International Journal of Heat and Mass Transfer 101 (2016) 198–204

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Efficient heat removal via thorny devil nanofiber, silver nanowire, and graphene nanotextured surfaces

Hyun Yoon [a,1], Min-woo Kim [a,b,1], Hayong Kim [a,1], Do-Yeon Kim [a], Seongpil An [a], Jong-Gun Lee [a], Bhavana N. Joshi [a], Hong Seok Jo [a], Jeehoon Choi [c], Salem S. Al-Deyab [d], Alexander L. Yarin [a,e,*], Sam S. Yoon [a,*]

[a] *School of Mechanical Engineering, Korea University, Seoul 136-713, Republic of Korea*
[b] *Green School, Korea University, Seoul 136-713, Republic of Korea*
[c] *LG Electronics Inc, Seoul, Republic of Korea*
[d] *Petrochemicals Research Chair, Dept. of Chem., King Saud University, Riyadh 11451, Saudi Arabia*
[e] *Department of Mechanical and Industrial Engineering, University of Illinois at Chicago, 842 West Taylor Street, Chicago, IL 60607-7022, United States*

ARTICLE INFO

Article history:
Received 4 December 2015
Received in revised form 6 May 2016
Accepted 6 May 2016

Keywords:
Water cooling
Heat removal
Nanotextured surface
Nanomaterials

ABSTRACT

Several types of nano-textured surfaces were studied with the goal to enhance heat removal rate in a cooling device (a heat sink) with water flow-through. The nano-textured surfaces where heat removal to flowing water took place included: (i) electrospun copper-plated thorny-devil nanofibers deposited on the copper substrate, (ii) graphene oxide flakes sprayed on the copper substrate, and (iii) silver nanowires spin-coated on a separate copper substrate. Their cooling performance was monitored by measuring the difference between the outlet and inlet temperature of water flowing through the heat sink and the temperature of the nano-textured copper substrate in the heat sink. The effect of the macroscopic vortex generator (wires) on cooling of the heat sink surface was less than that of the nano-textured surfaces, which revealed that the latter provide a much larger interfacial area, rather than an extra flow mixing, to enhance heat transfer rate. Of the nano-textured surfaces the most significant cooling enhancement was achieved with silver nanowires.

1. Introduction

Nano-textured surfaces having at least one dimension in the nanometer range are in high demand in various applications such as electronics, photonics, advanced materials and biomedical devices [1–3]. Such nano-textured surfaces also hold great promise for electronic cooling due to their superior heat transfer properties [4–11]. Different micro/nano-textured materials were either synthesized or formed by deposition techniques having in mind enhanced cooling of high-heat-flux surfaces [12–14]. These micro/nano-textured materials and devices can provide efficient cooling systems for the miniaturized electronics, such as multicore processors, lasers, radars, lighting equipment, and power electronics by dissipating heat flux efficiently and thus, minimizing the malfunction probability or even failure of the devices [13]. However, removing heat has been a great challenge in the field of electronics cooling because it is essentially limited by the surface area and coolant types, which is difficult to modify [15,16]. A space to which a cooling device is employed in electronics is in general extremely confined. Power consumption should be minimized for energy saving reason and to minimize acoustic noise driven by pumps or fans at higher convective heat transfer. Nano-texturing can provide an alternative route to meet the desired goal under these challenges. Nano-texturing can also facilitate enhanced cooling via, first, the increased surface areas and, second, by generating numerous small-scale structures that promote an extra mixing.

In general, water or air have been used as coolants because of their facile availability. In the case of water cooling, hydrophobic rough surfaces can transfer heat faster by inducing faster boiling [17]. Refs. [12,17] reported use of scratched silicon and nanowire arrays of silicon and copper for their boiling studies. The use of such textured substrates has increased the heat transfer by creating more active sites for boiling. The authors of Ref. [13] deposited different ZnO nano-structures on copper, aluminium and silicon substrates for a micro-reactor for faster cooling of a heated device.

