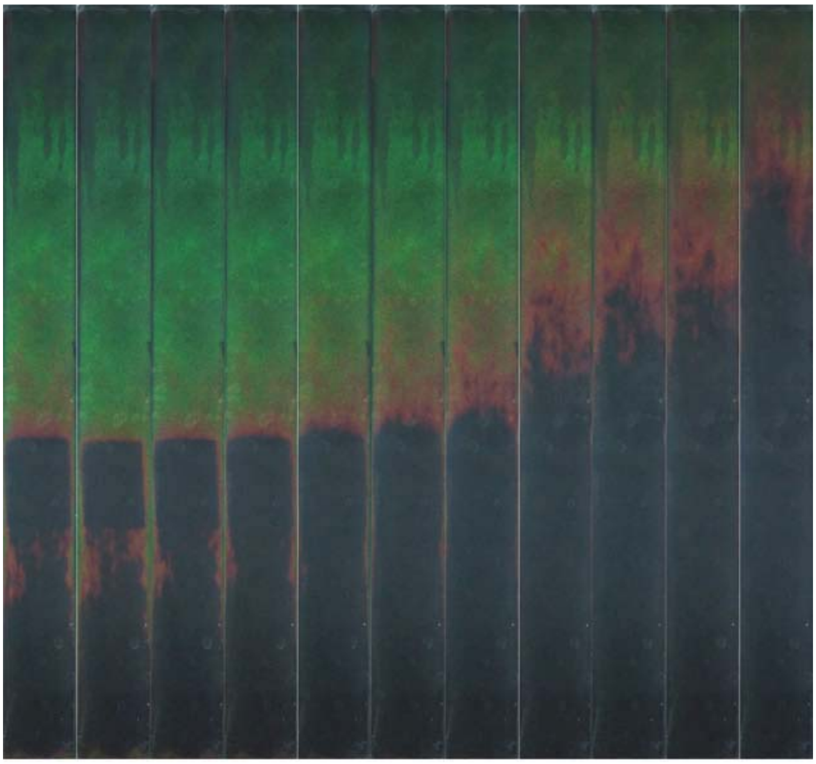
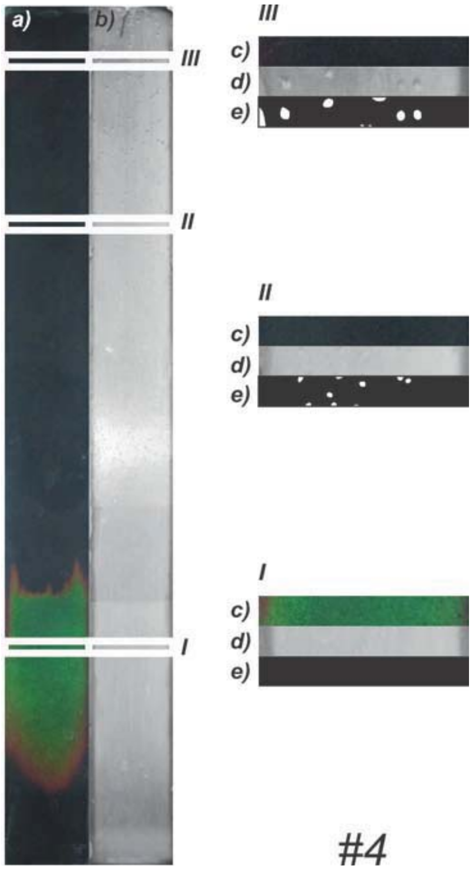
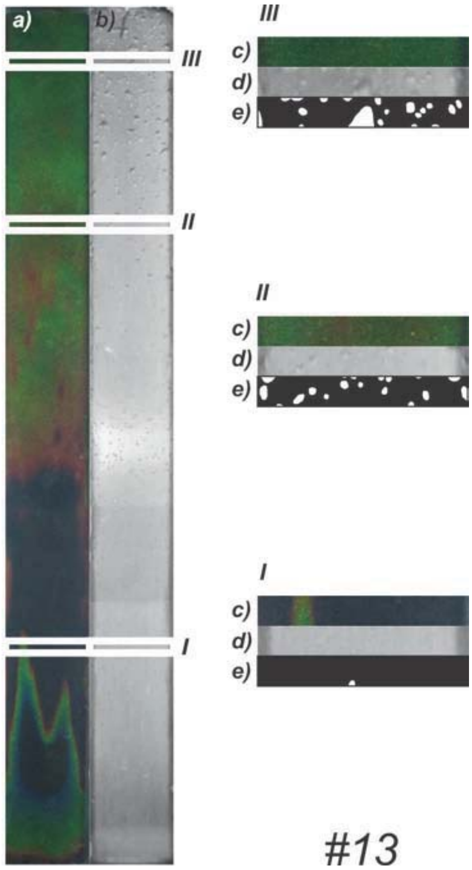


