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APPLYING ENHANCED HEATING SURFACES IN HEAT TRANSFER DEVICES

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ABSTRACT: The paper presents some aspects of the use of enhanced heating surfaces in heat transfer devices. The first one refers to the test section with a minichannel. Flow boiling heat transfer of fluoroinert FC-72 in the channel of 1 mm depth, 40 mm width and 360 mm length is discussed. The thin foil with micro- and mini-recesses distributed on one side acts as an enhanced heating surface. The temperature distribution was measured on the external side of the foil using liquid crystal thermography. Flow structures were observed on the enhanced side of the foil, which was in direct contact with the fluid inside the minichannel. Local temperature of the heating surface, fluid and saturation were identified and the examples of the resulting boiling curves and local transfer coefficient distributions were shown. The second device includes the hybrid solar collectors with enhanced absorbers' surfaces as the external surface of the pipe system. The raw analysis of results indicates that the application of enhanced surfaces allows achieving effective heat transfer.

NOMENCLATURE

A	– cross section area, m^2	q_w	– heat flux density, W/m^2
G	– mass flux, kg/(m^{2}s)	T	– temperature, K
I	– current supplied to the foil, A	w	– width, m
p	– pressure, Pa	x	– distance along the channel length, m

Greek symbols

α	– heat transfer coefficient, W/(m^2 K)	δ	– depth, m
ΔT_{sub}	– inlet liquid subcooling, $(T_{sat} - T_f)_{in}$, K	λ	– thermal conductivity, W/(m K)
ΔU	– the voltage drop across the foil, V		

Subscripts

F	– foil	in	– at the inlet
f	– fluid	sat	– saturation

1. INTRODUCTION

Transferring large heat fluxes is one of the most significant issues of today's technology. There are many devices where improved efficiency of heat transfer is needed. Applying the heat transfer process on an enhanced surface usually can allow more effective cooling/heating process. In order to increase the heat transfer coefficient corresponding to heat transfer enhancement, various technological processes which modify surfaces by means of passive or active methods are applied. The properties and the structure of a heating surface can be modified using chemical, thermal, mechanical or combined mechanical and thermal processes. Thermal processes, such as laser surface texturing, electromachining (spark erosion), sandblasting were used in the presented studies for processing the surfaces of heat transfer devices. Among others, an increase in heat transfer enhancement resulting from producing recesses on the heating surface corresponds to the increase in the number of nucleation sites. It also contributes to an increase in the surface-to-volume ratio.

2. HEAT TRANSFER DEVICES WITH AN ENHANCED HEATING SURFACES

2.1. THE TEST SECTION WITH THE MINICHANNEL

The test section comprises a rectangular minichannel (Fig. 1a, #1), 1 mm deep, 40 mm wide and 360 mm long. The test section could be oriented at various inclinations in relation to the horizontal plane. In this study the inclination of 45^{o} (for a level plane) was taken. The heating element for FC-72 is thin foil (#2), with the enhanced side contacting the fluid in the channel. Both surfaces of the channel are observed through the glass panes. One pane (#4a) allows observing changes in the temperature distribution on the plain side of the foil (Fig. 1b) thanks to the liquid crystal thermography. The latter one (Fig. 1a, #4b) allows observing the two-phase flow patterns on the enhanced foil side (Fig. 1c). K-type thermocouples and pressure converters (Fig. 1a, #7) are installed in the inlet and outlet of the minichannel.

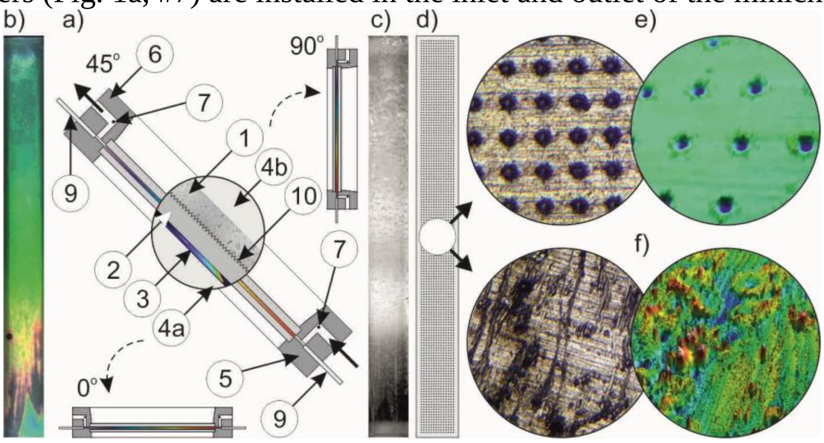

Fig. 1. a) The schematic diagram of the measurement module: #1-minichannel, #2-heating foil, #3-liquid crystals, #4-glass pane, #5-front cover, #6-channel body, #7-thermocouple, #8-pressure converter, #9-copper elements; b) images on the smooth surface with a liquid crystal layer; c) images of two-phase structures registered from the enhanced foil surface shown in part (d); e), f) photos and 3D topographies enhanced heating foil obtained by: laser drilling (e) and spark erosion (f)

