TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

No. 128, 2015, 59–72

EWELINA STRĄK[1], ROBERT PASTUSZKO,
ROBERT KŁOSOWIAK and RAFAŁ URBANIAK

Study of heat transfer during pool boiling on minifins surface coated with carbon nanotubes

Kielce University of Technology, Aleja Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland

Abstract

The article describes the study of heat transfer during pool boiling on minifins surface coated with nanostructure. This is a molecular level technology used in engineering or mechanical factory. A surface with carbon nanotubes (CNTs) is highly effective in reducing the superheat incipience and enhancing both the heat flux and heat transfer coefficient. The paper focuses on the comparison of the surfaces, on which pool boiling heat transfer occurs, i.e., on minifins coated with carbon nanotubes (MF+N) with surfaces formed by sintering the woven copper wire mesh to the minifins tips (MF+M) and with plain minifins surface (MF). The experiments were carried out for two boiling fluids: water and ethyl alcohol. The purpose of the presented study was to find out which of those tested surfaces and fluids could be the best alternative for use in the cooling of electronic devices and which surfaces could be used as thermosyphon or heat pipe evaporator.

Keywords: Pool boiling; Carbon nanotube; Heat transfer coefficient; Minifins; Power electronic cooling

Nomenclature

a	–	mesh aperture, mm
CHF	–	critical heat flux

[1]Corresponding Author. E-mail address: enadstawna@tu.kielce.pl

HTC	–	heat transfer coefficient
h	–	minifin height, mm
l	–	distance, mm
MF	–	surface code (minifin)
MF+N	–	surface code (minifins with carbon nanotubes)
p	–	minifins pitch, mm
q	–	heat flux, kW/m^2
q^+	–	increasing heat flux
s	–	distance between minifins, mm
T	–	temperature, K
w	–	width, mm

Greek symbols

α	–	heat transfer coefficient, kW/(m^2 K)
δ	–	thickness, mm
ΔT	–	superheat referred to the micro-fin base, K
λ	–	thermal conductivity, W/(m K)
ρ	–	density, kg/m^3

Subscripts

bs	–	base
Cu	–	structure material (copper)
G	–	grease
sat	–	saturation

1 Introduction

Structures in the nanometer scale have an interesting and often surprising properties. Understanding these characteristics allows us to know the processes at the micro- and macroscale. This knowledge leads to the production of more and more high-tech materials, to design new facilities and to increase the efficiency of existing devices by optimizing their construction and working conditions based on the fundamental processes at the atomic and molecular level.

Cooling high power density devices presents a constant challenge to thermal engineers. Some of the surface modifications have been introduced include minifins [1], pins, grooves, minirecesses [2], increasing surface roughness [3,4], etc. Many of these modifications have been successful in increasing thermal performance, however heat transfer in minichannels still needs to be enhanced.

Small and large-scale modifications to the boiling surface have been shown to enhance pool boiling by augmenting the pool boiling heat transfer coefficient, reducing the surface temperature that corresponds to boiling incipience and delaying the critical heat flux (CHF). Thome in [5] has provided a comprehensive review of both the fundamental and practical aspects of boiling enhancement.

Biercuk *et al.* were the first who conduct research on a single-walled carbon nanotubes (SWCNT)-polymer epoxy. They reported a 70% increase in thermal conductivity at 40 K. The thermal conductivity increased with increasing temperature [6].

New methods employing molecular level structures created in nanotechnology have been proposed in [7,8]. For this purpose, some nanostructures based on copper and aluminum have been introduced due to their relatively high thermal conductivity.

Park *et al.* [9] presented a measurement of heat transfer coefficients (HTCs) and CHFs on a smooth square flat copper heater in a pool of pure water with and without carbon nanotubes. The experiment was performed using multiwalled carbon nanotubes (CNTs) whose volume concentrations were 0.0001%, 0.001%, 0.01%, and 0.05%. Pool boiling HTCs for all tested fluids were in the range from 10 kW/m^2 to the critical heat flux. Test results showed that the pool boiling HTCs were lower than those of pure water but the CHF increased by 200% at the CNTs concentration of 0.001%. The authors wrote that the thin CNTs layer provided thermal resistance and also decreased the bubble generation rate resulting in a decrease in pool boiling HTCs. The same layer decreased the contact angle on the test surface, extended the nucleate boiling regime to high heat fluxes, and reduced the formation of large vapor canopy at near critical heat flux.

