An application of enhanced heating surface with mini-reentrant cavities for flow boiling research in minichannels

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Abstract The paper presents the results of flow boiling heat transfer in a minichannel 1.0 mm deep and 40 mm wide, vertically oriented. The heating element for the working fluid (FC-72) that flows along the vertical minichannel is thin, single-sided enhanced alloy foil. In the selected area or on the entire enhanced side of the heating foil mini-reentrant cavities distributed unevenly were formed. Liquid crystal thermography has been used for measuring the two-dimensional temperature distribution on the plain side of the heating foil. Simultaneously, the observations of the flow structures have been carried out on the enhanced side of the heating foil contacting fluid in a minichannel. The results are presented as void fraction dependence along the minichannel length for the selected cross-sections. Exemplary boiling curves obtained from initial increasing and subsequent decreasing the heat flux supplied to the foil are also presented.

Abbreviations

A Cross section area, m²
BI Boiling incipience
G Mass flux, kg/(m²s)
hue Component of the system HSI
p Pressure, N/m²
q_v Volumetric heat flux, (capacity of internal heat source), W/m³
q_w Heat flux density, W/m²
T Temperature, K
U Velocity, m/s
V Volume, m³

X Distance from the minichannel inlet, m

Greek
ΔT_{sub} Inlet liquid subcooling, (T_{sat}−T_{inlet}), K
ϕ Void fraction, %

Subscripts
Ch Minichannel
F Foil
f Fluid
inlet At the inlet
l Liquid
sat Saturation
v Vapour
w Wall

1 Introduction

In recent years, an increasing number of high-tech heat exchange devices use heat transfer for cooling liquids flowing in narrow spaces, such as gaps, mini- and microchannels diversified in geometrical terms. They could be used in advanced electronic devices, nuclear reactors, water-cooled gas turbines, internal combustion engines, X-ray sources and certain components of particle accelerators. In past years, extensive efforts have been aimed at understanding boiling phenomena in such mini spaces. These efforts include theoretical analyses and models, direct experimental measurements and observations, empirical correlations, etc. The results of experimental research provide design information for cooling systems furnished with minichannel devices and can be applied in cooling, thermostabilization and thermoregulation of devices with high heat flux, especially for heat exchangers and electronic devices equipped with microscale cooling systems.
There have been many reports on experiments covering heat transfer and analyses of flow boiling heat transfer in minichannels varied in terms of their dimensions [1–3] contains the summary of relevant literature focused on heat transfer and flow patterns in rectangular minichannels. Although the literature review leads to the conclusion that heat transfer in minichannels has been widely discussed, the references do not lead to any generalized, universal equations helping to predict heat transfer for a minichannel. The equations for channel systems heated by smooth heaters are verified experimentally. In addition, the studies concentrating on enhanced structure systems attract attention due to their use in their theoretical enhancement potential for heat transfer.

2 Experimental stand

2.1 Main loops

The most important loops of the experimental stand are shown in Fig. 1. FC-72 cooling liquid flows in the main loop for the boiling process. This loop, besides the most important part, i.e. the test section-#1, consists of the following elements: #2a—a rotary pump, #3—a compensating tank (pressure regulator), #4—a tube type heat exchanger, with water as the coolant, #5a—a filter, #6—rotameters and #7a—a deaerator. Two pressure converters are installed in the inlet and outlet of the minichannel (#8). Before the boiling heat transfer experiment starts, a closed-loop calibration loop is actuated, with water circulating inside it. This auxiliary loop consists of: another rotary pump (#2b), a heater with an electric heater element (#9), two filters (#5b) and an additional deaerator (#7b). The heating surface in the minichannel is provided with electric current by an inverter welder (#10) as a current regulated DC power supply (up to 300 A). Regulation and control of the system are provided by: #11—a shunt, #12—an ammeter and #13—a voltmeter.

2.2 Experimental data and image acquisition system

The experimental data and the image acquisition system are shown in Fig. 2. It consists of the following elements: lighting systems, two digital cameras, the data acquisition system and a computer with special software. The use of thermography has been made possible thanks to the colour 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 patterns. The lighting system uses two powerful 2 × 1 kW halogen reflectors (#5) with forced air cooling and heat resistant casing. Experimental data is recorded with DaqBoard 2000 data acquisition station (#6) equipped with DASYLab software installed on a laptop (#7).

