EFFECT OF CONFINEMENT AND HEATER SURFACE INCLINATION ON POOL BOILING PERFORMANCE OF PATTERNED WETTABILITY SURFACES

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Boiling heat transfer is widely used in many practical applications due to its associated significantly high heat transfer coefficients (HTC). Several surface modification techniques are known to further improve heat transfer performance. Applications such as cooling of three-dimensional electronic stacks and portable electronic devices demand nucleate boiling in narrow gaps, often with inclined surfaces. In this regard, we experimentally investigated and compared the individual effects of confinement and orientation (horizontal and vertical) on the HTCs obtained during boiling on macroscale-patterned wettability surfaces with the baseline case of a homogeneous wettability bare surface. The baseline hydrophilic substrate was modified using macroscale hydrophobic dots with a sufficiently large pitch (greater than the bubble departure diameter, $D_b$) to avoid lateral bubble coalescence on the modified patterned wettability surfaces. For confined pool boiling conditions, the modified surface always demonstrated a better HTC than the bare surface. Furthermore, the boiling heat transfer performance of the modified surface was independent of surface orientation. The results from this study provide insight into the performance of patterned wettability surfaces in a practical scenario of confined boiling in the narrow gaps and portable devices typically encountered in electronic cooling applications.

KEY WORDS: confined pool boiling, surface orientation, patterned wettability, heat transfer coefficient

1. INTRODUCTION

The significantly high heat transfer coefficient (HTC) associated with nucleate boiling makes it an excellent mode of heat transfer used to dissipate very high heat fluxes at remarkably low surface superheat. Consequently, boiling is extensively implemented in various applications such as cooling of electronic stacks and nuclear reactors, power generation, compact heat exchangers, engine cooling, etc. (Bar-Cohen et al., 2009; Buongiorno et al., 2009; Stutz et al., 2009).
Contrary to single-phase heat transfer that depends on sensible heat and needs larger temperature differences/budgets, the liquid–vapor phase utilizes enthalpy of vaporization, thereby facilitating heat transfer at a smaller temperature difference. The second law of thermodynamics states that heat transfer at smaller temperature budgets implies high thermodynamic efficiency. Moreover, the low working temperature reduces the thermal stresses in electronic devices and thereby improves its reliability. However, continuous miniaturization of electronic devices and an increase in power requirements demand a strategy to enhance the boiling HTC in order to maximize the two-phase heat transfer efficiency.