Mo *et al.* [10] compared two surfaces – a smooth microchannel and a channel coated with carbon nanofins. They used lithography techniques, adhesive bonding and chemical vapor deposition to manufacture microcoolers with two-dimensional nanofins. The experimental characterization has indicated promising potential for the coolers. For further enhancement of the cooling capability, a low-cost method was proposed to extend the heat transfer surface but some possible reliability concerns were raised [10].

Launay *et al.* [11] fabricated seven Si surfa ces (silicon surfa ces): smooth, CNTs coated, pin-fins, CNTs pin-fins, 3D-structure and three-dimensional structure (3D-structure) with CNTs. Six of them were compared. The highest heat flux was obtained using the 3D-structure. The CNTs was effective only for small superheatings.

Yao *et al.* [12] compared water boiling on Si surfaces with varied nanowire heights – from 2 to 35 nm. As a result, the maximum heat flux of 1340 kW/m^2

was observed for the highest nanowire surface.

Zhong *et al.* [13] used computational fluid dynamics to examine the effects of CNTs microstructures on the surface of the microchannel walls. The microstructures, roughly about 1 mm×1 mm×100 μm, were placed on the surface of the microchannel. They were made up of hundreds of micro-fins across the surface area. These are the clusters of CNTs forced together mainly by the van der Waals interaction. Each microfin is made up of hundreds of CNTs. The effects of CNTs clustered together to form microstructures are still under investigation [13].

This article summarizes the results of the boiling heat transfer enhancement conducted on three types of enhanced surfaces: plain minifins surface – MF, minifins coated with minitubes – MF+M, minifins coated with nanotubes – MF+N for boiling water and ethyl alcohol. The purpose of this article was to find the surface with the highest HTC.

2 Experimental stand

The experiments were carried out at an atmospheric pressure. Table 1 presents the relevant properties of the experimental fluids. The experimental stand presented in Fig. 1 was the measurement system for determining boiling curves and heat transfer coefficients.

Table 1: Properties of water and ethyl alcohol [14,15].

Properties	Water	Ethyl alcohol
Normal Boiling Point, °C	100.0	78.3
Thermal Conductivity, W/m K	0.68	0.169
Liquid Specific Heat, J/kg K	4220	723
Liquid Density, kg/m^3	959	757
Latent Heat, kJ/kg	2251	963

The test rig consisted of the basic module (1) equipped with alternating power supply current (4) up to 230 V supplied through an autotransformer (3). The preliminary power measurement came from a wattmeter (2).

The basic module of the measurement system is presented in Fig. 2. It was instrumented with seven K-type thermocouples (NiCr–NiAl) with the following functions:

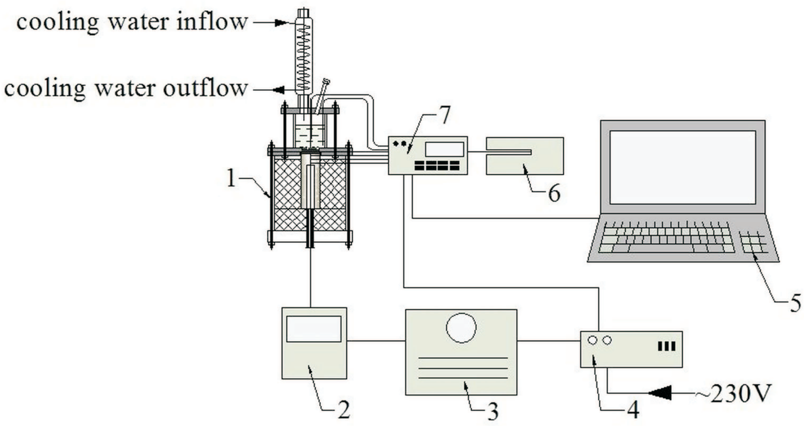

Figure 1: Measurement system: 1 – main module, 2 – wattmeter, 3 – autotransformer, 4 – power supply, 5 – computer, 6 – dry-well calibrator, 7 – data logger.