2.3 The test section

The diagram of the test section is presented in Fig. 3. The minichannel (#1) is 1 mm deep, 40 mm wide, 360 mm long and it was built in the test section. The heating element for the working fluid (FC-72) flowing along the minichannel is alloy foil (#2) stretched between the front cover (#6) and the channel body (#5). As the heater 0.004” (approx. 0.1 mm) foil designated as Haynes-230, made of Ni–Cr–W–Mo high-temperature alloy was selected. It constitutes one of the minichannel surfaces of the rectangular section. It is possible to observe both surfaces of the minichannel through two openings covered with glass...
plates. One plate (#4a) allows observing changes in the temperature of the foil surface. It constitutes a plain side of the heating foil (between the foil and the glass) and is covered with thermosensitive liquid crystal paint (#3). The opposite surface of the minichannel (from the enhanced side of the heating foil) can be observed through another glass plate (#4b), which helps recognize the vapour-liquid two-phase flow patterns. K-type thermocouples (#7) are installed in the inlet and outlet of the minichannel and on the glass plate near the minichannel outlet. On one side of the heating foil (#8), mini-reentrant cavities were formed and distributed unevenly in the selected area of the foil (40×40 mm), as shown in Fig. 4a or uniformly on the entire foil, Fig. 4b. The mini-reentrant cavities obtained by spark erosion, using electric-etcher and branding-pen (arcograph), are unevenly distributed. The height and depth of the craters of these cavities depend on the parameters of branding-pen settings. The layer of melted metal of the foil and the 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 exemplary photo of the enhanced foil with mini-reentrant cavities is presented in Fig. 5a and 3D topography of selected sample area is shown in Fig. 5b.

3 Experimental research

3.1 Auxiliary pre-research experiments: calibration of liquid crystals

Application of liquid crystals for the detection of the two-dimensional heating surface temperature distribution must...
be preceded by colour (hue)—temperature calibration. In the calibration process, water of the pre-set temperature is supplied, in the closed cycle, to the minichannel, see Fig. 1. Water is heated while it flows through a heater with an electric heater element. For a pre-set temperature a colourful image of the heating foil covered with a layer of liquid crystals is registered. Water temperature is controlled by the measurement data acquisition station. Then, the water is heated and a subsequent measurement is taken for the next pre-set temperature.

Colour image acquisition system based on three basic colours \( R \), \( G \) and \( B \) was used in the research. When the liquid crystals calibration and the measurements take place in identical and constant geometrical and lighting conditions, the HSI system allows conversion of the threecomponent RGB signal into one single hue matrix [3–5]. Recorded RGB components of the colour image are converted into a hue scalar as a value in compliance with the following equation:

\[
\text{hue} = \arctan \left( \frac{\sqrt{3}(G - B)}{2R - G - B} \right)
\]  

(1)

where: \( R \)—content of red colour, \( G \)—content of green colour, and \( B \)—content of blue colour.

Custom-made software, developed in Delphi ver. 5.0 is used for this application. As a result of the calibration the curve \( \text{temperature} = \text{function (hue)} \) is obtained. An exemplary boiling curve can be found in [1].

### 3.2 Experimental methodology

Firstly, the whole main flow loop with an open deaerating section (Fig. 1) 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 section of the main loop. The liquid at the temperature below its boiling point flows laminarly in the minichannel under study. The main experimental parameters: pressure, inlet fluid temperature and volumetric flow rate are set. Pressure measurements in the inlet and outlet are performed with an accuracy of \( \pm 0.1 \% \) of full scale. The flow rate is measured using the rotameters with an accuracy of \( \pm 2 \% \) of full scale. 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 (#9, Fig. 3) is controlled by an electrical system equipped with an inverter welder (#10, Fig. 1) and ancillary equipment described in Sect. 2.1. This leads to the incipience and then to the development of nucleate boiling. Next, the current supplied to the foil is gradually reduced. Owing 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 is observed simultaneously on the opposite side of the minichannel. The liquid crystal colour images, the monochrome images of two-phase flow as well as the other experimental parameters are acquired after the steady-state conditions are obtained.

Evaluation of the accuracy of heating foil temperature measurements with liquid crystals thermography and heat volumetric heat flux measurement error in the same experimental set-up were discussed in [1]. Mean temperature measurement error of heating foil by liquid crystal thermography equal to 0.86 K was obtained. The value of the relative volumetric heat flux measurement error amounted to 3.53 %. The data can be assumed as representative of the example under study because conditions of the investigation and the application of enhanced heating foil in the study does not affect error analyses.

