Condensation on hybrid-patterned copper tubes (II): Visualization study of droplet dynamics

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Abstract
Condensation heat transfer performance can be significantly enhanced by patterning the condenser surface with different wettability regions as shown by numerous studies, including part I of this study. In part I of this study, some patterned surfaces with alternative parallel straight stripes consist of hydrophobic (β) and less-hydrophobic (α) regions at different ratios exhibited higher heat transfer rate than others. In this Part II of the study, our objective is to analyse the droplet dynamics during water vapor condensation on hybrid-wettability patterned horizontal tube surfaces under saturation conditions near the atmospheric pressure. Three major outlines were found in the course of the droplets dynamic investigation. First, the existence of an optimum (β/α) ratio that maximized the condensation heat transfer rate, as demonstrated in part I of a sample carrying β and α-regions widths of 0.6 mm and 0.3 mm, respectively is justifiable. This is because the optimum ratio exhibits the maximum droplet departure frequency and the minimum droplet area coverage rate among other samples. Second, the reduction in the heat transfer rate resulting from any deviation from the optimum ratio is also identified. We observed that by increasing the α-regions width on the hybrid patterned surface, the condensation was dominated by the filmwise mode, thus reducing the condensation rate. In contrast, decreasing the width of α-regions less than the optimum ratio was found to be unfavourable due to the increase in the bridging droplets observed and discussed herein. Lastly, the undesirable observed bridging phenomenon found to occur on all tested hybrid patterned surfaces, can significantly influence the condensation heat transfer performance. A bridging droplet can be referred to a droplet joined (bridged) by two, three, or four neighboring α-strips. Increasing these unwanted droplets formation frequency can induce additional thermal resistance which can reduce the condensation rate. The most dominant and frequent bridging droplet type observed herein was found to be for droplets that were bridged by two α-regions, followed by those between three and four α-regions. A quantitative method (i.e. Bridging coverage area rate) was adapted herein to quantify the influence of the velocity, frequency, and size of the three types of bridging droplets on the condensation rate of the hybrid patterned surfaces.

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1. Introduction

Enhanced condensation surfaces can be rated mainly by the droplet rollover rate and the maximum departure diameter under the influence of either gravity or shear force induced by vapor flow. The wettability of these enhanced surfaces is subjected to the surface energy, roughness, and surface structure [1–7]. Reducing the surface wettability to achieve dropwise condensation (DWC) mode using (super) hydrophobic coatings is one of the most common approaches [8–16]. The condensing droplets on low wettability surfaces usually rollover at a faster rate compared to that of filmwise condensation (FWC) mode, and fallout from the condensing surface at higher rates allowing for more surface areas to be available for steam condensation. Since the condensate can have different behaviors depending on the promoter layer(s), numerous efforts besides the heat transfer have been taken to capture the droplet dynamics for a better understanding of enhanced condensation mechanisms, starting from the state of droplet nucleation to the state of complete departure under a variety of condensation modes [17–20]. Different visualization systems have been developed and used to better understand the condensation process on such engineered surfaces by visualizing the condensing droplet dynamics. These visual observations are essential, especially when the condensing surface combines both hydrophobic and hydrophilic regions. These surfaces with hybrid wettability can be formed
generally in nano/micro or mini-scale patterns/configurations. Aiming to enhance the DWC by promoting the droplet nucleation and removal rates, nano/micro scale patterned surfaces were considered by many studies [21–33]. For such a small scale of examination of droplets behaviors, environmental scanning electron microscopy (ESEM) is one suitable method for visual observation, and used to conduct a microscale condensation experiment [34], where condensate droplets in a diameter of 300 nm were found to preferably form on the hydrophilic dots formed on a hybrid wetting surface. The results of the droplets observation also show that the wettability can be adjusted by the location of the hydrophilic and hydrophobic regions formed on the condensing surface. ESEM is also used to observe and understand the influence of micropillar arrays with various spacing ratios on the droplet behavior during a condensation process [35]. The top surface areas of these square cross section micropillars array are hydrophobic, whereas the spacing and the sides are hydrophilic. The results show that the condensate droplets formed and grew on the hydrophilic top of the micropillars until they coalesced with the neighboring droplets. For micropillar spacing less than 50 μm, the droplets shed once they reach a certain size; however, for spacing of about 50 μm, the droplets were witnessed to fill the spacing and form thin liquid film, leading to dropwise-filmside condensation mode. This visual method is also used to observe nanoscale droplets on multiscale condensing surface comprising of nanograssed micropyramidal architectures that was developed to promote DWC via the coexistence of hybrid wettability [23]. The visualization study shows that combining two different wettability regions increases the droplet number density, rate of droplet growth, and rate of droplets departure. Similar investigations were also accomplished by other studies [19,36–38].

