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THE EFFECTS OF WETTABILITY AND SURFACE MORPHOLOGY ON HEAT TRANSFER FOR ZINC OXIDE NANOSTRUCTURED ALUMINUM SURFACES

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ABSTRACT

The development of hydrophilic surface coatings for enhanced wetting characteristics has led to improvement in heat transfer metrics like impinging droplet vaporization time and the heat transfer coefficient. Hydrothermal synthesis, a method of developing hydrophilic surfaces, has been previously shown to produce high performing heat transfer surfaces on copper substrates [1]. Our study applied this production method to aluminum substrates, which have the advantage of being cheaper, lighter, and a more widely used for heat sinks than copper. Previous experiments have shown that water droplets on ZnO nanostructure coated surfaces, at low superheats, evaporate via thin film evaporation rather than nucleate boiling. This leads to heat transfer coefficients as much as three times higher than nucleate boiling models for the same superheat. Our nanocoated aluminum surfaces exhibit superhydrophilicity with an average droplet liquid film thickness of 20-30 microns, which can produce heat transfer coefficients of over 25 kW/m²K. This study discusses characterization of ZnO nanostructured aluminum surfaces to better understand the related mechanisms which lead to such high heat transfer performance.

All ZnO nanostructured aluminum surfaces produced for this study exhibited superhydrophilicity, with sessile droplet contact angles of less than 5 degrees. The challenge of achieving accuracy for such low contact angles led to the development of a new wetting metric related to the droplet's wetted area on a surface rather than the contact angle. This new metric is predicated on the the fact that heat transfer performance is directly related to this wetted area, thickens, and shape of the expanding droplet footprint. Shape irregularity of droplets on these superhydrophilic surfaces is discussed in this study, where there appears to be advantages to irregular spreading compared with surfaces that produce symmetric radial spreading. One form of irregular spreading consists of liquid droplets spreading out both on top of the surface and within the microstructure of the surface coating. The liquid within the microstructure forms films less than 5 microns thick, making local heat transfer coefficients of greater than 100 kW/m²K possible. SEM microscope imaging provided additional insight to the underlying mechanisms which cause these surfaces to produce such exceptional spreading as well as irregular spreading, resulting in very good heat transfer performance.

Experimental work was coupled with computational analysis to model the contact line of the droplet footprint. Image processing of experimental photos helps to analyze spreading characteristics, which can be directly related to heat transfer due to film thickness at various points during spreading.

Approaches used to characterize these superhydrophilic surfaces advance understanding of the connections between nanoscale structural elements and macroscale performance characteristics in heat transfer. This understanding can reveal key insights for developing even better high performance surfaces for a broad range of applications.

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NOMENCLATURE

N_W	wetting	number
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- t_{ce} complete evaporation time
- A_{tot} total wetted contact area
- h_{lv} latent heat of vaporization
- k_l conductivity of water
- ρ water density

INTRODUCTION AND BACKGROUND

Interest in the field of surface coatings for heat transfer enhancement has been growing along with the demand for effective heat dissipation technologies. Liquid coolants are preferred over air cooling for high heat flux applications because of liquid's high latent heat and its ability to remove heat through evaporative cooling. One such application which employs effective evaporative cooling is the spray cooling used for large scale power plants. The cooling of condensers is used to boost efficiency in the thermodynamic power cycle, however the use of spray cooling for this process is very water intensive from an environmental standpoint. Motivated by this issue, this study explores how a Zinc Oxide (ZnO) nanostructured surface enhances hydrophilicity on aluminum. By using a scalable approach to surface production, it is feasible that this coating could be applied to condensers as a way to increase the effectiveness of evaporative cooling on their surface.

Earlier studies have explored the effectiveness of nanostructured surfaces on aluminum with the intention of developing specialized surfaces, both hydrophilic and hydrophobic. One such study manufactured micro grooves with 30μ m width and $10\mu m$ depth to create water repellant surfaces [2]. These types of surfaces are more challenging to scale, because of the intricacy of the manufacturing for the micro grooves. But, they offer very effective enhancement for hydrophobic surfaces. Other studies looked at specialized coatings to enhance the hydrophobicity of aluminum. Wang [3] applied his coatings onto the aluminum metal substrate and found that hydrophobicity was accomplished, but these coatings lack the rubustness to survive wear and tear over time. Study into surfaces that are hydrophilic have resulted in patents for hydrophilic surface coatings on aluminum [4] previously, but these manufacturing processes involve highly chemical immersion processes and do not produce long lasting hydrophilicity, as was discovered by other researchers.