#23 #24 #25 #26 #27 #28 #29 #30 #31 #32 #33

Figure 5: Colour heating foil images (a) and the corresponding two-phase flow structure images (b) while increasing (settings #1-#22) and later decreasing (settings #23-#33) heat flux supplied to the heating surface; experimental parameters: u=0.14 m/s, G =240 kg/(m^{2}s), p_{inlet}=124 kPa, ΔT_{sub}=48 K, q_V= 7.71$\cdot$10^4$\div$3.17$\cdot$10^5 kW/m^3, q_w = 7.84$\div$32.22 kW/m^2


a)
b)
III
II
I
c)
d)
e)
#4


a)
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#13

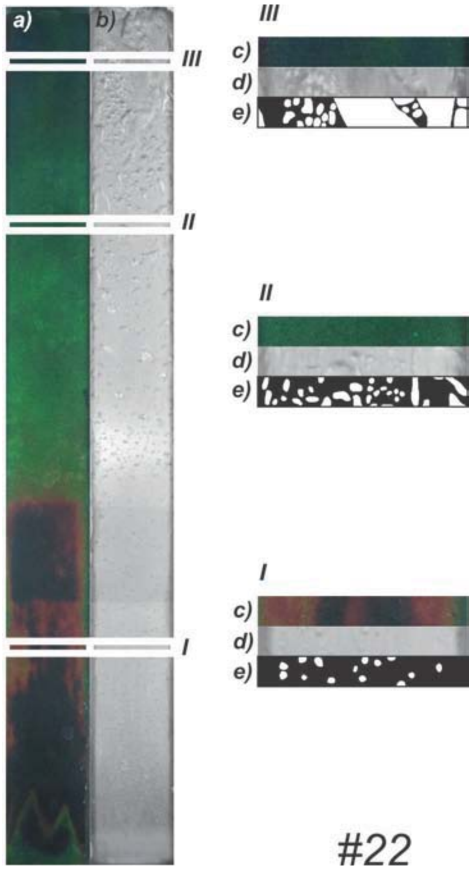

Figure 6: Images for settings #4, #13 and #22; a) selected colour heating foil images; b) the corresponding two-phase flow structure images; c) enlarged cross-sections of colour heat images real; d,e) enlarged cross-sections of two-phase flow structure images – real (d) and binarized (e), white colour refers to the vapour, and the black colour represents the liquid

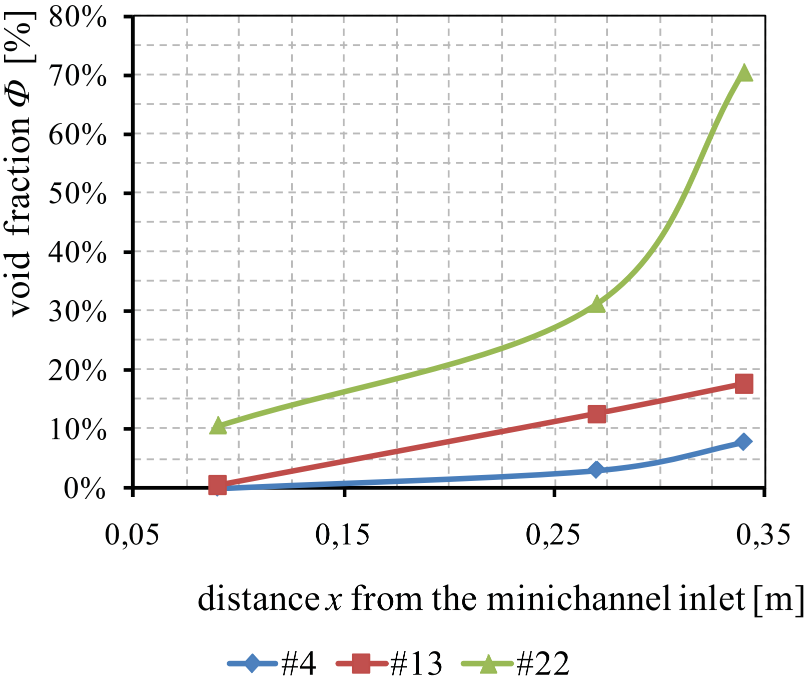

Figure 7: Void fraction dependence along the minichannel length for selected cross sections for settings: #4, #23 and #22

5. RESULTS

Different flow structures were observed when increasing the heat flux supplied to the heating surface. Bubble structure predominated at the stage of incipience and early growth. Further development of boiling was dominated by cork structure. The observed cork structure agglomerates were rather short and equally distributed.
In the area of developed nucleate boiling, the structures observed at the minichannel outlet coalesced locally to form large unevenly distributed areas. Due to possible damage to the liquid crystals layer on the heating surface, which had taken place on several occasions, the experiment was discontinued.
It was observed that the presence of the enhanced heating foil aborted the "boiling front" in the area with microrecesses. So far, in experiments in which smooth foil was used, a the "boiling front" shift from the minichannel oulet towards the minichannel inlet has been observed with the increasing heat flux [1-4,6,7]. Heating foil with the selected enhanced area changes the location of the "boiling front" slightly.
Generally, the observations have confirmed that the increase in void fraction takes place together with the increase in heat flux. After graphical processing of the flow structure photos and the use of Techystem Globe software for the analysis of phase volumes, the change of the void fraction was in the range 0-70%: from the value of approx. 0% for boiling incipience to the value of 70% for the developed nucleate boiling.

6. CONCLUSIONS

Boiling incipience was observed as the "boiling front" moving upstream when the heat flux density increased. It is accompanied by the occurrence of "nucleation hysteresis" phenomenon. It involves a considerable heating surface temperature drop.
It was observed that the presence of the enhanced heating foil aborted the "boiling front" in the area with microrecesses, but changes the location of the "boiling front" varied very slightly with the increase in heat flux.
The increase in void fraction takes place together with the increase in heat flux. The obtained change of the void fraction was in the range 0% - 70%.

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