---

[*] Corresponding authors at: The University of Illinois at Chicago (A.L. Yarin), School of Mechanical Engineering, Korea University, Seoul, Republic of Korea (S.S. Yoon).

E-mail addresses: ayarin@uic.edu (A.L. Yarin), skyoon@korea.ac.kr (S.S. Yoon).

[1] These authors have contributed equally.

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.05.030
0017-9310/© 2016 Elsevier Ltd. All rights reserved.

They have observed a ten-fold increase in heat transfer rate as compared to the bare substrate case in forced convection. Copper-plated electrospun nanofibers (thorny-devil nanofibers) were used in drop/spray cooling and pool boiling [4–11] as well as in air cooling [16]. In all these cases (drop/spray cooling, pool boiling and forced air convection) it was reported that copper-plated nanofibers increased the heat transfer rate dramatically.

The authors of Ref. [18] prepared flower-like copper oxide nanostructures, which were used to enhance heat transfer in pool boiling due to the high surface-to-volume ratio of these nanostructures and capillary wicking, which in turn, increased the critical heat flux by 58%. Different designs and dimensions of microchannel heat sinks have also been extensively studied [19,20], as well as it was demonstrated that microchannel flows of suspensions of carbon nanotubes filled with phase change materials could be beneficial as heat sinks [21]. The effect of particle-laden water on critical heat flux in pool boiling was demonstrated [22]. It was shown that inclusion of titania and alumina nanoparticles enhanced the critical heat flux as compared to that of pure water.

The above-mentioned references reveal that nano-texturing is useful for enhancing heat transfer rate. Herein, we employ various nanomaterials (thorny-devil nanofibers, reduced graphene-oxide (rGO), and silver nanowires) which yield different nano-textured surfaces and thus different heat transfer patterns in forced convection of water over such surfaces. All these nanomaterials possess high surface-to-volume ratios, and being deposited on a surface create a ‘‘fluffy” layer which facilitates enhanced heat transfer.

2. Experimental

2.1. Water cooling system

The experimental setup of the heat sink system used in the present study is shown in Fig. 1. The loop consists of a thermostat (Lab. Companion, RW-0525G), heat-sink (or often called as ‘‘cold plate”), data acquisition unit (MV-1000, YOKOGAWA, Japan), and power supply. Working fluid (water) at 15 ± 1 °C was pumped from the thermostat though the heat-sink inlet and then from its outlet to the thermostat.

The flow rate (3.1–9.1 mL/s) of the working fluid was measured with an accuracy of ±1%. The temperature of the heat-sink was measured, at the bottom side, by T-type thermocouples (probe size = 1.0 $\varnothing \times$ 150 mm), with an accuracy of ±0.1 °C. The data were collected by the data acquisition unit.

The test module consisted of a top cover, rubber sealing, middle frame, copper plate, bottom cover, and a heater as illustrated in Fig. 2(a). Top and bottom cover are bolted with the middle frame using Hex Socket-Head Cap Screw. A detailed schematic of the heat sink, thermocouple, copper substrate, and heater (the bottom copper plate decorated with sprayed nano-textured material) are shown in Fig. 2(b). The heat sink was fabricated from stainless-steel. The top cover of the heat sink was 0.5 cm in thickness, 6.5 cm wide and 3.0 cm deep. Water flow was passing through the channel cross-section of 1 cm × 1 cm as shown in Fig. 2(a). Nano-textured materials were sprayed onto the copper bottom and were located on its side facing the impinging water flux.