Two kinds of enhanced heating foil: with micro- and mini-recesses, were applied [2,4-7]. The micro-recesses were performed by laser drilling. The diameter of the single micro-recess is usually 10 μm, its depth is 3 μm. 5-7 μm high layers of melted metal deposit annularly around the recesses, forming structures that can be named as “craters”. They are evenly distributed every 100 μm in both axes. The mini-recesses were obtained by spark erosion. The layer of melted metal from the foil and an electrode material, a few μm high, reaching locally 5 μm, accumulates around the cavities. The depth of the cavity craters is usually below 1 μm. The photos and 3D topographies of the specified structured foils are presented in Fig. 1e,f. The schematic diagram of the main loops at the experimental stand is shown in Fig. 2. Application of the liquid crystal thermography for the detection of two-dimensional heating surface temperature distribution must be preceded using colour (hue); temperature calibration is required. In order to collect data for calculations, current supplied the heating foil, voltage drop, volumetric flow rate and pressure in the inlet and outlet to the channel were measured.

The 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% [3,7]. The absolute error of the void fraction was assumed to be equal to 0.0064 mm^2; it is derived from the resolution of the image taken by a digital camera [3,6].

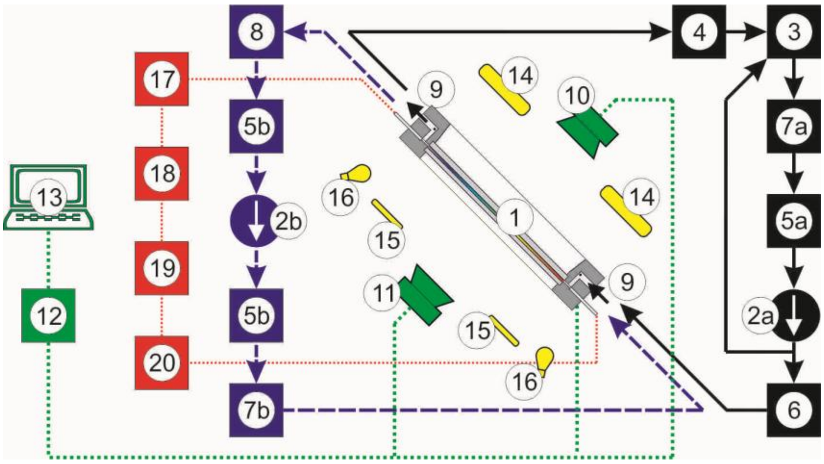

Fig. 2. The schematic diagram of the main loops at the experimental stand: #1-test section with a minichannel: #2a,b-rotary pump; #3-compensating tank/pressure regulator; #4-tube-type heat exchanger, #5a,b-filter, #6-rotameters; #7a,b-deaerator, , #8-a heater with an electric heater element, #9-pressure regulator, 10-digital SLR camera, #11-digital camera, #12-data acquisition station, #13-laptop, #14-halogen reflectors, #15,16-fluorescent lamps, #17-inverter welder, #18-shunt, #19-ammeter, #20-voltmeter

2.2. HYBRID SOLAR COLLECTORS WITH THE ENHANCED SURFACE

Solar collectors are some of the most energy-efficient devices used to generate heat rather than electricity, with the latter being the case of solar photovoltaic cells. Solar energy converted by heat exchangers is stored in hot water tanks to be used for hot water supply or to support the heating system in the heating season. Applying a hybrid variant seems an optimal solution. Photovoltaic/thermal hybrid systems are some of the world’s most commonly studied concepts in the field of renewable energy. In the proposed prototype hybrid solar collectors the photovoltaic cells and the solar panel are used. The absorber - the key element of solar collectors responsible for the conversion of solar energy into heat - should have a structure featuring the high heat absorption coefficient. Its surface should be extended to improve the thermal conductivity and the level of radiation absorption. Two passive methods of modifying properties and structures of absorber's surfaces with thermal treatment have been used: electromachining (spark erosion) and sandblasting [5].

