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Pool boiling in deep and shallow vessels and the effect of surface nano-texture and self-rewetting

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Abstract

Pool boiling of ethanol and self-rewetting fluids on bare copper surface and copper surface with polymer nanofibers were studied experimentally. No significant effect of the depths of ethanol layer on the heat removal rate was found. That indicates that only the heat transfer in the liquid microlayer near the heater surface is a dominant factor. As a result, one can expect that self-rewetting fluids can significantly affect boiling performance. Accordingly, several alcohol solutions including the self-rewetting ones were investigated as working fluids in the boiling chamber. It was found that at the 0.1% (v/v) concentration, only the high carbon-alcohol, n-heptanol in aqueous solution, improved boiling heat transfer considerably. Furthermore, the experimental study of the effect of surface nano-texture on boiling characteristics was undertaken. For that aim, polyacrylonitrile (PAN) nanofibers were deposited onto the copper heater surface. Measurements of the boiling curve revealed a detrimental effect of such nano-texture in the case of such working fluids as ethanol and self-rewetting n-heptanol solutions. On the other hand, when polystyrene (PS) nanofibers were deposited onto the copper heater surface instead of PAN nanofibers, a significant improvement in boiling heat transfer was observed. The more hydrophobic nature of PS compared to copper is responsible for this effect, i.e. is the reason of the heat transfer enhancement on such a nano-textured surface compared to the pure copper one. In addition, the critical heat flux in the case of n-heptanol solution was found to be reduced considerably on the PS nano-textured surface compared to the pure copper one. This stems from the increased propensity of the heater surface to be covered by vapor, while the rewetting is insufficiently effective at high heat fluxes in presence of PS nanofibers.

1. Introduction

Pool boiling is of considerable interest due to its high heat transfer coefficients, which is attractive for heat removal from high-power microelectronics [1]. The physical and engineering aspects of pool boiling of pure liquids and the accompanying technological developments prior the year 1998 were reviewed in Ref. [2]. A critical review of different mechanisms of heat transfer on nucleate pool boiling is also available in Ref. [3]. Heat removal in microgravity is one of the main concerns and the peculiarities of heat transfer in

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Conflicts of interest

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pool boiling under microgravity conditions were discussed in Refs. [4,5]. The effect of the heater size on heat removal in boiling has been extensively studied; cf. Refs. [6–8]. Boiling has been found to be buoyancy-dominated for heaters above a certain minimum size and to be surface-tension-dominated below this minimum heater size. Such a transition is characterized by the ratio of the heater length scale (L_h) to the capillary length (L_c). The corresponding value of the ratio L_h/L_c is generally found to be between 2.1 and 2.8; cf. Refs. [6,8].

Altering the surface characteristics of the heater is attractive as one of the passive enhancement strategies in boiling heat transfer. Different approaches to achieve micro/nano-textured heater surfaces used in boiling heat transfer are detailed in Ref. [9]. Various methods used for this aim include several mechanical techniques, coating, chemical processes and micro/nano-electro-mechanical system techniques [9]. A further review of the performance of the micro/nano-engineered surfaces in pool and flow boiling is given in Refs. [10,11]. In particular, in Ref. [10] it was concluded that in general micro-textured surfaces provided heat transfer enhancement comparable to that of the nano-textured surfaces and there is room for improvement of the latter. It should be emphasized that several aspects of heat transfer in boiling, such as nucleate boiling and an increase in the critical heat flux (CHF) attracted significant attention. The enhancement of nucleate boiling heat transfer (NBHT) depends upon an increase in the number of nucleation sites and the bubble departure frequency; cf. Ref. [9]. The micro/nano-texture of the heater surface is supposed to increase NBHT by increasing the number of the active nucleation sites and promoting bubble initiation and growth; cf. Ref. [9].

Wettability of the heater surface is a very important factor in determining the heat transfer rate in pool boiling. The concept of biphilic surface patterning was explored using surface modification techniques. Bi-philic surfaces are formed with patterns of hydrophobic surface juxtaposed on hydrophilic surface; cf. Refs. [12–14]. Significant improvements in boiling performance have been reported when super-hydrophobic micro-spots on a super-hydrophilic surface were employed; cf. Refs. [12–14].