The interest in producing hydrophilic nanostructures surfaces on aluminum marks a departure from standard hydrophilic coatings on surfaces, usually the result of chemical immersion. Previous studies with ZnO coatings, like those in this study, were done with copper substrates. These studies have shown that ZnO nanostructures result in hydrophilic characteristics and have the potential to greatly enhance heat transfer performance [1,5]. This is a result of the specific wetting regimes that are caused by surface hydrophilicity. As nanostructured surfaces move into the superhydrophilic regime, the wetting regime that results is often not a typical Wenzel wetting state as shown in Fig.1.



FIGURE 1. A typical Wenzel wetting regime where water permeates into the rough surface structure directly beneath the droplet [6]

In the Wenzel wetting regime, a deposited liquid droplet on the surface does not merely sit on top of any roughness or pillar-form microstructure, but rather fills in the spaces between the rough structure, thus removing any air gap. This is a desirable wetting arrangement for heat transfer because liquid encounters increased surface area and thus more direct contact with a heated surface for heat transfer. However, an even more desirable wetting regime known as the sombrero effect has been observed for highly wetting surfaces, such as those in this study. This wetting regime, previously observed on copper nanostructured surfaces [7], has been discussed in detail by other authors, referencing how the surface roughness can have direct relation to the wetting and spreading of water on the surface [8–10]. These coated copper surfaces have shown the potential for superhydrophilicity with a tendency to spread out past the contact line of the droplet above the surface, and create an ultrathin layer of water surrounding the droplet that is completely within the microstructure of a nanocoated surface. This wetting regime is shown in Fig.2 and represents the most desirable arrangement of a droplet on a surface for maximum heat transfer, and thus the highest potential for evaporative cooling.



FIGURE 2. Side graphic of the sobrero effect on a pillar-array microstructured surface (left), and a top view of a Zinc Oxide coated copper surface with superhydrophilic characteristics that result in a sombrero wetting regime. (right)

Knowing that use of copper as the substrate for these ZnO nanstructures produced such highly wetting characteristics, we

chose to focus this study on aluminum. Aluminum, as a lighter weight and cheaper metal is more often used in heat transfer and heat exchanger applications than other conductive metals like copper. Developing surface coatings that are high performing and robust on aluminum surfaces is desirable precisely because of this wide usage and affordability, opening the door for many diverse applications to increase heat transfer performance.

The hydrothermal synthesis method of surface enhanement has never before been used on aluminum surfaces and is beneficial both in its ability to be scaled up as well as it's durability as a surface enhancer. This opens the possibility for widespread implementation in heat transfer and heat exchanger development in industry and energy sectors.

For this study, we focused on several different aluminum nanstructured surfaces, created using hydrotheral synthesis with ZnO nanoparticles. The different iterations of this process were designed to produce different length scales for the nanostructures on these surface, thus affecting wetting characteristics observed on the macroscale as well as surface morphology on the microscale.

Computational models were developed to replicate the spreading of droplets on these aluminum nanostructured surfaces. This kind of modeling can be enhanced to predict average film thickness, and ultimately heat transfer performance. It is the goal of this study to approach these promising aluminum nanostructured surfaces from both experimental and computational angles to gain valuable insight on the best techniques to implement for a variety of heat transfer applications.

ZINC OXIDE SURFACES WITH SUPERHYDROPHILICITY

The surfaces developed for this study are made of 6061 aluminum alloy substrate on which zinc oxide nanoparticles were grown. A technique known as hydrothermal synthesis was previously used on copper surfaces for creation of hydrophilic wetting characteristics. This scalable manufacturing process involves the cleaning and polishing of the surface substrate prior to a simple room temperature deposition of ZnO nanoparticles suspended in a diluted E₄OH solution. The concentration of this solution was one of the independent variables for the various surfaces made for this study (see Tab. 1) This ZnO and E₄OH nanoparticle seeding solution quickly dries after deposition, creating an incredibly thin nanoparticle coating on the polished surface. After the surface is annealed at 120°C, it is submerged in a solution of Zinc Nitrate Hexahydrate and Hexamethaline Tetramine dissolved in water. This solution acts as a growth agent for the ZnO nanoparticles on the surface, which are grown in the solution for a period of four or eight hours. The length of time for growth has a direct correlation to the scale and density of the nanostructures on the surface once it is finished with thermal growth. The consistent superhydrophilicity of the ZnO nanostructured aluminum surfaces produced was experimentally observed by sessile water droplet deposition.