Mini-scale wettability gradient patterning method (same method adapted herein) has been used to enhance the overall DWC performance, and usually high speed cameras are the choice of observation method. This scale of wettability patterning was adapted to mainly promote the removal of the condensing droplets by inducing capillary force. An early work conducted by Kumagai et al. [39] demonstrated such an approach by using straight stripes patterns combining both hydrophobic and hydrophilic regions on the condenser surface. The regions were selected based on the relation to the capillary length scale and found to enhance the condensation heat transfer coefficient (HTC). This method mainly helps to increase the droplets drainage rate and control the droplet maximum diameter. Such a technique is demonstrated by various studies [40–42], including studies conducted by Ghosh et al. [43,44] where both straight and (staggered) interdigitated configurations hybrid patterns were etched on aluminium flat condensing surfaces and experimentally tested with various patterns widths. An enhancement of 20% and 5% in the HTC was attained for the interdigitated patterns compared to that of the complete hydrophobic and the straight patterns, respectively. Their visualization study captured the behavior of the condensing droplets on such hybrid patterns including the transition from one region to the other and droplet removal induced by the coalescence. Despite that, the droplet dynamic was neatly captured, the study did not consider droplet behaviors under saturated conditions or at a wide range of subcooling temperatures (high condensation rates). These conditions may cause such a design to either maintaining its high performance or probably exhibiting a lower one due to possible flooding or bridging phenomena that will be explained later in this work. Another group [45,46] designed circle islands and tree configurations hydrophilic patterns on copper surfaces to enhance condensation rate. Hydrophilic circular islands with diameter of 0.25 mm (0.2 mm edge to edge spacing) on an otherwise hydrophobic surface gained the highest HT performance in their study, which is about 7.5% higher compared to that of a complete hydrophobic surface. Their visualization study captured the droplets nucleation, growth, coalescence, and departure process on both designs. It shows that condensing droplets prefer to form on the hydrophilic islands and the 0.2 mm spacing provides suitable coalescence and higher departure frequency compared to the others. While on the tree design, the droplets were found to form on the edges of the condensing surface and on the corners of the hydrophilic branches of the tree design, showing a lower departure frequency. The study specified that smaller islands ensure smaller droplets, which can coalesce easier and depart at a higher frequency. In another study [47], straight hydrophilic patterns were fabricated on a flat copper surface. The optimum ratio was found to be 0.55 mm for the hydrophobic-stribs, showing an enhancement of about 23% higher than that of the complete DWC. The visualization study was used to capture the droplets behavior, such as computing the maximum diameter and droplets size distribution on the hydrophobic stripes versus the width of these stripes. Moreover, the study suggests that the hydrophilic-widths should be as narrow as possible to assure a smooth drainage condition. However, no visualization studies of stripes widths less than 0.45 mm of this ideology or for islands diameters less than 0.25 mm of the earlier study were provided. We suspect that narrowing the hydrophilic stripes or reducing the hydrophilic islands diameter may not increase the condensation heat transfer performance due to the bridging phenomena as observed herein.

The condensation heat transfer performance for all tested horizontal tubes including the one with hybrid patterns consist of alternative parallel straight strips of hydrophobic (β) and less-hydrophobic (α) regions, were characterized by two methods. The first method was by a careful experimental measure of the heat flux and heat transfer coefficient as a function of the subcooling degree (shown in details in Part (I) of this study). The second method is by observing and analyzing the droplets dynamics based on recorded visualizations during experimental testing, which will be discussed in detail herein. In this part, the main objectives are: first, to demonstrate the feasibility of using wettability gradient by fabricating hybrid patterns on tube configuration and to observe the condensate behavior under condensation of water vapor at saturation conditions near the atmospheric pressure; second is to justify the existence of an optimum ratio found in the Part I; third is to investigate the mechanism that hinders some hybrid patterned samples with a certain (β/α) ratios to outperform a surface with complete DWC. To conclude, this study provides a new insight of droplet dynamics of water vapor condensation on hybrid patterned horizontal copper tubes.