Low cost, simple and straightforward methods of forming micro/nano-textured surfaces which can be scaled-up for commercialization are desired. Spraying, electrospinning and electroplating and their modifications are of particular interest due to the ease of formation of nano-textures on surfaces; cf. Refs. [15–20]. Pool boiling on a copper heater with deposited copper-plated electrospun nanofibers revealed an enhancement of heat transfer in pool boiling in comparison with bare copper surface when ethanol and water were used in Ref. [15]. Similar improvements were found with copper-plated supersonically-blown nanofibers deposited on heater surface when ethanol, Novec 7300, and water-n-heptanol solution were used as working fluids [16,17]. Pool boiling of Novec 7300 on polymer (PAN) nanofibers formed by supersonic solution blowing also revealed a significant increase in heat removal rate; cf. Ref. [18]. The same nano-textured surface with DI water being the working fluid revealed a small improvement in comparison to the bare copper surface, as per Ref. [18]. These results indicate that boiling performance would depend on the molecular interaction between the working fluids and the heater surfaces.

Another method claimed to improve boiling performance is related to modification of the working fluid. Introducing nanoparticles into the working fluid (nano-fluids) has been extensively investigated in reviews in Refs. [21,22]. Nanofluids may increase or decrease NBHT and, in general, they are found to increase CHF; cf. Refs. [21,22]. Most of the effects of nano-fluids on boiling including CHF might be attributed to change in surface characteristics, as per Refs. [21,22]. Additionally, an increase in thermal conductivity and a decrease in surface tension of the working fluid can favor an increase in NBHT, as per Ref. [22]. However, it was clearly shown that there is no anomalous increase in thermal conductivity of nano-fluids, and the one observed follows the classical effective medium theory, as per Ref. [23].

Self-rewetting fluids are another group of working fluids which can improve boiling heat transfer; cf. Refs. [24,25]. In general, surface tension of liquids decrease with an increase in temperature. This phenomenon (the thermal Marangoni effect) promotes dewetting of surfaces as liquids are pulled away from the hotter regions. However, in boiling of binary mixtures of two miscible fluids, in addition to the thermal Marangoni effect, evaporation-induced concentration gradient of the more volatile component at the surface leads to the concentration Marangoni flow which can be favorable for surface re-wetting when such a component possesses a lower surface tension than the less volatile one. Note also, that some alcohol solutions have revealed an increase in surface tension with temperature (self-rewetting) which can prevent surface dry-out in boiling, as per Refs. [24–26]. Hence, self-rewetting liquids are mixtures with unique properties due to which both thermal and concentration Marangoni flows are directed to the hot regions resulting in rewetting of the heater surface. This is attractive for the thermal management systems, for example, heat pipes employing evaporation/ boiling phenomena (cf. Refs. [25,27]) and space systems, as per Refs. [28,29]. Generally speaking, self-rewetting liquids could be beneficial to multiple thermal management systems relying on pool boiling.

The present work aims at the experimental investigation of the effect of the depth of liquid layer on heat removal rate in pool boiling. It also aims at the effect of nano-texture of the heater surface and the self-rewetting coolants on the cooling rate.

2. Experimental

2.1. Materials

Polyacrylonitrile (PAN, $M_w = 150$ kDa), Polystyrene (PS, $M_w = 192$ kDa), N,N-Dimethyl formamide (DMF) anhydrous- 99.8%, n-heptanol, n-butanol and methanol were obtained from Sigma–Aldrich. Ethanol (200 proof) was obtained from Decon Labs Inc. Oxygen-free high-conductive (OFHC) 101 grade copper rods purchased from McMaster-Carr were used as heated substrates.

2.2. Supersonic solution blowing

Electrically-assisted supersonic solution blowing was carried out using 5 wt% PAN solution following the procedure detailed elsewhere, in Ref. [16]. The polymer solution flow rate was 0.2 mL/h. PAN nanofibers were collected directly on a copper substrate (the heater surface)

for 10 min. Similarly, polystyrene (PS) 10 wt% solution in N,N-Dimethylformaldehyde (DMF) was prepared to form PS nanofibers. In this case, the polymer solution flow rate was 0.2 mL/h and PS nanofibers were collected for 5 min.

2.3. Observations

Scanning electron microscopy (SEM) of nanofiber-covered surfaces employed JEOL JSM-6320F (Research Resource Center, RRC UIC) with a cold emission source. High-speed images were captured using a Phantom V210 camera. Nikon D3100 camera was used for static contact angle measurements.