- termocouples T1 and T2 – to measure the saturation temperature in the boiling fluid (2),
- thermocouples T3 and T4 – to extrapolate the temperature under the sample (6) to the mini-fins base,
- thermocouples T5, T6 and T7 – to determine the temperature gradient in the bar at 5, 20 and 35 mm depth (7).

The basic module consisted of the cylindrical glass vessel (4) situated between the top flange (3) and the investigated sample. The samples were soldered to a 170 mm long copper heating cylinder 45 mm in diameter. A power (11) was delivered to the heating cylinder. The glass vessel (4) was filled with boiling fluid (5). The evaporated liquid was recovered by the condenser (1) connected to the top flange. The basic module stood on a teflon base (10). The copper bar was insulated with ceramic insulation (8) present also under the copper bar (9). Before assembly, the heater was coated with a thermal grease to decrease thermal resistance between the heater and the cylinder material and to eliminate air spaces. The whole system worked as a thermosyphon or heat pipe evaporator.

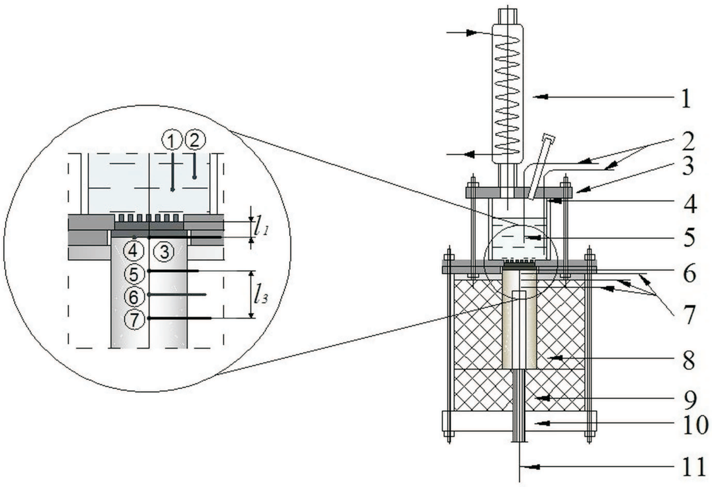

Figure 2: The diagram of the basic module of the experimental stand with details: 1 – condenser, 2 – thermocouple T1 and T2, 3 – upper lid, 4 – glass vessel, 5 – boiling fluid, 6 – thermocouple T3 and T4 underneath the sample MF+N-1.0-1.0, 7 – thermocouple T5, T6 and T7 in the heating cylinder, 8 – insulation, 9 – bottom insulation, 10 – teflon base, 11 – power.

3 Experimental methodology

At first, the glass vessel was filled with boiling fluid. Then the heat flux was applied to the heater until the incipience of pool boiling took place. This was continued to degas the covering.
Next, the fluid was heated to the saturation temperature corresponding to the atmospheric pressure. Further experiments were conducted in order to increase heat flux until boiling crisis took place. The boiling crisis for boiling water was not reached and the maximum heat flux was limited to 700 kW/m^2. The data was recorded every 10 minutes at increasing heat flux and every 15 min at decreasing heat flux.

The temperature distribution was assumed to be linear along the heating cylinder axis. The heat transfer from the cylinder to the base of the tested surface was assumed to be one-dimensional and was calculated with the following formula:

$$q = \frac{\lambda_{Cu} \Delta T_{T5-T7}}{l_3} \ , \tag{1}$$

where l_3 is the distance between thermocouples T5 and T7, shown in Fig. 2 (left).