The prototype hybrid solar collectors have enhanced absorbers as the external surface of the pipe system. Two various options formed developed surfaces were applied. In the first option electric-etcher and branding-pen manually controlled were applied to obtain the enhanced surface of the absorber's pipes. As a result of the spark erosion the mini-recesses are distributed unevenly on the pipe surfaces. In the second option, sandblasting was used to develop mini-recesses on the absorber's pipes. Figure 3 presents a diagram (a) and photo (b) of the selected prototype hybrid solar collector. It has the enhanced surface of the absorber's pipes with mini-recesses obtained by spark erosion.

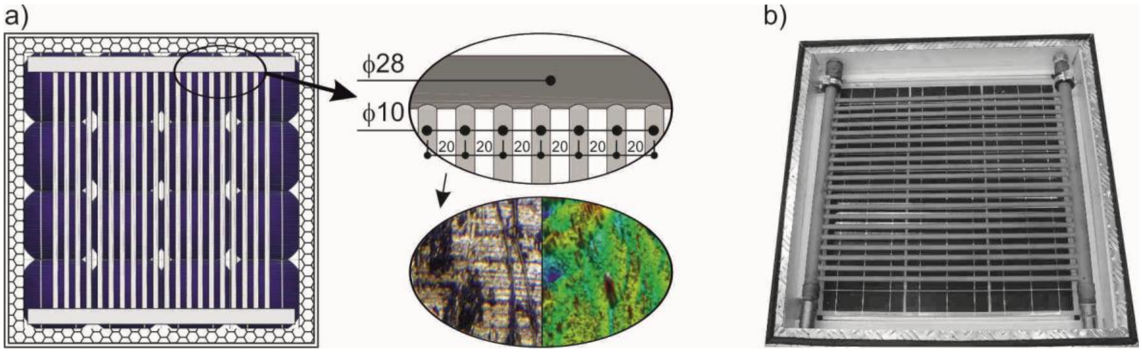

Fig. 3. a) Diagram with photo and 3D topography of the enhanced surfaces of the absorber's pipes; b) photo of the hybrid solar collector

3. RESULTS OF HEAT TRANSFER RESEARCH USING A MINICHANNEL

Colour (hue) - temperature calibration must precede the application of liquid crystals for determining the two-dimensional temperature distribution on the heating surface.

After deaeration the gradual increase in the power supply to the heating foil results in an increased heat flux transferred to the FC-72 flowing in the minichannel (Fig. 4, settings from #1 to #16). This leads to the boiling incipience (recognizable as "boiling front") and next to the development of nucleate boiling. Then power supply to the foil is reduced gradually (settings from #17 to #25). Thanks to the liquid crystal layer located on its surface contacting the glass it is possible to measure temperature distribution on the heating wall. At the same time, the flow structure is observed at the same time at the opposite side of the minichannel.

Figures 4÷6 shows the data for subsequent sets selected from the measurement series as thermographic images of the plain surface of the foil (Fig. 4), heating foil dependence on the distance along the channel length (Fig. 5), local temperatures of the heating surface in 3D layout obtained by liquid crystal thermography for the selected image - setting #16 (Fig. 6a) and dependences between liquid temperature, saturation and heating surface as a function of the distance from the inlet to the channel for settings #10 and #16 (Fig. 6b) and local heat transfer coefficient as a function of distance from the minichannel inlet - all settings, Fig. 6c.

A simple, one-dimensional approach is used for heat transfer coefficient calculation [4]. The resulting heat transfer coefficient was determined by the following equations: for subcooled boiling - eq. (1) and for saturated boiling - eq. (2).

$$\alpha(x) = (I \cdot U / A_F) / \left[T_F(x) - T_f(x) - (I \cdot U / A_F) \cdot (\delta_F / \lambda_F) \right] \tag{1}$$

$$\alpha(x) = (I \cdot U / A_F) / \left[T_F(x) - T_{sat}(x) - (I \cdot U / A_F) \cdot (\delta_F / \lambda_F) \right] \tag{2}$$