2.4. Experimental setup and procedure

The schematic of the pool boiling setup is shown in Fig. 1. The setup employed here is the same as the one described in full detail elsewhere, in Refs. [16,18]. In brief, copper substrate is heated from below by cartridge heaters enclosed in a copper cylinder. Silver paste is utilized for all interfaces (except the heater surface) to ensure high heat conductance. The heater setup is enclosed in Teflon to provide thermal insulation. The boiling chamber is a glass chamber which contains the working fluid and has a condenser at the top. The boiling chamber is also provided with a vent at the top to maintain atmospheric pressure inside the chamber. The heater surface is a 1.9 cm diameter copper substrate. The heater surface was polished using sandpaper with grit size 2000 before each trial.

When ethanol was used as a working fluid, experiments were conducted for different initial depths of ethanol layers. The initial depth was calculated from the liquid mass used. Note that in the case of the initially small depths, the current depth in the experiment can vary, even though a vapor recuperation system is used in the setup. This is because some amount of condensate can be currently accumulated on the top surface or be in the vapor form. Ethanol was pre-boiled for degasification. For the liquid depths above 30 mm, during the experiments ethanol was maintained at saturation temperature by the immersion heater. For smaller depths, the saturation temperature of ethanol was not enforced so explicitly (the immersion heater was not switched on), even though it is reasonable to assume that it was achieved. Additionally, the temperature just under the surface of the ethanol foam was measured with a thermocouple and found to be 77.8 LC validating the above assumption. It should be emphasized that equilibrium data cannot be acquired near the critical heat flux (CHF) as it is a runaway situation. Regardless, the boiling curves include such data points too (typically the last two to three data points) to facilitate understanding of the entire boiling curve in case of pure ethanol boiling.

In the experiments with alcohol solutions, the solutions were prepared within an hour before boiling. The solutions were also pre-boiled in the boiling chamber for half an hour before the beginning of the experiments. During the pre-boiling both copper substrate and the immersion heater were switched on so that air trapped on the surface had been removed. Power delivered to the copper surface which sustained boiling was increased in steps using the transformer. The equilibrium thermocouple readings were recorded for each setting. In the experiments with DI water and alcohol solutions, the power of the transformer did not

exceed 66% due to safety concerns. Accordingly, CHF was not observed in most of the cases presented. Note that when CHF was observed it is explicitly stated.

Static contact angles were measured from optical images of stagnant sessile droplets deposited from a 25-gauge needle. The droplets were deposited either on bare copper (polished by 2000 grit sandpaper) or a polymer film (solidified PAN or PS) obtained by drying the corresponding polymer solution in DMF.

3. Results and discussion

3.1. Pool boiling of ethanol: effect of pool depth and surface nano-texture

The boiling curves measured in the cases with different initial depths of ethanol over the copper heater are presented in Fig. 2. Note that the case with the initial depth of 5 mm reveals a small dip in the heat flux before transition to the actual runaway situation (CHF). This is due to the reduced amount of ethanol and the entire heater surface not being wetted in this region (bracketed in Fig. 2, corresponds to the formation of dry spots; cf. Fig. 3). However, the most part of the boiling curve for the depth of 5 mm is almost identical to those for the depths 6.5 mm and 14 mm in Fig. 2. It should be emphasized that the holes formation mentioned here refers to the existence of a macroscopically visible spot free from coolant during boiling. This essentially, means formation of a dry spot, as revealed by the high-speed video. Therefore, the tendency to form dry spots would persist, in particular close to the CHF.

Fig. 3 shows the comparison of the data for the 60 mm and 6.5 mm initial depths with the further trials added to that of Fig. 2 to evaluate the scatter. The results in Fig. 3 show that the deviation between the data for the 60 mm and 6.5 mm initial depths is within the overlapping error bars, and thus, these results are essentially indistinguishable. The boiling curves are essentially similar in all the plots for different layer depths above 5 mm. One can say that the results revealed that the depth of liquid layer above the heater appears not affecting the heat flux at all. This is an important observation because it hints that buoyancy does not determine transition to the film boiling (CHF).