Two independent variables were adjusted for creating these surfaces: the concentration of the deposited nanoparticle seeding solution and the time that the surface was immersed in the growth solution. The four surfaces that will be discussed in this paper, shown in Tab.1, include two aluminum substrate ZnO nanostructured surfaces, S1 and S2 that were coated with a 0.04 molar solution of nanoparticles and placed in the growth solution for 4 and 8 hours respectively, as well as surfaces S3 and S4. These two were both grown in solution for 8 hours but S3 used a 0.02 molar solution of nanoparticles for deposition while S4 used a 0.08 molar solution. These variations in growth time and nanoparticle concentration produced a differences in the wetting characteristics of the surfaces.

NANOSCALE FEATURES THAT ENHANCE WETTING AND HEAT TRANSFER

In order to better understand the nature of these surfaces that leads to their superhydrophilicity, a Scanning Electron Microscope (SEM) was used to image the surfaces of the different nanostructured aluminum pieces produced for this study. By comparing the different observed features to the macroscale wettability characteristics, it is possible to begin making correlations for the specific features that are most beneficial for optimized surface enhancement.



FIGURE 3. ZnO nanostructured aluminum surface (Surface S1 – See Table 1) grown for 4 hours with a 0.04 molar ZnO seeding solution.

The most commonly observed feature on all four of the surfaces studied in this report was a porous base structure that

had grown out from the nanoparticles to create a base for the growth of pillarlike structures. This is most apparent in Fig.3 on surface S1, which had the shortest growth time of the four types of surfaces studied. The majority of the surface on this test piece was covered with thin, tightly packed membranes on the order of several nanometers thick. This surface served as a base for the growth of some pillar-like structures, shown in the center of Fig.3. On surface S1, the prevalence of these pillar growths were few and far between. We suspect that the growth time was a factor in the sparseness of the pillar growth. Previous studies of this same nanostructure growth technique on copper surfaces resulted in near complete coverage with nanostructure pillars [11].

This hypothesis is supported by the observations made on surface S2 under the SEM Microscope. This surface was deposited with the same 0.04 molar concentration nanoparticle solution as S1, but was baked for a total of 8 hours, or twice as long as surface S1. The resulting predominance of pillar structures showed a distinct difference between the shorter baked of the two. In Fig.4, the pillars that grew on surface S2, on top of the porous base, were tightly packed and randomly angled. The density of the pillars changed on various parts of the surface, but the size of the pillars remained the same with an average length of $6-8\mu$ m and a diameter of less than 1μ m.



FIGURE 4. ZnO nanostructured aluminum surface (Surface S2 – See Table 1) grown for 8 hours with a 0.04 molar ZnO seeding solution.

These two surfaces with a ZnO molar seeding concentration of 0.04 are contrasted with surfaces S3 and S4 which are coated with ZnO nanoparticle seeding concentrations of 0.02 and 0.08 respectively. Both S3 and S4 were baked for a total of 8 hours in the growth solution after the deposition of the nanoparticle solution.



FIGURE 5. ZnO nanostructured aluminum surface (Surface S3 – See Table 1) grown for 8 hours with a 0.02 molar ZnO seeding solution.

Surface S3, like surface S1 had a low prevalence of pillar structures. The majority of the surface for S3 displayed a rough porous structure, with the occasional polyp, similar to that shown in the center of Fig.5. This was contrasted with surface S4, shown in Fig 6, which had an abundance of pillars. Notably, the pillars are much smaller than the pillars on surface S2 in Fig.4. Where the pillars on Surface S2 formed with a 0.04 molar solution of ZnO of nanoparticles are approximately 8-10 μ m long and have diameters of 0.5-1 μ m, surface S4 with double that molar concentration of ZnO nanoparticles produced pillars a whole order of magnitude smaller. These pillars in Fig.6 are less than 2μ m in length and have diameters on the order of several nanometers.

These different characteristics observed on the microscale resulted in differing wetting characteristics as well as heat transfer characteristics.