2. Experiment

2.1. Test samples

Copper tubes with a total length of 120 mm, exposed length of about 92 mm, wall thickness of 0.9 ± 0.15 mm, and a diameter of 6.3 ± 0.8 mm were used as the testing samples. As specified in Table 1, three samples with hybrid patterned surfaces R2, R1.5 and R1.2, fully hydrophobic (F-β), and less-hydrophobic (F-α) were considered in the investigation herein. The letter R in the Name/label column of Table 1 represents the ratio of the β to α-region, and the digit represents the value of that ratio. For the samples preparation, detailed experimental procedure, and the testing setup, please reference part I of this study.

2.2. Data reduction and calibration

In part (I), the HT performances for the testing samples were computed based on an experimental measurement method
(Exp.). In this part, however, the HT performances of some of the same samples were computed based on the droplet analysis method (DA). In this method, recorded movies of tube surfaces undergoing water vapor condensation were used to study the droplet dynamics. As shown in Table 1, only five testing samples were selected to avoid data redundancy and cluttering in the graphs. The results were also compared to the identical tests results computed by the Exp. method in part I of this study.

The visualization system consists of a high speed camera (Phantom V7.3) equipped with a macro lens (Sigma EX – DG MACRO – 105 mm 1:2.8, depth of field: 10–20 mm) and a light-emitting-diode light source. The video clips were recorded at a rate of 200 frames per second within an increment of 10 °C of the coolant inlet temperature varied within a range of 35–85 °C. This leaves 10 recorded video clips for each sample to be analyzed and 10 points to be presented in the graphs. The recording duration of each video clip was around 10 s containing about 2000 frames, which was sufficient for the DA method. For a fair comparison, all the points of all tested samples were taken at the same coolant inlet temperatures within a variation of 0.5 °C.

Each image of an original recorded video, Fig. 1a, was first modified by an imaging processing software, in which imaging corrections such as smoothing, defining edges, and black and white adjustment were applied. The final processed image contained well defined droplets white in color with a black background. After modifying the original image to a form suitable for the MATLAB script, the final modified image was found to contain droplets somewhat larger in size compared to the same one in the original image. To account for such change in droplet size, a sampling method to present the whole population was used in which the diameters of randomly selected droplets were measured before and after applying image modification. The two averaged values were then compared to determine the percentage increase in the droplets diameters. Fig. 1 shows a visual comparison of the same samples were taken at the same coolant inlet temperatures (Exp.). The modified image was then processed through a MATLAB analysis script, where information such as droplet diameter, volume, count, traveling velocity, and departure location were determined. For the global droplet analysis framework, the area, volume, count, traveling velocity, and departure location were determined. The analysis script, where information such as droplet diameter, volume, count, traveling velocity, and departure location were determined. For the global droplet analysis framework, the area, volume, count, traveling velocity, and departure location were determined. The analysis script also computed the droplet x and y-locations which determines droplet velocity, and departure location. The droplet departure frequency was determined by considering the total number of droplets and the recording duration of each movie.

The heat transfer rate based on the DA method \( (Q_{DA}) \) was determined as follows:

\[
Q_{DA} = m_i h_g = \rho_i V F h_g
\]

where \( m_i \) is the condensate mass rate, \( \rho \) is the density of the saturated vapor, \( V \) is the average volume of the departure droplets, \( F \) is the droplets departure frequency, and \( h_g \) is the latent heat. By condensing the tube surface area \( (A_t) \), the condensation heat flux \( (q_{DA} = Q_{DA}/A_t) \) was also computed.

By considering the mean standard error \( (SE) \) of the analyzed sampling \( (SE = \sigma/\sqrt{n}) \) where \( \sigma \) is the standard deviation, and \( n \) is the number of droplets, and error propagation associated with the computed areas of droplets, the error bars in the graphs were determined using Kline and McClintock method [48].