Fig. 4 depicts partial transition to the nucleate boiling regime. In the case of a shallow liquid layer of 6 mm depth shown in Fig. 4a, the entire layer turns into a foam, and buoyancy seems to play not too much role. On the other hand, in the case of 60 mm a more typical pattern with vapor bubble formation on the heater surface is seen in Fig. 4b. These bubbles are driven upward by buoyancy, and coalescence and foaming are not observed in distinction from Fig. 4a. Fig. 5b shows that in the case of a 60 mm-deep layer bubbles are forming the characteristic vapor columns, which raise due to buoyancy. In the case of the shallow 6 mm liquid layer shown in Fig. 5a large foam bubble or a few large bubbles encompass the entire heater surface or even occasionally spread beyond it. No visual holes through the breaking foam to the heater were seen in the case of Fig. 5a up to the critical heat flux (CHF) set in. In the case of the 6 mm ethanol layers forming foam in Figs. 4a and 5a the buoyancy-driven raise of the bubbles is not present at all, whereas in the case of the deep 60 mm layers shown in Figs. 4b and 5b it is dominant. Nevertheless, the boiling curves for these cases shown in Fig. 3 practically overlap, which probably means that the flow/boiling structure near the very

heater surface is not that different in these cases. The capillary length (L_c) is defined $L_c = \sqrt{\sigma/\rho g}$, where σ and ρ are the surface tension and density of the liquid, respectively, and g is the gravity acceleration. Taking $\sigma = 20.72$ mN/m and $\rho = 772.01$ kg/m³ at 40 °C (according to Ref. [30]), the capillary length $L_c = 1.65$ mm. Hence in the present case the ratio L_h/L_c is approximately equal to 11 (with L_h being the diameter of the copper substrate). This is considerably larger than the critical ratio (2.1–2.8) below which boiling is surface tension controlled. Therefore, one expects a buoyancy-dominated boiling, as per Refs. [6,8]. However, the insensitivity of the heat removal rate to the layer depth implies that the microlayer evaporation under the bubble footprint at the heater surface discussed in Refs. [2,31] is the main mechanism of heat transfer in this case in comparison with the effect of evaporation from the bubble cap, as per Ref. [3].

In the additional experiments, the copper heater surface was covered with supersonically-blown PAN nanofibers. The SEM image of the copper heater surface covered with PAN nanofibers of ~ 100 nm cross-sectional diameter is shown in Fig. 6a. The boiling curves measured on such heaters in the cases of the 60 mm layer are shown in Fig. 7 in comparison with the corresponding boiling curves measured without nanofibers. It is seen that for the same surface superheat the heat removal rate is lower at the heater covered with supersonically-blown PAN nanofibers in the case of ethanol boiling. This is in contrast to the previous results (cf. Ref. [18]) where considerably higher heat flux was obtained for the same surface superheat on surfaces covered with supersonically blown PAN nanofibers in the case of boiling of Novec 7300. Also, a slightly higher heat flux was obtained for the same surface superheat on surfaces covered with supersonically blown PAN nanofibers in the case of boiling of DI water; cf. Ref. [18].

The detrimental effect of supersonically-blown nanofibers on heat removal in ethanol boiling might be due to the difference in wettability of PAN and copper. Namely, ethanol wets PAN surface (a solidified PAN film) completely and reveals the static contact angle close to 0°. On the other hand, the static contact angle of ethanol on copper surface is about 30°. Therefore, ethanol should be pulled to PAN nanofibers, thus de-wetting the copper substrate. Note also, that in the present case of boiling of ethanol the nanofibers were found to delaminate during boiling as the SEM image reveals a reduced coverage by nanofibers after boiling: Fig. 6b in 1 μ m scale. Note that similar images taken in 10 μ m scale reveal a very small number of fibers which is difficult to recognize, consistent with fiber delamination.

The effect of the nanofiber-covered surface on pool boiling of a thin layer is elucidated in Fig. 8. There were many instances of hole formation (only in high speed video) in the present case of pool boiling of relatively thin ethanol layers with PAN nanofibers. A case where a large bubble breaks up revealing a considerable area of a dried-out heater surface is depicted in Fig. 8a and b. The dry-out seemingly stems from ethanol pull-out to the surrounding PAN nanofibers. This is corroborated by the fact that one can also observe that there are smaller bubbles being generated near the hole, indicating the effect of nanofibers. The hole gradually disappears (Fig. 8c). However, the tendency to rewet the dried-out area is relatively low.