QUANTIFYING SURFACE WETTABILITY

In order to discover relations between surface morphology and wettability, tests were run on surfaces S1, S2, S3, and S4 to determine droplet spreading and wicking rate for water droplets on room temperature surfaces. These sessile droplet observations are frequently performed in the literature as a way to assess wetting characteristics and most of these studies use contact angles as the metric of choice for quantifying surface wettability [12–14]. However, this metric became challenging to quantify as the water droplets on this study's surfaces spread out so significantly that measurement of the near-zero contact angles was either innacurate or impossible. Previous discussion regarding the challenges of using the contact angle as a wetting metric for superhydrophilic surfaces was had in further detail in



FIGURE 6. ZnO nanostructured aluminum surface (Surface S4 – See Table 1) grown for 8 hours with a 0.08 molar ZnO seeding solution.

previous papers by Kunkle [7]. Here, the author lays out the motivation for finding a better metric for highly wetting surfaces. The alternative choice of wetting metric became something known as the wetting number. In this case, the total wetted area of a sessile droplet is measured by taking an aerial photograph of the droplet on the surface. This area measurement is then nondimensionalized with a calculated area for a droplet of equal volume on a surface with a 90° contact angle. This wetting number, N_w , is defined in Eq. 1.

$$N_w = \frac{A_{wetted}}{A_{90}} \tag{1}$$

The wetting number is able to accurately relate the spread of the droplet to the surfaces wettability by showing much more wetting a surface is compared to a constant counterpart surface that would produce a 90° contact angle. Any error in these measurements is a function of camera accuracy, and pale in comparison to inaccuracies in measuring near zero contact angles of a droplet on a superhydrophilic surface. Wetting numbers for the 4 surfaces discussed in this paper are in Table 1. Higher wetting numbers correlate to more wetting surfaces while the wetting numbers closer to one are less hydrophilic. As discussed later in the paper, many of the surfaces exhibited nonhomogeneous wetting characteristics. It is worth noting, then, that the wetting number values shown in Table 1 represent the most wetting parts of the surface.

As shown in Table 1, the surface S2 exhibited the highest wettability with a wetting number of 63.45, showing that it was 63.45 times more wetting than a same volume droplet on a 90° contact angle surface. The wetting numbers for Surfaces S1 and S2 represent equivalent contact angles of roughly 0.3 to 0.5

degrees, while the much lower wetting numbers of surfaces S3 and S4 represent nearly 50° contact angles. The contact angle approximations are made using geometric relations assuming spherical cap spreading. Assuming spherical cap spreading, however, is not always accurate for these hydrophilic surfaces and it is much more accurate to calculate the wetting number by direct wetted area measurements. This is done by measuring experimental wetted areas for a sessile water droplet deposition in room temperature conditions, after initial production of the surfaces. The hydrophilicity can change over time, sometimes by as much as 50% but still maintain high heat transfer performance. Some of these differences between the four surfaces can, in part, be attributed to the non-homogeneity of the surface as well as the tendency for hydrophilic surfaces to adsorb particles onto their surface. The non-homogeneity appears to be a unique advantage after studying the performance of the four surfaces.

While surface S2 had a consistent pillar formation across nearly 80% of the surface when viewed through the SEM microscope (see Fig.4), S3 and S4 had less than 40% coverage and this inconsistency affected the spreading of droplets. In Table 1, there is also a column noting the observation of a sombrero effect. As discussed in the introduction, a sombrero effect can act as a great enhancer of heat transfer due to the creation of ultra thin liquid layers on the surface within the coating microstructure. It was observed in experimental tests that it was also this nonhomogeneous spreading that often was related to the sombrero effect. Of the four surfaces discussed, it was S2 that had the most apparent sombrero effect as well as non-symmetry in spreading. This is shown in Fig.9.

To further study these surfaces and thoroughly understand the wetting characteristics they exhibit, a high speed camera was used to provide visualization of the surface as droplets impinge and spread on them. With the capability to record over 10,000 frames per second, we identified two distinct stages spreading regimes for deposited droplets on the nanostructured surface. The first stage begins from the moment that the water droplet touches the surface and begins spreading, with the contact line above the nanostructured surface moving outwards. Shown in Fig.7, this initial wetting phase consists of the droplet in a Wenzel wetting state, where the liquid is both above the coating as well as interspersed between the microstructures within the nanostructured surface, directly beneath the dome of the droplet.



