Experimental study of flow boiling heat transfer in a rectangular minichannel by using various enhanced heating surface

Magdalena Piasecka
Chair of Mechanics, Kielce University of Technology, Al. 1000-lecia P.P. 7, 25-314 Kielce, Poland
tmpmj@tu.kielce.pl

Abstract. The paper presents the results of flow boiling heat transfer in a horizontal minichannel, 1 mm deep, 40 mm wide and 360 mm long. The heating element for FC-72 which flows along the minichannel is a thin enhanced alloy. It is possible to observe both surfaces of the minichannel through an opening covered with two glass panes. The first one allows observing changes in the temperature of the foil surface due to liquid crystal thermography. The second allows the identification of the two-phase flow patterns. The experiments employed the enhanced heating foil with various depressions, distributed diversely on the surface. Two types of enhanced heating surfaces: with micro re-entrant cavities evenly distributed, and with mini re-entrant cavities unevenly distributed, were used for the purpose of the investigation. The main objective of the paper is to determine the void fraction for cross-sections of selected images for increasing heat fluxes supplied to the heating surface. The results are presented as the void fraction dependence along the minichannel length for the selected cross-sections. Exemplary boiling curves derived from data obtained from initial increasing and subsequent decreasing the heat flux supplied to the foil are also presented. The investigation has been intended to determine the correlation for the calculations of the Nusselt number as a function of variable parameters.

1. Introduction
Over recent years, the range of applications for the flow boiling heat transfer through minichannels with different geometries has been widened considerably, extending over a new generation of various systems. Extensive efforts to understand boiling phenomena in mini- and microchannels include theoretical analyses, experimental measurements, etc. The results provide design information for cooling systems furnished with minichannel devices and can be applied in cooling, thermostabilization and thermoregulation. The application of enhanced surfaces in boiling heat transfer in minichannels has not been studied sufficiently. The studies on enhanced structure systems attract attention due to their use in their theoretical enhancement potential for heat transfer.

The results of investigations of heat transfer flow boiling conducted in test sections with rectangular, vertical, uniformly heated minichannels, at the flow of distilled water and/or methanol, were presented in [1,2]. Orozco and Hanson, [3] investigated boiling in asymmetrically heated minichannels of various depths, inclined at different angles. Hollingsworth et al. [4], dealt with heat transfer in R 11 flow through a vertical minichannel, by using liquid crystal thermography. Ammerman and You [5] studied FC-87 flowing through an asymmetrically heated horizontal
minichannel with different square cross-sections. In [6], the authors investigated flow boiling heat transfer characteristics of water and hydrocarbons in mini- and microchannels. Infrared (IR) thermography was employed for determining wall temperatures. The analysis of flow boiling heat transfer in a rectangular minichannel with different cross-sections was discussed in [7]. In [8] the authors focused on friction and heat transfer coefficients in micro- and minichannels. Experimental research on flow boiling heat transfer, pressure drop and flow patterns in rectangular narrow channels is discussed in [9], including the experiments on flow boiling of water in rectangular vertical channels. The exhaustive, critical and different reviews by Kandlikar [10] and Thome [11] present the current knowledge of boiling heat transfer in minichannels in many aspects, including boiling incipience phenomenon, the impact of selected parameters on boiling heat transfer in minichannels and numerical methods to solve heat transfer problem.

2. Experimental stand
The main loops of the experimental stand are presented in Figure 1a. The main loop consists of the following elements: #1-the test section with the minichannels, #2a-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 (#9) are installed in the inlet and outlet of the minichannel. This auxiliary loop includes: #2b-additional rotary pump, #8-a heater with an electric heater element, #5b-two filters and #7b-additional deaerator. The data from the experiment and image acquisition system include: #11-Canon G11 digital camera, #15-LED lamps and #16-fluorescent lamps, both emitting “cool white light”, #10-Canon Eos 550D digital SLR camera and #14-two 1 kW halogen reflectors with forced air cooling and heat resistant casing. Experimental data have been recorded with DaqBoard 2000 data acquisition station (#12) equipped with DASYLab software installed on a laptop (#13). The heating surface in the minichannel is provided with electric current by an inverter welder (#17) as current regulated DC power supply (up to 300 A). Regulation and control of the system are provided by: #18-a shunt, #19-an ammeter and #20-a voltmeter.