In comparison to PAN nanofiber-textured surface, the bare surface at a similar heat flux did not develop visible holes, as the high speed video shows (Fig. 9). Fig. 9b reveals a large bubble breaking, however, dry spot was not found in this frame or in the subsequent frames leading to Fig. 9c. It should be emphasized that at even higher heat fluxes, the 6.5 mm ethanol layer in pool boiling without nanofibers did reveal dry spots, which increased and would lead to the CHF. Hence, the comparison is a qualitative evidence indicating a delay in the appearance of dry spots in Fig. 9 (the bare surface), rather than their existence in the case of the surface covered with wettable PAN nanofibers (Fig. 8).

Also, in the case of the 5 mm ethanol layer the formation of a central dried-out hole resulted in a significant increase in the surface superheat (cf. the bracketed section of the corresponding boiling curve in Fig. 2). This delay in rewetting the heater surface with nanofibers might be the reason of the detrimental effect observed with PAN nanofibers.

3.2. Pool boiling of alcohol solutions

Fig. 10 shows the comparison of the boiling curves of DI water and the 0.1% alcohol solutions on bare copper surface. It is seen that 0.1% n-heptanol solution enhances heat removal in comparison to DI water. The 0.1% n-butanol solution reveals a small improvement at high heat flux values, however, is within the error bars for the DI water case. The 0.1% ethanol or 0.1% methanol solution reveal no enhancement in heat removal compared to DI water. The saturation boiling point of the pure components at atmospheric pressure and their molar enthalpy of vaporization (ΔH_{vap}) at the boiling point are listed in Table 1. However, it should be emphasized that for such low alcohol concentrations as those studied here the saturation temperature and enthalpy of evaporation of the mixture were practically the same as those for DI water.

Methanol and ethanol in the solutions studied are more volatile than water and are expected to evaporate preferentially compared to the latter (note, however, that at high concentration of ethanol >96% v/v, DI water would be more volatile, which is related to molecule-molecule interaction of ethanol and water; cf. Refs. [30,32]). N-butanol and n-heptanol (pure liquids) are less volatile compared to water. However, at low alcohol concentrations of n-butanol and n-heptanol in the solutions studied, these alcohols are more volatile compared to water. Hence, all solutions of n-butanol and n-heptanol used here exhibited 'positive' soluto-capillary stresses, i.e. the more volatile component in the mixture simultaneously possessed a lower surface tension than the solvent (water), as per Ref. [33].

Traditionally, n-butanol and n-heptanol are considered as self-rewetting fluids owing to the existence of a minimum in the dependence of surface tension on temperature, as per Ref. [24]. The authors of Ref. [33] studied surface tension of n-butanol, n-pentanol and n-hexanol in a closed system (with vapor condensed back to liquid) and revealed a small increase in surface tension with temperature only at high concentrations. Further-more, they showed that the concentration-gradient-induced Marangoni flow at constant temperature would be strong for a high-carbon-content alcohol; cf. Ref. [33]. Specifically, the surface tension at constant temperature decreases stronger as the number of carbon atoms in the alcohol increases from n-butanol to n-hexanol, as per Ref. [33]. For example, surface tension decreases approximately by 1 mN/m from pure water to 0.1% n-butanol solution (at 25 °C),

whereas in case of 0.1% n-heptanol it decreases by approximately 30 mN/m compared to pure water (at 20 °C), as per Ref. [34]. Accordingly, for the same change of alcohol concentration due to evaporation, the concentration-gradient-induced Marangoni flow at constant temperature would be stronger for a high-carbon-content alcohol; cf. Ref. [33]. The 0.1% (v/v) n-heptanol aqueous solution studied in the present work is within solubility regime and close to the maximum solubility. Accordingly, an enhancement of heat removal in pool boiling found for the n-heptanol solution would have a major contribution from the soluto-Marangoni flow facilitated by a weak thermally-induced Marangoni re-wetting flow (from the cold to hot regions), as per Ref. [33]. In the case of n-butanol aqueous solutions, the concentration of 0.1% v/v is low compared to the maximum solubility (~9% v/v at room temperature, as per Ref. [33]). Hence, the soluto-Marangoni flow, though existing, would be weak in comparison to that for the 0.1% v/v n-heptanol aqueous solution. In addition, at such low concentrations as 0.1% v/v n-butanol does not reveal self-rewetting, as per Ref. [33], and therefore, thermal-Marangoni flow should still be from the hot to cold regions. Both ethanol and methanol are miscible/soluble in water at any concentration. Then, again one would expect the soluto-Marangoni flow being directed from the cold to the hot regions (cf. Ref. [26]), yet its effect would be negligible. The latter corresponds to the fact that no change in the heat transfer in boiling was found for the ethanol and methanol solutions.