### 4 Results

#### 4.1 Visualisation of two-dimensional temperature field by liquid crystal thermography

#### 4.1.1 The liquid crystal colour images of the heating foil and temperature field analyses

The liquid crystal colour images of the heating foil are presented for the minichannel with foil enhanced in the selected area (Fig. 6), and for the entire enhanced foil...
Figures 6 and 7 show images of every second setting for each measurement series. The phenomenon accompanying variation of the heat flux supplied to the heating foil will be discussed on the basis of the results obtained for the minichannel with foil enhanced in the selected area, Fig. 6.

When the current supplied to the heating foil increases gradually, it can be noticed that the process is driven by single phase forced convection. Then the gradual hue changes of the liquid crystals in the direction of the flow indicate the gradual temperature increase across the heated surface. It is characterized by the stable pressure and smooth increase in temperature of the fluid in the inlet to the minichannel. The appearance of boiling and the so-called “boiling front” are clearly visible in images from #1 to #19 (designated as BI). The “boiling front” is recognizable as the hue sequence pattern, which indicates a gradual hue changes of the liquid crystals (in accordance with the spectrum sequence) and then sharp hue changes of the liquid crystals (inversely to the spectrum sequence). Out-of-sensitivity-range temperatures are shown in black. The boiling incipience is identified with the maximum value of the heating surface temperature in “boiling front” image. A sharp temperature drop follows further out. The “boiling front” moves in the direction opposite to the direction of the liquid flow in the channel with the increase of the heat flux supplied to the foil. This phenomenon of the occurrence of nucleation hysteresis was discussed in [2, 6].

When the heat flux continues to increase, the black hue is replaced with a new hue sequence in upper parts of images (visible in images from #9 to #23). It occurs when developed nucleate boiling is in progress in the minichannel. It is accompanied by a pressure increase in the channel, flow fluctuations, a sharp increase in the liquid temperature in the flow core and flow resistance fluctuations. All these suggest that the amount of the vapour phase in the boiling vapour-liquid mixture has grown and developed nucleate boiling appeared. Then the current supplied to the foil is gradually reduced following the occurrence of the saturated navy blue hue on the foil surface (images from #25 to #27). 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, the heat transfer returns to the forced single phase convection. This experiment is accomplished when the black colour of the background paint is seen which means that the temperature of the heating foil is lower than the bottom limit of the active range of liquid crystals.

Results of the heating foil temperature distribution obtained on the basis of hue distribution based on liquid crystal thermography are presented in the form of foil temperature dependence on the distance along the channel length in the Fig. 8 (for the minichannel with foil enhanced in the selected area) and Fig. 10 (for the minichannel with the entire enhanced foil). The two-dimensional temperature distribution of the heating foil for setting #8 (for the minichannel with foil enhanced on the selected area) is shown in Fig. 9.
4.1.2 Boiling curves

Boiling curves are obtained on the basis of data, while increasing and later decreasing the heat flux supplied to the heating foil. They are usually constructed for the selected points in the channel (at selected distance from the inlet), where heat flux density depends on the heating surface superheating $T_w - T_{sat}$ at some specified points in the channel. The boiling curves are sometimes plotted as heat flux density depends on the difference $T_w - T_f$. Such forms of boiling curves can be found in relevant literature.

Observations indicate that during subcooled boiling at high subcooling in the inlet the local value of the saturation temperature might be equal or even higher than the heating surface temperature. The temperature of the liquid layer adjacent to the heating wall is much higher than the temperature of the liquid in the core, the mean temperature may be lower than the local saturation temperature. Thus, relying on the temperature difference $T_w - T_{sat}$ would lead to a false conclusion that the surface is not superheated when compared with the mean temperature of the fluid. The instance given here refers to a vapour bubble, generated on the heating surface, which at the same time, condenses intensively in core of the flow because of the low liquid temperature. Therefore, it becomes a very active heat sink, which results in the heating surface temperature drop below the local liquid saturation temperature.
Exemplary boiling curves for the selected distance near the minichannel inlet are presented: in Fig. 11 (for the minichannel with foil enhanced in the selected area) and Fig. 12 (for the minichannel with the entire enhanced foil). Here the heat flux density depends only on the difference $T_F - T_f$, because the presentation of data in $T_w - T_{sat}$...
function is not possible due to insufficient superheating of the heating surface.

Typical boiling curves in heat flux density distribution depend on the heating surface superheating $T_w - T_{sat}$ derived for selected points in the channel outlet using the entire enhanced foil and they are shown in Fig. 13a,c,e. At the same time, Fig. 13b,d,f present the boiling curves for the same positions, but plotted as heat flux density depends on the difference $T_w - T_f$.