### 3. Results and discussion

#### 3.1. Global droplet analysis

The DA method within the global framework was focused on analyzing all droplets that completely detached and departed the condenser surface passing the area showing in Fig. 1a. By analyzing the departure droplets considering the calibration procedure, the heat flux for the four selected samples (i.e. R2, R1.2, F-β, and F-γ) were determined by Eq. (1). To assure the DA method can provide accurate results, the condensation heat flux result was compared to the one computed by the Exp. method of part I. Fig. 2 shows the heat flux computed by the DA and Exp. methods, which presented by the symbols and dashed lines, respectively. The dashed lines showing in Fig. 2 represent the curve fitting lines of the experimental results of part I without the error bars for a clear comparison. The graph also shows that there is a good agreement between the two methods results, indicating that the DA method is an accurate technique. Hence, additional investigations were carried out on the droplets departure to study the droplet departure diameter, frequency, and departure location.

**Droplet departure diameter**

Droplet departure diameter is one of the criteria first considered to be analyzed during condensation. As R2 has the upper most heat transfer rate, one may expect that the droplet departure diameter of R2 would be relatively smaller than those of other samples, however, this was not the case. As illustrated in Fig. 3a, the droplet diameter for R2 was slightly larger than both R1.2 and the F-β. In addition, the departure diameter range of R2 and R1.2 are slightly larger than that of the F-β, implying that the hybrid patterned surfaces did not significantly reduce the departure droplets diameter compared to the F-β. Although the droplet maximum base diameter was significantly reduced from 2.2 ± 0.02 mm on the F-β surface to a diameter of 0.56 ± 0.02 mm on the β-region of the hybrid patterned surfaces (found in part I), the droplet departure diameters of the hybrid patterned samples were not affected. This might be due to three reasons. First, the coalescences of the draining and sweeping droplets near the bottom of the tube and just prior to the departure can be relatively greater at a higher condensation rate, leading to a slightly larger droplet diameter. Second, droplets at the bottom of the tube merge just prior to the departure due to the bridging effect between the α-stripes during the condensation process. Third, and more interestingly, Fig. 3a shows that the droplet departure diameters of all samples were slightly increased when the subcooling was increased. This indicates that at a higher

### Table 1

**Samples categorization.**

<table>
<thead>
<tr>
<th>β-stripes width [mm]</th>
<th>α-stripes width [mm]</th>
<th>Name/label (β/α)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.6</td>
<td>R2</td>
</tr>
<tr>
<td>2</td>
<td>0.6</td>
<td>R1.5</td>
</tr>
<tr>
<td>3</td>
<td>0.6</td>
<td>R1.2</td>
</tr>
<tr>
<td>4</td>
<td>Full</td>
<td>F-β</td>
</tr>
<tr>
<td>5</td>
<td>Full</td>
<td>F-γ</td>
</tr>
</tbody>
</table>

### Calculated droplet diameters

\[
\text{Droplet diameter} = \frac{\text{Area}}{\pi}^{1/2}
\]

where \( \text{Area} \) is the computed area of droplets, the error bars in the graphs were determined using Kline and McClintock method [48].

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*Note: The table and equations are not directly translated into a Markdown format due to the complexity and specific nature of the content.*
condensation rate, higher rate of droplet coalescence can occur, resulting in a slightly larger departure droplet diameter. Hence, R2 with a relatively higher condensation rate can exhibit larger droplet departure diameters. On the other hand, the low heat transfer performance due to dominant FWC on F-α surface lead to significantly larger droplet departure diameters as shown in the graph of Fig. 3a. Original images of some falling droplets (circled by red solid lines) during condensation tests for sample F-α including R2, R1.2, and F-β, are represented in Fig. 3-b for a visual comparison.