The effect of PAN and PS nanofibers deposited on the copper heater surface on pool boiling of the 0.1% n-heptanol aqueous solution is illustrated in Fig. 11. It is seen that PAN nanofiber-textured surface has a negative effect on the boiling heat transfer, whereas the PS nanofiber-textured surface revealed an improvement in boiling heat transfer. It should be emphasized that unlike Refs. [15–17], nanofibers were not electroplated with copper. Hence, the interaction between the working fluid and the nanofiber polymer material could be important in determining the boiling dynamics. Therefore, the static contact angles of droplets of the 0.1% n-heptanol aqueous solution on polymer films and copper surface were measured (cf. Fig. 12). The contact angles of the 0.1% n-heptanol aqueous solution averaged over 3 trials in each case for copper, PAN and PS surfaces are $57^\circ \pm 3^\circ$, $37^\circ \pm 3^\circ$ and $66^\circ \pm 3^\circ$, respectively. These values show that the n-heptanol aqueous solution wets PAN surface more than the copper surface. On the other hand, PS surface appears to be the most phobic. Such change in the surface wettability can be the primary reason that the PAN nanofiber-textured surface is detrimental for increasing the NBHT. PAN fibers seemingly pull the working fluid and, as a result, de-wet the pure copper surface encompassed by fiber crossbars. Also, an excessive wettability of PAN nanofibers delays the incipience of bubble nucleation and departure in comparison to the bare copper surface.

Fig. 13 depicts the boiling curve for DI water on bare copper and PS nanofiber-textured surfaces. The PS nanofiber-textured surface clearly reveals a strong enhancement in the boiling heat transfer. The static contact angles of DI water on the copper surface and the PS film are shown in Fig. 14, with the average values being $70^\circ \pm 2^\circ$ and $87^\circ \pm 2^\circ$, respectively. These values explain the positive effect of the PS nanofibers on copper surface. The results in Fig. 13 reveal the onset of DI water boiling at lower surface superheat, similar to that observed with the 0.1% n-heptanol aqueous solution on the PS nano-textured surface. In addition, the heat removal rate on the PS nano-textured surface is much higher at the same

surface superheat. For instance, at surface superheat of 8° C, the heat flux on bare surface is about 20 W/cm², whereas on the PS nano-textured surface, the heat flux is nearly fivefold.

Supersonically-blown PS nanofibers were comparatively larger in diameter than the PAN ones, ranging from a few hundred nanometers to micrometer. SEM image of the heater surface with supersonically-blown PS nanofibers before boiling is shown in Fig. 15a. The overall fiber distribution seen in Fig. 15 is essentially uniform. The average surface coverage by fibers measured from three SEM images (similar to that of Fig. 15a) taken at randomly chosen locations is $4.5 \pm 0.2\%$, which means that the average surface porosity is 95.5%. Fig. 15b shows the surface after boiling (after the entire boiling curve in Fig. 13 was acquired for approximately 2.5 h). It is seen that the PS nanofibers stay intact after such a prolonged vigorous boiling in DI water, albeit some sintering is evident at their junctions. The sintering is clearly visible in the magnified image of the same surface in Fig. 16. It also shows that the background copper surface has changed considerably after boiling in DI water in comparison to the metal surface before boiling. This is due to the formation of copper oxides, which equally appear on the bare copper surface after boiling in DI water (see the inset in Fig. 16), as has already been reported in Ref. [17].

