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Pool boiling on nano-textured surfaces comprised of electrically-assisted supersonically solution-blown, copper-plated nanofibers: Experiments and theory

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ABSTRACT

Pool boiling of ethanol, water and their binary mixtures on nano-textured surfaces comprised of copper-plated nanofibers was studied experimentally. The nanofiber-covered surfaces were formed using polymer nanofibers produced by the electrically-assisted supersonic solution blowing process followed by copper-plating. The pool boiling data on the nano-textured surfaces did not follow the standard boiling curve and showed a sharp deviation. In particular, the heat flux and accordingly, the heat transfer coefficient, were found to be significantly higher at low surface superheats. It was also demonstrated that the nano-textured surfaces developed in the present work are robust and do not deteriorate after several cycles of pool boiling experiments. The process features uncovered in the present experiments are attractive for cooling of high-power microelectronics. A novel theoretical approach to pool boiling modeling introduced in this work revealed several detailed morphologies of fluid motion in the pool boiling process observed experimentally.

1. Introduction

With the growing demand for communications, automations and computing, effective heat removal from electronic equipment is one of the biggest challenges. Pool boiling is one of the most promising tools for handling the heat management problem. However, it is limited by vapor film formation on the heated surface resulting in loss of performance. Pool boiling on hot smooth and rough, intact and porous, plane and cylindrical surfaces was investigated using various liquids (water, alcohols, refrigerants, and fluorinerts) in a number of works [1–8]. Voluminous data sets were acquired, and based on them numerous empirical and semi-empirical models were proposed for pool boiling under normal gravity conditions [9–14]. Pool boiling over nano-textured surfaces was recently explored experimentally and theoretically, and it was shown that such surfaces dramatically increase bubble nucleation rate because liquid temperature around bubbles in nano-cavities is significantly increased [15,16]. It was also reported that nanostructures can prevent bubble merging and affect transition to film boiling [16].

Pool boiling under microgravity conditions in relation to cooling of microelectronics during space missions attracted attention as early as in 1959 [17]. Later on, several additional experiments on pool boiling were conducted under different gravity conditions, and it was reported that gravity has a minor effect on cooling rate of smooth surfaces [18–21]. In addition, it was also found that the cooling rate under normal gravity was reduced in comparison to that under supergravity (>1 g) [22]. A detailed review of such studies is available in Ref. [23].

Having in mind a further enhancement of heat removal under normal gravity and especially at zero gravity, pool boiling of water over superhydrophobic smooth surfaces was studied [24–26]. Under normal gravity the measured cooling rates were in the range of 1–4.5 W/cm^2. For comparison, pool boiling of water over electrospun copper-plated nanofibers (the nano-textured surfaces) studied in Ref. [15] revealed the maximum heat flux close to 65 W/cm^2. On the other hand, these values are lower than the value of 190 W/cm^2 achieved in pool boiling on nano-textured electrospun copper-plated surfaces in Ref. [27]. It should be

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emphasized that in the latter work pool boiling was observed in shallow puddles produced due to an improper operation of a drop generator in several cases at zero gravity when it issued multiple droplets instead of a single droplet. On the other hand, in the full-scale pool boiling in thick liquid layers in reservoirs, a significant reduction in the heat removal rate was observed, which was attributed to the absence of buoyancy force [28,29]. It was assumed that under such conditions vapor bubbles are removed from the boiling surface due to the thermo-capillary Marangoni flow [30], which is driven by the surface of a much larger bubble located at some distance from the surface. The Marangoni flow generated by the big bubble subjected to the temperature gradient pulls the small bubbles from the surface of boiling toward the big bubble, thus "feeding" it [28,29]. In the latter works, electrohydrodynamic forces were proposed as a means of enhancement of vapor bubble removal from the boiling surface under zero gravity conditions.

Pool boiling of pure ethanol and pure water on surfaces comprised of electrospun nanofiber mats were conducted in [15]. These nanofiber mats revealed an increase in the heat flux but an associated drawback was that in some cases they were subjected to delamination from the heater surface. In the present work nanofiber mats were formed using a novel process of the electrically-assisted supersonic solution blowing [31]. This process results in the 100–200 nm PAN nanofibers with a strong adhesion to the heater surface, which allows them to withstand pool boiling without delamination. Such fiber can be also copper-plated using the approach already applied for metal-plating of electrospun nanofibers [32,33]. The present work also aims at the theoretical description of boiling process under the normal gravity conditions.