FIGURE 7. Water droplet impinging on an 8 hour grown ZnO nanocoated surface. Time scale for this initial spread process is 0.05 seconds for a 2μ l droplet (Diameter = 1.56mm)

Surface Description **Droplet Volume** [µl] Sombrero Effect N_w **S**1 4 hour bake, 0.04 ZnO Nanoparticle Concentration 2 46.45 Yes S2 8 hour bake, 0.04 ZnO Nanoparticle Concentration 2 63.45 Yes **S**3 8 hour bake, 0.02 ZnO Nanoparticle Concentration 2 1.49 No **S**4 8 hour bake, 0.08 ZnO Nanoparticle Concentration 2 1.92 No

TABLE 1. Wetting Numbers for the four aluminum surfaces coated in ZnO nanoparticles, quantifying wettability for different bake times and different ZnO nanoparticle concentrations

For Figures 7, 8, and 9, the size of the deposited droplet was 2μ l, corresponding to a droplet diameter of 1.56mm. The three frames shown in Fig.7 occur over a very short period of time that is usually less than 0.05 seconds, reaching the classical Wenzel state, looking like the droplet shown in Fig.8.



FIGURE 8. Water droplet at the end of the first phase of spreading on 8 hour grown ZnO nanocoated surface, S2

The droplet spreading does not stop here, but rather continues outwards in a second phase of spreading, creating a sombrero effect as described in the previous literature [7]. As it continues to spread, there is a departure from this strict contact line shown in Fig.8 as liquid spreads within the zinc oxide nanostructure, past the contact line from Fig.8. This sombrero effect is shown in Fig.9 and was characterized by the continued spread of water within the surface coating, while the contact line of the above-surface droplet remained fixed.

Our high speed camera study found that the transition from this first phase of wetting, to this second somberero phase occurred very early on when the droplet was approximately 10% of the way to its final steady state wetted position. This early departure into the second phase of wetting is beneficial for heat transfer because it also signals a transition to the growth of ultra thin films around the perimeter of the droplet. As the liquid spreads outward, pushing out the solid-liquid contact line, within a micro-layer structure, the liquid-solid-air contact line stays fixed. Knowing the volume of the droplet, we can calculate the heat transfer benefits of this by first imaging and measuring the



FIGURE 9. Water droplet in its final sessile state after impinging on the 8 hour baked ZnO nanocoated surface, S2

dimensions of the microstructures created by growing zinc oxide nanoparticles on the aluminum substrate.

HEAT TRANSFER BENEFITS FOR NANOSTRUCTURED ALUMINUM SURFACE

The surface with the highest wettability based on experimental testing was surface 2 (S2). Using this surface, the heat transfer performance of ZnO nanostructured aluminum surfaces was quantified in two ways. First, evaporation time was measured through a series of experimental tests. These results were then used to calculate heat transfer coefficient using a simple thermodynamic model. Evaporation of the droplets on these new superhydrophilic aluminum surfaces was taken for a variety of superheats and compared to previously collected data for droplet evaporation for nanocoated copper surfaces [1].

Drop volumes for the data shown in Fig.10 are all for $2\mu l$ droplets (1.56mm diameter) of water deposited on the different heated surfaces from drop heights of less than 5mm. The general observed trend of decreasing evaporation time with increased superheat is to be expected. Droplets on the ZnO coated aluminum show equal or, in some cases, faster evaporation time than the similarly ZnO coated copper counterparts. For both copper and aluminum, the nanostructured surfaces are significantly better at quickly evaporating droplets than the bare aluminum and copper samples. Particularly with the higher



FIGURE 10. The time for complete evaporation for a 2μ l droplet on ZnO nanostructure copper hydrophilic surfaces [Surface S2] [1] compared to the time for evaporation of the same size droplet on ZnO coated aluminum surfaces.

superheats of 20° +, the coated surface also provided suppression of nucleate boiling. While high speed video showed rippling and disturbance on the surface of the droplet, no bubbles formed or broke on the surface even at these higher superheats. This was different than the bare copper and aluminum, which demonstrated full nucleate boiling for all experiments past 18° superheat.

Data shown in Fig.10 was further used to validate a computational thermodynamic model to calculate evaporation time. This calculation of time for complete evaporation, t_{ce} , discussed in detail in earlier literature for ZnO copper nanostructured surfaces [7], is a function of the wetting number from Eq. 1 and is shown in Eq. 2.

$$t_{ce} = \frac{A_{tot}}{N_w^3} \cdot \frac{2\gamma}{3\pi} \cdot \frac{\rho h_{lv}}{k_l \cdot \Delta T}$$
(2)

In Eq.2, the A_{tot} is the complete wetted area for a sessile droplet in adiabatic conditions and γ is a constant that is set to 1, but can be adjusted based on matching experimental data. The correlation between experimental results and evaporation times from Eq.2 are shown in Fig.11.