Also, such hydrophobic nano-textured features at the copper heater surface result in an early onset of nucleate boiling, albeit reducing the CHF, as per Refs. [35,36]. Heater leopard-like surfaces with hydrophilic and hydrophobic domains can potentially provide a middle ground where the hydrophobic regions provide nucleation sites and the surrounding hydrophilic regions constrain the base diameter of the departing bubbles; cf. Ref. [36]. Additionally, hydrophobic domains frequently leave a localized dry spot after the bubble departure where the next evaporation cycle results in the next bubble growth. Accordingly, the bubble departure frequency on a hydrophobic surface increases compared to that of the hydrophilic one. Hence, with the deposition of PS nanofibers, the latter serve as the active nucleation sites. Hence, the bubble nucleation and departure rate increases even at a low superheat resulting in the early onset of boiling. For hydrophobic elements smaller than the critical size (which is in the millimeter scale) a stick-slip bubble contact line motion was observed; cf. Ref. [36]. This is due to the contact line pinning at the hydrophobic domain boundary. With the further growth of bubble the contact angle reckoned from the liquid side decreases. Then, on reaching the receding contact angle of the hydrophilic domain, the contact line moves (slips) outwards practically instantaneously. Additionally, the maximum bubble base diameters would increase in the presence of such hydrophobic elements as the PS nanofibers; cf. Ref. [36]. The maximum bubble base diameter depends on the size and spacing between the hydrophobic domains, as per Ref. [36]. Another performance indicator, the CHF, diminishes due to the presence of the hydrophobic PS nanofibers, as they promote coverage of the heater surface by the vapor film. However, in the case of DI water, the CHF was not reached in the present experiments on the PS nanofiber-textured heater (cf. Fig. 13). Therefore, a verification of the latter phenomenon was impossible. On the other hand, in the case of the 0.1% n-heptanol aqueous solution a considerable decrease in the CHF was observed on the PS nanofiber-covered surface (cf. Fig. 11).

A comparison of the simultaneous effects of self-rewetting and nanofibers deposited on the heater surface reveals a complex pattern, with the best option depending on the surface

superheat (or accordingly, the heat flux value). Fig. 17 shows that at low heat fluxes, the self-rewetting provides the best option to facilitate the boiling heat transfer compared to the case of DI water on PS nano-textured surface. On the other hand, at higher heat fluxes, the vapor coverage on the nanofiber-textured surface appears to be the dominant factor leading to an earlier CHF in the case of 0.1% heptanol solution.

It should be emphasized that when polymer nanofibers are present at the heater surface, the effective thermal conductivity between the heater surface and the working fluid is essentially reduced. This can lead to a reduction in the heat transfer in the microlayer adjacent to the surface. However, heat transfer in boiling in the presence of the hydrophobic PS nanofibers has still been improved due to the early onset of boiling, the additional active nucleation sites and an increase in the bubble departure frequency. These factors outweigh the effect of the diminished thermal conductivity. The present results show that hydrophobicity of the PS nanofibers enhanced the NBHT. An additional control of the inter-fiber spacing in the nanofiber crossbars (cf. Fig. 14 and Ref. [37]) can possibly facilitate engineering surfaces even more and improve both the NBHT and CHF.

4. Conclusion

Pool boiling experiments with different depths of ethanol as a working fluid were conducted. The resulting boiling curves corresponding to thin and thick layers revealed insignificant differences suggesting that buoyancy was not a dominant factor in pool boiling heat transfer. There is a considerable difference in the characteristics of boiling between the 60 mm and 6 mm liquid layers when foam is formed in the latter case. Foam formation significantly affects the interface between the air/vapor gap and liquid. However, the results related to the boiling curve reveal that in these two cases the interface between the heater and the liquid is insignificantly affected. This is the reason that the boiling curve is minimally affected by the change in the liquid depth. Self-rewetting behavior of the 0.1% v/v n-heptanol aqueous solution explored in the present work revealed an enhanced boiling heat transfer. However, the alcohols with a lower carbon content (such as n-butanol, ethanol and methanol at the same concentration) were ineffective. In addition, modification of the heater surface by deposited relatively hydrophobic polystyrene (PS) nanofibers revealed a significant improvement in the boiling heat transfer, albeit a CHF reduction. This effect is attributed to the fact that hydrophobic PS nanofibers resulted in an early onset of boiling, multiple additional active nucleation sites and an increase in the bubble departure frequency. On the other hand, such relatively hydrophilic nanofibers as polyacrylonitrile (PAN) nanofibers were not advantageous.

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Fig. 1.
Schematic of the pool boiling experimental setup.

Fig. 2. Pool boiling curves for different initial depths of ethanol above the heater surface. The bracket shows the plateau behavior due to de-wetting of some parts of the heater in the case of 5 mm layer. The legend in the panel lists the layer depths studied.

Fig. 3.
Pool boiling curves for different initial depths of ethanol above the heater surface. The average value and standard deviation for 3 trails (including those of Fig. 2) are shown.