Droplet departure frequency

Since the diameter of the departure droplets of the hybrid patterned surfaces appeared to be not the direct cause of the significant enhancement in the HT performance, further investigation was carried out to examine the droplets departure frequency instead. Fig. 4 shows the droplet departure frequency of the four samples. Notice that each point on the graph presents an average droplet departure frequency at a given subcooling degree, regardless of the departure location. The graph shows clearly R2 has the highest departure frequency compared to all other samples followed by F-β, R1.2, and F-α, which matches the trend of the condensation heat flux curves presented in Fig. 2. This suggests that the reason behind the enhancement in the heat transfer performance is primarily due to the increase in the droplet removal rate from the condenser surface. The existence of the α-regions at certain ratios significantly increased the droplets removal from the β-

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Fig. 1. Calibration to the size of falling droplets detected by (a) the original image and (b) the modified image. [Note: Sample R2 is showing in (a) and (b)]. A histogram of a case study of the percentage increase in the size of randomly selected droplets is presented in (c) which shows that the increase in the droplets size after the image modification was 30 ± 5% of the original. The rectangular with the dashed black lines in (a) present the studied area of the global frame work.

Fig. 2. Heat transfer performance for R2, R1.2, F-β, and F-α undergoing water vapor condensation under saturation condition near the atmospheric pressure. The heat flux as a function of the subcooling temperature computed by the Droplet Analysis (DA) and Experimental (Exp.) methods are represented by the symbols and the dashed lines, respectively. The dashed lines present the curve fitting for the experimental results of part I of the same samples. The error bars determined by the error propagation associated with the computed area of the droplets.

Fig. 3. Comparison of droplet size for sample R2, R1.2, F-β, and F-α is presented in the graph of (a) the average droplet departure diameter (computed by the DA method) as a function of the subcooling temperature. (b) Photographs of the condensing tubes undergoing condensation under saturation condition near the atmosphere and at coolant inlet temperature of 40 ± 0.5 °C. Random droplets circled by the same size rings for visual comparisons.

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regions because of two main reasons. First, the two $\alpha$-regions bonded each $\beta$-region created wettability gradient which allows droplets to rapidly migrate from the $\beta$ to $\alpha$-regions via capillary driven force. In addition, the hybrid pattern limited the maximum diameter of a growing droplet to a significantly smaller size, which decreased the thermal resistance of larger droplets on the $\beta$-regions. The droplet critical diameter on the surface of F-$\beta$ is 2.2 ± 0.02 mm and found to be reduced to a base diameter of 0.56 ± 0.02 mm on the $\beta$-regions of all hybrid patterned surfaces. Second, the suitable width of the $\alpha$-regions of the hybrid patterned surface offered trails that easily drained the migrated droplets off the condenser surface with the assist of gravitational force. Sample R2 represents an example of an optimum case, in which high drainage and droplets removal rates, and minimum droplet bridging rate was observed. The time lapse images of Fig. 5 illustrate a comparison for droplet departure frequency of water vapor condensation on sample R2, F-$\beta$, and F-$\alpha$. For a random duration of 25 ms, it was found there are 8, 6, and 2 departure droplets observed, respectively. Which confirmed the width of the $\alpha$-regions can significantly influence the droplet removal rates, and proper widths should be selected based on the wettability degree of the two regions.

**Droplet departure location**

Another interest was given to the influence of the location on the droplet departure frequency and diameter in the x-direction of the tube length showing in Fig. 6. The length of the tube was divided to nine 10 mm-long sections in this analysis. The droplet departure frequency of each section was computed individually and independently of the others. The results of all samples were found to follow the same behavior. Therefore, one case study as an example is presented in Fig. 6. The results in this figure were computed under the same condensation conditions (i.e. saturated water vapor condensation under the atmospheric pressure and a coolant inlet temperature of $40 \pm 0.5 ^\circ C$). As shown in Fig. 6, sample R2, R1.2, and F-$\beta$ exhibited uniform fluctuation and even distributed droplet departure frequency along the length of the tube. However, sample F-$\alpha$ showed uneven fluctuation and distribution as illustrated by the absent of droplets in the last two sections, shown in Fig. 6. This can be explained by the increase of coolant temperature inside the tube and toward the outlet, and by the existence of the dominant water film that reduces the condensation rate at the last two sections.

Worth mentioning, we observed samples exhibiting a dominant FWC mode such as F-$\alpha$, tend to have lower droplet departure sites. In addition, these droplet departure sites favored certain locations on the tube, in which droplets tend to depart these sites significantly more frequent compared to other locations, as shown in section two and seven of sample F-$\alpha$, see Fig. 6. Other tested samples exhibited no significant enhancement or reduction in terms of the number of droplet departure sites pertaining to the x-position. For the influence of the x-direction on the droplet departure diameter, we observed no significant variation in the droplet size on all condensing surfaces.