Compared with the results of the two-dimensional approach presented in [1,5-7], the results of the one-dimensional approach fluctuated within the range of several or several dozen percent, depending on the stage of developed boiling. Typical boiling curves are presented in Fig. 7. Boiling incipience increases the heat transfer coefficient very rapidly, but values of local heat transfer coefficients are relatively low. In the case of the developed boiling, the heat transfer coefficient increased fast and reached high values. As the distance from the minichannel increases, there is a clear decrease in the heat transfer coefficient in the area of developed boiling, first rapid, then mild for higher volumes of the vapour phase. Issues of the experimental void fraction determination based on stereological analysis of the two-phase flow images and vapour quality determination were presented in [2-4,6,7]. Flow pattern maps, two-phase flow pressure drop determination and the heat transfer mechanism during flow boiling on the basis of experimental data were discussed in [4]. Analysis of the data obtained for various orientations of the channel led to conclusion that its spatial orientation had the highest impact on the two-phase flow structures and pressure drop. The development of the enhanced heating surface that affects the fragmentation has an impact on the nature and appearance of flow structures. Generally, the boiling incipience was noticed to occur at lower heat flux applied to the enhanced heating foil, compared with the results obtained from the minichannels with plain foil used [2,4]. Thus, the heating surfaces with the proposed arrangement of cavities provide a large number of nucleation sites, which in turn intensify the heat flux transferred from these surfaces and ensure earlier boiling incipience.

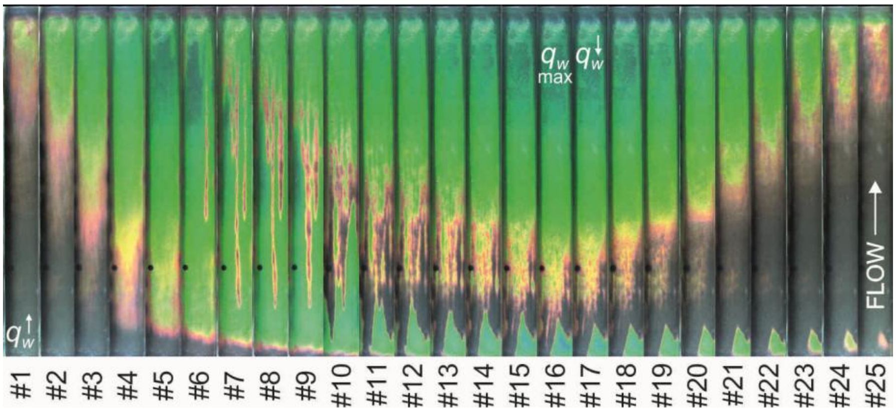

Fig. 4. Colour heating foil images, while increasing and later decreasing heat flux supplied to the enhanced heating surface, inclination of the minichannel in relation to the level plane - 45°, experimental parameters: G = 211 kg/(m^{2}s), p_{in} = 129 kPa, ΔT_{sub} = 42 K, q_w = 9.60÷22.45 kW/m^2

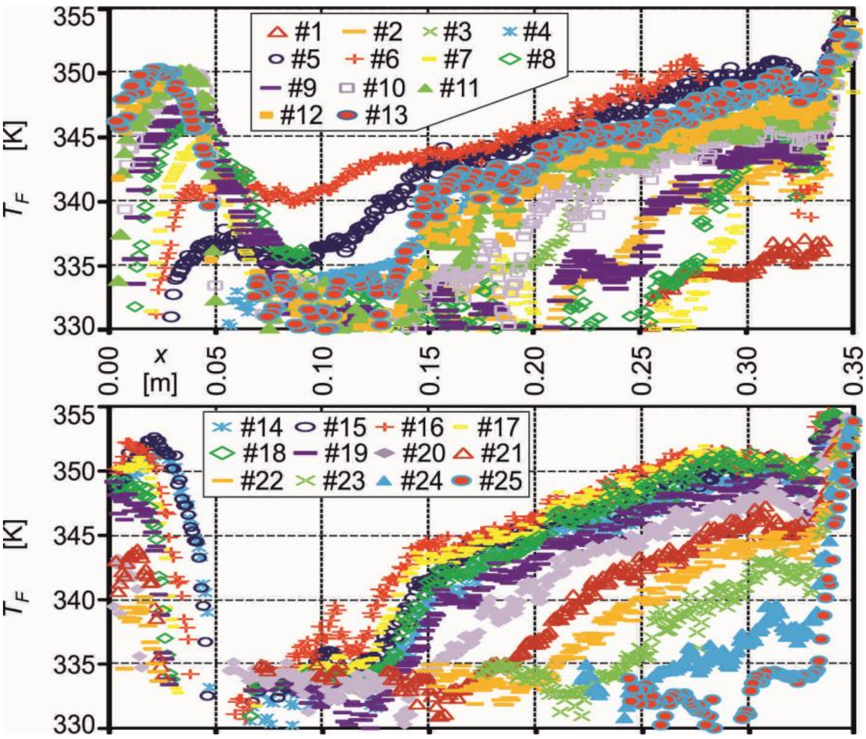

Fig. 5. Heating foil dependence on the distance along the minichannel length, experimental data as for Fig. 4

