Enhanced Dropwise Condensation Via Wettability Contrast Mechanism

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ENHANCED DROPWISE CONDENSATION VIA WETTABILIT Y CONTRAST MECHANISM

by

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DEDICATION

I would like to dedicate my work to my loving mother and my two daughters.
ACKNOWLEDGEMENTS

At 2013 with a bachelor and master degree both majored in mechanical engineering received from University of South Carolina in 2011 and 2013, respectively, I fortunately joined Dr. Chen Li’s group to work in his laboratory, Micro/Nanoscale Transport Lab. Since then, condensation was the phase change topic of my interest. With a little knowledge to begin with and the tremendous support provided by Dr. Chen Li, who not only professionally supervise my academic journey, but made it very pleasurable experience, many challenges were overcome. Therefore I would like to present my especial thanks to his kind and rich in knowledge personality. I would like also to present my especial thanks for the Mechanical Engineering Department’s chair, Dr. Jamil Khan, who always provide an endless support for the department, and have always inspired me by his great mind and humble personality. I would like also to include his administrative assistances, Misty O'Donnell, and Lalitha Ravi.

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ABSTRACT

Condensation heat transfer performance can be improved by many methods including the most common used method, which is by increasing the droplet removal rate of the condensing surface. Commonly, this approached can be achieved by promoting a dropwise condensation mode in which super/hydrophobic coatings can be applied on the entire condenser surface to reduce the surface wettability degree. In this dissertation, two main approaches were adapted to enhance the condensation heat transfer performance of the condensing surface via wettability contrast mechanism. Three approaches of investigation were performed to better understand such dropwise condensation promoter methods.

In the first part, alternative mini-scale straight patterns consisted of hydrophobic (β) and less-hydrophobic (α) regions were formed on surfaces of condenser copper tubes. The existence of the two adjacent regions carrying different surface energy generates wettability gradient which can mitigate condensate and increase its removal rates. A parametric study was conducted to experimentally determine the influence of (β/α) ratio on the condensation heat transfer performance and the droplet dynamic under saturation condition near the atmosphere pressure with the presence of non-condensable gases (air). The results reveal that all patterned surfaces exhibited a drastic enhancement in terms of condensation heat transfer coefficient and heat flux compared to those of filmwise condensation. More interestingly, some (β/α) ratios significantly outperformed a surface with a complete dropwise condensation. In addition, an optimum (β/α) ratio of (2/1)
exists with β and α-regions widths of 0.6 mm and 0.3 mm, respectively. The heat transfer coefficient of the sample with the optimum ratio peaked at a value of 85 kW/m² K at subcooling temperature of 9°C, which was about 4.8 and 1.8 times that of a complete filmwise and dropwise condensation, respectively. This term of investigation also demonstrated that the β-regions served mainly as droplet nucleation sites with rapid droplets mobility; whereas the α-regions promoted droplet removal from the neighboring β-regions, and served as drainage paths, where condensate can be drained quickly under gravitational force. Furthermore, the existence of both α and β-regions on the condensing surface controls the droplets maximum diameters of the growing droplets on the β-regions. The maximum diameter is approximately 0.56 ± 3% mm, which is 26% the size of the droplets maximum diameter on a full β-region surface.

In the second part of the study, the main objective was to analyze the droplet dynamics during condensation on hybrid-wettability patterned surfaces of horizontal oriented tubes, and to investigate why 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. Three major outlines were found in this course of the droplets dynamic investigation. First, the existence of an optimum (β/α) ratio that maximized the condensation heat transfer rate was justified due to exhibiting the maximum droplet departure frequency and the minimum droplet area coverage rate relative to other tested samples. Second, the reduction in the heat transfer rate resulting from any deviation from the optimum ratio was also identified. We observed that by increasing the α-regions width, the condensation was dominated by a filmwise condensation mode, thus reducing the condensation rate. In contrast, decreasing the width
of α-regions less than the optimum ratio was found to be unfavorable 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 that joined or bridged by two, three, or four neighboring α-stripes. 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.

In the third part of the investigation, the same hybrid wettability concept was applied however at a nanoscale instead. A bi-philic surface consist of nanoscale hybrid wettability regions was developed by depositing different numbers of hydrophilic nickel oxide layers on smooth nickel tubes surfaces via atomic layer deposition method (ALD). The deposition nature of the ALD method allows for a certain amount of carbon, which is hydrophobic in nature, in combination with the NiO to be deposited on the surface. The existence of the contrast in wettability degree of the condensing surface helped in droplet mitigation and improved the droplet removal rate. Moreover, the choice of nickel as a material for such investigation can be justified by its relative stability among other common condenser metals and their oxide. Most of the metal surfaces will be oxidized when exposed to the ambient containing water vapor, such as the extreme situation of
saturation conditions of water vapor during condensation process. The deposition of NiO layers on the Ni surface is basically mimicking the oxide layer that would be formed on nickel surfaces during real applications. The condensation heat transfer performances for all samples with different NiO layers, i.e. 50, 100, 200, and 400 cycles of ALD. A significant enhancement was achieved especially for the sample with least deposition number of NiO ALD cycles. The maximum condensation heat transfer coefficient achieved was at subcooling temperature of about 3.5°C with a value of 100 kW/m² K, which is 4.2 times the FWC. While, the heat flux max out at subcooling temperature of about 11.0°C with value of about 700 kW/m² which is 3.9 times the FWC. The coexistence of the hydrophobic carbon and hydrophilic NiO at atomic concentration ratio of about 3 to 1 (i.e. 74.3 % to 25.7 % for carbon to NiO, respectively) allows for a proper droplets mitigation due to the existence of bi-philic condensation mode which was driven by the capillary force.

In summary, this capillary-driven mechanism allows droplets to be expediently removed from the condensing surface at higher rates, allowing more surface area to be exposed to the surrounding vapor and leading to a substantial enhancement in the condensation heat transfer coefficient. Such mechanism can be achieved by introducing two or more regions with different wettability degrees on the condensing surface following a pattern. The patterns can be studied and designed in such away it can deliver suitable scale and ratio that match wettability contrast degree of these regions.
PREFACE

Many methods were developed to enhance the condensation heat transfer performance by reducing the surface wettability to achieve a dropwise condensation. The literature review in Chapter 1 includes mainly three categories. The first category will discuss methods, which were used to reduce the surface free energy to achieve dropwise condensation. In the second category, the discussion will include condensing surfaces exhibiting hybrid wettability at nano/microscale aiming mainly to increase the droplet nucleation and removal rates [47-50, 52-57, 75-77]. The third category will discuss surfaces that exhibited wettability gradient at the mini-scale, which is the same approach adapted in Chapter 2, aiming to promote droplets mitigation via the capillary driven force [59-64, 81, 82].

Following the literature review is Chapter 2, which proposing a method to enhance the overall dropwise condensation via a capillary-driven force, which mitigates the condensate. This mitigation of condensing droplets is achieved by forming straight patterns on copper tubes. These patterns exhibit both hydrophobic and hydrophilic strips at a mini scale, the former mainly acted as nucleation sites for condensate, whereas the latter acted mainly as condensate drainage paths. The experimental investigations in this section have two main parts. The first part will focus on the condensation enhancement, which will be categorized by the condensation heat transfer performance. Whereas, the second part of Chapter 2 will focus on analyzing the droplet dynamic and behavior during the condensation process of water vapor. The analysis will conclude that using hybrid
wettability patterns can increase the droplet departure frequency for certain hydrophobic to hydrophilic ratios. However, the study will also show that some other ratios cannot gain a significant enhancement due to a bridging phenomenon found existing during condensation on such hybrid surfaces. The phenomenon and its influence on the reduction in condensation heat transfer performance will be discussed.

Chapter 3 will discuss the nanoscale wettability contrast, which was achieved by depositing nickel oxide layers on nickel surfaces via atomic layer deposition method to mimic the oxidation layer that would be formed in industrial application. The determined heat transfer measurement and visualization recording will be used to investigate the influence of combining two wettability degrees at nanoscale. The contrast in the wettability was identified by the surface chemical components, which consisted of hydrophilic nickel oxide and hydrophobic carbon. The ratio between nickel oxide and carbon can significantly enhance the condensation rate.
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\( A \) \hspace{1em} \text{surface area of the tube (m}^2\text{)}
\( C \) \hspace{1em} \text{constant of Eq. (5)}
\( c_p \) \hspace{1em} \text{specific heat capacity (J/kg K)}
\( D \) \hspace{1em} \text{diameter (m)}
\( \mathcal{F} \) \hspace{1em} \text{droplet departure frequency (1/s)}
\( g \) \hspace{1em} \text{gravitational acceleration (m/s}^2\text{)}
\( h \) \hspace{1em} \text{heat transfer coefficient (W/m}^2\text{K)}
\( h_{fg} \) \hspace{1em} \text{latent heat of evaporation (J/kg)}
\( k \) \hspace{1em} \text{thermal conductivity (W/m K)}
\( L \) \hspace{1em} \text{tube length (m)}
\( \dot{m} \) \hspace{1em} \text{mass flow rate (kg/s)}
\( Nu \) \hspace{1em} \text{Nusselt number}
\( P \) \hspace{1em} \text{pressure (Pa)}
\( Pr \) \hspace{1em} \text{Prandtl number}
\( Q \) \hspace{1em} \text{heat transfer rate (W)}
\( q^* \) \hspace{1em} \text{condensation heat flux (W/m}^2\text{)}
\( R \) \hspace{1em} \text{resistance (K/W)}
\( Re \) \hspace{1em} \text{Reynold number}
\( T \) \hspace{1em} \text{temperature (K)}
\( \bar{U} \) overall heat transfer coefficient (W/m\(^2\) K)
\( \bar{V} \) average volume of departure droplets (m\(^3\))
\( \Delta \) difference (–)
\( \rho \) density (kg/m\(^3\))
\( \mu \) dynamic viscosity (Pa s)
LIST OF SUBSCRIBES

c........................................................................................................................................coolant
c.conv.................................................................coolant convection inside the tube
cond .....................................................................................................................................condensation
Cu ...........................................................................................................................................copper
c.w .........................................................................................................................................coolant at wall temperature
f .................................................................................................................................................film
i ........................................................................................................................................................inner
i.cs ........................................................................................................................................inner cross section of the tube
in.c ........................................................................................................................................inlet of the coolant
l ........................................................................................................................................................liquid
LMTD ...........................................................................................................................................log mean temperature difference
o................................................................................................................................................outer
out.c..........................................................................................................................................outlet of the coolant
sat .................................................................................................................................................saturation temperature
tot ................................................................................................................................................total
v ........................................................................................................................................................vapor
w......................................................................................................................................................wall
LIST OF ABBREVIATIONS

α ............................................................ less-hydrophobic region(s)

AFM ............................................................ atomic force microscope

ALD ............................................................ atomic layer deposition

β ............................................................ hydrophobic region(s)

DWC ............................................................ dropwise condensation

FWC ............................................................ filmwise condensation

HT ............................................................ heat transfer

HTC ............................................................ heat transfer coefficient

Ni ............................................................ nickel

NiO ............................................................ nickel oxide

R ............................................................ ratio

XPS ............................................................ X-ray photoelectron spectroscopy
CHAPTER 1:
AN INTRODUCTION OF DROPWISE CONDENSATION PROMOTORS

Condensation is an essential and yet widespread process that can be found in many small-scale and industrial applications such as in power plants, water desalination and harvesting, HVAC (Heating, Ventilation, and Air Conditioning), and dehumidification [1-4]. Increasing the condensation performance efficiency can significantly reduce the energy and materials consumption as well as capital and operational costs. Condensation heat transfer (HT) performance can be enhanced using diverse methods which are presented throughout numerous research studies. One of the most common methods is by promoting dropwise condensation (DWC) mode since first recognized by Schmidt et al. showing that the heat transfer coefficient of DWC can be five to seven times that of the filmwise condensation owing to its superior heat transfer rate to that of filmwise condensation (FWC) mode [5-9]. In general, an effective DWC can be achieved when nonwetting superhydrophobic or incomplete wettable surfaces are used as the condensing surface. These surfaces usually have higher drop nucleation site densities, coalescence and droplet roll-off rates, resulting in a higher replenishment frequency at smaller droplet diameters [10-14].

Many methods are developed to enhance the condensation heat transfer performance by promoting DWC. Such promotors can be found in an experimental study by [15], where the condensation heat transfer performance of vertical titanium plates with different surface energies were investigated. Three titanium surfaces were prepared and
tested. The first sample was for a bare titanium surface without any modification resulting in a contact angle of 86.06°. The second sample was chemically etched with hydrofluoric solution to reduce the surface energy resulting in a contact angle of 60.87°, resulting in a hydrophilic surface exhibiting a filmwise condensation. For the third sample, the surface was chemically etched and treated with hydrogen peroxide solution resulting in a hydrophobic surface with a contact angle of 100.41°. The condensation heat transfer performances of all samples were measured using saturated water vapor under the atmospheric pressure. The results show that a mixed condensation modes consist of dropwise and rivulet filmwise condensation was achieved by the first sample, whereas, the second sample exhibited a complete filmwise condensation. The third sample with a high surface contact angle displayed a complete DWC. In addition, the effect of the subcooling temperature (surface to vapor temperature difference) on the condensation rate was also investigated. The results show the subcooling degree has a minor influence on the condensation rate for the second and third samples, which determined by the measured heat transfer coefficient, whereas a significant influence was observed on the first sample. Upon increasing the subcooling degree, the ratio of area covered by droplets was reduced, which lead to an increase in the departure diameter and reduction in the heat transfer performance.

One of the developed methods used to achieve dropwise condensation is the ion implantation method, which used to reduce the surface free energy by applying different alloy composites on the condenser surfaces made from variety of materials, such as titanium, stainless steel, and aluminum [16-18]. The influence of different parameters, roughness, and oxidation effects on these surfaces was also considered. In their study,
plasma-ion implantation method was used to achieve DWC on tubes made of stainless steel [19]. This method allows doping nitrogen ion on the stainless steel tubes surfaces with two different doses, $10^5$ and $10^{16}$ cm$^{-2}$. The treated stainless steel surfaces were first tested under the identical conditions to investigate the effect of different ion doses on the condensation rate. In the second testing approach, the samples with higher treated dose ($10^{16}$ cm$^{-2}$) were tested under different steam pressures, 1000, 1500, and 2000 mbar and compared to untreated bare stainless steel surface to investigate the influence of different operation pressure values on such coatings. Results show that the higher ion dose case increased the condensation heat transfer coefficient due to the reduction of the surface free energy. In addition, the heat transfer performance of both treated samples, the $10^5$ and $10^{16}$ cm$^{-2}$, were significantly higher than the FWC by a factor of 3.2 and 2.2, respectively. For the different pressures testing case, results show that the increase in the operating pressure leads to an increase in the heat transfer coefficient. The study reasoned the cause by two possibilities. First, the increase in the operating pressure caused a reduction in the mass transfer interfacial resistance at the liquid-vapor interface. Second, the increase in the steam temperature corresponding to the increase in the steam pressure decreased the surface tension of the condensing droplets. The later leads to reduction in the drop running off diameter, which increases the heat flux density and heat transfer coefficient.

In the effort to promote a stable dropwise condensation on flat disc surface made of aluminum alloys AL 6951 and AL 3003, ion beam implantation technology was used [20]. The ion dose was $10^{16}$ N$^+$ cm$^{-2}$ with implementation energy of 20 KeV, and the average surface finish was about 0.15 µm and 0.5 µm. The experimental study examined
the effect of the surface finish/roughness, the surface material alloys types, and the implementation ion on the DWC performance. Two types of experiments were conducted, one to measure the heat transfer performance under saturation conditions of at pressure value of 1200 and 1400 mbar, and the other to test the durability of the coatings. For the surface finish, the results show that for aluminum alloys a polish surface is preferable for ion implementation as it provide dropwise condensation, whereas for the unpolished surfaces filmwise condensation was achieved. In addition, the results show that a small change in the alloy composition influenced the ion implementation and with applying different parameters changes, dropwise condensation can be achieved. On the other hand, all the samples without ion implementation treatment showed filmwise condensation. For the heat transfer performance, Al 6951 alloy with ion implementation described earlier gained the upper most heat transfer performance. The heat transfer coefficient of this sample was twice the FWC. For the durability test, the sample maintained the same performance for 8 months. The sample then exposed to the ambient air for two months and put back in the condenser for another test. The results show DWC was observed for few hours then a FWC was gradually dominating the condensation mode due to the build oxide layer that covered the condensing surface.