The desired enhancement in the HTC can be achieved by employing active (Alangar and Pandiyur, 2016; Wei et al., 2018) and passive (Orman, 2016) techniques, or a combination of active and passive techniques. Since passive techniques do not consume any additional energy, they are predominantly preferred over active techniques. Passive techniques either incorporate heater surface modification at the nano/microscale (Mori and Utaka, 2017) or modify the fluid via adding surfactants and nanoparticles (Liang and Mudawar, 2018). Among these techniques, modifying the surface morphology by fabricating micro/nanostructures (Alangar, 2015; Cao et al., 2019; Gouda et al., 2018; Jaikumar and Kandlikar, 2015; Kim et al., 2014; Rahman et al., 2014) are prominently known to enhance the heat transfer performance. In addition, heat transfer can also be enhanced by improving the thermal properties of the working fluid by adding nanoparticles (Dareh, 2018; Kamatchi, 2018; Kwark et al., 2010) or reducing the surface tension via surfactant additives in the boiling fluid (Kumar et al., 2018; Raza et al., 2016). High manufacturing costs and clogging of voids in micro/nanostructured surfaces by contaminants have prevented the commercial scaling up of the aforementioned techniques (Rahman et al., 2014). Nanofluids, when subjected to boiling, tend to foul the heater surface and increase the thermal resistance, thereby prohibiting its long-term use in practical applications (Sarafraz et al., 2016). Furthermore, the stability of nanoparticles in the working fluid is of critical importance for applications (Kim, 2011; Surtaev et al., 2016).
Modifying the heater surface wettability significantly affects the nucleate boiling heat transfer performance. Parameters that define the bubble dynamics, such as the bubble departure diameter, frequency, onset temperature of nucleate boiling, bubble coalescence, and nucleation site density, are considerably influenced by the wettability (Kim et al., 2016). Hydrophilic surfaces tend to have a high critical heat flux (CHF) relative to hydrophobic surfaces. At low heat flux, hydrophobic surfaces deliver higher HTC’s compared with hydrophilic surfaces. However, at moderate and high heat flux, the coalescence of the adjacent bubbles significantly deteriorates the HTC relative to hydrophilic surfaces (Phan et al., 2009). Therefore, to simultaneously exploit the advantages of hydrophilic and hydrophobic surfaces, patterned/heterogeneous wettability surfaces are preferred over homogeneous wettability surfaces (Betz et al., 2013; Hsu et al., 2012; Jo et al., 2011; Kumar et al., 2017; Liu et al., 2019; Motezakker et al., 2019; Sarode et al., 2020; Shen et al., 2019). Patterned wettability surfaces (biphilic surfaces) have hydrophobic regions that act as active nucleation sites, while their hydrophilic counterparts prevent coalescence of adjacent bubbles. HTC enhancement is primarily attributed to the very high number of active nucleation sites and continuous bubble generation without interruption. Superbiphilic surfaces (a combination of superhydrophobic and superhydrophilic regions) that have the maximum difference in the contact angle have demonstrated 100% enhancement in the HTC relative to hydrophilic surfaces (Betz et al., 2013). Hydrophobic dots on hydrophilic heater surfaces improved the HTC compared with homogeneous wettability surfaces (Jo et al., 2011). Hsu et al. (2014) showed that the heat transfer performance of a patterned wettability surface depended on the wettability gradient. They attributed the enhancement in the heat transfer performance to the bubble movement enforced by the surface energy gradient. For the best heat transfer performance of patterned wettability surfaces in terms of the CHF and HTC, there exists an optimum hydrophobic-to-hydrophilic area ratio (Motezakker et al., 2019).

Many practical applications demand nucleate boiling under inclined conditions and in narrow gaps due to space constraints (Bar-Cohen et al., 2009; Stutz et al., 2009). The bubble dynamics and heat transfer characteristics are significantly distinct under these conditions. Various researchers have investigated the impact of orientation (Mei et al., 2018; Jun et al., 2016; Kim et al., 2017; Rainey and You, 2001; Sadaghiani et al., 2017) and confinement on boiling heat transfer performance of modified heater surfaces (Liu and Yang, 2013; Tasaki and Utaka, 2006; Utaka et al., 2019; Xie et al., 2019; Yang and Liu, 2013). For high thermal conductive microporous coating, the boiling HTC remained unaffected by the surface orientation (0°–180°) up to high heat flux. However, beyond 90° (vertical orientation), the CHF significantly deteriorated with an increase in the orientation (Jun et al., 2016). Similarly, the boiling HTC was independent of orientation in the case of a graphene-coated heater surface. However, the difficulties with vapor removal beyond the 90° orientation decreased the CHF (Kim et al., 2017). Yang and Liu (2013) showed that the thickness of the microporous coating (which provides an increase in the HTC relative to the bare surface) affects the boiling HTC under confined conditions. They concluded that this enhancement depends on the number of nucleation sites, thermal resistance of the coating, and bubble leaving resistance. A spatially non-uniform heater surface helps to improve the HTC and CHF by providing vapor removal and liquid re-supply pathways (Utaka et al., 2019). The wettability of the heater surface also plays a dominating role in deciding the confined boiling heat transfer performance (Tasaki and Utaka, 2006).

To the best of the authors’ knowledge, no study exploring the impact of surface orientation and confinement on the nucleate boiling heat transfer performance of patterned wettability surfaces has been reported. Therefore, this study experimentally investigates the influence of orientation and confinement on the boiling HTC of patterned wettability surfaces. This paper includes...
details of macroscale-patterned wettability surface fabrication, experimental methodology, and data reduction, followed by a discussion of the results and concluding remarks.