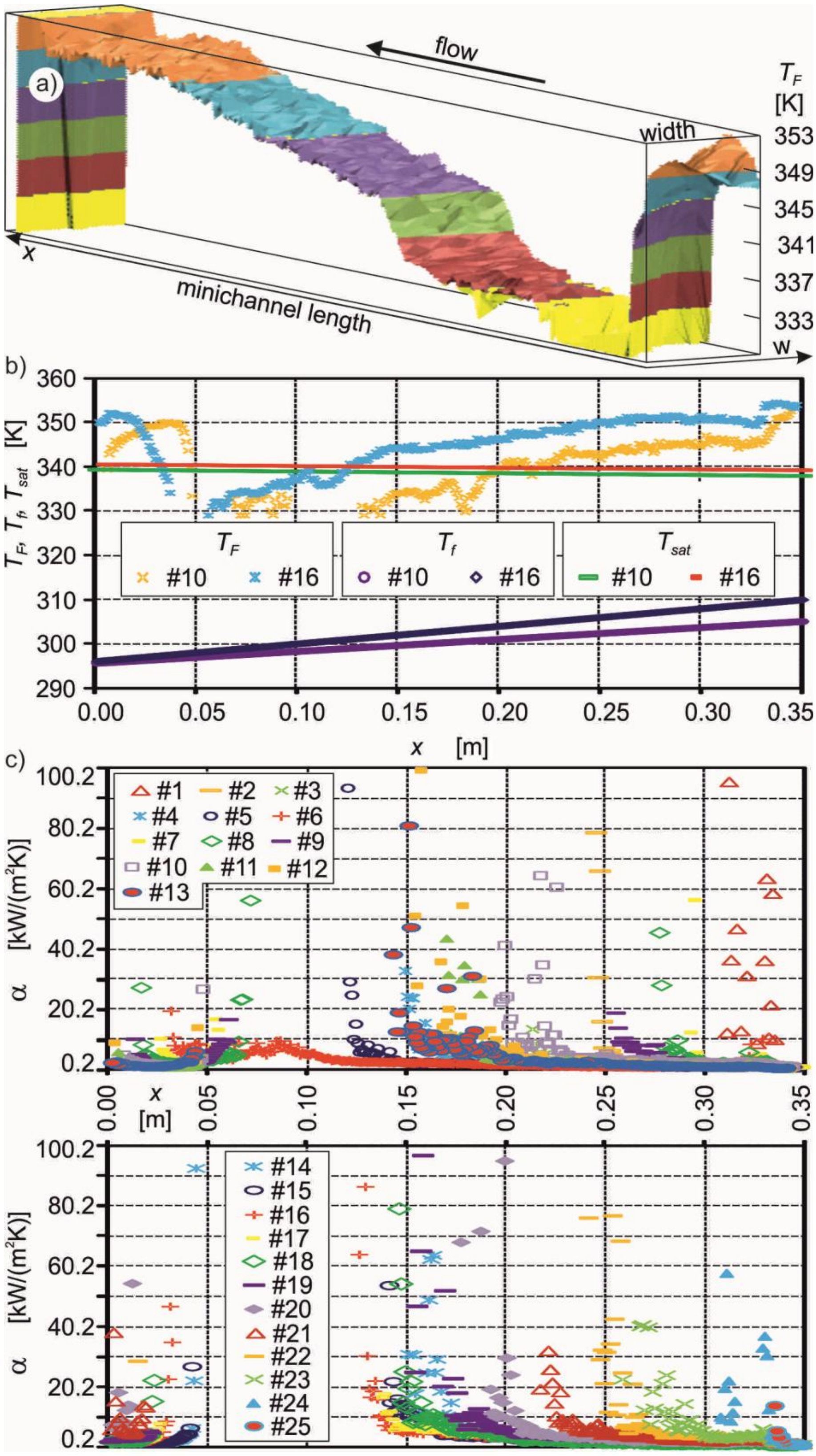

Fig. 6. a) 3D local temperature distribution of the heating foil for setting #16; b) dependences between liquid temperature, saturation and heating surface as a function of the distance from the inlet to the channel for settings #10 and #16; c) local heat transfer coefficient as a function of distance from the minichannel inlet (all settings); experimental data as for Fig. 4