2.1. The test section
The test section (Figure 1b) with a horizontal minichannel (#21) of 1 mm depth, 40 mm width, 360 mm length, is the most important part of the experimental stand. The heating element for the working fluid (FC-72) flowing along the minichannel is an alloy foil (#22) stretched between the front cover (#26) and the channel body (#25). This thin foil (approx. 0.1 mm) designated as Haynes-230 constitutes one of the minichannel surfaces of the rectangular section. The foil is enhanced on one side (#28 - the side of the fluid flowing in the minichannel). The foil is energized by copper elements (#29) with direct current of controlled intensity. It is possible to observe both surfaces of the minichannel through two openings covered with glass panes. One pane (#24a) allows observing changes in the temperature of the foil surface. It is a plain side of the heating foil (between the foil and the glass) and is covered with thermosensitive liquid crystal paint (#23). The opposite surface of the minichannel (from the enhanced side of the heating foil-#28) can be observed through the other glass plane (#24b), which helps recognize the vapour-liquid two-phase flow patterns. K-type thermocouples (#27) are installed in the inlet and outlet of the minichannel.

Two types of enhanced heating surfaces: one with micro-reentrant cavities distributed evenly and the second with mini-reentrant cavities distributed unevenly were used in the study. The micro-reentrant cavities were performed by laser drilling. They are evenly distributed every 100 μm in both axes. The diameter of a single micro-reentrant cavity is 10 μm, its depth is 3 μm. A 5-7 μm high layer of melted metal accumulates annularly around the micro-recesses forming the structure of “craters”. The total diameter of the micro-reentrant cavity with a crater is 30 μm; total height of the micro-recess with a crater is about 10 μm. The mini-reentrant cavities are obtained by spark erosion. The layer of melted metal of the foil and an electrode material, a few μm high, reaching locally 5 μm, accumulates around the cavities. The depth of the craters of cavities is usually below 1 μm. The photos and 3D topographies of the specified enhanced foil are presented in Figure 1d-g.
3. Experimental research

Application of liquid crystals for the detection of two-dimensional heating surface temperature distribution must be preceded by colour (hue) temperature calibration [12-15]. Evaluation of the accuracy of heating foil temperature measurements with liquid crystal thermography were discussed in [12]. Mean temperature measurement error of heating foil by liquid crystal thermography equal to 0.86 K was obtained.

In the beginning, the main flow loop with open deaerating section (see Figure 1a) actuates once the fluid is degassed. Next, the deaerating section is closed and there is a laminar flow of FC-72 working fluid in the main loop. When the desired pressure and flow rate are reached, the gradual increase in the electric power supplied to the heating foil results in an increased heat flux transferred to the liquid in the minichannel. The current supplied via copper elements to the heating foil (#29, Figure 1b) is controlled by an electrical system equipped with an inverter welder (#17, Figure 1a). This leads to the incipience and next to the development of nucleate boiling. Next, the current supplied to the foil is reduced gradually. Thanks to the liquid crystal layer located on its surface contacting the glass it is possible to measure the temperature distribution on the heating wall. Flow structure observation is carried out simultaneously at the opposite side of the minichannel.
4. Results

4.1. Analyses from images obtained by liquid crystal thermography

The liquid crystal colour images of the heating foil are presented for the minichannel using the enhanced foil with mini-reentrant cavities (Figure 2a).

When the current supplied to the heating foil increases gradually (images from #1 up to #23), it causes the occurrence of incipience of boiling. The "boiling front" is recognizable as the hue sequence pattern, which indicates a gradual hue changes to the liquid crystals (in accordance with the spectrum sequence) and then sharp hue changes in the liquid crystal layer (inversely to the spectrum sequence). Out-of-sensitivity-range temperatures are shown in black. This phenomenon of the occurrence of nucleation hysteresis was discussed in [15]. When the heat flux continues to increase, a new hue sequence in the upper part of images appears (from #8 onwards). This occurs when developed nucleate boiling is in progress in the minichannel. It is accompanied by pressure increase in the channel, flow fluctuations, a sharp increase in the liquid temperature in the flow core and flow resistance fluctuations. Then the current supplied to the foil is gradually reduced (images from #24 up to #30). Mild hue changes, in the direction opposite to the spectrum sequence, are observed to accompany the decrease of current supplied to the foil. As a result, heat transfer returns to forced single phase convection. Results of the heating foil temperature distribution presented in the form of foil temperature dependence on the distance along the channel length are shown in Figure 2b.

4.2. Boiling curves

Exemplary boiling curves are obtained from the data, while increasing and later decreasing the heat flux supplied to the heating foil, for selected distance from the minichannel inlet (Figure 3). Here, the heat flux density $q_w$ depends on the difference: heating foil temperature $T_F$ - fluid temperature $T_f$.

The typical shapes of boiling curves are presented in Figure 3b. While increasing the heat flux density (A-BI), the heat transfer between the heating foil and subcooled liquid flowing upward the minichannel proceeds by means of single phase forced convection. In the foil adjacent area, the liquid becomes superheated, whereas in the flow core it remains subcooled. The increase in the heat flux density results in vapour nuclei activation on the channel heating surface. Spontaneous nucleation (point BI) causes the heating surface temperature drop, for nearly constant heat flux density (BI-C). Further increase in the heat flux density leads to developed nucleate boiling (C-D). Decreasing the heat flux proceeds along the same line but in the opposite direction (D-C). Leap heating surface temperature decreases results from spontaneous formation of vapour bubbles in the wall adjacent layer. The bubbles function as internal heat sinks, absorbing a significant amount of energy transferred to the liquid [12-15].