2. EXPERIMENTAL METHODOLOGY

2.1 Sample Preparation and Characterization

The baseline hydrophilic copper surface was modified with a commercially available room temperature vulcanized (RTV) silicone sealant (Anabond Auto Gasket Maker Red) to obtain the patterned wettability surfaces. RTV silicone can sustain temperatures as high as 320°C. The patterned wettability surfaces were fabricated by using a conventional screen printing technique (Sarode et al., 2020). The fabrication procedure is schematically presented in Fig. 1 along with a snapshot of the fabricated patterned wettability sample used in the experiments in this work. After polishing the copper surface (99.99% purity) with P1500 emery paper to remove oxides, it was subsequently rinsed with acetone and deionized (DI) water [Fig. 1(i)]. The surface roughness of the polished surface was measured by a surface finish measuring instrument (Handysurf E-35B; Tokyo Seimitsu Co. Ltd.) and was found to be \( \approx 0.15 \) µm. A mask (100 µm thick) of the desired pattern was cut using a laser cutting machine (EVA 32; Mehta CAD CAM Systems Pvt. Ltd.). The mask was then placed on the polished copper surface, on which RTV silicone was subsequently applied [Fig. 1(iii)]. Uncured extra RTV silicone was instantly removed and the sample was cured at room temperature [Fig. 1(iv)]. After curing, the mask was peeled from the surface to obtain the patterned wettability surface [Fig. 1(v)].

As seen in Fig. 2(a), the thickness of the hydrophobic coating was measured to be \( \approx 100 \) µm. The water contact angles on the copper and RTV silicone surfaces were measured to estimate the

FIG. 1: Steps to fabricate a patterned wettability surface (all dimensions are in millimeters)
difference in wettability. Figure 2(b) depicts that the copper surface was hydrophilic at a contact angle of 76°, while the RTV silicone surface demonstrated hydrophobicity at a contact angle of 116° [Fig. 2(c)]. Therefore, the characterization confirmed that the fabricated samples can be considered to be patterned wettability samples.

2.2 Experimental Setup

A schematic illustration of the pool boiling facility is shown in Fig. 3. The facility is analogous to experimental setups reported in the literature (Dadjoo et al., 2017; Sarode et al., 2020); however, with a few essential changes. The boiling chamber was made of SS304 with glass windows for visualization and was mounted onto a frame. During the experiment, an immersion heater with a capacity of 400 W was used to maintain the saturation temperature of the DI water since
The boiling chamber was not thermally insulated to prevent heat loss to the atmosphere. The bulk temperature of the water was monitored using a T-type thermocouple. Holes were drilled on top of the boiling chamber to ensure atmospheric pressure during the boiling experiments. Air-cooled aluminum condensers placed on top of the boiling chamber condensed the vapor and recirculated liquid back into the chamber. The heater assembly incorporated a copper foil (35 × 35 mm² × 0.1 mm thick) soldered to a copper bar (20 × 20 mm² × 80 mm long) [Fig. 3(b)]. The soldered copper foil acted as the boiling test surface. The provision of an additional surface area [Fig. 3(d)] prevented edge nucleation and facilitated unobstructed boiling visualization. The thickness of the solder film used in the current work was less than 50 µm; accordingly, the thermal resistance of the soldered layer was safely assumed to be negligible in comparison to the overall resistance (Deng et al., 2016; Sezer et al., 2019). The copper bar was insulated on the sides by low thermal conductivity Teflon to prevent radial heat loss and ensure one-dimensional heat transfer in the lengthwise direction (Kumar et al., 2018; Raza et al., 2016). Three T-type
thermocouples (1.6 mm in diameter; ± 0.4°C uncertainty) were embedded in the copper bar to calculate the heat flux and surface superheat. Two 200 W Marathon cartridge heaters were embedded from the bottom in the copper bar, as seen in Fig. 3(b). A polycarbonate plate (20 × 20 mm²), shown in Fig. 3(c), was used as a confinement plate to perform the pool boiling experiments. Spacers (1 mm thick) were used to maintain a gap (s) between the test surface and the confinement plate.

2.3 Experimental Procedure and Data Reduction

Prior to the experiment, all components of the pool boiling facility were thoroughly cleaned with acetone followed by a DI water rinse. A pre-decided volume of DI water was filled in the boiling chamber before starting the experiment. The power supply to the immersion heater was switched on to heat the water to the saturation temperature. After reaching the saturation temperature, the experiment was initiated by supplying power to the heater assembly through a voltage regulator. Steady-state temperatures measured by thermocouples (T₁, T₂, and T₃) were recorded at 1 Hz for 2 minutes for every power step using a data acquisition system (NI 9214; National Instruments). The recorded data were later used to calculate the heat flux and wall superheat. For the purpose of safety of the test facility, the experiments were not conducted beyond 75 W/cm².