The same group in another similar experimental study used ion beam implementation of N$^+$ on the condensing surface made of titanium, which was stabilized by a peroxidation procedure [21]. The heat transfer performance was measured showing the heat transfer coefficient of the ion implemented titanium with $10^{16}$ cm$^{-2}$ at 20 KeV was enhanced by a factor of 5.5 compared to that of the FWC. The results also show that
the ion implementation parameters did not significantly affect the HTC. Those deviations in the results of the various samples were small and within the measurement uncertainty.

Both ion-plating and ion-beam mixing were used to develop different alloy layers on copper condenser surface to reduce its wettability [22]. DWC can be achieved using this method which allows for preparing diverse alloys on metallic surfaces to reduce sometimes their surface energy by altering the surface microstructure and chemical composition. In their study [22], various surface alloys were prepared using elements such as Cr, Fe, Al, N, Bi, Sb, Sn, and In to be applied on copper tubes surfaces. The testing tubes have a length of 400mm and diameter of 25/22mm. Only four alloys on the copper surface exhibited dropwise condensation with a contact angle of about 90°, Cr, Fe, Al, and N, whereas the copper surfaces that contain Bi, Sb, Sn, Se, and In, filmwise was the dominant condensation mode. Between these four samples that show dropwise mode of condensation, small patches of film mode condensation were observed after several hours of testing on the surfaces coated by Al and N alloy. The patches gradually converted to a complete FWC after ten hours. The study stated that the heat transfer coefficient of DWC is higher than the filmwise condensation by a value of 1.7 to 4.2 times.

Multi-ion beam mixing implementation system was used as apparatus for surface material modification as another approach to achieve dropwise condensation [23]. In this system, vacuum arc plasma beams, an electron beam, and a sputtered atom beam were used simultaneously under different energies to synthesized very thin film of about 0.1 µm of polytetrafluoroethylene or PTFE on brass and stainless steel substrates. This polymer film with property of DWC heat transfer was prepared with a deposition rate of
1 mn/min, an argon ion beam current density of 20 µA/cm², and ion energy of 5 KeV. Condensation experiments under the saturation conditions of the atmosphere were conducted displaying a stable dropwise condensation for both substrates. The freshly prepared samples of both substrates exhibited the upper most heat transfer performance. The samples were also tested after two months of storage showing a slightly lower heat transfer coefficient. After a use of about 300 h and 350 h of the brass and the stainless steel, respectively, both condensing surfaces were tested again showing a slightly lower performance. The heat transfer coefficients of all cases were compared with substrates without PTFE coating, showing a significant increase in the heat transfer performance.

Dynamic ion-beam mixed implantation technique are used with different surface processing conditions to form, for instance, a polytetrafluoroethylene polymer film on different condensing surfaces tube surfaces made of brass, copper, stainless steel, and carbon steel [24]. Among other tested metals, brass at certain preparing conditions exhibited the maximum heat transfer performance. Nine brass samples were prepared with different processing conditions and tested under atmospheric saturation condition. The maximum heat transfer coefficient was achieved by one of the coated brass sample resulting in a value of about 185 kW/m²K at subcooling temperature of about 5 K. Compared to FWC, the polymer coated brass surface with a contact angle of 107° has 4.6 and 28.6 times higher condensation heat flux and heat transfer coefficient, respectively.

Surfaces with low wettability degree can also be formed by depositing layers of barium stearate molecules using the Langmuir-Blodgett method [25], which promote DWC. In their experimental study this method was adapted to prepare one and three layers of barium stearate monomolecular film(s) on copper plate surfaces. The testing
samples show the copper surface coated by Langmuir-Blodgett film with three layers of barium stearate exhibited higher condensation heat flux then the one with the one layer. The maximum heat flux achieved was about 1.6 MW/m\(^2\) at subcooling degree of about 4.5 K under saturated water vapor condition. Result indicates that the forming layers promoted an excellent DWC and the heat transfer coefficient maintained was more than 30 times higher than that of the FWC.

Another technique to reduce the surface wettability is to use chemical vapor deposition method to form for example amorphous layers of hydrogenated diamond-like carbon [8, 26, 27], or a grafted polymer layer on the condensing surface to achieve sustained DWC [28].

In their study [8], thin silicon-modified amorphous hydrogenated carbon films of different thicknesses were coated on vertical flat copper plates to reduce the surface wettability, hence promoting a DWC mode. These types of coating exhibited similar mechanical and chemical properties to that of diamond. The experimental results reveal that the diamond-like properties attained a long lasting DWC that lasted up to 500 hours. The achieved maximum heat flux was about 1.72 MW/m\(^2\); the heat transfer coefficient was 10 times the uncoated surface with a dominant FWC. The study also investigated the effect of the partially hydrophobic with different ratio of hydrophilic regions; this is to explore the influence of degradation of such coating under long operation time. Three different hydrophilic to hydrophobic ratios were adapted and taste, 19%, 36%, and 53% taking a form of hydrophobic circular islands with a diameter of 10mm on a hydrophilic backgrounds. By comparing the results with a complete dropwise and filmwise condensation, it found out that all sample exhibited higher heat transfer performance than
the FWC but not the complete DWC. Moreover, inclined surfaces with different angles also were investigated and compared with the vertical (90°) surface. Six different surface inclinations were tasted and compared under heat fluxes range of 0.3 to 1.0 MW/m². The results show that there are no significant changes for different heat fluxes for a specific inclination angle. Moreover, they found that inclined surfaces show lower heat transfer coefficient compare to that of the vertical surface.

Similar in chemistry surface was used to promote DWC by Koch et al. [26]. They initially formed a base of amorphous layers of hydrogenated Diamond-Like Carbon on the condensing copper flat surface, which has an equilibrium contact angle of about 74° when water was used. To further reduce the wettability or increasing surface energy, plasma enhanced chemical vapor deposition method was used to add a layer of fluorine, silicon, and a combination of silicon with oxygen, which resulted in contact angles of 65 ± 2°, 90 ± 2°, and 90 ± 2°, respectively. The results show that the DWC heat transfer coefficient for the second and third samples was 11 times higher than that of the FWC, whereas for the fluorine treated sample and the sample without treatment, the HTCs were 3.5 and 7 times the FWC, respectively. In addition, the sample without treatment maintained DWC up to a heat flux of 1.54 MW/m², whereas for the other samples, a mixed condensation mode was achieved. Nevertheless, no instability was observed for such coatings under 500 h of operation testing time.

A combination of wet chemical etching and oxidation process followed by applying a SAM coating was used to form a superhydrophobic consists of a layer of copper (II) hydroxide nanowire layer formed on copper substrates. This is to sustain high condensation performance under a relatively longer period of time [29]. To test the
condensation performance the superhydrophobic surfaces were undergo flow condensation under saturated vapor at high temperature around 110°C. The nanostructure functionalized surface has a contact angle of $159° \pm 2°$ with a nearly zero sliding angle at a room temperature. For comparison, a hydrophilic oxidized copper surface was used. The heat transfer measurement procedure was carried out for 6 days for both samples under three different vapor flow velocities 6, 12, and 18 m/s. For the heat transfer performance, the maximum value of the heat flux achieved was about 620 kW/m$^2$ at wall subcooling of about 10 K, under a vapor shear velocity of 18 m/s. The testing results indicate that the vapor flow caused the superhydrophobic surface with DWC to convert to a FWC mode following Wenzel state after the fifth day of testing. However, due to the shear forces of the vapor flow during condensation, the departure droplets removal rate was enhanced and the droplets departure critical size was also reduced. During the sixth day, the performance of the hydrophobic surface was found to be even lower than the sample with FWC, which kept its constant performance throughout the testing duration.

In addition, a method combined chemical oxidation, etching process, and chemical vapor deposition was used to deposit a silanized copper oxide layer featuring knife-like functionalized nanostructure on copper surfaces to achieve both Jumping-droplets and DWC modes [30, 31]. Such a method is also used to deposit an ultrathin layer of graphene coating on copper surfaces showing chemically stable and low thermal resistance hydrophobic surfaces [32, 33].

Miljkovic group [30] demonstrated an increase of 25% of the overall heat flux and 30% of the condensation heat transfer coefficient compared to the state-of-the-art hydrophobic condensing surface at low supersaturation ($S$), which defined as the ratio of
the vapor pressure to the saturation pressure corresponding to the sample surface temperature. The superhydrophobicity created by using silanized copper oxide surface prepared by a simple fabrication methods using chemical oxidation-based CuO nanostructuring, resulting in a surface with a contact angles of $172.0 \pm 3.2^\circ$ and $167.8 \pm 3.2^\circ$ for the advance and receding, respectively. The superhydrophobic nanostructured surface promotes droplet jumping mechanism, which occurred due to the coalescence of the condensing droplets associated with the release of the excess surface energy. The chemical-oxidation-based CuO nanostructuring fabrication method exhibits low parasitic conduction thermal resistance with a thermal conductivity of about $20 \, {W/m \cdot K}$ due to its self-limiting growth behavior and low characteristic oxide thickness of about $1\mu m$. Moreover, the knife-like nanostructure features performed as nucleation sites within the structure; and show small characteristic length scale of the nanostructure spacing of about $1\mu m$, which allows for high nucleation site densities and thus higher supersaturations prior to surface flooding. Additionally, the study confirmed the independency of the condensation process on both hydrophilic and hydrophobic surfaces to the supersaturation degree; whereas the condensation on the nanostructured CuO surface was significantly depended and influenced by the supersaturation. At the low supersaturation of about 1.08 the droplet removal and jumping mechanism were efficient, which show numerous microscale droplets with a radius of about $8 \, \mu m$ populating on the surface. On the other hands, at high supersaturation of about 1.54, achieved by lowering the temperature of the cooling water, a transition from high mobile jumping droplets to high pinned Wenzel droplets was eventually occurred. This transition caused 40 % reduction in heat transfer coefficient compared to that of the smooth surface with a DWC.
This transition justified by reaching a flooding point leading to a complete wetting of the cavities of the nanostructure.

A continuous process of DWC and droplet jumping removal mechanism without any external force was also achieved using superhydrophobic surface [34]. This spontaneous removal of condensing droplets occurred due to the release of surface energy during the coalescence process resulting in an out-of-plane jumping motion. The experimentation work conducted on two-tier roughness superhydrophobic substrate that placed on a horizontal cold copper plate. The plate temperature maintained at 5.5 ± 0.5 °C, whereas the laboratory ambient temperature kept around 19 °C with 74 % relative humidity. They categorized the process of the condensation on such surfaces into three stages. Throughout the first stage which named “initial growth without coalescence”, the drops nucleated and grow with negligible interaction showing insignificant surface coverage observation. During the second stage, “immobile coalescence”, noticeable surface coverage was observed showing large enough droplets capable to produce coalesce frequency, however the center of these coalescence droplets were not move significantly before and after the coalescence process. During the third stage, “mobile coalescence”, droplet mobilization and rapid removal of the merged droplets were occurred. An out-of-plane jumping motion was observed to be associated in this stage and upon reaching the threshold value of the droplets diameter during the coalescence which was 10 µm in size.

Another study [31], also investigated the droplets dynamic of 1000 jumping droplets on copper oxide nanostructure superhydrophobic surface to justify the reason of such phenomena. Three mechanisms were found to be responsible of such jumping. The
first was related to the coalescence actions between two droplets. The second was associated with the multiple droplets coalescence such as between three droplets or more. The last was related to the droplets that were returning to the surface after the coalescence occurred between two or more droplets. No experimental heat transfer measurement was conducted in their study.

Dropwise condensation (DWC) also can be achieved by mean of graphene coatings. In their study, the condensation performance of a graphene coating with a wetting transparency on copper surfaces was investigated [33]. The study indicates that the graphene layer has the ability of passivating a surface without disruption its wetting properties. This provides a protection layer for a surface whether it is a hydrophobic or hydrophilic. Since the formed oxide layer on common copper surfaces responsible of alternating the surface wettability to hydrophilic during condensation, a graphene layers were formed on a copper oxide surface and compared to that graphene on bare copper. The results show that the extreme thinness of the graphene layer has the ability to protect and passivate the oxide layer without even changing the intrinsic interaction between water and the copper surface. The condensation heat transfer testing was performed under a relative humidity of about 10 % and ambient temperature of 60 °C. The results show that the heat transfer coefficient of the monolayer graphene-coated copper surface exhibited 30 % to 40 % increase over a wide range of subcooling temperatures compare to that of the bare copper surface. In addition, the study reveals that the increase in the number of layers of graphene can eliminate the transparency effect, and in order for this affect become apparent the thickness of the graphene coating on the copper surface has to be less than 0.34 nm which is the thickness of graphene.
In another similar study, the condensation heat transfer performance was enhanced by applying a scalable graphene coating on a copper tube surface [32]. Chemical vapor deposition method was also used to develop ultrathin scalable graphene coating exhibiting a high chemical stability and maintain a low thermal resistance due to promoting a DWC. The experimental testing was performed using water vapor under saturation condition of the atmospheric pressure. The graphene coated copper was compared to a bare copper surface and a fluorocarbon monolayer coated copper surface. The graphene coated copper demonstrated an enhancement in the heat transfer coefficient by a factor of 4 times compared to that of the FWC of the bare copper surface. For the fluorocarbon monolayer coating, a full degradation of the DWC occurred under just 12 hours, whereas for the graphene coating surface the DWC maintained over two weeks.

DWC can also promoted by using slippery condensing surfaces, which can exhibit high droplet mobility and high droplet sweeping rates. Such surfaces were prepared by lubricating a condensing surface consists of a layer of hierarchical micro-nanoscale texture [35, 36]. These types of surfaces repulse micro-scale condensed droplets due to the reduction of the liquid-solid pining effect. However, long time operation can reduce the effect since some of the surface lubricant can be disseminated by some means.

Organic coatings formed by self-assembled monolayer (SAM) method were also widely used to reduce the free surface energy of the condensers and achieve DWC [37]. Lan Zhong group [38] experimentally investigated the influence of the surface free energy and surface morphology on DWC. Two different surface structures using copper substrates were prepared and coated by SAM coatings, a nanostructured and a mirror-polished finish surfaces. Their experimental testing results data shows that the
nanostructured surface exhibited lower heat transfer performance despite that it shows a superhydrophobicity, which indicated by the measure large apparent contact angle in air atmosphere. The study reasoned the responsibility to the fractal like nanostructure, which was filled or partial flooded by the condensate during the condensation process. Whereas, due to the lower free surface energy of the mirror-like polished surface, it shown a better performance with an enhancement factor of 3 compared to the nanostructured surface.

Due to the challenge of maintain DWC for prolong period of time, many experimental studies have been conducted to extended the surface durability and performance. In their study, self-assembled mono layers of n-octadecyl mercaptan (SAM-1) and stearic acid (SAM-2) were used as coatings on copper alloy surfaces to lower their wettability degree [39]. The SAM-1 coated surface showed an condensation heat transfer enhancement of about three times that of the FWC under vacuum conditions at 33.86 kPa, and about eight times under the atmospheric pressure. In addition, the sample maintained a good DWC mode even after the experimentation testing carried out for 500 h. However, the SAM-2 coated surface showed a good contact angel of about 155° at the beginning of the experiment. Then it started to gradually turn to a filmwise condensation mode reaching a contact angle of 61.1°. The weak electrostatic attraction of hydrogen bonding to the SAM-2 surface at high temperatures was the determinant factor of such condensation mode alteration.