Boiling curve presented in Figure 3a does not show the whole process because data covering single phase convection have not been recorded. The shapes of these experimental boiling curves differ from the typical boiling curve referred to, especially in the region of developed nucleate boiling. Such boiling curves demonstrate “multistepped” courses of nucleation hysteresis in the region of developed nucleate boiling and are usually characterized by smaller temperature drops. They are similar to II type hysteresis occurring in pool boiling investigations [16].

Over the years of research on flow boiling heat transfer during cooling liquid flow in minichannels, untypical boiling curves were observed in few experiments, in a long distance from the minichannel inlet. In some experiments, various boiling curves were observed: typical curves in a small distance from the inlet, untypical “1-stepped” ones in longer distances; untypical “multistepped” curves were recorded just by the outlet. It seems that the occurrence of untypical boiling curves is affected by roughness of the heating surface; it is supported by published data on diversified enhancement values. The fact that untypical boiling curves are observed in a long distance from the inlet indicates that they do not occur in subcooled boiling. This issue will be discussed in future papers. More accurate analysis of the phenomena is planned.
Figure 2. a) Colour heating foil images while increasing and later decreasing heat flux supplied to the foil, b) heating foil temperature $T_f$ dependence on the distance along the minichannel length $x$; data for enhanced foil with mini-reentrant cavities, experimental parameters: flow velocity 0.17 m/s, mass flux 285 kg/(m$^2$s), inlet pressure 120 kPa, inlet liquid subcooling 43.6 K, volumetric heat flux $1.10 \times 10^5 \div 2.99 \times 10^5$ kW/m$^3$, heat flux density $11.17 \div 30.37$ kW/m$^2$, BI-boiling incipience, $q$-heat flux.

Figure 3. Boiling curves constructed for the minichannel using the enhanced foil with: a) micro-reentrant cavities at 0.183 m from the inlet, b) mini-reentrant cavities at 0.201 m from the inlet (b).

4.3. Analyses from two-phase flow images and void fraction determination
The analyses of flow structures were based on the monochrome images of flow structures, obtained on the side contacting fluid flowing in a minichannel from SLR camera. After the two-phase flow had been analysed graphically and the image had been binarized, phase boundaries were determined in Corel software. Due to the low depth of the minichannel (1 mm), the curvature of bubbles in the
normal direction in respect to the surface of the heating foil (channel depth) was not taken into account. Techsystem Globe, analytical software, was used in stereological analyses of digital images for quantitative assessment. It allowed the determination of the areas of the two phases and/or the percentage of the defined phase. In evaluation, the absolute error of the void fraction was assumed to be equal to the area (point) comprising 0.0064 mm$^2$; it results from the resolution of the image.

Four settings for increasing of heat flux supplied to the heating surface were selected for analysis in the experiment using enhanced foil with mini-reentrant cavities, shown in Figure 2a. Exemplary colour image - setting #23 (Figure 4a) was employed for the analysis and accompanied by flow structure images (Figure 4b). In the case of four cross-sections of each image (5 x 40 mm) marked as I, II, III, IV, the void fraction is determined. Cross-sections are placed at the distance of 90 mm (I), 133 mm (II), 270 mm (III) and 336 (IV) from the inlet to the minichannel. Subsequent cross-sections of both images and the binarized image of two-phase flow structure image (black and white) adopted for analysis in Techsystem Globe are also shown in Figure 4c. The void fraction $\Phi$ was determined according to the formula (1) and the vapour quality $X$ according to the formula (2) as follows:

$$\Phi = \frac{V_v}{V_v + V_l} = \frac{A_v \cdot \delta}{(A_v + A_l) \cdot \delta} = \frac{A_v}{A_v + A_l} \quad (1)$$

$$X = \frac{m_v}{m_l + m_v} = \frac{\Phi \cdot \rho_v}{(1 - \Phi) \cdot \rho_l + \Phi \cdot \rho_v} \quad (2)$$

where: $V$-volume, $A$-cross section area, $\delta$-minichannel depth, $m$-mass, $\rho$-density, letters in subscript apply to the following phases: liquid ($l$ in subscript) or vapour ($v$ in subscript). The results are presented in Figure 4d-g as the void fraction (d,e) and vapour quality (f,g) dependences along the minichannel length.