The heat flux supplied to the test section was calculated by Fourier’s law as follows:

\[ q'' = -k_{Cu} \frac{dT}{dx} \]  

(1)

The temperature gradient \((dT/dx)\) was estimated using the best linear fit. Figure 4 depicts the spatial distribution of the temperature at different values of the heat flux. The value of the coefficient of determination \((R^2)\) in the linear fit was close to 1, indicating negligible heat loss through the insulating Teflon cover.

FIG. 4: Temperature distribution along the length of the copper bar
The surface temperature was obtained from Eq. (2) as follows:

\[ T_w = T_1 - q'' \left( \frac{x}{k_{Cu}} \right) \]  

(2)

where \( T_w \) is the temperature of the test surface; \( x \) is the distance between the test surface and the \( T_1 \) thermocouple; \( q'' \) is the heat flux; and \( k_{Cu} \) is the thermal conductivity of copper.

The boiling heat transfer coefficient \((h)\) was calculated as follows:

\[ h = \frac{q''}{\Delta T_{sup}} \]  

(3)

where \( \Delta T_{sup} \) is the temperature difference between the surface and saturation temperatures.

The experimental setup was validated by comparing the obtained boiling curve with the data reported in the literature (Quan et al., 2017; Rohsenow, 1951). Figure 5(a) depicts good agreement in the shape of the curve. Figure 5(b) shows the percentage of uncertainty \( U(q'') \) in the heat flux compared with the experimental heat flux. The uncertainty in the heat flux was in good agreement with the uncertainties reported in the literature (Jaikumar and Kandlikar, 2015). Moreover, the uncertainty in heat transfer coefficient \( U(h) \) was estimated to be less than 10% beyond \( \approx 30 \text{ W/cm}^2 \) of heat flux. For further details on the uncertainty analysis, the reader is referred to our previous work (Sarode et al., 2020). The test cases considered in this study are summarized in Table 1. The heat loss from the additional non-heating area was numerically estimated to be less than 6% and 2% at lower (\( \approx 10 \text{ W/cm}^2 \)) and higher (\( \approx 69 \text{ W/cm}^2 \)) heat fluxes, respectively.

3. HEAT TRANSFER PERFORMANCE

3.1 Effect of Patterned Wettability

This section discusses the effect of patterned/heterogeneous wettability on the nucleate boiling heat transfer performance. To compare the bubble nucleation cycle of a patterned wettability

![FIG. 5: Comparison between the pool boiling curve and the data reported in the literature (a) and the relative uncertainty in the heat flux (b)](image-url)
TABLE 1: Test details of the various cases reported in this study

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Surface Type</th>
<th>Orientation</th>
<th>Gap (s)∗ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bare</td>
<td>Horizontal upward (0°)</td>
<td>Unconfined</td>
</tr>
<tr>
<td>2</td>
<td>Bare</td>
<td>Horizontal upward (0°)</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Bare</td>
<td>Vertical (90°)</td>
<td>Unconfined</td>
</tr>
<tr>
<td>4</td>
<td>Patterned wettability</td>
<td>Horizontal upward (0°)</td>
<td>Unconfined</td>
</tr>
<tr>
<td>5</td>
<td>Patterned wettability</td>
<td>Horizontal upward (0°)</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>Patterned wettability</td>
<td>Vertical (90°)</td>
<td>Unconfined</td>
</tr>
</tbody>
</table>

surface with a bare surface, the ebullition cycle of a single nucleation site was recorded at 1000 frames per second using a high-speed camera (Photron FASTCAM Mini UX) at ≈ 17 W/cm². Through visualization, it was confirmed that for a hydrophilic nucleation site the waiting period was ≈ 24 ms; conversely, due to residual vapor there was no waiting time for the hydrophobic site, demonstrating continuous vapor generation. This observation was consistent with the data reported in the literature (Lim and Bang, 2020; Nam et al., 2009; Surtaev et al., 2018).