For comparison, Fig. 14 shows boiling curves, constructed for the experiment employing plain heating foil with similar experimental parameters. Other boiling curves

Fig. 11 Boiling curves for the selected point in the minichannel at the distance of: a 0.068 m, b 0.095 m, c 0.112 m from the inlet, parameters as for Fig. 6

Fig. 12 Boiling curves for the selected point in the minichannel at the distance of: a 0.059 m, b 0.077 m, c 0.139 m from the inlet, parameters as for Fig. 7
obtained from experiments with plain surfaces, performed in a similar stand, in studies employing cooling liquids R123 and R11 are discussed in [2, 3, 6].

The typical shape of a boiling curve will be discussed on the basis of the results obtained for the minichannel with foil enhanced in the selected area, shown in Fig. 11a. While increasing the heat flux density (from point A to point B1—nucleate boiling incipience), the heat transfer between the heating foil and subcooled liquid flowing upward the minichannel proceeds by means of the single phase forced convection. In the foil adjacent area, the liquid becomes superheated, point B1, whereas in the core of the flow it remains subcooled. The increase in the heat flux density results in vapour nuclei activation on the channel heating surface. Boiling incipience comes spontaneously for the superheating, point B1. Spontaneous nucleation causes the heating surface temperature drop, for almost constant heat flux density. It is visible as a drop from point B1 to point C. Further increase in the heat flux density leads to developed nucleate boiling, section C–D.

Decreasing the heat flux, starting at point D, proceeds along the same line in boiling curves, in the opposite direction, section D–C abrupt heating surface temperature decrease results from vapour bubbles spontaneous.
formation in the wall adjacent layer. The bubbles function as internal heat sinks, absorbing a significant amount of energy transferred to the liquid [1–3, 6–8].

The shape of the experimental boiling curve, Fig. 12c, similarly as in [2, 6], differs from the typical boiling curve referred to. The differences are far more clearly seen in the shape of the boiling curve shown in Fig. 11a, in the region of developed nucleate boiling. Such a boiling curve demonstrates several “stepped” courses of nucleation hysteresis in the region of developed nucleate boiling. So far, the similar hysteresis course, corresponding to II kind hysteresis, has manifested itself in pool boiling investigations, carried out for capillary-porous, metal and fibrous micro-surfaces, produced by various techniques [9]. The above-mentioned boiling curves are characterized by smaller temperature drops. In the case of boiling curves for nucleate boiling shown in Fig. 12c, the increase in the heating surface superheating while the heat flux grows, is carried out at far lower densities of the heat flux, sections C–D, than in the case of heat flux diminishment, sections D–E.

The results obtained by the author of this paper have been compared with the results from the literature, which...

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**Fig. 14** Boiling curves for the selected point in the minichannel at the distance of: a 0.095 m, b 0.112 m, c 0.139 m, d,e 0.320 m from the inlet, data for the experiment employing plain heating foil surface, experimental parameters: \( u = 0.17 \text{ m/s} \), \( G = 285 \text{ kg/(m}^2\text{s)} \), \( p_{\text{inlet}} = 250 \text{ kPa} \), \( \Delta T_{\text{sat}} = 40 \text{ K} \), \( q_V = 1.01 \times 10^3 + 3.39 \times 10^7 \text{ kW/m}^2 \), \( q_w = 10.26 + 34.44 \text{ kW/m}^2 \).
can be found in [10]. This paper presents results from the study on FC-72 employing a small (10 mm x 10 mm) plain surface heater placed in a horizontal conventional channel (5 mm high and 30 mm wide), under flow boiling conditions. Smooth and enhanced chips, the so-called micro-pin-fins, were used in the experiment. Figure 15 shows the results published in [10] for one of the applied micro-pin-fins in flow and pool boiling conditions; this figure also presents the boiling curve constructed by the author, shown previously in Fig. 12a. Data comparison shows that the results of the experiment presented in [10], conducted in flow boiling conditions, have been obtained for heat flux values higher by several dozen times than those applied in this paper, but for approximate values of the superheating of the heating surface. In turn, the data presented here approach the pool boiling results shown in [10]. It should be noted, however, that flow boiling heat transfer conditions in minichannels and conventional channels can differ significantly, the layouts of measurement modules in these two cases vary, and there are basic differences in enhanced heating surfaces (cavities and pins), pressure and spatial orientation applied in the experiment. The issue of heat transfer in issues related to the application of various enhanced heating surfaces under pool boiling and flow boiling in minichannel conditions will be discussed in future papers.