In a comparable study, SAM coatings were applied on the condensing surfaces to attain not only a good DWC, but also longer high performance duration. In a comparison to the previous study, which show DWC performance that lasted up to 500 h, this study achieved a duration of about 2600 h instead [40]. Two SAM types were prepared using
stearic acid solution (SAM-1) and n-octadecyl mercaptan solution (SAM-2) to form an ultrathin organic hydrophobic film on copper surfaces. However, before the SAM coating was applied in this study, an oxide layer was formed on the substrate. The oxide layer found to improve the bounding between the SAM coatings and the substrate, which increase the coating durability. For the SAM-2 the experimental results show that the heat transfer coefficient under vacuum condition around 33.86 kPa was increased by a factor of about 3 and 1.8 h after 100 h and 2600 h, respectively. The SAM-2 maintained a good DWC and higher heat transfer performance than SAM-1 because it has a covalent bonding with substrate, whereas the SAM-1 has hydrogen bonding which displays weak electrostatic attraction with tube surface allowing it to be dissolve at high temperature of operation. The DWC of SAM-1 that has contact angle of 155° coating gradually turns to a FWC with a contact angle of 61.1°, which measured after the experimentation. Whereas, the SAM-2 turn from 148.5° to 111.2° degree after duration of 2600 h of experimentation.

Despite the additional thermal resistance induced by thick organic coatings, DWC for a period over 12,000 hours or 500 days with a six times higher heat transfer performance compared to FWC was realized [41]. By applying an ultra-thin film of SAM-n-octadecyl-mercaptan layer on a copper surface, an excellent DWC can be achieved leading to an enhancement in the condensation heat transfer performance of about 300 % and 180 % compared to FWC under vacuum conditions for a period of 100 hours and 2,600 hours, respectively. Under atmospheric pressure, the enhancement in the condensation rate can reach with such technique up to eight times [39, 40].
Investigation on the influence of SAM coatings deposited on different substrates in terms of wettability and condensation rate was also done. To promote DWC, SAM coatings were applied on condensing tubes surfaces made of gold-coated aluminum, copper, and copper-nickel alloy by chemisorption of alkylthiols [42]. This is to lower the surface free energy and reduce the wettability degree of the condensing surface. The experimentation testing results were compared with bare gold-coated aluminum surface and complete filmwise case. The contact angles of the three surfaces were greater than 100°, whereas comparing to a bare-gold surface the contact angle was less than 90°. The condensation experiments were conducted using water saturated vapor under atmospheric and vacuum conditions. The heat transfer coefficient under the atmospheric condition of the SAM coatings on copper, gold-coated aluminum, and copper-nickel tubes were about fourteen, nine, and fourteen times that of the FWC, respectively. Whereas, under vacuum conditions, the enhancement factor in the heat transfer coefficients of the same samples were about five, five, and 3.8 times the filmwise condensation, respectively. In addition, the bare-gold-coated aluminum surface (without SAM coating) achieved a heat transfer coefficient of about 3.5 and 2.4 times that of the FWC under atmospheric and vacuum conditions, respectively. The study also considered monitoring the recorded videos for all samples noticing that the drops quality of these three coated surfaces with SAM’s was very similar. However, the gold-coated aluminum surface showed slightly a better quality. Moreover, the recording videos indicate that droplets located on the top and bottom of the tube, “dead” drops, were relatively larger than the vertical sides of the tube and their diameter ranged from 2 to 3 mm. These types of droplets found to be responsible for the relatively lower heat transfer performance of the tube configuration.
comparing to that the flat vertical condensing surface. They demonstrate that these droplets stay at the top and the bottom of the tube for a relatively longer period of time causing additional thermal resistance, whereas, droplets on the vertical flat surface would shed, sweep and depart the surface at a higher rate leading to a higher heat transfer performance.

In the investigation by Sangsoo et al., four micro/nano-scale porous surfaces were fabricated using three different methods: self-assembled technique, polymer based thin coatings, and a surface etching technique [43]. This is to first promote DWC to enhance the condensation heat transfer performance. Second is to examine the surface properties of the treated samples since thin coatings can enhance the overall heat transfer but it can be weak and fail to maintain a long life span. On the other hand, thick coatings can last longer however they can induce extra thermal resistance leading to a lower heat transfer performance. Two types of polymer based coatings with polyPhenylene sulphide and carbon nano tube or PPS/CNT and with PolyTetraFluoro Ethylene or PTEF. In addition, a surface prepared by self-assembled layer described by [40], and an acid etched surface were prepared on copper alloy tubes. The surface morphologies and the contact angle were determined using Scanning Electron Microscopes (SEM) and contact angle measurement apparatus under ambient conditions, respectively. Condensation heat transfer tests were conducted using saturated water vapor at a pressure ranged from 97.8 to 67.5 kPa, and a subcooling temperature range of 0 – 20 K. The obtained results show that the heat flux and heat transfer coefficients of the etched surface were higher compared to other samples and Nusselt model of FWC. Alternatively, the polymer based coated surface and the sample with the self-assembled layer exhibited a low heat transfer
performance even in compare to Nusselt model of FWC. Despite that these layers or coatings exhibited dropwise condensation, they added additional heat transfer thermal resistances which delayed the surface renewal rate and lead to a larger condensing droplets size.

Using superhydrophobic surfaces with a capillary length scale structure can enhance the condensation process due to the reduced activation energy of these heterogeneous nucleation of such surfaces compared to that of the homogenous once. N. Wang et al. considered the importance of the local energy barriers of a nanostructured surfaces to better understand the growth process and nucleation density of the non-equilibrium droplet morphologies [44]. The nanostructure consists of nanopillars with a length range of 100 nm to 10 μm. The study demonstrates that there exist three general droplet growth morphologies, which were observed by examining the condensation behavior on the nanostructured surface: suspended droplets nucleating on the pillar tips, droplets nucleated on the pillar sides, and droplets nucleation within the unit cell, which defined as the space between four pillars. The droplets in the first morphology exhibited unconditional stability when eliminating the influence of the droplets interaction or other external forces. The second growth morphology lead to a wetting for some portions of the pillars, however these droplets were not connected to the base of the pillars. The third morphology especially at its initial stages where the nucleating droplets were filling and growing beyond the unit cell lead to either a partial wetting Cassie or complete wetting Wenzel state. This initial wetting behavior could be determined by the characteristic energy barrier, which defined as the ratio of the top to the side energy barrier of the nanopillars. When the characteristic energy barrier was larger than 1, i.e. when the top of
the pillars is the dominant droplet bounding energy barrier, droplets indulged wetting into the neighboring unit cells, and a droplet growth within a single unit cell was observed. Whereby, if the characteristic energy barrier was smaller than 1, droplets were growing above the unit cell. The former lead to a complete Wenzel state, whereas the ladders lead to partial Cassie wetting state.

Investigation of the influence of the non-condensable-gas (NCG) on the DWC was considered by Xue-Ha Ma et al. [45]. The condensation of saturated water vapor tests on vertically oriented copper plates were conducted under two operational pressures, 0.1 MPa and 0.16 MPa. Variety of concentrations of NCG ranges as follow: 0.5%, 1%, 2%, 3%, and 5% of air molar concentration were introduced to the system. To promote dropwise condensation in this study, a polymer fluorocarbon coating exhibiting high thermal stability and low free surface energy with a static contact angle of 85.2° was used and applied on the testing surface. The computed heat transfer result shows clearly that the NCG can significantly affect the condensation heat transfer performance. The presence of only 1% concentration of air or NCG caused a significant reduction in the heat flux that reached up to 50%. This influence of the NCG on the heat transfer performance is very strong compare to the thermal resistance produced by the coating to promote DWC. By compare the influence of the NCG to the influence of the change in the subcooling degree and the operation pressure, the influence of the NGC concentration in the steam was the dominant factor. A 0.5 % to 5 % of air concentration can alter the heat transfer coefficient enhancement within a range of 30 % to 80 % compared to that of the FWC. The study also shows that at 0 % of NCG, the condensation heat transfer performance reached its maximum peak compared to other cases containing NCG. In
addition, the increase in the pressure from 0.1 MPa to 0.16 MPa positively influenced the condensation heat transfer performance and in some cases increases the subcooling temperature range.

In another investigation work performed to explore the influence of NCG on the heat transfer performance of DWC and FWC, Bum-Jin Chung et al. examined the influence of different orientation on the condensation rate by varying the inclined angle of the copper plate [46]. To promote DWC over an extended time of about 600 hours, thin layers coatings consist of nickel and chromium was applied on the copper surfaces. Whereas, the FWC was achieved by applying an oxide layer made by blast shot and exposing the surface to a mixture of steam and air over 50 hours until stable oxidation layer was formed on the condensing surface. The condensation experiments were carried out using steam under the pressure of the atmosphere using plates with inclined angles of 5°, 20°, vertical, upward, and downward orientations. The results indicate that for FWC of pure steam, the inclination angles at a low steam flow have no effect on the heat transfer performance. On the other hand, for DWC of steam and air mixture, a significant influence on the heat transfer performance was observed, which was due to the dominant thermal resistance of the air-rich layer. Under the test case of the pure steam, the DWC heat transfer performance reached three to six times that of the FWC. For the orientation influence, the upward facing plate exhibited higher condensation heat transfer rate than the downward facing for the pure steam case due to the spreading of the water film. However, under the air and steam mixture framework, the downward facing showed higher heat transfer rate than the upward facing due to buoyancy effect resulting from the density difference between both the air and the steam, and due to the disturbance of the
air-rich layer. Moreover, the heat transfer performance for the vertical plate and most other cases using pure steam was higher than the cases where the NCG were presented.

While the discussed studies showing that the present of NCG can significantly reduce the heat transfer performance, other studies show contrary results, which demonstrates that the present of NCG can enhance the condensation rate on superhydrophobic surfaces [37]. Two SAM treated copper surfaces were put in condensation chamber and tested using saturation water vapor under the ambient pressure. The first superhydrophobic roughened surface features two-tier micro/nanostructures with a contact angle of 160° ± 5°. The second hydrophobic smooth surface has a contact angle of 116° ± 4°. During the investigation of the wetting behavior of the condensate droplets, a transition from the Wenzel to Cassie-Baxter wetting mode was observed when the NCG concentration increased. The study justified such transition occurred due to the air trapped in the cavity of the superhydrophobic micro-nanostructure sample when the concentration of the NCG was increased, which also helped in maintaining the superhydrophobicity feature. A unique phenomenon called “a condensate sinkage mode” was observed on roughened-induced superhydrophobic surfaces. It shows the increase in the concentration of the NCG during steam condensation, especially at very high concentration rate, can enhance the superhydrophobicity of the surface. No such behavior was observed to the smooth hydrophobic surface due to absence of such hierarchical roughness structure on the surface.

Regard all the difference methods discussed previously, these studies aimed to reduce the wettability of the condensing surface over the entire condensing surface to assure a uniform DWC all over the surface. However, promoting DWC can also realized
by manipulating different wettability regions on the condenser surface at nano- or microscale level. Such examples of such approach can be inspired by nature, such as by mimicking the lotus leaves by means of short nanotubes deposited on micromachined posts [47], or by mimicking the Namib dessert beetles using hybrid surfaces with high-contrast wettability patterns [48]. Other examples can follow man-made designs such as using a hierarchical structure which combines both nanograss and micropyramidal architectures [49], introducing nanoscale hydrophilic lines on hydrophobic surfaces [50], or by forming hydrophilic dots on hydrophobic surfaces [51], and many other studies [52-57]. However, these methods can be too expensive and challenging to be implemented in industrial scale, especially when the condensing surface is in a tubing geometry. Moreover, these nano/micro-scale structures tend to be flooded at high condensation heat flux or at high degree of subcooling [30, 56].

In experimental study conducted by Chuan-Han Chen group, a two-tire roughness textured surface through hexadecane-thiol coating was used to mimic the lotus leaves effect and retaining superhydrophobicity during and after the condensation testing [47]. The micro-/nanostructure superhydrophobic surface was formed by a deposition of short carbon nanotubes on micromachined posts or pillars. The micropillars were etched and squarely positioned on a silicon substrate by deep reactive ion etching. The secondary roughness, the short carbon nanotubes, found to plays two noticeable roles. First role was due to the top surface of the solid nanopillars, which served as the wetting regions with high surface energy. The second role was due to the rigidity of the nanopillars, which helped in preventing the bundling from occurring between the nanotubes due to existence of the capillary forces. The two texture roughness of such surface allowed achieving a
continuous DWC and maintaining a superhydrophobicity during and after the laboratory condensation testing.

Another example of a multiscale nano and microstructure roughness structure can be found by [49]. In their experimental study, nanograin coating was applied on micropyramids tops and the floor spacing between the micropyramids. This is to promote a DWC by promoting both droplet nucleation and droplet departure as these combinations are essential for such effective condensation mode. This three-dimensional heterogeneous surface yields first a global superhydrophobicity, i.e. the top and the spaces between the micropyramids, which promotes spontaneous droplet departure without a pinning effect to the substrate, and second a local nucleation sites at the same time, i.e. the smooth sidewalls, which promotes droplet growth and preferential coalescence actions. The static contact angle of the surface was about 160°. The condensation tests were performed using an environmental scanning electron microscope (ESEM). The flat oriented sample fixed at tilt angle of about 45° from the horizontal, and placed on a controlled stage temperature that kept around 1 °C. The vapor pressure inside the chamber kept just above the supersaturation pressure around 5.1 torr. The maintained results indicate that multistructured surface allowed for an increase of about 65 % in the condensing droplets density, and an increase of about 450 % in the droplet self-removal compared to a flat superhydrophobic surface with only nanostructure coating. In addition, the hierarchical roughness of the surface helps to achieve significant increase in the droplet growth rate, the droplet departure rate, and the surface coverage by smaller drops which have lower thermal resistance. This combination found to be the reason to enhance the DWC heat transfer performance.
In another study similar in the concept, an enhanced heat transfer DWC was achieved by introducing hydrophilic nanoscale lines with a contact angle of $85 \pm 5^\circ$ on a hydrophobic background with a contact angle of $104 \pm 2^\circ$ [50]. The lines were formed in a resolution of 10 nm by focused ion beam irradiation, which deposited lines with a width ranged from 40 to $170 \pm 15$ nm and a spacing of about 100 nm. The water vapor condensation experiments were conducted using an ESEM, which allows monitoring relatively small droplets diameters of about 800 nm, especially those droplets that were forming on the hydrophilic lines. Three patterned samples were prepared with different hydrophilic lines widths, $40 \pm 5$, $85 \pm 15$, and $170 \pm 25$ nm, which measured by an atomic force microscopy (AFM). The results conclude that the hydrophilic lines attract water molecules; based on this molecular coverages degree the surfaces were evaluated. It was found that the ratio of the width of the hydrophilic lines to the hydrophobic area has a significant influence on the surface coverage and droplets nucleation rate. The results also show that a narrow hydrophilic lines lead to a higher droplet nucleation density within a given testing conditions, and promoted the condensation heat transfer rate including the initial stages of condensation. In addition, the hydrophilic regions with narrow lines found to induce a higher coalescence frequency; however, these narrow lines were triggering droplets attachment showing a not sufficient droplets removal mechanism.