In the experiment involving enhanced foil with mini-reentrant cavities, the boiling front was observed similarly to the plain heating foil, discussed in [12-15]. However, it should be emphasized that in the case of horizontal position of the minichannel the boiling front is not always clearly seen. As regards the experiment with enhanced foil with micro-reentrant cavities, a very short and fuzzy boiling front was observed; it was accompanied by the lower temperature of the heating surface and considerably lower surface superheating during the incipience of boiling in comparison to that obtained for the heating surface with mini-reentrant cavities. At the same time the local heat transfer coefficient turned out to be higher for enhanced foil with micro-reentrant cavities than for mini-reentrant cavities, especially for developed boiling.

When increasing the heat flux supplied to the heating surface, it has been observed that the bubble structure predominated in the stage of incipience and in early growth, similarly to that observed for minichannel with plain heating foil. Further development of boiling was also dominated by cork structures, but they are distributed more uniformly and fragmented in comparison to data on plain foil.

4.4. Correlation

In order to estimate the values of regression parameters, 2 444 measurement results for boiling in the minichannels of 0.7÷2 mm depth, 20÷40 mm width and different spatial orientations, using FC-72, R-123 and R-11 were accounted for. Most data (90%) applies to boiling incipience conditions, while remaining data are related to various boiling areas, up to developed flow boiling (data from locations per cross-sections marked in Figures 4ab). The dependence for the Nusselt number was as follows:

$$Nu_{th} = 18 \cdot Re \cdot Bo^{0.87} \cdot Pr^{0.4} \cdot \left(\frac{\rho_v}{\rho_l}\right)^{0.24} \quad (3)$$

where the definitions for dimensionless similarity numbers have been taken in accordance with definitions from relevant literature and they designate respectively: Reynolds number, boiling number and Prandtl number, $\rho$-the designation has been given above. The application of void fraction correlation did not lead to satisfactory results, similarly to the introduction of the parameter typical of the diversified enhancement values of the heating surface.
Figure 4. a–c) An exemplary image (setting #23) from the experiment using enhanced foil with mini-reentrant cavities: colour heating foil image (a); the corresponding two-phase flow structure image (b), real and binarized cross-sections (c) - white colour refers to the vapour, and the black colour represents liquid, d, e) void fraction and f, g) vapour quality dependences along the minichannel length \(x\) for selected cross sections with enhanced foil with micro-reentrant cavities (d, f) and mini-reentrant cavities (e, g), h) correlation (eq. 3) for flow boiling heat transfer in the minichannels.
The Nusselt number calculated from eq. (3), $Nu_{th}$, was compared with the Nusselt number determined experimentally, $Nu_{exp}$, Figure 4h. Standard errors of the calculated Nusselt number amount to approx. 0.07. Determination coefficient $R^2$ is the measure of regression line matching accuracy amounting to 0.95. The equation demonstrated congruence with over 93.4 % of experimental results, the tolerance being ±25%. This dependence refers to the following ranges of parameters: $2.76 \leq Nu_{exp} \leq 79.64$; $411 \leq Re \leq 4703$; $9.78 \cdot 10^{-5} \leq Bo \leq 1.86 \cdot 10^{-1}$; $2.86 \cdot 10^{-3} \leq Pr \leq 15.46$; $9.78 \cdot 10^{-4} \leq \rho_v/\rho_l \leq 8.63 \cdot 10^{-3}$. Figure 4h also presents data obtained by using selected known correlations, i.e. Lazarek and Black as well as Dittus-Bolter ones. Results were not satisfactory in terms of Lazarek and Black equation; they were quite good as regards Dittus-Boelter correlation.

5. Conclusions
Flow boiling incipience in minichannels with enhanced heating foil with micro- and mini-reentrant cavities was observed as the “boiling front” moving upstream when the heat flux density increased. It was accompanied by the occurrence of “nucleation hysteresis” phenomenon. It was noticed that the lower temperature of the heating surface and higher heat transfer coefficient occurred during the incipience of boiling for the heating surface with micro-reentrant cavities.

It was observed that the boiling incipience occurs mainly in the lower heat flux supplied to the enhanced foil in comparison to the results from the studies on similar minichannels employing plain foil. Probably, the enhanced heating surface allowed to provide a large number of nucleation sites which leads to the intensification of the heat flux transferred from the surfaces.

The observations confirmed that the gradual increase in the void fraction occurs together with the increase in heat flux from the value of ca. 0% for boiling incipience, up to above 60% for developed nucleate boiling; at the same time, higher void fraction was obtained for the experiment employing micro-reentrant cavities on the enhanced surface.

The numbers chosen by the author to develop correlations, namely $Re$, $Bo$, and $Pr$ and vapour density/liquid density ratio yield the best results. They are generally considered to denote boiling incipience heat transfer in minichannels of 1÷2 mm deep for cooling fluids such as refrigerants.

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