Temperature superheat (ΔT) was related to the minifins base. Due to the shift of the temperature measurement point, the superheat was calculated with the following relationship:

$$\Delta T = \frac{T_{T3} + T_{T4}}{2} - \frac{q\,l_1}{\lambda_{Cu}} - \frac{q\,l_2}{\lambda_G} - T_{sat} \ , \tag{2}$$

where l_1 is is the distance between the mini-fins base and the upper plane of the groove, shown in Fig. 2 (left); l_2 is the thickness of the grease layer between the upper plane of the groove and thermocouple T3 or T4 (Fig. 5).

Heat transfer coefficient was expressed as:

$$\alpha = \frac{q}{\Delta T} \ . \tag{3}$$

The error was calculated taking into account measurement errors at the lowest and highest heat flux values. The relative error of heat flux for q = 17 kW/m^2 was 18% and 0.7% for q = 545 kW/m^2. The coefficient relative error of heat transfer for q = 17 kW/m^2 was 56% and 1.2% for q = 545 kW/m^2. The absolute error of the temperature referred to the base of the mini-fins was calculated to be 0.2 K.

4 Test surfaces

Three types of structural surface, presented in Figs. 3, 4 and 5, were used:

- 1 mm high plain minifins (MF),
- enhanced surface formed by sintering minifins tips with the copper wire mesh (MF+M),
- enhanced surface made by coating minifins and unfinned surface between minifins with the copper carbon nanotubes (MF+N).

For MF, MF+M and MF+N, the tunnel width in one direction (Tab. 2) was constant.

4.1 MF surface

The square in shape copper surface with a side of 26.5 mm is presented in Fig. 3. It had 112 plain minifins uniformly spaced on the base surface. The parameters of these surface are shown in Tab. 2.

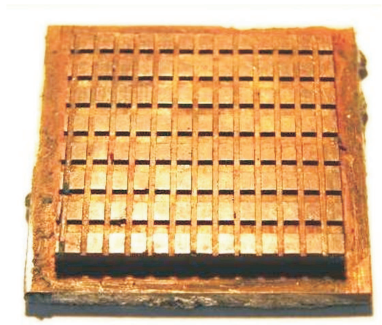

Figure 3: Photograph of the plain minifins test surface, MF.

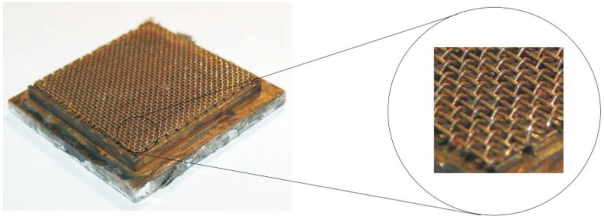

Figure 4: Photograph of the test surface formed by sintering the woven copper wire mesh to the minifins tips, MF+M.

4.2 MF+M surface

These surface were formed by sintering the woven copper wire mesh to the minifins tips. The modifications of plain mini-fins surface were made by using wire with diameter 0.14, 0.20, and 0.32 mm. The surface are shown in Fig. 4 and their parameters are presented in Tab. 2.

Table 2: Denotation and dimensions of tested surfaces in milimeters.

Sample code	δ	s	p_{tun}	w_{tun}	h	h_{total}	a	p_p
MF-1.0-1.0	2.0	1.5	2.0	1.0	1.0	5.5	–	–
MF+M-1.0-1.0-0.3	2.0	1.5	2.0	1.0	1.0	6.0	0.32	0.52
MF+M-1.0-1.0-0.4	2.0	1.5	2.0	1.0	1.0	6.0	0.375/0.4	0.51/0.54
MF+M-1.0-1.0-0.5	2.0	1.5	2.0	1.0	1.0	6.0	0.5	0.82
MF+N-1.0-1.0	2.0	1.5	3.5	1.0	1.0	5.5	–	–

The surface parameters are described in Fig. 5.