**3.2. Local droplet analysis**

Under the local frame work, the droplet dynamic analysis was applied to condensates that located on the condenser surface and have not left the condenser. For a fair comparison, the same surface area of analysis was applied for all samples. The area of the analysis present only one third of the total area of the tube, which was facing the visualization window. The main objective of this analysis is to further investigate the bridging droplet dynamic and justify the variation in the heat transfer performances of hybrid patterned samples with different ($\beta/\alpha$) ratios.

**Bridging phenomenon**

Introducing $\beta$ and $\alpha$-regions on the condensing surfaces at certain ratios can significantly influence the heat transfer performance as shown in this study. An optimum ratio (R2) was found to exist and offer the maximum condensation rate. Increasing the $\alpha$-regions to a width larger than that of the optimum led to a dominant FWC mode. However, decreasing the $\alpha$-regions width to values smaller than the optimum width (such as the case in R1.2 and R1.5), led to reduction in the heat transfer performance. During condensation on all hybrid patterned samples, we observed some larger droplets were joining (bridging) two neighboring $\alpha$-regions. Such type of droplets called herein “bridging droplets” and can be bridged not only between two neighboring $\alpha$-regions, but also between three, four, and rarely five $\alpha$-regions, shown in Fig. 7. The $\beta$-regions between the $\alpha$-regions of a bridging droplet were also covered. For instance, a (3-stripes) bridging droplet bridged over three $\alpha$-regions and two $\beta$-regions, as shown in Fig. 7a. Increasing the bridging phenomena can reduce the heat transfer performance due to the increase of the thermal resistance resulting from larger water droplets on the condensing surface. Therefore, additional investigations were carried out to determine the influence of these types of bridging droplets on the condensation rate on hybrid patterned condenser.

The bridging droplet frequency, bridging droplet base diameter, and bridging droplet sliding/travel velocity in the direction of the gravity were considered herein, and carefully analyzed under the local frame work. In this investigation, only three types of bridging droplets were analyzed, droplets that cover two, three, and four $\alpha$-regions. Bridging droplets that covered five $\alpha$-regions were not considered due to their absence in some of the testing samples, and due to their insignificant influence on the results. The analysis was applied on sample R1.2, R1.5, and R2, under the same condensation testing conditions and coolant inlet temperature for a fair comparison. Fig. 8 shows histograms of the population of all bridging droplet types that were analyzed to compute the bridging droplet base diameter. The same population also used to compute the bridging droplet frequency and velocity. Notice that each bridging droplet in Fig. 8 was carefully analyzed independently.
(\(\beta/\alpha\)) ratios (i.e. sample R1.2, R1.5, and R2) for those bridging droplets between two \(\alpha\)-regions (2 \(\alpha\)-stripes), followed by (3 \(\alpha\)-stripes), and (4 \(\alpha\)-stripes), presented in Fig. 9. For the bridging frequency, Fig. 9a, the results indicate that all bridging droplet types increased when the (\(\beta/\alpha\)) ratio was increased. The figure also shows among all bridging droplets types, R2 has the highest bridging frequency compared to other ratios due to its relatively short \(\alpha\)-regions width. Practically, increasing the bridging frequency such as the case of R2 can reduce the heat transfer performance; however this was not the case and further variables were needed to be examined.

Other consideration was given for the influence of the bridging droplet size. Fig. 9b shows the average bridging droplet base diameter as a function of (\(\beta/\alpha\)) ratios. It indicates that the diameters of the bridging droplets were decreased by the increase in the ratio. Since R2 has the shortest \(\alpha\)-regions width, all bridging droplet types were relatively smaller in size compared to other samples as shown in Fig. 9b. Smaller base diameter indicates less surface area of the condenser will be covered, which can lead to lower thermal resistance and higher condensation rates. Although, the decrease in droplet size can reduce the thermal resistance, however smaller bridging droplets will have lower sliding velocity due to the lower gravitational force on a lighter weight droplet compared to the adhesive force between the droplet and the condenser surface.