The experimental data and the calculated data for time of complete evaporation correlated linearly for $\gamma = 1$ in Eq.2. For both ZnO nanostructured copper and aluminum, the correlation produces an estimate for evaporation that could reasonably be plugged into a heat transfer coefficient calculation to determine heat transfer performance for these superhydrophilic surfaces. The assumptions for this model are that there is no nucleation happening on the surface. Because of the enhancement provided by the ZnO coating, nucleation is generally suppressed at temperatures where it would normally be occurring for a bare metal



FIGURE 11. Comparison of the experimental versus the calculated complete evaporation time for ZnO nanostructured copper and aluminum surfaces [Surface S2]

surface. This allows for enhanced, non-nucleating evaporative heat transfer at the periphery of the droplet where the liquid is thinnest.

Enhanced Heat Transfer Coefficients

The heat transfer coefficient, h, for these aluminum surfaces was determined based on the experimental time of complete evaporation and a mean thickness, th, calculated from the wetted area and the volume of the droplet. Equation 3 is the simple thermodynamic model for calculating this heat transfer coefficient.

$$h = \frac{\rho \cdot th \cdot h_{lv}}{\Delta T \cdot t_{ce}} \tag{3}$$

For Eq. 3, the density and latent heat values are for water as a liquid, since these tests were run without liquid nucleation in the droplet. The resulting values of the heat transfer coefficient on the nanostructured aluminum surface were compared to calculated values from nanostructured surface evaporation times and are shown in Fig.12

The enhancement in the heat transfer coefficient, as a result of decreased evaporation time compared to bare metal surfaces is a direct result of the reduced thickness of droplets on the surface. An average liquid thickness of the droplets can be back-calculated from the volume and spread area of the droplets on nanostructured and bare metal surfaces. Figure 13 shows how dramatically this mean thickness changes for two different surface types.

The mean thickness of water droplets on the ZnO nanostructured surfaces are, in the case aluminum, one fifth of the mean thickness of the bare aluminum droplet. Based on the calculations in Eq. 3, this will result in a heat transfer coefficient



FIGURE 12. The calculated heat transfer coefficient for nanostructured copper surfaces and nanostructured aluminum surfaces. Both show heat transfer coefficients well above a typical plain copper or aluminum surface.[Surface S2]



FIGURE 13. Calculated mean thickness of liquid layer for water droplet droplet on ZnO nanostructured and bare metal surfaces for both copper and aluminum

that is larger because as mean thickness decreases, the time of evaporation also decreases at a much greater rate (shown by the wetting number in Eq. 2).

The accuracy and error for experimental measurements of this kind is particularly important as small changes in surface wettability can lead to great changes in heat transfer performance. For this study, the accuracy of measurements for evaporation time and heat transfer coefficients are a function of the thermocouples used for temperature measurement. These were accurate to 0.5°C. Therefore, error for the evaporation time and the heat transfer coefficient ranges from 2.5% to 5% for 10° and 20° superheats respectively.

MODELING THE IMPORTANCE OF REGULAR VERSUS IRREGULAR SPREADING

For these advanced hydrophilic surfaces, it is useful to put together models that can better predict the performance characteristics of these surfaces. In the case of comparing copper and aluminum nanostructured surfaces, one of the defining differences in the ZnO growth patterns was the homogeneity of the surface morphology under the SEM microscope. As droplets spread on surfaces that have nonhomogeneous growth of pillar like nanostructures, the contact line deviated from a radially symmetric growth pattern. This increased the overall length of the contact line and we believe this could enhance heat transfer. These different spreading patterns on the macroscale can be seen in Fig.14. Observing in this figure the difference between the smooth contact line for the copper surface and the more jagged line for the aluminum, there is a clear difference in their spreading symmetry. The aluminum surfaces, which tended to have microscale morphology that was less homogeneous, displayed spreading patterns that are less symmetric, while symmetric radial spreading was observed for copper coated surfaces with more consistent surface morphology. The SEM image of Surface S2 shown in Fig.14 differs from that of the S2 SEM image shown in Fig.4. This is an example of the nonhomogeneity in the aluminum coated surface. When droplets were deposited on certain sections of the sample surface, they spread more symmetrically, while in some spots they spread in non-symmetric ways (shown in Fig.9). Droplets deposited on S2, in general, demonstrated more symmetric spreading which is believed to be a result of consistent pillar formationl, like that shown in Fig.4. However, there were portions of the surface on S2 with nanoscale morphology like that shown in Fig.14. It is parts of the surface like this that still demonstrated extreme wettability, but had less symmetric spreading capabilities. In general, the less symmetric spreading areas had a higher instance of the sombrero effect.