4.3 MF+N surface

These surfaces were made by coating the carbon nanotubes on the entire surface of the minifins using the nanotechnology method. The sample was made at Poznań University of Technology, the Department of Heat Engineering. Carbon nanotubes (CNTs) can considerably improve microchannel cooling performance. The molecular structure of CNTs provides good physical and mechanical properties such as great flexibility, high mechanical strength and low weight. Their mechanical and chemical stability ensures the resistance against damage from external chemical and physical factors [16]. After the modification, the surfaces changed color from copper to black/graphite. Schematic view of this sample is presented below; its denotation and dimensions are summarized in Tab. 2. The detailed view in Fig. 5 shows the location of the thermocouple in the groove below the tested surface.

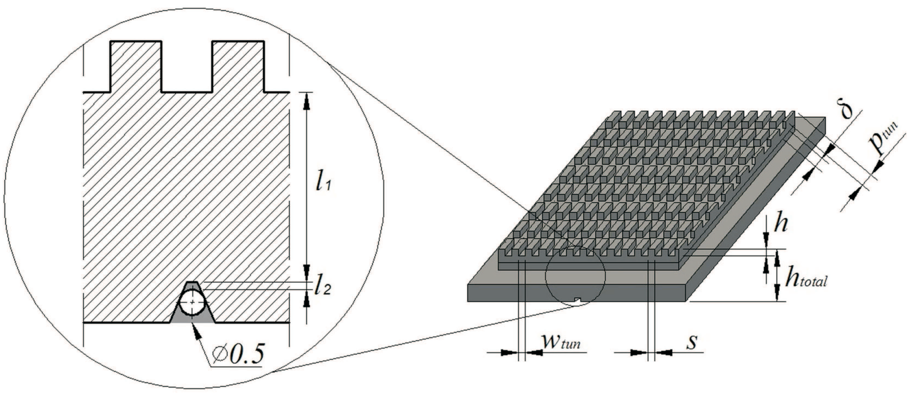

Figure 5: Cross section and schematic view of minifins surface coated with carbon nanotubes, MF+N.

5 Experimental results

5.1 Water boiling

Figure 6 presents heat transfer coefficients for water at increasing heat flux for MF, MF+M and MF+N surface types. The measurement data for the MF+M surface were taken from [17]. For small and medium heat fluxes, that are ranging between 25 and 90 kW/m^2, the highest heat transfer coefficients were recorded on the surface with 1 mm minifins covered with wire mesh (mesh aperture 0.375/0.4 mm). This surface (MF+M-1.0-0.6-0.4) allowed heat transfer coefficients to reach about 17 kW/m^{2}K at heat flux range from 65 to 90 kW/m^2. For high heat flux range, that is more than 320 kW/m^2, the highest heat transfer coefficients were recorded on the surface MF+N. From 13.3 kW/m^2 to 160 kW/m^2, all the surfaces with the sintered mesh gave higher heat transfer coefficients than for plain minifins and minifins with CNTs. The CHF for plain minifins and minifins with wire mesh was from 300 to 320 kW/m^2. For mini-fins surface with CNTs the maximum value of heat flux was 543 kW/m^2, which correspond with the highest heat transfer coefficient equal to 29 kW/m^{2}K. For water boiling the surface with coated CNTs enhanced both the heat flux and heat transfer coefficient better than the surface with sintered wire mesh and plain minifins.