Another surface exhibiting hybrid wettability at the microscale level was constructed using hybrid microscale patterns that were developed on a gold surface [56]. The design of the patterns were prepared by patterning the adsorption of $\omega$-functionalized alkanethiolates in SAM. The heterogeneous patterns allow the condensing droplets to
form on the surface with different sizes, densities, and distributions that were corresponding to the surrounding environment factors. The variations in behavior of the condensing droplets allowed the light to be reflect in different manner. By using the reflection of a laser light and monitoring the light diffraction throughout the process of droplets formation on the surface, the surface can also be used as a sensor, which was the main aim of their study. The experiments were conducted under the atmospheric pressure with a constant relative humidity and initial surface temperature of 20 °C. The observation indicated that when the surface temperature was decreased, the water droplets initially were favoring to form on the hydrophilic patterns instead of the hydrophobic regions. Though, with a further decrease in the surface temperature, droplets bridging occurred between the hydrophilic patterns due the increase in the condensation rate, which reduced the condensation performance.

A similar approach of combining two distinct wettability regions but at mini-scale patterns was developed earlier by S. Kumagai [58] to promote droplet shading using alternating hydrophobic and hydrophilic stripes in vertical and horizontal orientations on the condensing surface. Higher HT performances were obtained on these hybrid wettability condensing surfaces compared to a surface with complete FWC. However, their performances were still below that a surface with complete DWC. Different configurations and geometries of these hybrid-patterns were also adapted and formed on a condensing surface by various studies. For example, a condensing surface inspired by the back of the Stenocara beetles in the Namib Desert was developed by sintering hydrophobic copper mesh/gauze on a polystyrene hydrophilic flat sheet, and used for efficient fog harvesting [59].
Another example of such mini-scale patterned can be found by the condensing surface that was made of aluminum and consist of two different wettability regions [60]. The surface was created by etching interdigitated patterned designs inspired by the vein network layout of banana leaves. An improvement up to 19 %, compared to that of a bare surface without the patterns, was achieved in the overall condensation collection rate. The hydrophilic patterns similar to the vein network of the banana leaf were chemically etched on a superhydrophilic background. The wettability contrast of the hydrophilic and hydrophobic regions was categorized by the contact angles, which esteemed of about 78° and close to 0°, respectively. The coexistence of DWC and FWC modes on such surface showed an enhancement in the heat transfer performance. Straight strips patterned surfaces with varied widths and a mirror finish plain aluminum surface were also examined in this study for a comparison purposes. The results of the heat transfer coefficient and the water collection rate of all samples were then determined and compared under two different testing conditions of dry bulb temperatures of 20 °C and 35 °C and a relative humidity of 80 %. The results indicated that the straight patterned design show an enhancement in the heat transfer coefficient of about 20 % and 7 % compare to that of the complete dropwise condensation of the bare aluminum surface for the first and second case, respectively. The small improvement in the heat transfer coefficient maintained in the second case was due to the difficulty in the drainage process at higher rate of condensation. For the bioinspired interdigitated pattern surface, the heat transfer coefficient enhanced by 19 % and 12.7 % under both conditions, respectively. The improvement in the heat transfer performance achieved in this study was mainly due to the control of the maximum droplets size, which was significantly reduced leading to a
reduction in the surface thermal resistance that can be induced by the condensing droplets on the surface. The computed average maximum size of the condensing droplets on the hydrophilic domain was equivalent of 42% of that of the strip width.

The same group conducted another experimental study on the same hybrid interdigitated pattern design, however this time the similar pattern was designed in a staggered configuration [61]. This configuration exhibited higher efficiency than the regular interdigitated design since it provided higher droplets removal rates. The maximum enhancement in the heat transfer coefficient was about 34.4% and 35.9% compare to that of the complete dropwise condensation for first and second cases, respectively.

Similar patterns but with a staggered design were also developed, showing enhancements of about 34.4% and 30.5% in both the heat transfer coefficient (HTC) and water collection rate, respectively, at dry bulb temperature of 20°C and a relative humidity of 80% [61]. However, the condensation HTC was not computed under saturated conditions or a wide range of subcooling degrees, i.e. higher condensation rates, which may cause such a design to either hold its high HT performance or exhibit lower one, due to possible flooding to the patterns or the high thermal resistance of the bridging droplets that are found and explained in Part II of Chapter 2 of this study.

Many efforts are put to investigate condensation on surfaces consisted of both hydrophobic and hydrophilic regions, which their coexistence create difference in the surface energies leading to a mitigation of the condensing droplets under the influence of the capillary driven force. In their experimental study [62], the condensation heat transfer of a copper surface patterned with hydrophilic 1.5 mm in diameter circular islands
formed on hydrophilic background was investigated. The circular island patterns were formed by applying a Teflon coating followed by masking procedure with the selective patterns. Then a plasma etching technique was used to etch away the patterns and expose the hydrophilic bare copper from the Teflon coating. The experiments were conducted using saturation water vapor under the atmospheric pressure with a vapor inlet velocity varied from 0.05 to 5 m/s. The patterned condensing surface consisted of hydrophilic to hydrophobic region ratio of 25 % to 74 % by area, respectively. The results were then compared to a sample with a complete hydrophobic wettability, which has a contact angle of about 115°, and a sample with a complete hydrophilic wettability, which has a contact angle of about 60°. The comparison shows that the condensation heat transfer performance of the patterned surface was greater than the complete hydrophilic surface, however lower than that of the complete hydrophobic surface. The maximum heat transfer coefficient of about 32,000 W/m² K, which was 2.5 times the complete hydrophilic surface was achieved.

In another similar study by the same group [63], the condensation heat transfer performance of surfaces consisted of hydrophilic circular islands diameter on the hydrophobic background with varied diameter sizes, 1.5 mm, 0.75 mm, 0.5 mm, and 0.25 mm was investigated [62]. In addition, the heat transfer performances of such surfaces were compare to that of a complete hydrophobic, complete hydrophilic, and Tree-pattern surface. The hydrophilic Tree-pattern design was formed in the same manner of the circular island. Among all the samples, the patterned sample with the 0.25 mm diameter hydrophilic island gained the upper most condensation heat transfer rate in comparison to other samples. The heat transfer coefficient maintained was around 34,000 W/m² K,
which is 7.5% higher than the complete hydrophobic surface. On the other hand, the heat transfer coefficient of the Tree-patterned surface was about 22,600 W/m² K. The results also show that the heat transfer coefficient of the island patterns surfaces was increased as the island diameter decreases from 1.5 mm to 0.25 mm. Moreover, observation of the droplet dynamic during condensation indicates that the droplets were mainly nucleated and grow on the hydrophilic patterns then they departed upon coalescing with the neighboring droplets. Besides, the suitable island diameter of 0.25 mm lead to a smaller droplets departure diameter and a higher departure frequency compared to that of a complete hydrophobic surface.

In another study, hybrid wettability pattern of straight stripes configuration with different widths were formed on the condenser surfaces. The vertical straight strips patterns were formed on copper flat surfaces. The hydrophobic regions wettability was categorized by a contact angle of about 120° ± 5°, whereas the hydrophilic contact angle was about 50° ± 5. The surfaces were experimentally tested using water vapor under saturation conditions of the atmosphere. The results revealed an enhancement of about 23% in condensation HTC compared to that of complete DWC at a subcooling degree of 2.0 K was achieved [64]. The radius of the condensing droplets on such surfaces was also studied showing that the value of the maximum droplets radius increased when the hydrophobic strips width was increased. However, the droplets population density was decreases correspondingly. Therefore, the condensation heat transfer performance increased when the hydrophobic widths were increased due to the reduction in the maximum droplets radius and the increase in the population density. Nevertheless, with a further increase in the hydrophobic width, the heat transfer performance started to decline
indicating an existence of an optimum hydrophobic stripes width. For the hydrophilic region width, the heat transfer performance was found to decrease when the hydrophilic stripes width was gradually increased. This indicates that the hydrophilic regions width can be narrowed as possible with an assurance of maintaining a smooth drainage mechanism. The optimum configuration of the tested hybrid surfaces found to be for the sample with hydrophobic stripes width of 0.55 mm, which showed an increase in the heat transfer performance of about 23 % higher than that of the sample with a complete DWC at surface subcooling of 2.0 K with a corresponding maximum droplets radius of 0.25mm. The need to develop a condensing surface exhibiting higher rates of condensation under saturation conditions and a wide range of subcooling degree is essential for industrial applications and fundamental research of condensation.

Moreover, the wettability of these enhanced patterned surfaces is subjected to the surface energy, roughness, and surface structure [65-71]. 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 exposed to the surrounding vapor. 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 [72-74]. 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 dropwise condensation by promoting the droplet nucleation and removal rates, nano/micro scale patterned surfaces were considered by many studies [47-50, 52-57, 75-77]. 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 [51], where condensate droplets in a diameter of 300 nm were found to preferably form on the hydrophilic dots formed on a hybrid wettability 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 [78]. 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-filmwise 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 dropwise condensation via the coexistence of hybrid wettability [49]. 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 [34, 74, 79, 80].

Mini-scale wettability gradient patterning method (same method adapted in Chapter 2) 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 S. Kumagai, [58] 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 [59, 81, 82], including studies conducted by Aritra Ghosh et al. [60, 61] 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 behaviour 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 behaviours 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 [62, 63] designed circle islands and tree configurations hydrophilic patterns on copper surfaces to enhance condensation rate. Hydrophilic circular islands with diameter of 0.25mm (0.2mm 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 0.2mm 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 [64], straight hydrophilic patterns were fabricated on a flat copper surface. The optimum ratio was found to be 0.55mm for the hydrophobic-stripes, showing an enhancement of about 23% higher than that of the complete DWC. The visualization study was used to capture the droplets behaviour, 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 0.45mm 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.

Despite the many adapted methods used to promote DWC, the durability is still remained up to today the most challenge facing the condensation process especially at the industrial scale. The high tendency of clean metals and metal oxides to contamination due to their high surface free energies can alter their wettability degree [83-85]. However, nickel (Ni) exhibits relatively higher durability, chemical stability, corrosive resistance and high strength [86, 87]. Additionally, Nickel oxide (NiO) exhibits similar stability and other unique properties such as alteration of the electronic property when treated for example by ultraviolet/ozone [88], and possible reduction to metallic Ni when heated with hydrogen/carbon or annealing process [89]. In addition, the defective and hydrophilic nature state of the NiO allows it to be used in many applications such as electrochemical supercapacitors [90-94].

Nevertheless, it has been reported that NiO under certain conditions can exhibit diverse influence on Ni surfaces which causes inconsistence surface wettability alteration. In their study, Ni micro-nano cones array film was electro-deposited on copper substrate, which exhibited a contact angle of about 5 ° when freshly prepared; however, after exposed to the air for 15 days, the wettability was significantly decreased and switched to hydrophobicity with contact angle of 153.6 °. It was found that the surface morphologies remain the same during this transition. Whereas, the change in the surface chemical was the reason responsible of the wettability alteration due to formation of hydrophobic NiO [95]. Very similar results can be found by Khorsand et al. study with
consideration to the roughness [96]. Smooth and micro-nano structured Ni surfaces were freshly prepared exhibited a hydrophilic wettability for both. However, after 14 days of storage in air, both surfaces wettability transitioned to hydrophobic and superhydrophobic, respectively. The results also show the surface morphology remained the same in both cases, whereas the transition in the wettability was due to the change in the surface chemical composition, i.e. the formation of NiO. Similar experimental investigation was conducted by Wang et al. shows similar wettability transition of copper oxide after about 21 days due to the oxygen adsorption [97].

Alternatively, the wettability transition of metal surfaces can be also maintained by altering the surface morphology instead of mainly the chemical composition. Zhao et al. reports a high efficiency dropwise condensation can be maintained by electrodepositing ultrathin nickel nanocone films on copper substrate [98]. Another surface wettability transformation due to the change in the surface morphology was observed for a Ni surface after applying a wet-chemical process which created a nanoflowers structure [99]. Guo’s study shows a similar wettability switching for titanium surface via a facial thermal oxidation and immersion process which did modify the surface morphology as well [100]. Many other studies archived similar transition as well [101-106].

To further understand the wettability influence of NiO layer(s) formed condensing surfaces made of Ni on the condensation heat transfer performance, in Chapter 3, we mimic such oxide formation on nickel tubes surfaces made of nickel alloy 200/201 as the substrates, whereas different layers of NiO were formed on the tubes by atomic layer deposition (ALD) method [107, 108]. The ALD method allows deposition of ultra-thin
films at the atomic level. The film layers depositing rate depends on several conditions such as the temperature, precursor, and substrate [109-112]. The NiO ALD deposition rates can be varied within a range of about 0.17 to 1.6 angstrom/cycle leaving a thickness in the order of $1 \times 10 \text{ nm}$ considering the range number of ALD cycles used in this study [113-119]. With such range of thickness and the relatively high average thermal conductivity of NiO ranging from about 5 to 50 $W/m \cdot K$ [120, 121], the thermal resistance of the deposited NiO films can be neglected in this study of condensation heat transfer.
CHAPTER 2:
CONDENSATION ON MINISCALE HYBRID-WETTABILITY SURFACES\(^\text{12}\)

*Concept*

The main purpose for introducing \(\alpha\) and \(\beta\)-regions on the condensing surface is to control the maximum base diameter of the condensing droplets by inducing capillary-driven phenomena. The existence of wettability gradient on the condensing patterned surface allows condensates to be rapidly shed at a smaller diameter. As a result, more surface areas would be exposed to the steam, leading to a higher condensation rate. These \(\alpha\)-regions can be formed in any configurations, scales, and ratios. In this study, we adopted a pattern with a parallel straight-stripes configuration owing to its manufacturing simplicity, which allows applying this pattern to large surface areas. Herein, the width of the \(\beta\)-stripes was set at 0.6 mm throughout all experiments. Other \(\beta\)-stripes widths (scale) such (1.0, 0.5, and 0.2 mm) were experimentally tested, but their performances were found to be lower than 0.6 mm. Therefore, we choose 0.6 mm as the case in this study as fixed scales, whereas, the \(\alpha\)-stripes width was varied from 0.2 mm to 0.6 mm within an increment of 0.1 mm.


During a condensation on hybrid patterned surface, droplets initially prefer to nucleate on the $\alpha$-region rather than on the $\beta$-region, however, with a continuous condensation, a liquid film covers the $\alpha$-region and reduces its surface temperature, eventually the droplets prefer the $\beta$-region due to its availability to the surrounding vapor [56, 122]. Conceptually, in the straight pattern design, each $\beta$-region is bordered by two $\alpha$-regions, as schematically shown in Figure 2.1. When a growing condensing droplet comes in touch with the $\alpha$-regions-boundary, an immediate migration would occur due to the capillary force established between these two different wettability regions.

For those droplets that are more likely to originate near the center of the $\beta$-regions, their base-diameters can reach a maximum size that is equivalent to the width of the $\beta$-regions, Figure 2.1a. After which the growing droplet boundary will touch the $\alpha$-region and relocation would occur, Figure 2.1b; eventually, the gravitational force will drain the relocated droplets within the $\alpha$-region (Figure 2.1c), and completely departing the condenser. Basically, the existence of wettability gradient on the condensing surface mainly services first, in controlling the maximum diameter of the condensing droplets on the $\beta$-regions, second, in increasing the droplet removal rate from $\beta$ to $\alpha$-regions with the assist of the capillary driven force, and third, in increasing the drainage rate due to the existence of the drainage paths, i.e. the $\alpha$-regions.
Figure 2.1 Concept of droplet migration mechanism between two different wettability regions. (a) A condensing droplet grows on the β-region until its boundary touches with the neighboring α-regions. (b) The capillary-driven phenomena due to the existence of the two wettability neighbouring regions, drags the droplet(s) from the lower wettability region to higher one, that is from β to α region, respectively. (c) Complete droplet removal and drainage occur within the higher wettability region under gravitational force.