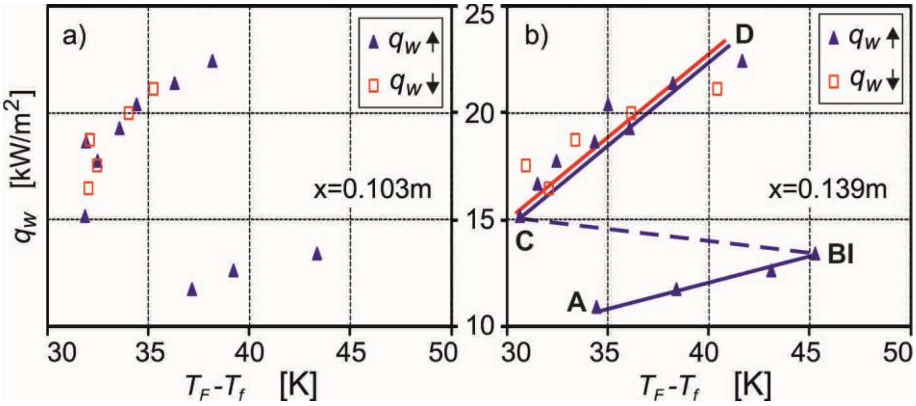

Fig. 7. Typical boiling curves for the distance: a) 0.103 m, b) 0.139 m from the minichannel inlet, experimental data as for Fig. 4

4. OBSERVATIONS AND CONCLUSIONS

Practical aspects of the application of enhanced surfaces in heat transfer research by using the two types of heat exchangers devices were underlined. The first one is test section with a minichannel with an enhanced heating surface. The application of liquid crystal thermography allowed the measurement of temperature distribution on the plain side of the heating foil. The latter includes prototype hybrid collector consists of the photovoltaic cells and the solar collector with enhanced surface of the absorber's pipes.

The use of liquid crystal thermography helped determination heating surface temperature during the flow of FC-72 through a minichannel. Analysis covered local heat transfer coefficient dependence on the distance along the channel length and the boiling curves. The previous observations have confirmed experimentally 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 channels employing the plain foil. Thus, the heating surfaces with the proposed arrangement of recesses make it possible to provide a large number of nucleation sites.

It was found that prototype hybrid solar collectors with mini-recesses formed on the surface of the absorber's pipes have higher energy efficiency in comparison with the collectors with plain absorbers.

To sum up, the analysis of all results of the discussed studies indicates that the application of enhanced surfaces allows achieving effective heat transfer.

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ANWENDUNG VON ENTWICKELTEN HEIZOBERFLÄCHEN IN WÄRMEÜBERGANGSGERÄTEN

ZUSAMMENFASSUNG: Dargestellt wurden in der Arbeit einige ausgewählte Aspekte der Anwendung von entwickelten Heizoberflächen in Wärmeübergangsgeräten.. Den ersten von ihnen bildet das Testmodul mit dem Minikanal. Besprochen wurde der Wärmeübergang beim Sieden im Durchfluss des FC-72 durch den 1 mm tiefen, 40 mm breiten und 360 mm langen Minikanal. Eine dünne Folie mit Mikro- und Minivertiefungen, gelegen auf einer Seite, bildete die entwickelte Heizoberfläche. Gemessen wurde die Temperaturverteilung auf der Außenoberfläche der Folie bei Anwendung von LC-Kristallen. Die Durchflussstrukturen wurden von der Seite der entwickelten Oberfläche her beobachtet, die in direktem Kontakt mit Flüssigkeit im Minikanal stand. Identifiziert wurden die lokalen Temperaturen der Heizoberfläche, der Flüssigkeit und der Sättigung und es wurden die Beispiele für Ergebniskurven vom Sieden sowie für lokale Wärmeübernahmekoeffizienten dargestellt. Die zweite Art von Geräten bilden die hybriden Sonnenkollektoren mit entwickelter Oberfläche der Absorber als Außenoberfläche der Rohrleitungssysteme. Eine grobe Analyse der Ergebnisse zeigt, dass die Anwendung von entwickelten Oberflächen einen effektiveren Wärmeübergang gewinnen lässt.

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