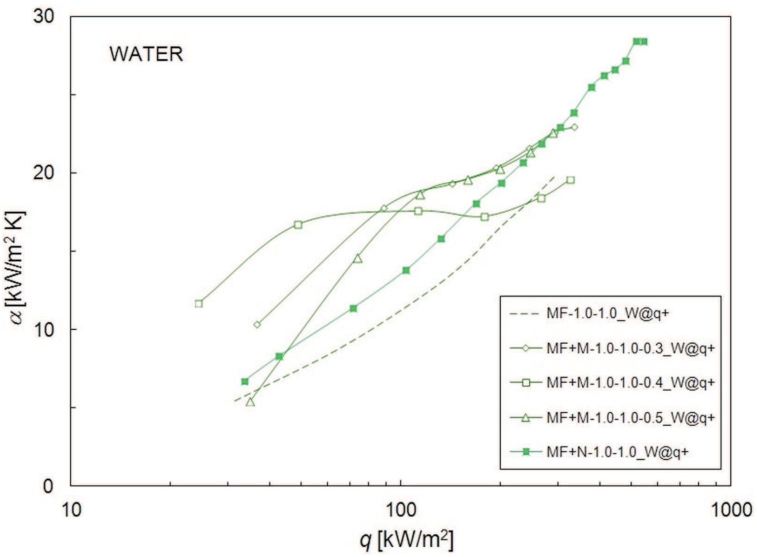

Figure 6: Boiling heat transfer data for water.

The surface with CNTs revealed almost 35% better enhancement than for plain mini-fins and surface with sintered wire mesh (with mesh aperture 0.375/0.4). The MF+M-1.0-1.0-0.3 and MF+M-1.0-1.0-0.5 revealed almost 20% worse enhancement than for surface with CNTs.

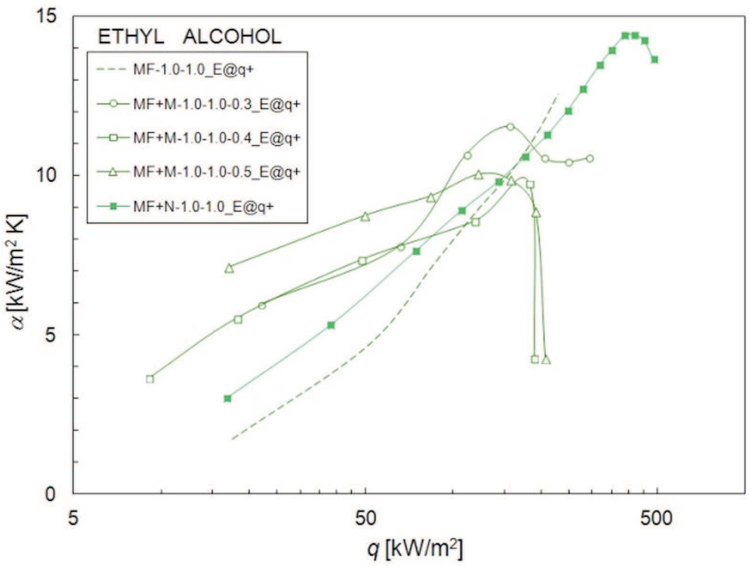

Figure 7: Boiling curves for ethanol.

5.2 Ethyl alcohol boiling

Figure 7 presents heat transfer coefficients for ethyl alcohol at increasing heat flux for MF, MF+M (data from [15]) and MF+N surface types. The boiling curves for ethyl alcohol are similar to boiling curves for water. In small and medium heat flux ranges, that is, 17–95 kW/m^2, the highest heat transfer coefficients were recorded on the surface MF+M with mesh aperture 0.5 mm. In high heat flux ranges, that is, from 145 to 225 kW/m^2, the CHF was reached for all surfaces tested, except surface with deposited CNTs. For minifins surface coated with CNTs, the critical heat flux was almost 400 kW/m^2, which corresponds with the highest heat transfer coefficient equal to 14.5 kW/m^{2}K. In water boiling, as in ethyl alcohol boiling, the surface with CNTs enhanced both the heat flux and heat transfer coefficient better than the surface with sintered wire mesh and plain minifins. The surface coated with CNTs enhanced the HTC relative to:

MF-1.0-1.0 (plain minifins) – by about 13 %
MF+M-1.0-1.0-0.3 – by about 21%
MF+M-1.0-1.0-0.4 – by almost 32%
MF+M-1.0-1.0-0.5 – by almost 31%.