Test samples

Copper tubes (Cu-101 from McMaster-Carr, 99.99% purity) with a total length of 120mm and effective condensing length of 92mm, a diameter of 6.35±0.8mm, and wall thickness of 0.9±0.15mm were used as the testing sample for all experiments. Tube geometry instead of flat plate was considered due to its common use in real applications as well as the scarcity of studies that investigate condensation on tube configurations with hybrid wettability. It was a challenge to form a hybrid wettability pattern on a surface of tube. Fortunately with the method developed herein, we were able to successfully form a “straight stripes” pattern on copper tubes. Five samples with different (β/α) ratios were fabricated, and tested, then compared to a sample with a full β-region (F-β), a full α-region (F-α), and Nusselt model of FWC. Table 2.1 shows the samples categories that
were used as the main case in this study. The letter R in the Name/label column denotes to the ratio of the β to α-region, and the digit represents the value of that ratio. Notice that the β-regions width kept constant throughout this case of the study, whereas, the α-region width was varied to attain different (β/α) ratios as shown in the table.

**Table 2.1** Samples specifications and labeling.

<table>
<thead>
<tr>
<th></th>
<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>0.2</td>
<td>R3</td>
</tr>
<tr>
<td>2</td>
<td>0.6</td>
<td>0.3</td>
<td>R2</td>
</tr>
<tr>
<td>3</td>
<td>0.6</td>
<td>0.4</td>
<td>R1.5</td>
</tr>
<tr>
<td>4</td>
<td>0.6</td>
<td>0.5</td>
<td>R1.2</td>
</tr>
<tr>
<td>5</td>
<td>0.6</td>
<td>0.6</td>
<td>R1</td>
</tr>
<tr>
<td>6</td>
<td>full</td>
<td>-</td>
<td>F-β</td>
</tr>
<tr>
<td>7</td>
<td>-</td>
<td>full</td>
<td>F-α</td>
</tr>
<tr>
<td>8</td>
<td>-</td>
<td>-</td>
<td>Filmwise</td>
</tr>
</tbody>
</table>

**Surfaces preparation**

**Hybrid wettability patterned surface:**

The copper tube surface was mechanically polished (Grids #: 800, 1200, and 2500), rinsed with sulfuric acid, acetone, ethanol, and deionized water consecutively, then dried by a nitrogen stream. The hybrid pattern preparation was then applied following the procedure illustrated in Figure 2.2. First, an ordinary laser printer was used to print the selected art work (straight stripes) using black colour ink on a regular transparent sheet. The transparent sheet was then fixed flatly on the top of the photoresist sheet (IKONICS Imaging - RapidMask High Tack – 2 mil thickness) in which the printed side was facing the photoresist sheet, Figure 2.2a. Second, both sheets were exposed to an ultra violet (UV) light source for about 2-3 minutes (IKONICS Imaging – Letralite – 15 watts), Figure 2.2b. Because the transparent sheet side was facing the light source
during the light exposure process, the black ink print of the transparent sheet blocks the light source from reaching the photoresist sheet. As a result, the unexposed areas of the photoresist sheet remained at the same original rubbery condition, whereas the exposed areas of the photoresist sheet turned brittle. The photoresist sheet was then carefully cut to a length matching the outer circumference of the tube and wrapped around the copper tube with the assist of its adhesive side facing the tube surface. Third, a sandblasting process was applied using a micro abrasive jet machine (Airbrasive Jet Technologies, LLC, Micro Abrasive Blasting Unit-Model K) and aluminium oxide powder (S.S White Technologies Inc., Accubrade-27). The sandblasting stream was applied using a hand held micro-jet nozzle (Airbrasive Jet Technologies, LLC, nozzle Type C, 1.14 mm in diameter). The sandblasting stream was aimed perpendicularly and about two to three inches from the surface of the tube which was held and rotated by hand inside an abrasive blast cabinet. The sandblasting stream only targeted the outer surface areas of the tube that were located beneath the brittle region of the photoresist sheet, Figure 2.2c. Fourth, the mask was removed and the tube was cleaned and dried. Thus, the copper tube surface area with two-roughness regions was prepared. Finally, the sample was immersed in 0.0025 mol/L solution of n-Octadecyl Mercaptan and ethanol for one hour at 70°C followed by rinsing and drying procedures, Figure 2.2d.

Hydrophobic surface (F-β):

It followed the same initial polishing and cleaning procedure of the hybrid surface, except no mask or sandblasting was applied. The sample was then immersed in the solution to create the SAM coating.
Figure 2.2 A schematic drawing of the main procedures of preparing a hybrid wettability pattern on the condensing surface of this study. (a) Fixing the printed transparent sheet
which carries the designed pattern on top of the photoresist sheet. (b) Exposing both sheets to a UV light source that is facing the transparency sheet side. Only the regions of the photoresist film that is exposed to the light will be brittle which will be identical to the printed design of the transparent sheet. (c) Carefully fixing the photoresist sheet with the assist of the adhesive layer on top of the condensing surface. Applying a micro-abrasive blasting process on the photoresist side; the fine stream can only target the condensing surface areas beneath the brittle regions of the photoresist sheet. This allows the creation of roughened regions matching the pattern design of the photoresist sheet (d) Removing the photoresist sheet residual from the condensing surface followed by cleaning procedure, then immersing the condensing surface that carried the roughened pattern in the SAM solution for an hour.

Sandblasted surface (F-α):

It followed same procedure of preparing F-β surface; however, before the immersion in the n-Octadecyl Mercaptan and ethanol solution, sandblasting process was applied uniformly on the entire surface.

Hydrophilic surface (Filmwise):

The copper tube was polished, rinsed and dried as mentioned above. Then it was immersed into the 30% H₂O₂ solution for about 3.5 hours at ambient temperature, then rinsed with ethanol and deionized water and dried again. Thus, a copper tube with hydrophilic coating was prepared showing a static contact angle of about 30° with water.

The SAM coating applied on the condenser herein has different effects on the final surface wettability which was related to the surface roughness. Regardless of the reduction in the α-region wettability that could be due to a flooding for the surface texture or transition to Wenzel state [78, 122-125], our main aim is to create wettability gradient by the existence of neighbouring β and α regions during the condensation process. The average advancing/receding contact angles were found to be 125±10°/52±4° for the SAM coated β-regions and F-β, whereas 138±4°/73±10° for the SAM coated α-regions and F-α. However, the surface static contact angles computed by imaging process during a
condensation under saturation conditions were found to be $90^\circ \pm 2^\circ$ and $66^\circ \pm 4^\circ$, respectively. In addition, scanning electronic microscopy (SEM) images of the surface of β-region and α-region are shown in Figure 2.3a and b, respectively. SEM images of the interface line between the two regions were also considered, showing in Figure 2.3c and d.

![Figure 2.3](image.png)

**Figure 2.3** Scanning electronic microscopy images of the self-assembled monolayer coating on (a) β-region, (b) α-region, and (c, d) the interface between β and α-region of the patterned surface.
**Figure 2.4a** shows an image of R2 as an example of the finished product undergoing condensation test at a subcooling temperature of about 9°C and saturation conditions near the atmosphere. In addition, an enlarged image of a small section of the surface is showing in **Figure 2.4b**. The enlarge image shows the β and α regions, which can be identified by the light and dark stripes, respectively. A schematic of the enlarge image shown in **Figure 2.4c** clarifies the two regions.

![Figure 2.4 Condensation image of deionized water vapor on patterned copper tube, R2, in the experimental chamber under saturation condition of the atmosphere at subcooling temperature of 9°C is shown in (a). The β and α-regions are displayed in the enlarged image of a small section of the condenser surface area of (b), and illustrated by the schematic drawing in (c).](image)
Experimental setup

The experiment setup shown in Figure 2.5 consists of four main sections: (i) a condensation testing chamber, (ii) a water vapor generating system, (iii) a water coolant system, and (iv) a data acquisition/computer system. The 10 x 20 x 24 cm³ aluminum condensation chamber is equipped with four cartridge heaters installed at the chamber’s corners and controlled by a proportional-integral-derivative (PID) temperature controller; in addition, the chamber outside walls are wrapped with thermal insulation layers to prevent condensation on the chamber walls during experimentation. The chamber is also equipped with a 6” diameter window made of heat-resistant borosilicate glass and two flexible-polyimide-etched-foil-heaters (Briskheat-ENP-R-775-01) installed on the glass window. This is to avoid condensation on the inner wall of the window, allowing for clear visualization and observation. A high-speed camera (Phantom v7.3) and a light-emitting-diode light source are used for visualization. Three calibrated T-type thermocouples and pressure transducer (Omega PX01C1-050A5T) were installed to monitor and record the saturated vapor temperature and pressure, respectively. Precalibrated fine tip K-type thermocouples were used for measuring the inlet and outlet coolant temperatures inside the tube.

A stainless steel water vapor reservoir (10 liters capacities) equipped with two controlled heaters was used to generate steam. The main and auxiliary heaters have output powers of 3500W and 550W, respectively, allowing for generating steam at a desired rate. The generated steam was delivered to the condensation chamber through a 19.05mm diameter and 1524mm long vibrating resistance stainless steel hose. A cord heater (BriskHeat- HTC451003-3657mm long and diameter of 4.7mm) was wrapped
around the hose and controlled by a temperature controller (BriskHeat-SDC120KC-A SDC) to assure a delivery of dry steam. Both the hose and the heater are wrapped with thermal insulation layers.

**Figure 2.5** A schematic drawing of the experimental setup. The blue dashed lines represent the coolant system. A close loop system was adapted to circulating the coolant from a heated water tank to the test section at a constant flow rate. The red solid lines show the path of the deionized water vapor. The condensate drainage is represented by a double blue line. All the measurement instruments are connected to the data acquisition system as shown by the dotted green lines.

A 0.056 m³ capacity galvanized-steel water tank, which is equipped with a stainless steel 2000W-immersion-heater (with temperature controller) and a T-type thermocouple, was used to supply coolant at varied temperatures to a gear pump
(SHURflo - GMBN4VA53 - 9.7 GPM – 125 Psi). Two valves installed at the pump discharge line and were used to control the water flow rate as shown in Figure 2.5.

![Figure 2.5](image)

**Figure 2.5** A photograph of the condensation setup showing the main components.

The coolant flow rate was monitored by a flow meter (OMEGA-FMG-92, 0.26-6.6 GPM, with an accuracy of ±1%) that was integrated along the coolant line. Prior to the test section, a controlled 7315 mm long 1440 W-cord-heater (BriskHeat- HWC1240) was wrapped around the delivered coolant line to provide an additional temperature control of the inlet temperature before the test section within a maximum range of approximate 5°C. After the test section, the water was pumped back to the water tank for reuse. Two push-to-connect branch tee adapters were used to connect the testing samples to the coolant line. The tee adapters also allow the two fine-tips thermocouples to be
inserted to the center of the coolant flow to measure the coolant’s inlet and outlet temperatures. A data acquisition system (Agilent 34972A) was interfaced with a computer for data collection and recording. The actual condensation experimental setup used in all testing is shown in Figure 2.6.

**Experimental procedure**

For all experiments, the coolant flow rate inside the tubes was maintained at 3±2% L/min. whereas, the inlet temperature of the coolant was varied from 28ºC to 85ºC, corresponding to the Reynolds’s number ranging from 18,000 to 40,000, respectively. The continuous increase of the inlet temperature during the experiment was caused by three heating sources: the immersion heater of the water tank, the inlet heater, and the condensation. The rate of temperature increase and the data sampling rate were considered prior to the data collection to assure collecting steady state data. Before the coolant water was pumped in the coolant side, the dry steam was assured to be delivered to the condensation chamber until a steady state saturation condition was reached for at least 10 mins. Monitoring the inside temperature and pressure of the chamber as well as the chamber wall temperature allows for the confirming of a steady state saturation condition. The near atmosphere pressure inside the condensation chamber was measured and found to be ranged between 0.106 to 0.112 ± 0.002 MPa for all experiments. For each testing sample, three sets of experiments were conducted, two for HT characterizations, and one for the visualization study. The two HT experiments were performed before and after the visualization study, respectively, to confirm if there is any change in terms of HT performance during the experiments. In the visualization study,
the window’s heaters and LED light source were applied. Whereas, during the HT measurement experiments both the window’s heaters and light source were disabled to avoid errors resulting from radiation on the temperature measurements.

**Data reduction**

Using the measured inlet ($T_{in,c}$) and outlet ($T_{out,c}$) temperatures of the coolant side, the measured mass flow rate ($\dot{m}_c$), and the coolant specific heat ($C_{p,c}$), the total HT rate through only the tube surface ($Q$) can be determined by Eq. (1). The heat loss ($Q_{loss}$) in Eq. (1) was computed by calibration experiment as detailed in section 2.6. After ($Q$) was determined, the condensation heat flux ($q^\sim = Q/A_o$) can be computed by considering the outer surface area of the tube ($A_o$).

\[
Q = \dot{m}_c \ C_{p,c} \ (T_{out,c} - T_{in,c}) - Q_{loss} \tag{1}
\]

The overall HTC ($\bar{U}$) which is a function of only measured parameters was determined by using ($Q$), ($A_o$), and the logarithmic mean temperature difference ($\Delta T_{LMTD}$) as follows:

\[
\bar{U} = \frac{Q}{A_o \ \Delta T_{LMTD}} \tag{2}
\]

\[
\Delta T_{LMTD} = \frac{(T_{sat} - T_{in,c}) - (T_{sat} - T_{out,c})}{\ln \left( \frac{T_{sat} - T_{in,c}}{T_{sat} - T_{out,c}} \right)} \tag{3}
\]
Where, $T_{sat}$ is the measured saturated temperature of the water vapor inside the condensation chamber.

To compute the condensation HTC ($h_{cond} = 1/A_0 R_{cond}$), the corresponding condensation resistance ($R_{cond}$) was calculated by considering all resistances in the system as follow:

$$R_{cond} = R_{tot} - R_w - R_{c,conv}$$

(4)

Where, $R_{tot} (= 1/A_0 \bar{U})$ is the total resistance, $R_w (= \ln(D_o/D_i)/2\pi k_{Cu} L)$ is the wall radial conduction resistance, and $R_{c,conv} (= 1/A_i h_c)$ is the convection resistance inside the tube. To determine the convection HTC inside the tube ($h_c = Nu_c K_c / D_i$), A Sieder-Tate correlation for the coolant side was used to calculate the coolant Nusselt number ($Nu_c$) inside the tube [126].

$$Nu_c = C \frac{Re_c^{0.8} Pr \frac{1}{3}}{\left(\mu_c / \mu_{c,w}\right)^{0.14}}$$

(5)

Where, $C$ is a constant of 0.035 as determined experimentally in this study [127], $Re = (\rho_c \dot{m}_c D_i / \mu_c A_{i,cs})$ Reynold’s number, $Pr$ Prandtl number, $\mu_c$ viscosity of the coolant at average bulk temperature, and $\mu_{c,w}$ the viscosity of the coolant at wall temperature. An iterative scheme was carried out to determine the reference temperatures at which appropriate mean values of the fluid properties can be selected. After $h_{cond}$ was computed, the temperature difference between the tube’s outer surface and the saturated
water vapor inside the chamber ($\Delta T$) was determined using the condensation HTC definition:

$$
\Delta T = \frac{Q}{A_o h_{cond}} \text{ (6)}
$$

**Calibration of the system**

To determine the heat transfer rate through only the condenser surface, a calibration experiment was conducted to account for the heat added to the system by any source but not the condenser tube, such as the tube fittings and connections. In this experiment, a copper tube similar to the testing tubes and well insulated with moisture resistance silicon foam on the outer surface was placed in the testing section. A condensation experiment procedure identical to all other experiments was then performed, and the HT rate was computed which in this case it presents the heat loss $[Q_{loss} = (\dot{m}_c \ C_{p.c} \ (T_{out.c} - T_{in.c}))_{insulated \ tube}]$. This accounted for all HT by conduction or condensation through the tube fittings and connections. Moreover, the calibration test also accounts for the thermocouples temperature difference behavior associated with the increase in the inlet and outlet temperatures within the testing range. An example of the measured HT rate plotted versus Re of the coolant side is shown in **Figure 2.7**.