Figure 6 shows the bubble departure diameters at the hydrophilic and hydrophobic sites. As seen in Fig. 6, the bubble departure diameter for the hydrophobic site (Dₔ ≈ 4.5 mm) was bigger than that for the hydrophilic site (Dₔ ≈ 2.4 mm). The experimentally measured bubble departure diameter in good agreement with the theoretical value derived from the balance between the buoyancy and surface tension forces (Lim and Bang, 2020). Consequently, a larger volume of departing bubbles relative to the bare surface indicates a greater amount of heat transfer by the latent heat of vaporization. It is important to note that the pitch of the hydrophobic dots was chosen to be larger than the Dₔ value in order to prevent lateral coalescence of the departing bubbles (Pontes et al., 2020; Sarode et al., 2020).

Figure 7 compares the heat transfer performance of the patterned wettability surface with that of the bare (homogeneous) wettability surface. As seen in Fig. 7(a), the boiling curve for the patterned wettability surface has been shifted leftward, indicating a maximum drop of ≈ 5.5°C in the surface superheat at a heat flux of ≈ 70 W/cm². Consequently, a maximum enhancement of ≈ 46% in the HTC for the patterned wettability surface relative to the bare surface was observed at a heat flux of ≈ 40 W/cm², as shown in Fig. 7(b).

FIG. 6: Bubble departure diameter for the hydrophilic nucleation site (a), hydrophobic nucleation site (b), and separate vapor removal/liquid re-supply pathways (c)
The hydrophobic region assists in early nucleation and reduces the onset of the nucleate boiling temperature relative to the bare surface (Betz et al., 2013; Sarode et al., 2020; Surtaev et al., 2018). For the patterned wettability surface, the distance between the adjacent hydrophobic dots was sufficiently larger than the bubble departure diameter, preventing coalescence between neighboring bubbles. This facilitated separate vapor removal/liquid re-supply pathways, as shown in Fig. 6(c). Therefore, the improvement in the HTC for the patterned wettability surface relative to the bare surface can be attributed to controlled nucleation, large bubble departure diameter, and minimal bubble coalescence among adjacent departing bubbles (Jaikumar et al., 2018; Rahman et al., 2015).

3.2 Effect of Confinement and Orientation on Patterned Wettability Surface

This section discusses the individual effect of confinement and heater surface orientation on the heat transfer performance of patterned wettability surfaces. The characteristics of the pool boiling performance under confinement are significantly distinct from unconfined boiling. The degree of impact on boiling performance depends on the Bond number (Bo), defined as the ratio of the confinement gap to the capillary length of the fluid (Stutz et al., 2009). Confinement gaps with Bo < 1 have a considerable effect on heat transfer performance (Misale et al., 2011). In this regard, the Bo value for a confinement gap of 1 mm considered in this work is 0.4. Removal of vapor away from the heater surface with the aid of buoyancy is restricted in confined nucleate boiling. Consequently, this affects the liquid re-supply toward the heater surface, influencing the overall heat transfer performance. Confinement causes the liquid near the heater surface to superheat and increases the nucleation site density of the heater surface, thereby ensuring early onset of nucleate boiling (ONB) (Carey, 2008; Sharma et al., 2019). Furthermore, the confinement plate forces bubbles to coalesce and expand laterally within the narrow gap between the confinement plate and the heater surface, as seen in Fig. 8. Due to distortion of the bubbles, additional microlayer evaporation of the liquid held beneath the bubbles improves the heat transfer (Stutz et al., 2009). The improvement in heat transfer and early ONB causes a leftward shift of the boiling curve at low heat flux, as seen in Fig. 9. Eventually, the bubbles expand beyond...
the confinement plate to depart from the sides, allowing the liquid re-supply to rewet the heater surface. These events are then repeated in a cyclic manner. However, the rate of vapor generation increases with the heat flux that resists the liquid re-supply to the heater surface. Moreover, unlike low heat flux, the heater surface becomes dry at high heat flux, rendering the advantage of microlayer evaporation ineffective. Together, these effects result in the development of dry spots, demonstrating deterioration in the HTC at relatively high heat flux, as seen in Fig. 9(b).
As seen in Fig. 10, the heat transfer performance of the patterned wettability surface was found to be affected by the confinement. The HTC was enhanced at low heat flux due to microlayer evaporation. However, at high heat flux resistance to the liquid re-supply and lack of liquid microlayer evaporation resulted in a low HTC value. While the effect of confinement on the patterned wettability surface was similar to that of the bare surface, critical differences in the heat transfer performance are presented in Fig. 11.