2.2. Fabrication of nano-textured surfaces

2.2.1. Copper oxide nanofibers

The electrospun nanofibers were prepared from 6 wt% of polyacrylonitrile (PAN, $(C_3H_3N)_n$; M_w = 150 kDa; Sigma–Aldrich) in N,N-Dimethylformamide (DMF, $HCON(CH_3)_2$; anhydrous 99.8%; Sigma–Aldrich), while stirring by magnetic stirrer for 24 h at room temperature. To prepare the electroplating solution, sulfuric acid (10 g, H_2SO_4; 97%; Matsunoen Chemicals Ltd.), hydrochloric acid (1 g, HCl; 35%; Duksan Chemical), copper(II) sulfate (32 g, $CuSO_4$; 99.99%; Sigma–Aldrich), and formaldehyde solution (20 g, HCHO; 35%; Samchun Chemicals) were mixed with 200 mL of deionized (DI) water. Sulfuric acid increased solution conductivity to enhance the electroplating process.

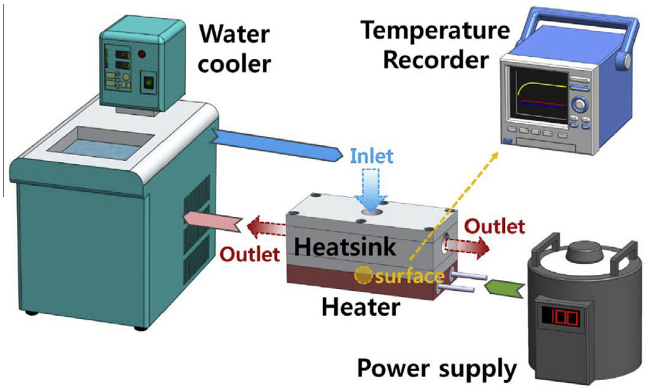

Fig. 1. Schematics of the heat-sink system. Cold water is supplied into the inlet of the heat-sink, which incorporates nano-textured surfaces. The heater is cooled therefore and the heat transfer from the nano-textured surface of the heater to cold water takes place. A thermocouple is embedded at the bottom of the heater surface to monitor its temperature. The heated water exits back to the water cooler/chiller and the cold inlet temperature is reset.

The PAN 6 wt% solution was supplied by a syringe pump (KDS LEGATO 100) at the flow rate of Q = 150 μL/h to a needle with the inner and outer diameters of 0.25 and 0.52 mm, respectively (EFD 25 gauge). The needle was attached to a DC source (Glassman High Voltage Inc., EL40P1). The applied voltage was in the 5–6 kV range. The nozzle-to-substrate distance was 10 cm. The PAN nanofibers were electrospun onto a copper substrate and subsequently copper-plated on top of it, thus creating a nano-textured surface.

2.2.2. Reduced graphene oxide

To form another type of nano-textured surface, the rGO solution consisting of rGO flakes (N006-P, Angstron Materials, USA) dispersed in dimethylformamide (DMF) was purchased from Duksan Chemical, Korea, used as dispersant. More detail on the rGO flakes used can be found in Table 1. The rGO solution atomized in the Laval nozzle and formed supersonic kinetic spray as reported in our previous paper [23]. The copper substrate was located at 60 mm from the Laval nozzle exit. The nozzle exit was installed on a maneuvering stage that traversed the 50 mm length. The moving nozzle could, in principle, traverse the length of any fixed substrate that might be required to cover a larger coating area. The atomized rGO suspension droplets moved through open air at room temperature until they were deposited onto the copper substrate and formed nano-textured rGO coatings.

2.2.3. Silver nanowires

Silver nanowires (AgNW, 0.15 wt%) dispersed in isopropyl alcohol (IPA) were purchased from AIDEN Co. The nanowires possessed an average diameter and length of 20 nm and 15 μm, respectively. A transparent and homogeneous suspension of AgNWs was stirred with magnetic bar and subsequently aged for 1 h. Then, AgNWs were spin-coated on a pre-cleaned copper substrate (53 mm × 20 mm). A 0.5 mL drop of AgNW suspension was dripped onto a copper substrate, which was spun for 30 s at 4000 rpm using a spin coater. Then, the substrate was pre-annealed at 250 °C on a hotplate. This process was repeated eight times to form a copper surface with AgNW nano-textured structure. Finally, such surfaces were annealed in air using a two-step