4.2 Visualisation of two phase flow structures

4.2.1 Monochrome images of flow structure analyses

The analyses of flow structure concern the minichannel with foil enhanced in the selected area. It was based on the monochrome images of flow structures of the heating foil taken by a SLR, obtained on the side contacting fluid flowing in a minichannel. They were processed using 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 Tchystem Globe software. The software made it possible to obtain volumes of two phases in the selected cross-section for the chosen area. Experimental results present monochrome two-phase flow structure images, the binarized images and void fraction dependence on the distance along the minichannel length.

4.2.2 Void fraction

Six settings for increasing the heat flux supplied to the heating surface of the foil were selected for analysis in the two experiments, i.e. one for minichannel with the foil enhanced in the selected area and one for the minichannel with entirely enhanced foil. Colour images were employed for the analysis (see Figs. 6, 7) and accompanied by flow structure images. In the case of four cross-sections marked as I, II, III, IV of each image (5 x 40 mm) 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. They are marked with white lines on to the real two-dimensional image of the surface temperature distribution (Figs. 16a, 17a) and with black lines on the two-phase flow structure image (Figs. 16b, 17b). Subsequent cross-sections of both images and the binarized image of two-phase flow structure image (black and white) adopted for analysis in Tchystem Globe are also shown in Figs. 16c, 17c.

The void fraction was determined according to the following formula:

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

Liquid and vapour cross-section areas were obtained from phase image analysis performed by means of Tchystems Globe software. The results were presented in the Figs. 18 and 19 as void fraction dependence along the minichannel length.
4.3 Observations

It was observed in the research that boiling incipience occurs in lower heat flux supplied to the enhanced foil. It is a heating surface of the minichannel when compared to results presented in Fig. 14 and obtained from the studies on similar minichannels employing plain foil [2, 3, 6]. Probably, the heating surfaces with the proposed arrangement of mini-reentrant cavities allowed to provide a large number of nucleation sites. This leads to intensification of
the heat flux transferred from the investigated surfaces and earlier occurrence of the boiling incipience.

Moreover, a slight heat flux supplied to the heating foil was necessary to examine the incipience of the experimental boiling with foil enhanced in the selected area in comparison with the entire enhanced foil. Both experiments were carried out under similar liquid conditions and at the same flow velocity, but they differed in pressure parameters. Boiling incipience is somewhat unstable and sometimes cannot be captured under strictly defined experimental conditions.

In the two cases, i.e. one obtained for the minichannel with foil enhanced in the selected area and in the case of

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**Fig. 17** Images for settings: #4, #10, #16, #22, #28, #33; a colour heating foil image; b the corresponding two-phase flow structure image; c cross-sections of: colour heating foil image, real and binarized two-phase flow structure image; white colour refers to the vapour, and the black colour represents the liquid, parameters as for Fig. 7
the minichannel with the entire enhanced foil, the boiling front was clearly observed similarly to the plain heating foil [1–3, 6]. No impact of the development of the surface on boiling incipience and the heat flux “boiling front” moving towards the minichannel inlet were observed. Despite the locations of mini-reentrant cavities in the selected area of the foil did not lead to the occurrence of “boiling front” in his area.

Apart from similar shapes of boiling curves with typical nucleation hysteresis available in the literature, several stepwise courses of the phenomenon were observed, similar to type II hysteresis, characteristic of nucleate pool boiling on developed micro-surfaces.

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 early growth, similarly to that observed for the minichannel with plain heating foil. Further development of boiling was also dominated by cork structure, but it was more uniformly distributed and fragmented in comparison to data on plain foil.

Generally, slightly higher values of the void fraction representative of settings for increased heat flux (approx. 80 %) for the experiment with foil enhanced in the selected area when compared with the results of the experiment employing entire enhanced foil (approaching 60 %) were noted. This issue seems very interesting and the distribution and dimensions of mini-reentrant cavities in the foil surface should be adjusted appropriately to the enhanced heating surface in follow-up research results.

5 Conclusions

It was observed in the research that boiling incipience occurs in lower heat flux supplied to the enhanced foil which constitutes a heating surface of the minichannel in comparison to results from the studies on similar minichannels employing plain foil. Thus, the heating surfaces with the proposed arrangement of mini-reentrant cavities make it possible to provide a large number of nucleation sites. This leads to intensification of the heat flux transferred from the investigated surfaces and the earlier occurrence of the boiling incipience.

The observations have confirmed that the gradual increase in void fraction takes place together with the increase in heat flux from the value of approx. 0 % for boiling incipience, to the value of 60–80 % for the developed nucleate boiling.

Acknowledgments The research has been financially supported by the Polish Ministry of Science and Higher Education, Grant No. N N512 354037 for the years 2009-2012.

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