Section 2 describes preparation of nanofiber mats on the heater surface: materials used, solution preparation and supersonic solution blowing, as well as copper-plating of the resulting nanofibers. Section 3 describes the pool boiling experiments: the experimental setup developed and used in these experiments, and the experimental procedure implemented. Section 4 is devoted to the experimental results and discussion, in particular, to the optical observations, and pool boiling curves of pure ethanol, pure water and different ethanol–water mixtures. In Section 5 devoted to modeling of pool boiling process under the normal (earth) gravity conditions, a novel continuum approach is introduced, which combines the fluid mechanical and thermal balance equations, and the molecular balance equation with the temperature-dependent diffusion and intermolecular interactions in the fluid bulk modeled by the Lennard–Jones potential. This section describes the governing equations, as well as some results of their numerical solution. Conclusions are drawn in Section 6.

2. Preparation of nanofiber mats on heater surface

2.1. Materials

Polyacrylonitrile (PAN; $M_w = 150$ kDa) was obtained from Polymer Inc. N-Dimethyl formamide (DMF) anhydrous-99.8%, sulfuric acid, hydrochloric acid, copper sulfate, formaldehyde were obtained from Sigma–Aldrich. Oxygen-free high-conductive (OFHC) 101 grade copper plates were purchased from Mcmaster-Carr to be used as anode in copper-plating. Ethanol (200 proof) was obtained from Decon Labs Inc. Copper rods of super-conductive grade were obtained from McMaster-Carr. They were cut into cylindrical pieces and used as substrates. Prior to deposition of nanofiber mats, copper plates were roughened using a 3M Pro Grade sand paper P80 and P180.

2.2. Preparation of solutions

Supersonic electrically-assisted solution blowing was conducted with 6 wt% PAN solutions in DMF. Electroplating bath was prepared by mixing sulfuric acid (5 g), hydrochloric acid (0.5 g), copper sulfate (16 g) and formaldehyde (10 g) in 100 mL of deionized (DI) water.

2.3. Electrically-assisted supersonic solution blowing

The electrically – assisted supersonic solution blowing was conducted as in the previous work of this group [31]. A 6 wt% PAN solution in DMF was pumped through a 25 gauge needle using the syringe pump at a flow rate of 0.1 ml/h. A supersonic Laval nozzle 209-L, obtained from Silvent, was employed for supersonic blowing of air. The nozzle was connected to house pressure line operating at 70 psi. The horizontal and the vertical distances between the needle and the nozzle were kept at 1 and 2.5 cm, respectively. Electric potential was set up between the needle and the nozzle with the nozzle being grounded, and the voltage was sustained at 6 kV. The electrically-driven polymer jet issued from the needle was attracted to the nozzle core and then entrained and swept away by the high speed air flux issued from the nozzle. The air velocity measured using a probe of diameter 0.256 mm and a flow meter (Omega), was 564.6 m/s at the exit of the nozzle. The polymer jet underwent a tremendous stretching by such a strong air blow, accompanied by an additional stretching due to bending instability, thinned significantly, while solvent had been evaporating in flight, and the resulting dry nanofibers were collected on Cu disks for 5 min at a distance of 23.5 cm from the nozzle. A schematic of the experimental setup used for deposition of nanofiber mat on Cu disks by supersonic solution blowing is shown in Fig. 1.

2.4. Copper-plating of nanofiber mats

Since polymer nanofiber mats have a relatively low thermal conductivity, they were copper-plated as a post-processing. Since PAN nanofibers are non-conductive (electrically), the nanofiber mat had to be sensitized for a proper copper-plating. Accordingly, the polymer nanofiber surfaces were coated with 7.5 nm Pt-Pd layer using Cressington Sputter Coater. After that, the mats were soaked in the electroplating solution, and copper-plated using a Cu disk with the nanofiber mat as a cathode and OFHC Cu plate as an anode. Such post-processing allowed copper-plating the nanofiber surfaces uniformly and bonding them to the substrate. The copper-plating process of the sputter-coated nanofiber mats employed the Electroplating Station HSEPS-10 and followed the procedure of Ref. [32].

2.5. Observations

Scanning electron microscopy of copper-plated nanofiber mats was done using JEOL JSM-6320F with a cold emission source, while the optical images were taken using optical microscope Olympus BX-51.

3. Pool boiling experiments

3.1. Experimental setup

A setup for the experimental investigation of pool boiling on nano-textured surfaces was designed and built having in mind experiments both under normal gravity and under microgravity conditions. The experimental setup is a further development of