Fig. 4.

Pool boiling pertaining to partial transition to nucleate boiling regime of ethanol above the heater surface at the initial layer depths of (a) 6 mm ($T_{\text{surface}} - T_{\text{sat}} = 9.6\text{ }^{\circ}\text{C}$), and (b) 60 mm ($T_{\text{surface}} - T_{\text{sat}} = 10.4\text{ }^{\circ}\text{C}$). The immersion heater has been turned off for the visualization purposes. Scale bars correspond to 1 cm.

Fig. 5. Pool boiling pertaining to fully developed nucleate boiling regime of ethanol above the heater surface at the initial depths of (a) 6 mm ($T_{\text{surface}} - T_{\text{sat}} = 13.3\text{ }^{\circ}\text{C}$) and (b) 60 mm ($T_{\text{surface}} - T_{\text{sat}} = 13.1\text{ }^{\circ}\text{C}$). The scale bar is 1 cm.

Fig. 6.
SEM image of the heater surface. (a) Coverage by supersonically-blown polymer nanofibers before boiling in ethanol. (b) A reduced coverage after boiling in a 60 mm layer of ethanol not reaching CHF.

Fig. 7.

Comparison of pool boiling curves measured with and without supersonically-blown PAN nanofibers on the copper heater surface with 60 mm ethanol layer. The average values and standard deviation for 3 trials are shown.

Fig. 8.

Pool boiling of a 6.5 mm ethanol layer on PAN nanofiber-textured copper surface at the heat flux ~ 40 W/cm². (a) At an instant t when a large bubble is about to break up. (b) At the instant $t + 0.019$ s when the large bubble has broken up revealing a hole underneath. (c) At the instant $t + 0.051$ s when the hole is gradually disappearing. The scale bar is 1 cm.

Fig. 9.

Pool boiling of a 6.5 mm ethanol layer on bare copper surface at the heat flux $\sim 40 \text{ W/cm}^2$.

(a) At time instant t , (b) at time instant $t + 0.019 \text{ s}$ when the bubble breaking and hole formation is visible, and (c) at time instant $t + 0.051 \text{ s}$. The scale bar is 1 cm.

Fig. 10.

Comparison of boiling curves of the 0.1% (v/v) alcohol solutions: n-heptanol (the average of 3 trials), n-butanol (2 trials), ethanol (2 trials) and methanol (3 trials), as well as DI water (3 trials).

Fig. 11.

Comparison of pool boiling curve for the 0.1% n-heptanol aqueous solution in the case of the bare copper surface heater (3 trials) with those of supersonically-blown PAN nanofibers (2 trials) and PS nanofibers (3 trials indicated by numbers) on the copper heater surface. The arrows mark the points where the CHF condition has been reached.

Fig. 12.
Static contact angles of the 0.1% n-heptanol aqueous solution on: (a) copper surface, (b) PAN film, and (c) PS film.

Fig. 13.
Pool boiling curves for DI water measured with (3 trials) and without (3 trials) supersonically-blown PS nanofibers on the copper heater surface.

Fig. 14.
Static contact angle of DI water on: (a) copper surface, and (b) PS film.

Fig. 15. SEM images of the heater surface. (a) Supersonically-blown PS nanofibers on the copper heater surface before boiling, and (b) after boiling in DI water.

Fig. 16.

Magnified SEM image of the heater surface shown in Fig. 15. The inset surrounded by red square shows the SEM image of the bare copper surface after boiling in DI water. The scale for the inset is same as that for the main image, i.e. 1 μm .

Fig. 17.

Pool boiling: the comparison between the 0.1% heptanol solution and DI water on PS nano-textured surface and bare surface. Nomenclature: HP-B – 0.1% heptanol solution on bare surface, W-PS – DI water on PS nano-textured surface, and HP-PS 0.1% heptanol solution on PS nano-textured surface. The additional numbers indicate trial number.

Table 1:

Boiling point (T_{sat}) at atmospheric pressure (101.325 kPa) and the corresponding molar enthalpy of vaporization (H_{vap}) at the boiling point of pure components, as per Ref. [30].

Component	T_{sat} (°C)	H_{vap} (kJ/mol)
Water	100.0	40.7
Methanol	64.6	35.2
Ethanol	78.3	38.6
n-Butanol	117.7	43.3
n-Heptanol	176.5	66.8