Figure 11(a) depicts that the relative HTC value, \( \beta = \frac{(h_{\text{con}} - h_{\text{uncon}})}{h_{\text{uncon}}} \), was higher for the patterned wettability surface than it was for the bare surface at low heat flux (≈ 11 W/cm\(^2\)). The patterned wettability surface generated a greater amount of vapor relative to the bare surface. Therefore, we believe that a larger volume of vapor considerably increases the

![FIG. 10: Effect of confinement on the patterned wettability surface in the horizontal orientation: (a) pool boiling curve; (b) HTC](image)

![FIG. 11: Comparison between the relative HTC, \( \beta \) (a), and the HTC (b) of the patterned wettability surface with the bare surface under confinement in the horizontal orientation](image)
additional microlayer evaporation relative to the bare surface, demonstrating higher \( \beta \) values. However, beyond \( \approx 20 \text{ W/cm}^2 \), the value of \( \beta \) was lower for the patterned wettability surface than it was for the bare surface. As discussed previously, a large amount of vapor resists the liquid re-supply to the heater surface. In an ebullition cycle, a nucleation site is replenished with fresh liquid, which is superheated during the waiting period. Nevertheless, the hydrophobic dots that facilitate continuous nucleation without any waiting period prevent the intermittent liquid supply toward the nucleation sites, thereby adding to the overall liquid re-supply resistance. Therefore, the liquid re-supply resistance was greater for the patterned wettability surface relative to the bare surface. It is also interesting to note that for the patterned wettability surface, the deterioration in the value of \( \beta(<0) \) began at relatively low heat flux compared to the bare surface. Despite this added resistance, the patterned wettability surface demonstrated a higher HTC than the bare surface, as shown in Fig. 11(b).

Figure 12 compares the nucleate boiling heat transfer performance of the bare and patterned wettability surfaces in vertical and horizontal orientations. As seen in Fig. 12, in the case of the bare surface, the vertical orientation has an insignificant effect on the surface superheat and HTC. This observation is consistent with the studies reported in the literature (Mei et al., 2018). Likewise, for patterned wettability, the surface orientation had an inconsiderable effect on the HTC of the patterned wettability surface. According to the literature (Kim et al., 2017), the HTC is affected only by larger orientation angles (beyond 90\(^\circ\)) when the buoyancy force opposes bubble removal away from the heater surface. Thus, orientation angles ranging from 0\(^\circ\) (horizontal) to 90\(^\circ\) (vertical) demonstrate a negligible effect on the heat transfer performance of homogeneous wettability surfaces, as discussed in the literature (Mei et al., 2018).

Thus, the experimental results imply that surface modification by macroscale patterned wettability can potentially improve the confined pool boiling HTC. Also, the surface orientation had no detrimental influence on the performance of the patterned wettability surface, suggesting its capability of effectively dissipating heat under vertical pool boiling conditions.

![FIG. 12: Effect of the orientation (without confinement) on the patterned wettability and bare surface: (a) pool boiling curve; (b) HTC](image-url)
4. CONCLUSIONS

In this work, we investigated the effect of confinement and surface orientation on the heat performance of patterned wettability surfaces. The major findings from this work are summarized as follows:

1. For the same heat flux, patterned wettability surfaces demonstrated a higher HTC than bare surfaces.

2. For bare and patterned wettability surfaces, confinement improved the HTC at lower heat flux due to additional microlayer evaporation. However, under confined pool boiling conditions, the modified surface always demonstrated a higher HTC in comparison to the bare surface.

3. Furthermore, the impact of confinement on the relative HTC was found to be dependent on the wettability of the heater surface.

4. Like the bare surface, the orientation (considered in this work) had an insignificant effect on the HTC of the patterned wettability surface.

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