The curve fitting equation of the data in **Figure 2.7** was then used in the second term of the right side of Eq. (1) to represent the amount of the heat loss during each condensation test. To compute accurately the condensation HTC, the same calibration
test was conducted every time when any of the thermocouples, flow meter, pressure transducer, working fluid, and the testing tube dimensions and material was changed.

Figure 2.7 An example of the measured HT rate based on the coolant side as a function of Reynold number inside the insulated tube during a calibration experiment showing on the graph with green dot symbols. A curve fitting line presented by the dashed red line was used to consider the heat dissipated by any parts of the assembly but not the condensing tube, and used in Eq. (1) as $Q_{loss}$.

Calibration of the experimental setup

The classic Nusselt model of FWC was used to validate and calibrate the experimental setup as showing in Eq. (7).

$$h_{filmwise} = 0.728 \left[ \frac{\rho_l (\rho_l - \rho_v) g h_{fg} k_l^{3/2}}{\mu_l D_o \Delta T} \right]^{1/4}$$  (7)
Where \( \rho_l, \rho_v, g, h_{fg}', k_l, \mu_l, \) and \( D_o \) are the liquid density, vapor density, gravity, corrected enthalpy of evaporation \( (h_{fg}' = h_{fg} \left[ 1 + 0.68 \left( C_{p,l} (T_{sat} - T_w)/h_{fg} \right) \right]) \) [128], liquid thermal conductivity, liquid dynamic viscosity, and the tube outer diameter, respectively. All these properties were computed at film temperature \( (T_f = T_w + 0.25 (T_{sat} - T_w)) \) [129], except for \( \rho_v \) and \( h_{fg} \) which were computed at \( T_{sat} \).

For experimental validation, a smooth copper tube treated with \( H_2O_2 \) (sample Filmwise) was used to conduct FWC condensation test. The measured HT data was then compared to Nusselt model of FWC. Multiple experiments were conducted to assure repeatable agreements of the results. **Figure 2.8** shows the FWC image of the tested sample during one of the condensation tests. For all experiments, FWC mode was maintained over the entire condensing surface.

**Figure 2.8** Image of a smooth copper tube treated with \( H_2O_2 \) (Filmwise) undergoing filmwise condensation of water vapor under saturation condition near the atmosphere pressure.

For a further validation of the calculated method in section 2.5, a direct measurement method of the surface temperature of the tube wall was used. A 0.508mm diameter T-type calibrated thermocouple with the tip coated with thermal grease (ZM-STG2) was inserted in a 0.5mm deep hole made on the tube wall (drill bit wire gauge-76). The inserted thermocouple was used to measure the tube local wall temperature...
during the condensation experiment. Then a soldering procedure was followed to keep
the thermocouple inside the hole and to prevent the influence of phase change on the
measurements. The soldering coating thickness was about 0.4mm above the tube outer
surface. The thermocouple hole was located at the center of the tube length and at the
midpoint of the tube height. The conductivity between the thermocouple’s tip and both,
the depth of the hole, and the soldering coating thickness were considered in the data
reduction. The FWC results based on both methods used in section 2.5 and the direct
measured method were compared and found to be in a good agreement with Nusselt
model of FWC, as shown in Figure 2.9. The red circular symbols represent the data of
the direct measurement using the thermocouples, whereas the green hollow square
symbols represents the data computed from the calculated method showing in section 2.5.

![Figure 2.9](image)

**Figure 2.9** Experimental results of condensation (a) heat flux and (b) HTC as a function
of surface subcooling temperature for “Filmwise” undergoing filmwise condensation of
water vapor under saturation condition near the atmospheric pressure. The before refining
two data sets in the graphs were determined by a direct surface measurement method (red
solid dots), see section 2.7, and by the computing method illustrated in the data reduction
section 2.5 (green hollow square), and compared with Nusselt model of filmwise
condensation.
DATA REFINING

The refining process includes averaging the mass flow rate values that were kept constant throughout all the experiments to reduce the fluctuations in the readings, and presenting both the inlet and the outlet temperatures of the coolant by a curve fitting method. The refining procedure was applied for all experimental data reduction. Moreover, due to a continuous data collection during the condensation test, some of the data points were skipped to avoid clattering presentation in the graphs. Figure 2.10 shows the final representation of the data of Figure 2.9 after applying the refining procedure.

Figure 2.10 The results of condensation (a) heat flux and (b) HTC as a function of surface subcooling degree for the same data sets presented in Figure 2.9 after the refining process and adding the error bars.

Non-condensable gases measurement

The percentage of the non-condensable gases (NCG %) was computed by comparing the chamber pressure that was measured directly via the pressure transducer
(\(P_1\)) to that pressure computed by the measurement of the saturated temperature using the thermocouples (\(P_2\)) as follow:

\[
NCG \% = \frac{P_1 - P_2}{P_1} \times 100
\] (8)

For all experiments, the percentage of NCG was ranged between 3.56\% and 6.84\%, as shown in Figure 2.11.

![Figure 2.11 Percentage of NCG as a function of (a) surface subcooling degree, and (b) the measured saturated pressure inside the testing chamber for all tested samples.](image)

**Error propagation**

The uncertainties in the measurements (\(\omega_R\)) associated with heat flux, the overall HTC, log mean temperature difference, and the condensation HTC were considered in the data reduction process following Kline and McClintock method [130], showing in Eq. (9).

\[
\omega_R = \left[ \left( \frac{\partial R}{\partial \nu_1} \omega_1 \right)^2 + \left( \frac{\partial R}{\partial \nu_2} \omega_2 \right)^2 + \cdots + \left( \frac{\partial R}{\partial \nu_n} \omega_n \right)^2 \right]^{\frac{1}{2}}
\] (9)
Where, \((R = R(v_1, v_2, ..., v_n))\) is a function of independent variables \((n)\), \(\omega_i\) is uncertainty in the variable \((v_i)\).

**Uncertainties in the measurements**

**Table 2.2** Instruments uncertainties.

<table>
<thead>
<tr>
<th>Experimental Measurement</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coolant inlet and outlet temperatures ((T_{in}, T_{out}))</td>
<td>0.5K</td>
</tr>
<tr>
<td>Flow rate of the coolant ((\dot{m}))</td>
<td>1%</td>
</tr>
<tr>
<td>Saturated vapor temperature ((T_{sat}))</td>
<td>0.2K</td>
</tr>
<tr>
<td>Saturated vapor pressure ((P_{Sat}))</td>
<td>2%</td>
</tr>
<tr>
<td>Condensing surface area ((A))</td>
<td>2%</td>
</tr>
<tr>
<td>Sieder-Tate correlation HTC ((h_i))</td>
<td>10%</td>
</tr>
<tr>
<td>Error associated with heat flux ((q^*)</td>
<td>4-9%</td>
</tr>
<tr>
<td>Error associated with HTC ((h_{cond})</td>
<td>13-57%</td>
</tr>
</tbody>
</table>

**PART I: CONDENSATION HEAT TRANSFER CHARACTERIZATION**

**Results and Discussion**

The condensation heat flux and HTC as a function of subcooling temperature of the patterned samples R2, R1.5, and R1.2 (see **Table 2.1** for details) are presented in **Figure 2.12a** and **b**, respectively, and compared with Filmwise sample and Nusselt model of FWC. As expected, all the samples treated with SAM-coating exhibited significantly higher HT performance compared to that of FWC mode. This is due to the influence of the surface energy reduction caused by the SAM’s coatings. However, since the main focus of this study is to investigate the influence of the coexistence of \(\alpha\) and \(\beta\)-regions on the condensing surface, sample F-\(\beta\), and F-\(\alpha\) were also experimentally tested.
and included in the comparison of Figure 2.12. The figure shows that among all samples, F-\(\alpha\) has the lowest HT performance indicating that the roughened region did not contribute in enhancing the HT performance due to the reduction of the surface wettability induced by the SAM coatings, instead it mainly acted as drainage path due its higher surface wettability during condensation process. More interestingly, Figure 2.12 shows that R2 and R1.5 outperform not only other samples, but also sample (F-\(\beta\)) which exhibits a complete DWC. The results also show that R2 gained the uppermost improvement in terms of the heat flux and HTC based on the wettability degree of \(\alpha\) and \(\beta\)-regions. The heat flux and HTC of R2, at a subcooling of 9 °C, are 780 kW/m\(^2\) and 85 kW/m\(^2\)K, respectively. This demonstrates that a maximum enhancement in the HT performance is approximately 1.8 and 4.8 times higher than those of a complete DWC and FWC, respectively.

Moreover, the condensation HTC curves of all patterned surfaces increased with the increase in the subcooling temperature followed the same behavior of a complete DWC. This demonstrates that the HT performances of the hybrid-patterned surfaces were enhanced due to promoting the overall dropwise condensation mode [131]. If the dropwise condensation was dominant, the slope of HTC-\(\Delta T\) curve would have the tendency to follow a positive steeper slope. That is the slope of the HTC-\(\Delta T\) curves which start with the minimum value demonstrated in the case of R1.2, and gradually increase as the (\(\beta/\alpha\)) ratio increased up to the optimum ratio, R2, showing higher dropwise condensation HTCs.
Figure 2.12 Experimental condensation HT performance as a function of subcooling ($\Delta T = T_{sat} - T_w$) for sample surfaces R2, R1.5, R1.2, F-β, F-α, and Filmwise undergoing water vapor condensation under saturation conditions near the atmospheric pressure (0.106 - 0.112 ± 0.002 MPa), and compared with Nusselt model of filmwise condensation. Both the condensation heat flux and HTC as functions of subcooling temperature for same samples sets are showing in (a) and (b), respectively. The error bars of all data computed by the method detailed in section 2.10.

Existence of an Optimum ($\beta/\alpha$) Ratio

By examining the performances of all patterned samples presented in Figure 2.12, we confirmed that the condensation heat flux and HTC was significantly influenced by the variation of the ($\beta/\alpha$) ratio. The figure also displays that R2 has the upper most HT performance among all other samples, and hence the optimum ($\beta/\alpha$) ratio. Any deviation from this ratio would result in a lower HT performance as illustrated by the graph of the heat flux versus ($\beta/\alpha$) ratio in Figure 2.13. In this figure, R1 and R3 were also included and compared with all hybrid patterned samples at five different subcooling degrees (note: R1 and R3 were not included in Figure 2.12 to avoid redundancy and clatter of the data). Figure 2.13 shows that when ($\beta/\alpha$) ratio was reduced lower values than R2’s ratio, the performance was reduced as the case in R1.5 and R1.2. Whereas, when ($\beta/\alpha$) ratio was increased to higher values than the one of R2, the HT performance was reduced as
the case in R3. The heat flux and HTC of R1.5 were higher than F-β, however lower than the optimum ratio. The maximum heat flux and HTC of R1.5 were about 757 kW/m² and 71 kW/m²K at a subcooling degree of ~10.7°C, respectively. On the other hand, the maximum heat flux and HTC for R1.2 were about 633 kW/m² and 42 kW/m²K at a subcooling of 15.0°C, respectively, showing a lower heat flux than not only R2 and R1.5, but also lower than that of the complete dropwise condensation. The irregular drop in the heat flux of R1.2 in Figure 2.13 may be explained by reaching a point at which the dropwise condensation on the β-regions can be dominated by the droplet bridging phenomenon (explained in detail in part II). The 0.5 mm width of the α-region of sample R1.2 allowed for high droplet bridging coverage rate, which induces a high thermal resistance and reduces the condensation rate (See figure 12 of part II).

In addition, Figure 2.13 suggests that (β/α) ratio of the hybrid patterned surface plays a major role in enhancing the condensation HT performance and by choosing a proper scale and ratio (i.e. β and α widths) the performance can be maximized. In this study, based on the wettability degree of β and α-regions, the optimum (β/α) ratio was found to be (2/1). Whereas, based on the average maximum droplet base diameter of the hydrophobic surface (F-β), which was 2.2 ± 0.02 mm, the scale (i.e. the width of β-regions) was found to be 0.6 mm, which is about 27% of the base diameter of the average maximum droplets as observed on a F-β surface. Likewise, we contemplate that the optimum ratio would change if the wettability of β and α-region varied.

In addition, other pattern scales (i.e. other β-regions widths) were also studied, such as 0.5, 0.7, and 1.0 mm; however the optimum scale found and considered herein was the 0.6 mm, and chosen to be the main scale in this study investigation.

Figure 2.14 shows an example of the HT performance results of a group of patterned samples having a scale of 1.0 mm. Whereas, the α-regions width of this group
was varied from 0.3 mm to 0.7 mm within an increment of 0.1 mm. The figure shows that all the samples but one exhibited lower HT performance than that of F-β. In addition, the figure shows that there also exists an optimum ratio based on this β-regions width of 1.0 mm which was for α-regions width of 0.4 mm. However, the HT performance of this optimum ratio was not significantly higher than the sample with a complete DWC (F-β).

---

**Figure 2.13** Condensation Heat flux as a function of the (β/α) ratio for sample R3, R2, R1.5, R1.2, R1, F-β, and F-α at 5, 6, 7, 8, and 9°C of surface subcooling under saturation pressure of (0.106 - 0.112 ± 0.002 MPa). The zero and infinity values presenting in the x-axis refers to sample Sandblasting and F-β, respectively.
Figure 2.14 Condensation (a) heat flux and (b) HTC as a function of subcooling temperature for hybrid patterned samples with fixed β-regions width of 1.0mm and varied α-regions width (from 0.3 to 0.7), compared with F-β, F-α, and Nusselt model of FWC undergoing water vapor condensation under saturation conditions near the atmospheric pressure (0.106 - 0.112 ± 0.002 MPa).

Droplet Dynamics

Careful attentions were paid to investigate why some patterned samples with certain (β/α) ratios exhibited higher HT performance than others. In other words, why there exists an optimum ratio? Using the integrated visualization system, a close observation was given to the droplet motion mechanism during condensation. We observed that the β-regions with lower wettability acted mainly as nucleation sites where DWC was dominant, whereas the α-regions with higher wettability acted mainly as drainage sites, promoting droplets migrations from the adjacent β-regions. In addition, besides the coalescence of condensates, and the direct vapor condensation on both the condensates and condenser surfaces [11, 14], two unique capillary driven droplet mitigation mechanisms were observed herein owning to existence of neighboring α and β regions.
The first reported mechanism is due to the relatively smaller droplet on the β-region and near the β-α boundary. When a growing droplet boundary touched the α-region, a direct droplet migration and confinement within the α-region occurred and followed by a drainage action under the gravitational force (see the red highlight in Figure 2.15). The second witnessed mechanism is accounted to the migration process of a relatively larger droplet (droplet that was nucleated near the center of the β-region or away from the α-regions boundaries). In this case, migrations to the α-region occurred with larger momentum compared to the former case. As highlighted in green in Figure 2.15, the large droplet enters the α-region from one side to bounce partially out the other side boundary while its base still pinned to the α-region to reach and coalesce with other droplets in the neighboring β-regions. This contributes to coalescence and drainage actions of more droplets; hence, higher rates of surface renewal can be achieved. To summarize, combining regions with two different wetting properties (i.e. β and α) on a condensing surface may allow for a better droplet drainage, and a higher droplet departure frequency; and by introducing α-region on β surface within a suitable scale and ration ratio, the condensation rate can be increased to outperform a surface with a complete DWC.

Moreover, the experimental results and the integrated visualization show that decreasing (β/α) ratio leads to a dominant FWC mode due to an increase of α-regions, yet resulting in a lower HT performance. On the other hand, increasing (β/α) ratio which can be realized by two different approaches: either by increasing the width (scale) of the β-regions or by decreasing the width of the α-regions. The formal approach was not adapted herein, and the width kept constant throughout this study due to the scale effect on the
dynamic of the growing droplets on the β-regions. Basically, by increasing the scale (i.e. the width of the β-stripes), the droplets on the β-regions can grow to larger droplet base diameters; hence, the thermal resistance can be increased.