Therefore, the sliding velocities of all bridging droplet types were also considered, shown in Fig. 9-c. The figure shows R2 has the lowest sliding velocities among other ratios for all bridging types, which was corresponding to the gravity influence on the mass of droplets. Lower sliding velocity also indicates that the bridging droplets can spend more travel time over the condenser surface, which induces a larger thermal resistance. In short, the result of the sliding velocity and the frequency indicates that R2 should have the minimum heat transfer performance since R2 has the lowest velocities and the highest frequency for all bridging droplet types. On the other hand, R2 has the minimum base diameter for all bridging types indicating that R2 has the minimum thermal resistance leading to higher condensation rates.

To solve this contradiction, the three bridging droplet variables were considered simultaneously, in which a product of the three variables (i.e. Frequency × Base Diameter × Velocity) was computed, the quantity of the product presents the bridging droplet coverage area rate, shown in Fig. 10. Increasing this rate would increase the thermal resistance, because larger surface areas of the condenser will be covered by these unwanted bridging droplets per unit time. Fig. 10 also shows that (2 \(\alpha\)-stripes) was the most
dominant type of bridging droplet for all ratios, and the most influential one. Within this type, R2 has the minimum bridging coverage area rates indicating the minimum thermal resistance, whereas, R1.2 has relatively the most thermal resistance. For the other two bridging droplet types (3 and 4 α-stripes), the change in the ratio did not influence the coverage area rate significantly. To conclude, the key factor that contributes to leave R2 with the optimum ratio (i.e. minimum bridging coverage area rate), is the relatively smaller bridging droplet diameter of the most frequent bridging droplet type (i.e. 2-stripes).

Fig. 7. Bridging droplet phenomenon during condensation on hybrid patterned condensers. (a) A schematic illustrating the three types of bridging droplets that were considered herein. (b) A photograph showing three types of the bridging droplets circled by red dashed lines forming on surface R2 that was undergoing water vapor condensation under saturated conditions of the atmosphere, and a coolant inlet temperature of 40 ± 0.5 °C. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 8. Histograms of the bridging droplets base diameter for bridging droplet occurred between (a) 2 α-stripes, (b) 3 α-stripes, and (c) 4 α-stripes, for sample R1.2 (row 1), R1.5 (row 2), and R2 (row 3). The analyzed bridging droplets population of the three samples were taken under the same condensation test conditions and coolant inlet temperature of 40 ± 0.5 °C.
4. Conclusions

In this analysis study, the droplet dynamic of water vapor condensation on hybrid patterned condenser surface was systematically investigated. The patterned condenser tubes surfaces consist of alternative parallel straight stripes of hydrophobic (β) and flooded hydrophobic/hydrophilic (α) regions at different ratios. The main outcomes of this part of the study are summarized as follow:

1. We demonstrated that the condensation heat transfer performance of tube configuration condensers can be enhanced by hybrid wettability patterning method owing to the capillary driven force. The capillary force substantially increased the rate of droplet shedding from the β to α-regions if a proper width of the β and α-regions were selected such as the case in R2 and R1.5.

2. The developed droplet analysis (DA) method adapted herein allows estimating the condensation heat transfer performance, by just a careful observation of the departure droplets during condensation tests.

3. A bridging phenomenon exists on all hybrid patterned surfaces. This phenomenon refers to those droplets that were bridged between two, three, or four neighboring α-stripes. These bridging droplets were found to have a significant influence on the heat transfer performance due to the increase of the thermal resistance, which was categorized by the bridging droplet coverage area rate.

4. Based on the droplet dynamic analysis, two reasons were found to be responsible of the existence of the optimum (β/α) ratio. First is regard to the suitable width of the β-regions (0.6 mm), which reduced the average maximum droplet base diameter from 2.2 ± 0.02 mm (found on the surface of F-β in part I) to an average value of 27% of that width. Second, the α-regions width of 0.3 mm found to assure smooth condensate drainage and least bridging actions.

5. For those condensers with hybrid pattern (β/α) ratio showing a lower HT performance than the fully hydrophobic surface (F-β), the α-regions width was either too large where the FWC was more dominant, or too narrow where the bridging phenomena occurred more frequently, resulting in higher thermal resistance.

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