Looking at the copper surface shown in Fig.14, there was complete coverage of pillar-like structures visible in the SEM imagery. In contrast, the aluminum surfaces, specifically the latter surfaces S3 and S4 displayed as low as 20% coverage with pillar-like structures. This noticeable difference resulted in changes in wettability, but still maintained heat transfer performance equal to, and at times better than the copper coated surfaces. For Surface S2, there was approximately 80% coverage of the pillar formations. The other 20% demonstrated less symmetric wetting for deposited droplets. There is further investigation needed as to the effect of surface irregularity and the resulting non-radial spreading of droplets on the surface.

The initial work focusing on this irregularity is done through modeling the wetting, spreading, and final spread area and profile of a droplet on a superhydrophilic nanostructured surface. In doing this, comparisons can be drawn as to the correlation between



FIGURE 14. Comparison of regular versus irregular spreading for a copper and an aluminum surface and the related SEM morphology that affects this spreading pattern. Contact line segmentation from python coding program also shown.

wetting characteristics and microscale surface morphology. The spread areas shown in Fig.14 demonstrate the difference in spreading area for a droplet of $2\mu l$ on two different surfaces, which in turn greatly affects the thickness of the droplet. The copper droplet pictured in Fig.14 has a wetted footprint area of 14mm² while the droplet on the aluminum nanostructured surface is nearly 8 times that at 89mm². This affects the heat transfer coefficient, noted in Fig.12. For low superheats, when evaporation does not include nucleation, the superheat does not effect the heat transfer coefficient, and it can be seen that several of the surfaces with nanostructures on aluminum have heat transfer coefficients that rival the copper surfaces. Further study into the evaporative benefits of the irregular spread areas is being explored. It is expected that since the perimeter around the droplet that is represented by the contact line is the area where the droplet is thinnest, it would likely be where the highest heat transfer can be achieved. Continued testing will be able to reveal whether this tendency on nanostructured aluminum surfaces towards irregular spreading is the variable that causes any heat transfer advantage.

CONCLUDING REMARKS

The Zinc Oxide nanostructures created in this study are seen as the first attempt to reproduce the successful creation of superhydrophilic surfaces from ZnO nanoparticles on copper substrates. Using aluminum as a substrate for these nanostructures promises an advantage over copper both in its manufacturability and cheaper cost. Additionally, the hydrothermal synthesis growth method of producing these superhydrophilic nanostructures is a scalable technique that offers the potential for coating large scale heat exchangers and greatly enhance heat transfer from their surfaces through liquid film evaporation.

The nanostructure coated aluminum surfaces in this study were found to have less homogeneous surfaces when viewed under SEM imagery than the copper surfaces with the same ZnO coating. The reason for this difference between copper and aluminum is hypothesized to be the result of aluminum oxide development on the surface, thus conflicting with the growth of the ZnO nano particles, as well as altering the chemical makeup of the surface. Further work with aluminum will include efforts to avoid the pollution of aluminum oxide. Regardless, the result of this non-homogeneity on the surface was a nonradial spreading of droplets on the aluminum surfaces. This did not have a negative consequence, however, on the heat transfer performance. The ZnO nanostructure coated aluminum surface still facilitated rapid droplet spread, sombrero effect, and very high heat transfer coefficients of over 20kW/m², up to 3 times higher than bare aluminum.

Further computation analysis can also help with the understanding of heat transfer enhancement for superhydrophilic surfaces, particularly modeling the outer thinnest regions of the droplet contact area. This can be further studied to develop robust heat transfer modeling for these unique nanostructured aluminum surfaces. The ultimate goal is to have robust, experimentally reinforced computational model for the heat transfer performance on superhydrophilic surfaces. This will allow for quicker manufacturing iterations and, ultimately, higher performing surfaces.

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