Figure 2.15 Time lapse snapshots via the recorded visualization during a condensation test on a hybrid/patterned surface. It illustrates the dynamic of the capillary driven droplets during condensation on a hybrid patterned surface for a sample with (β/α) of (0.7/0.3) at a subcooling degree of 16.2°C, and saturated pressure of 0.106 - 0.112 ± 0.002 MPa. The Red lines highlight a droplet undergoing direct migration from β to α-region, whereas green lines highlight a larger droplet undergoing first a direct migration from β to α-region, followed by bouncing and coalescing actions with neighboring droplet(s) as highlighted by the blue lines.

With further increase in the β-stripes, the HT performance will be similar to F-β exhibiting almost a complete dropwise condensation mode with maximum droplets diameter close to 2.2±0.02mm as witnessed on F-β. The latter approach which was maintained by keeping the width of β-stripes unchanged while varying the α–stripes width was adapted herein. We noticed that by decreasing the α-regions to less than the optimum ratio, the droplets on the two neighboring β-stripes can be joined (bridged) to
each other across the middle $\alpha$–stripe to form a larger droplet that covered three stripes all together (i.e. two $\alpha$–stripes and one $\beta$-stripe). We observed such interesting phenomena (Bridging) increased the thermal resistance due to the low conductivity of the larger bridging water droplets. With a further decrease of the $\alpha$–stripes, more bridging droplets occurred, resulting in different bridging types, such as bridging-droplets between two, three, four, or even five neighboring $\alpha$-stripes. The time lapse images of Figure 2.16 demonstrate an example of bridging droplet forming on R1.2 surface during condensation. The figure shows an already existing bridging droplet covering two $\alpha$-stripes was coalescing with surrounding droplets to form a larger bridging droplet covering three $\alpha$-stripes. This can induce a higher thermal resistance and yet deteriorates the condensation HT performance. More details about the Bridging phenomena will be presented in Part II of this study.

**Figure 2.16** Bridging phenomena under formation action. Time lapse snapshots via the recorded visualization during vapor condensation on R1.2 surface at a subcooling degree of 13.5°C, and saturated pressure of (0.106 - 0.112 ± 0.002 MPa).

Furthermore, we witnessed that the measured average maximum base diameter of droplets on the $\beta$-regions during the condensation was not identical to the $\beta$-regions width as conceptually predicted, but it was 94±3% of width. This is a result of the higher migrating rate of smaller droplets near the $\alpha$-boundaries coalescing with the large droplet and joining it with the $\alpha$-region before the large droplet boundary reaches the $\beta$-region.
An illustration of such action is presented in the schematic of Figure 2.17a, and by the time lapse images of Figure 2.17b. It was also noticed that the migration rate is at its peak value near the $\alpha$-boundaries; while as it is going farther, bigger droplets and lower population rates were observed, indicating that the possible maximum droplet diameter is probably originated near the center of the $\beta$-region or further as possible from the surrounding $\alpha$ boundaries similar to the observation found by Ghosh et al. [60].

![Figure 2.17](image)

**Figure 2.17** Mechanism of droplet under migration action from $\beta$ to $\alpha$-region due to the coalescence of small droplets near the $\alpha$-boundaries which prohibits a growing droplet to reach a diameter equivalent to the width of $\beta$-region is illustrated by the (a) schematic and (b) time lapse images for a patterned sample with ($\beta/\alpha$) ratio of (0.7/0.3) at subcooling temperature of 16.2°C, and saturated pressure of (0.106 - 0.112 ± 0.002 MPa).

**Conclusions**

The concept of introducing alternative parallel straight stripes consisted of hydrophobic ($\beta$) and less-hydrophobic ($\alpha$) regions at different ($\beta/\alpha$) ratios was applied on the surface of copper tubes. A parametric study was conducted to experimentally test and visually observe surfaces with different ($\beta/\alpha$) ratio underwent saturated vapor condensation near the atmospheric conditions. Accordingly, the following conclusions can be drawn:
1. The condensation HT performance can be significantly enhanced by the coexistence of $\beta$ and $\alpha$-regions. Compared to the condensation HT performance of a sample with a complete FWC and DWC, the hybrid patterned surface R2 showed an enhancement of 480% and 180% in the HTC, respectively.

2. There exists an optimum ($\beta/\alpha$) ratio corresponding to wettability degree of the $\beta$ and $\alpha$-regions adapted in this study. It was found that increasing the $\alpha$-region width can lead to a dominant FWC mode; however, decreasing it can increase the bridging phenomena and hence reduce the condensation rate. Careful attention should be given when selecting the scale and ratio of $\beta$ to $\alpha$-regions. We expected that the scale and ratio would vary depending on the wettability degree of both regions.

3. The visualization analysis of the condensates dynamic during condensation on the hybrid patterned surfaces revealed two main capillary-driven phenomena responsible for the enhanced condensation HTC. The first is given for the droplets that were migrating directly from $\beta$ to $\alpha$-regions. The second is for those relatively larger droplets that bound while their base pinned to $\alpha$-region during the migration, and collecting and draining droplets from the neighboring $\beta$-regions.

4. The coexistence of $\beta$ and $\alpha$-regions on the condenser surface not only provide better droplet drainage but also allow for the maximum diameter of the growing condensates on the hydrophobic ($\beta$) regions to be controlled during the condensation.
PART II: DROPLET DYNAMIC ANALYSIS

Selected 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 (more details can be found in Chapter 2) were used as the testing samples. As specified in Table 2.3, three samples with hybrid patterned surfaces R2, R1.5 and R1.2, fully hydrophobic (F-β), and flooded-hydrophobic/hydrophilic (F-α) were considered in the investigation herein. The letter R in the Name/label column of Table 2.3 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.

Table 2.3 Samples categorization.

<table>
<thead>
<tr>
<th></th>
<th>β-stripes width [mm]</th>
<th>α-stripes width [mm]</th>
<th>Name/label (β/α)</th>
</tr>
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<td>1</td>
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<td>0.3</td>
<td>R2</td>
</tr>
<tr>
<td>2</td>
<td>0.6</td>
<td>0.4</td>
<td>R1.5</td>
</tr>
<tr>
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<td>0.6</td>
<td>0.5</td>
<td>R1.2</td>
</tr>
<tr>
<td>4</td>
<td>full</td>
<td>-</td>
<td>F-β</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>full</td>
<td>F-α</td>
</tr>
</tbody>
</table>

Experiment 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 2.3, 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 – 105mm 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, Figure 2.18a, 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. **Figure 2.18** shows a visual comparison of the same droplet before (a) and after (b) the image processing circled by solid red lines. This calibration process was performed multiple times to a different population to account for the variations in the measurement due to the change in ambient light reflection on the droplet. The plot of **Figure 2.18c** shows an example of sampling method applied on a random population, in which the sampled droplet count was plotted as a function of the percentage increase in the diameter. The average increase percentage of all analyzed droplets was found to be 30±5%. The percentage was then considered in the MATLAB analysis script to compute accurate droplet information.

The modified image was then processed through a MATLAB analysis script, where information such as droplet diameter, volume, count, travelling velocity, and departure location were determined. For the global droplet analysis frame work, the area with a black dashed line border shown in **Figure 2.18a** was used to observe the falling droplets that departed the condenser surface. The recording rate allowed each falling droplet to be shown within an average of six frames, which was sufficient for the calculation. Based on image resolution (i.e. number of pixels per area) and a predefined scale, the number of pixels of each falling droplet was determined to compute the area, volume and diameter.

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:
\[ Q_{DA} = \dot{m}_c h_{fg} = \rho_v \bar{V} \mathcal{F} h_{fg} \] (10)

Where, \( \dot{m}_c \) is the condensate mass rate, \( \rho \) is the density of the saturated vapor, \( \bar{V} \) is the average volume of the departure droplets, \( \mathcal{F} \) is the droplets departure frequency, and \( h_{fg} \) is the latent heat. By condensing the tube surface area \( (A_o) \), the condensation heat flux \( (q_{DA}^* = Q_{DA}/A_o) \) was also computed.

By considering the mean standard error \( (\overline{SE}) \) of the analyzed sampling \( (\overline{SE} = \sigma/\sqrt{n}, \) 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 [130],

**Figure 2.18** 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.
RESULTS AND DISCUSSION

Global Droplet Analysis

The DA method within the global frame work was focused on analyzing all droplets that completely detached and departed the condenser surface passing the area showing in Figure 2.18a. 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-α) were determined by Eq.10. 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. Figure 2.19 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 Figure 2.19 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 Figure 2.20a, the droplet diameter for R2 was slightly larger than both R1.2 and the F-β.
Figure 2.19 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.

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 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 $\alpha$-stripes during the condensation process.

Third, and more interestingly, **Figure 2.20a** shows that the droplet departure diameters of all samples were slightly increased when the subcooling was increased. This indicates that at a higher 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 filmwise condensation on F-$\alpha$ surface lead to significantly larger droplet departure diameters as shown in the graph of **Figure 2.20a**. Original images of some falling droplets (circled by red solid lines) during condensation tests for sample F-$\alpha$ including R2, R1.2, and F-$\beta$, are represented in **Figure 2.20b** for a visual comparison.
Figure 2.20 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.

**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. Figure 2.21 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 Figure 2.19. 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-regions because of two main reasons. First, the two α-regions bonded each β-region created wettability gradient which allows droplets to rapidly migrate from the β to α-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 β-regions. The droplet critical diameter on the surface of F-β is $2.2 \pm 0.02$ mm and found to be reduced to a base diameter of
0.56±0.02mm on the β-regions of all hybrid patterned surfaces. Second, the suitable width of the α-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 Figure 2.22 illustrate a comparison for droplet departure frequency of water vapor condensation on sample R2, F-β, and F-α. 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 α-regions can significantly influence the droplet removal rates, and proper widths should be selected based on the wettability degree of the two regions.

**Figure 2.21** The average droplet departure frequency as a function of subcooling temperature for sample R2, R1.2, F-β, and F-α computed by the DA method under the global frame work.
Figure 2.22 The time lapse images for a random recorded duration of water vapor condensation on sample R2, F-β, and F-α surfaces showing in column (a), (b), and (c), respectively. All the images were captured under the same condensation conditions (i.e. saturated water vapor near the atmospheric pressure and a coolant inlet temperature of 40±0.5 °C). By considering the number of the droplets passing the area of the analysis (showing in the first image of column (a)) of the global framework, the droplet departure frequency can be computed.

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 Figure 2.23. 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 Figure 2.23. 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±0.5 °C). As shown in figure, sample R2, R1.2, and F-β exhibited uniform fluctuation and even distributed droplet departure frequency along the length of the tube. However, sample F-α showed uneven fluctuation and distribution as illustrated by the absent of droplets in the last two sections. 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 filmwise condensation mode such as F-α, 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-α, see Figure 2.23 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.

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 (β/α) ratios.

**Figure 2.23** Droplets departure frequency as a function of the location along the x-direction of the tube R2 (showing in the top of the figure). R1.2, F-β, and F-α, computed by the DA method under the global frame work. The results were computed under the same condensation conditions, and coolant inlet temperature. The x-direction length of the tubes was divided into nine 10 mm-long sections. Note that the flow direction of the coolant inside the tube was from left to right.

**Bridging Phenomenon:**

Introducing β and α-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 α-
regions to a width larger than that of the optimum led to a dominant filmwise condensation 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 Figure 2.24.

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 Figure 2.24a and b. 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.

![Figure 2.24](image)

**Figure 2.24** 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.
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.

Figure 2.25 histograms of the bridging droplets base diameter for bridging droplet occurred between (a) 2 $\alpha$-stripes, (b) 3 $\alpha$-stripes, and (c) 4 $\alpha$-stripes, for sample R1.2 (row 1), R1.5 (row 2), and R2 (row 3). The analyzed bridging droplets populations of the three samples were taken under the same condensation test conditions and coolant inlet temperature of 40±0.5 °C.
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. Figure 2.25 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 of the population presented in Figure 2.25 was carefully analyzed independently.

The bridging droplet frequency, bridging droplet base diameter, and bridging droplet velocity are plotted as a function of the three $(\beta/\alpha)$ 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 Figure 2.26.

For the bridging frequency, see Figure 2.26a, 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. Figure 2.26b 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 Figure 2.26b. 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 Figure 2.26c. 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.

Figure 2.26 The comparisons of the three bridging droplet variables for the three types of bridging droplets as a function of (β/α) ratio, are showing in (a) for the bridging droplet frequency, (b) for the bridging droplets base diameter, and (c) for the bridging droplets traveling/sliding velocity. [Note that all the results were computed under the same condensation test conditions and the same coolant inlet temperature].
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 Figure 2.27. 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. Figure 2.27 also shows that (2 α-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.

![Bridging Droplet Coverage Area Rate](image)

**Figure 2.27** Bridging droplet coverage area rate as a function of (β/α) ratio for the three types of bridging droplet.
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).

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).

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:

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 widths of the β and α-regions were selected such as the case in R2 and R1.5.
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.

A bridging phenomenon exists on all hybrid patterned surfaces. This phenomenon refers to those droplets that were bridged between two, three, or four neighboring $\alpha$-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.

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

For those condensers with hybrid pattern ($\beta/\alpha$) ratio showing a lower HT performance than the fully hydrophobic surface (F-$\beta$), the $\alpha$-regions width was either too large where the filmwise condensation was more dominant, or too narrow where the bridging phenomena occurred more frequently, resulting in higher thermal resistance.
CHAPTER 3: CONDENSATION ON NANOSCALE HYBRID-WETTABILITY SURFACES

In this part of the investigation, a condensing surface with nanoscale hybrid wettability regions was achieved. This wettability contrast was achieved via depositing different numbers of nickel oxide layers on smooth nickel tubes surfaces via atomic layer deposition method (ALD). The deposition nature of the ALD method allows for a combined deposition of carbon and nickel oxide (NiO), which found to exhibit hydrophobic and hydrophilic properties, respectively. The existence of the carbon and NiO developed a contrast in wettability, which enhances the condensation heat transfer performance by promoting droplets mitigation and increase the droplet removal rate.

TEST SAMPLES/SURFACE PREPARATION

The NiO ALD coated samples were prepared on 120 mm long and 6.35 mm outer diameter Ni tubes surfaces, which underwent first through a mechanically polishing procedure (up to grid #2500), rinsed, with acetone, ethanol, and deionized water consecutively, then dried by a nitrogen stream. Second, the samples were placed in the ALD chamber to deposit ultrathin layers of NiO on the samples surfaces.

The ALD system consists of a reactor tube, a gas flow control system, and a data acquisition and control system with LabVIEW, which was described in detail previously [107]. The NiO ALD was carried out at 350 °C and 3 torr using
bis(cyclopentadienyl)nickel (NiCp$_2$, from Alfa Aesar) and oxygen as precursors. Each cycle of NiO ALD consists of 6 continuous steps: NiCp$_2$ dose (10 s), N$_2$ flush (60 s), vacuum (30 s), O$_2$ dose (10 s), N$_2$ flush (60 s), and vacuum (30 s). The solid NiCp$_2$ precursor was loaded in a heated bubbler, which maintained at 110 °C to increase the vapor pressure of the precursor. During the reaction, the NiCp$_2$ precursor was carried into the reactor by nitrogen flow at a flow rate of 6 sccm, controlled by a MKS mass flow controller. In O$_2$ dose step, O$_2$ was introduced into the reactor at a flow rate of 6 sccm, which also controlled by a MKS mass flow controller. The feed lines were kept at 130 °C to avoid the excess adsorption of the precursor on the inner walls of the reaction system. The nitrogen purge process was employed between each dosing steps of these two precursors to remove unreacted precursors and any by-products to prevent possible chemical vapor deposition reaction.