6 Conclusions

The following conclusions can be drawn from the present study:

1. Pool boiling heat transfer of nanostructure size should be further investigated to compare the results and look for the best alternative for the cooling of electronic devices.
2. Both for water and ethyl alcohol at low and medium heat fluxes, the greatest enhancement of boiling heat transfer coefficients was obtained using the mesh-covered minifins, which can be explained by a large number of active nucleation sites.
3. Both for water and ethyl alcohol at high heat fluxes, the greatest enhancement of boiling heat transfer coefficients was obtained using the surface coated with CNTs.
4. The CNTs surface is highly effective in increasing critical heat flux at ethyl alcohol boiling (approximately 3.5-fold increase in the CHF) than the surface with wire mesh.
5. The lowest HTC was observed for plain mini-fins surface for both water and ethyl alcohol.

Acknowledgment The research reported here in was supported by a grant from the National Science Centre (No. DEC-2013/09/B/ST8/02825).

Received 20 March, 2015

References

[1] Pastuszko R., Nadstawna E.: *Pool boiling heat transfer on surfaces with plain minifins and minifins with perforated foil.* MATEC Web of Conf. **16**(2014), 01008-p.1–01008-p.6.

[2] Piasecka M.: *Heat transfer research on enhanced heating surfaces in flow boiling in a minichannel and pool boiling.* Ann. Nucl. Energ. **73**(2014), 282–293.

[3] Pastuszko R., Piasecka M., Nadstawna E.: *Pool boiling and flow boiling on surfaces with microcavities.* In: Proc. 15th Int. Conf. on Heat Transfer and Renewable Sources of Energy 2014. College Publisher of West Pomeranian University of Technology, 2014, 259–266.

[4] McHale J., Garimella S.: *Bubble nucleation characteristics in pool boiling of a wetting liquid on smooth and rough surfaces.* Int. J. Heat Mass Tran. **36**(2010), 249–260.

[5] Thome J.: *Enhanced Boiling Heat Transfer.* Hemisphere Publishing, New York 1990.

[6] Biercuk M., Llaguno M., Radosavljevic M., Hyun J., Johnson A.: *Carbon nanotube composites for thermal management.* Appl. Phys. Lett. **80**(2002), 2767–2769.

[7] Eastman J., Choi S., Li S., Thompson L., Lee S.: *Enhanced thermal conductivity through the development of nano-fluids.*. Proc. Symp. on Nanophase and Nanocomposite Materials II, Materials Research Society **457**, 1997, 3–11.

[8] Wang X., Mujumdar A.: *Heat transfer characteristics of nanofluids: A review.* Int. J. Therm. Sci. **46**(2007), 1–19.

[9] Park K. , Jung D., Shim S.: *Nucleate boiling heat transfer in aqueous solutions with carbon nanotubes up to critical heat fluxes.* Int. J. Multiphas. Flow **35**(2009), 525–532.

[10] Mo Z., Morjan R., Anderson J., Campbell E., Liu J.: *Nanotube microcooler for microelectronics applications.* In: Proc. Electronic Components and Technology Conf. 2005, 51–54.

[11] Launay S., Fedorov A., Joshi Y., Cao A., Ajayan P.: *Hybrid micronanostructured thermal interfaces for pool boiling heat transfer enhancement.* Microelectron. J. **37**(2006), 1158–1164.

[12] Yao Z., Lu Y., Kandlikar S.: *Effects of nanowire height on pool boiling performance of water on silicon chips.* Int. J. Therm. Sci. 2011, 2084–2090.

[13] Zhong X., Fan Y., Liu J., Zhang Y., Wang T., Cheng Z: *A study of CFD simulation for on-chip cooling with 2D CNT micro-fin array.* Proc. HDP 2007, 1–6.

[14] Pastuszko R.: *Boiling heat transfer in subsurface tunnels.* Kielce University of Technology, monography **M33**(2012), 37.

[15] Piasecka M.: *An application of enhanced heating surface with minirecesses for flow boiling research in minichannels.* Heat Mass Transfer **49**(2013), 261–271.

[16] Tullius J., Vajtai R., Bayazitoglu Y.: *A review of cooling in microchannels.* Heat Transfer Eng. **32**(2011), 527–541.

[17] Pastuszko R.: *Pool boiling on micro-fin array with wire mesh structures.* Int. J. Therm. Sci. **49**(2011), 2289–2298.