Four different numbers of cycles of NiO ALD (50, 100, 200, and 400) were employed on the Ni tubes leaving four ALD-NiO coated samples to be testes and compared to a bare Ni surface, shown in Table 3.1. All the samples with NiO ALD coating were tested in the condensation chamber after a 30 days of storage. Moreover, flat Ni plate where also prepared with the tubes samples for surface characterization and examination usage.

To achieve FWC on Ni tube for fair comparison with Nusselt mode of FMC, a smooth nickel tube was submerged in 10% sulfuric acid, triple rinsed with deionized water, sonicated in acetone for 10 min to remove any possible organic particles on the surface, triple rinsed with deionized water again, and then blown to dry by a nitrogen gun.
For the oxygen plasma etching process used to clean the surface from the carbon contents, compact benchtop plasma cleaning system (PE-50) was used at 100 W with a flow rate of 7.5 sccm to etch the surfaces of the samples for 10 mins.

**Table 3.1** Samples specifications and labeling.

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</tr>
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<td>4</td>
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</tr>
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<td>5</td>
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</tr>
</tbody>
</table>

**SURFACE CHARACTERISTICS**

To characterize the surface wettability and roughness, contact angle (CA) measurements and atomic force microscopy (AFM) system were used, respectively. The measured static, advance, receding, and hysteresis CA results for all the tested samples are compared and presented in **Figure 3.1**.

Due to the general possibility of the ALD method to increase the surface roughness [109], AFM used to considered the influence of NiO ALD depositing method on the surface roughness which can alter the surface wettability as well. The AFM results for all sample surfaces roughness were categorized by the average roughness (Ra), which is defined the average of the individual heights (asperities) and depths from the arithmetic mean elevation of the profile, and the root mean square roughness (Rq), which is defined as the square root of the sum of the squares of the individual heights and depths from the mean line. Ra and Rq are presented in **Figure 3.2** as a function of the number of NiO ALD depositing cycles including the smooth nickel surface for comparison.
**Figure 3.1** Surface characteristic presented by considering the surface wettability in (a) Contact angle measurement for the advance, receding, hysteresis, and static using water as the working fluid. Images showing in the top of the figures are for the static contact angles.
Figure 3.2 Atomic force microscopy results showing the surface roughness presented by Average roughness (Ra) [i.e. the average of the individual heights (asperities) and depths from the arithmetic mean elevation of the profile], and the root mean square roughness (Rq) [i.e. the square root of the sum of the squares of the individual heights and depths from the mean line].

To analyze the samples surface chemical composite, X-ray Photoelectron Spectroscopy (XPS) was used to determine the carbon, oxygen, and Ni contents of the prepared NiO ALD coated samples prior to the condensation experimentations. A Kratos AXIS Ultra DLD XPS system with a monochromatic Al Ka source operated at 15 keV and 150W and a hemispherical energy analyzer was used. The X-rays were incident at an angle of 45° with respect to the surface normal. Analysis was performed at a pressure below $1 \times 10^{-9}$ mbar. High resolution core level spectra were measured with pass energy of 40 eV and analysis of the data was carried out using XPSPEAK41 software. The XPS experiments were performed while using an electron gun directed on the sample, for charge neutralization.

The XPS results were analyzed for all samples. Only one sample (Ni-NiO-ALD-50) detailed result is presented herein in Figure 3.3 after refining process. This is to illustrate an example of the XPS data reduction and to avoid redundancy in presenting the data. The presence of the Ni and NiO components (Ni 2P) as a function of NiO ALD cycle number for all samples is shown in Figure 3.4. The graph shows clearly that NiO was increased by increasing the NiO ALD deposition layers confirming a successful deposition of NiO.
Figure 3.3 XPS result of the surface chemical components of sample Ni-NiO-ALD-50 prior to the condensation experiment. The figures from left to right present the peak intensity in arbitrary unit amount as a function of the binding energy for carbon, oxygen, and nickel oxide, respectively.

Figure 3.4 X-ray Photoelectron Spectroscopy (XPS) results show NiO components as a function of number of ALD-NiO cycles deposited layers.
Another factor that was considered herein is the presence of carbon since the nature of the ALD process allows for percentage of carbon contents to be presented on the coated surface. There are considerable efforts aiming to reduce the carbon/hydrocarbon contents found to be deposited during the ALD process [132-134]. Therefore, the mass concentration percentages of carbon were also computed along oxygen and nickel contents, shown in Figure 3.5. The results indicate that the oxygen and nickel mass concentrations were increased by the increase in the ALD-NiO cycles numbers agreeing with Figure 3.4; whereas, the carbon concentration exhibited inverse relationship to the number of NiO ALD cycles.

Figure 3.5 XPS results show the mass concentration percentage of carbon, oxygen, and nickel as a function of number of ALD-NiO cycles.
Experiment Procedure

The thermally-insulated testing condensation chamber is equipped with calibrated thermocouples to measure the saturated water vapor temperature, and a pressure transducer to measure the saturated steam pressure. The steam was delivered from the steam generator to the testing chamber by a heated steam-line to assure dry steam supply. The condensation chamber walls and window are carefully heated to avoid condensation on the inner walls of the condensation chamber and the window, respectively. A data acquisition system and a high speed camera were integrated to the testing system for data and visualization recordings. The measured saturated water vapor pressure inside the chamber and the percentage range of the non-condensable gases for all testing samples were $0.107 - 0.114 \pm 0.001$ MPa and $3.3$ to $5.5 \pm 0.3\%$, respectively.

For the coolant side, a heated water tank and a gear pump were used in a close loop system to deliver water inside the testing tubes at a constant mass flow rate of about $3 \pm 2\%$ L/min. The increase in the coolant temperature during testing, which was due to the coolant tank immersion heater, the cord-heater which was wrapped around the coolant inlet line, and the condensation heat transfer, causes Reynold number (Re) to decrease within a range of $(18,000 - 48,000)$, and hence the surface temperature of the condenser. The coolant inlet and outlet temperature, and the flow rate of the coolant were used to compute the condensation heat transfer rate. For details of the data reduction, experimental setup, experimental procedure, and system calibration please refer to the supplement material [135].
RESULTS AND DISCUSSION

The condensation heat transfer performances comparison of all testing surfaces are presented by the measured heat flux and HTC as a function of subcooling temperature in Figure 3.6a and b, respectively. The condensation HTC results show an inverse relationship to the number of deposition NiO ALD layers. The sample with the lower number of NiO layers cycles (Ni-NiO-ALD-50) exhibited the upper most heat transfer performance. The maximum heat flux and the HTC were about 3.9 and 4.2 times that of the FWC having values of about 700 kW/m² at subcooling degree of 11.0°C and 100 kW/m²K at subcooling degree of 3.5°C, respectively.

Figure 3.6 Experimental condensation heat transfer performance as a function of subcooling ($\Delta T = T_{sat} - T_w$) for sample surfaces coated with different number cycles of NiO ALD, 50, 100, 200, and 400 cycles undergoing water vapor condensation under saturation conditions near the atmospheric pressure, and compared with Nusselt model of filmwise condensation. Both the condensation heat flux and HTC as functions of subcooling temperature for same samples sets are showing in (a) and (b), respectively.

Additionally, the trend of the HTCs curves of all tested samples decreased with increases in the surface subcooling, as showing in Figure 3.7, which indicates the enhancements were not mainly due to promoting DWC mode even though sample Ni-NiO-ALD-50 show dropwise like condensation. Rather it was due to achieving a mix
mode in which the droplet dynamic behavior followed a Wenzel state [26]. Droplets pinning to the surface was observed and indicated by the measured high contact angle hysteresis (showing in Figure 3.1), and the hydrophilic nature of the deposited NiO.

Figure 3.7 Condensation heat transfer coefficient as a function of different number cycles of NiO ALD for all tested surfaces at four subcooling degrees, ΔT = 5, 6, 8, and 10 °C. Images in the figures represent the same surfaces undergoing water vapor condensation under saturation conditions near the atmospheric pressure at subcooling of about 5°C.

Moreover, by observing the droplet dynamic of the condensate located on surface Ni-NiO-ALD-50, it appears that the condensing droplets exhibited semi-spherical shape droplets similar to the DWC case. Based on the droplet analysis during the condensation
process, the computed average maximum droplet base diameter of these droplets was 3.4 ± 0.1 mm. Figure 3.8 shows the studied droplets population counts. Even though the condensation was in a droplet form, the large relatively size of droplets to the surface roughness lead to a wetting behavior dominant by a Wenzel state [136].

![Figure 3.8](image)

**Figure 3.8** Average maximum droplet base diameter of random droplets population during condensation on the surface of sample 50cyc - NiO ALD at different subcooling temperatures.

The nucleation course of ALD is very important for conformal ultra-thin films. However, the ALD film/spots may only nucleate at certain defect sites on the substrate if the ALD precursors did not react effectively with the initial substrate. During the early deposition stages (i.e. low deposition cycles numbers such as the case of Ni-NiO-ALD-
not only NiO was deposited in a form of nanoparticle instead of a conformal film [137, 138], but also high percentage of carbon content was observed [139-141]. There are many efforts been dedicated to reduce such high percentage of such carbon content [132-134]. As more deposition cycles were performed, the NiO film may develop to a continuous film in which the NiO nanoparticles will gradually fill in the gaps (such as the case of 100 and 200 NiO ALD cycles) exhibiting mixed condensation modes, and eventually a conformal film will be achieved, and FWC will gradually dominated the condensation mode following the dominant wettability of the NiO such in the case of Ni-NiO-ALD-400, see Figure 3.9a to d.

![Figure 3.9](image)

Figure 3.9 Photographs of condensation on the surfaces of the NiO ALD coated at inlet temperature of 35°C under saturation condition of the atmospheric pressure. Scale is 10mm.
For a further confirmation of the hydrophobicity induced by the carbon presence on the condensation surfaces, all the NiO ALD coated samples were cleaned by oxygen plasma etching technique to etching out the carbon atoms and any other organic contamination existing on the surfaces. Then a distilled water drops were placed carefully on the cleaned surfaces indicating low contact angles that are near to a zero degree, showing in Figure 3.10. This indicates the surface hydrophobicity wetting degree was due to mainly the presence of carbon contents on the condensing surface. Since all the carbon contents were etched away, all the surfaces returned to the original wettability of the dominant hydrophilic NiO.

Figure 3.10 Image of distilled water droplets placed on the surfaces of the testing samples after etching with plasma cleaning system for all samples coated by NiO ALD. The figure show very low contact angles near to zero since the carbon contents etched away.

Moreover, the existence of the high atomic concentration percentage of the hydrophobic carbon on the surface of sample Ni-NiO-ALD-50 was suitable to contrast the droplet pinning effect existed due to the presence of the hydrophilic NiO even at low
percentage, and lead to bi-philic condensation. The coexistence of the two different wettability degrees at a ratio of about 3 to 1 (i.e. atomic concentration percentage of 74.3 % and 25.7 % for carbon and NiO, respectively) generates capillary driven force that can suitably mitigate condensing droplets and increase their mobility on the condensing surface [142]. **Figure 3.11** shows an example of such droplet mobility on the surface of Ni-NiO-ALD-50 in which a droplet during coalescence process can move to all directions including upward against the gravity force. This random droplet including the observed downward movement similar to the zigzag paths provided proper droplets mitigation and increased the coalescence rate. Hence, more surface areas will be exposed to the surrounding steam allowing for higher condensation performance. In addition, the combination of the droplets pinning and faster droplets mobility allowed for high surface contact area between the condensing droplet and the condensing surface, and high surface renewability, which played a significant role in increasing the condensation heat transfer rate.

![Figure 3.11](image)

**Figure 3.11** Droplet dynamic on NiO ALD 50 cycles sample showing a random droplets movement in all direction including against the gravitational force.

To assure the change in the surface wettability of the condensing surfaces was not mainly due to the change in the surface morphology during the NiO ALD method deposition process, AFM were used to measure the surface roughness of all samples.
Since the condensing droplets on the surface are in a Wenzel state, increase the roughness can decrease the surface wettability. The results show that the surface roughness did not significantly increase with the increase in the NiO layers deposition. The average roughness was varied only within tenth of nanometers. Though, it was noticed that there was an increase in the density of the pin like structures on the surface which we believe it related to the NiO heterogeneous deposition process nature of ALD system, as shown in Figure 3.12. The relative slightly developed roughness of the control sample (i.e. Ni-NiO-ALD-0) was due to the original roughness of the nickel tubes received from the manufacture, which went through only surface cleaning, but not surface polishing. In brief, the surface roughness investigation indicates that the enhancement in the heat transfer performance is due to mainly the surface chemical components rather than only the surface morphology.

Figure 3.12 AFM results for surface roughness of the tested samples showing nano-scale pin-like structures as a function of the NiO ALD cycles numbers.
CONCLUSION

As a final point, this part of the study investigates the influence of NiO layers deposited by atomic layers deposition on nickel tube on the condensation heat transfer performance. The surface morphology, chemical component, roughness, and wettability degree were also examined. The following outcomes were achieved:

1. Different numbers of ultra-thin NiO layers were successfully deposited on nickel tubes using ALD method.

2. The condensation heat transfer performances for all Ni tubes with different layers of NiO coating were measured. The result showed with reducing the number of NiO layers, the condensation rate was increased. The relationship was justified by the increase in the hydrophobic carbon amount at lower numbers of NiO ALD cycles, which existed due to the nature of the ALD deposition technique.

3. The maximum condensation heat transfer coefficient achieved was for the sample coated with only 50 layers of NiO ALD. At subcooling temperature of about 11.0°C, the heat flux was about 700 kW/m² which is 3.9 times the FWC. While, the HTC max out at subcooling temperature of about 3.5°C with a value of 100 kW/m²K, which is 4.2 times the FWC.

4. The coexistence of the hydrophobic carbon and hydrophilic NiO at atomic concentration ratio of about 3 to 1 (74.3 % to 25.7 % for carbon to NiO, respectively) allows for a proper droplets mitigation due to the existence of bi-philic condensation mode which was driven by the capillary force.
OVERALL CONCLUSION

1. The condensation heat transfer performance can be enhanced by promoting dropwise condensation that can be attained by lowering the surface free energy or reducing the surface wettability.

2. Introducing wettability gradient on the condensing surface can significantly enhance the condensation rate. The wettability gradient can be achieved by combining two wettability degrees on a condensing surface.

3. The contrast in the wettability can be achieved by designing a pattern, which can be inspired by nature or by innovative minds. The pattern can be formed with a careful consideration of a suitable scale and a corresponding ratio. The pattern can be formed at a mini/microscale as demonstrated in Chapter 2, or nanoscale as deliberated in Chapter 3.

4. Hybrid wettability patterned surfaces can significantly mitigate condensing droplets on the condensing surface allowing droplets to shed at higher rates. This mechanism found to be very affective for enhancing the condensation rates.
FUTURE WORK

While this work demonstrated a significant enhancement in the condensation heat transfer performance using wettability contrast mechanism, many opportunities are still available to further extend such a path. Some of these are discussed below:

1. Investigate the influence of using diverse wettability contrast degrees on the values of the scale and ratio of the pattern. We believe that changing the wettability degree of these two regions can alter the values of the scale and ratio of the patterns. Therefore, the two regions can formed with different wettability degrees used in current study, which can be categorized by the contact angle measurements, and investigation on the optimum scale and ration should be considered. This is to highlight the possible corresponding shift in the optimum ratio and scale found herein.

2. Investigate droplet dynamic of condensate forming on a condenser surface that carries a hybrid pattern consisted of more than two regions. With such a range of wettability contrast, droplet can travel following a designed path and against the gravitational force.

3. Construct a model that can predict the optimum scale and ration of the patterns based on a given wettability of the two regions.
REFERENCES


[17] Z. Qi, D. C. Zhang, and J. F. Lin, "SURFACE MATERIALS WITH DROPWISE CONDENSATION MADE BY ION-IMPLANTATION TECHNOLOGY."


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