## IMECE2017-72679

### TUNING SUPERHYDROPHILIC NANOSTRUCTURED SURFACES TO MAXIMIZE WATER DROPLET EVAPORATION HEAT TRANSFER PERFORMANCE

Claire K. Wemp and Van P. Carey University of California Berkeley, CA, USA

#### ABSTRACT

Spraving water droplets on air fin surfaces is often used to augment performance of air-cooled Rankine power plant condensers and wet cooling tower heat exchangers for building air-conditioning systems. To get the best performance in such processes, the water droplets delivered to the surface should spread rapidly into an extensive, thin film and evaporate with no liquid leaving the surface due to recoil or splashing. This paper presents predictions of theoretical/computational modeling and results of experimental studies of droplet spreading on thin-layer, nanostructured, superhydrophilic surfaces that exhibit very high wicking rates (wickability) in the porous layer. Analysis of the experimental data in the model framework illuminates the key aspects of the physics of the droplet spreading process and evaporation heat transfer. This analysis also predicts the dependence of droplet spreading characteristics on the nanoporous surface morphology and other system parameters. The combined results of this investigation indicate specific key strategies for design and fabrication of surface coatings that will maximize the heat transfer performance for droplet evaporation on heat exchanger surfaces. The implications regarding wickability effects on pool boiling processes are also discussed.

#### NOMENCLATURE

- b = nanostructured layer height
- r = radial distance from center of droplet
- $r_d$  = upper droplet radius
- $r_{nl}$  = mean interface radius of liquid-vapor interface in nanostructured layer
- $P_a$  = ambient atmospheric pressure
- $P_d$  = pressure inside upper droplet
- $\Delta P_{cap}$  = nanolayer capillary pressure difference
- $\varepsilon = \text{porosity}$
- $\kappa$  = permeability

- $\phi_s$  = solid fraction at top surface of nanostructured layer
- $\theta_{ann}$  = apparent contact angle
- $\theta_{\rm F}$  = intrinsic contact angle

#### INTRODUCTION

Numerous recent investigations have examined the use of nanostructured surfaces to enhance features of water boiling or liquid water evaporation processes. Since prior research has shown that increasing surface wetting by the liquid generally improves boiling performance, it is not surprising that use of nanostructured hydrophilic surfaces has frequently been proposed as a means of enhancing nucleate boiling heat transfer and critical heat flux for pool boiling [1-16], suppressing wall dryout in flow boiling [17], and enhancing droplet spread and evaporation heat transfer in water spray cooling [18,19]. The use of superhydrophilic nanostructured surfaces would appear to offer the promise that substantial enhancement of water pool and liquid evaporation boiling processes, since superhydrophilic surface structures of this type have been found to exhibit rapid spreading of liquid over an initially dry surface [7,8,18]. Recent studies [18,19] have shown, for example, that surfaces of this type can quickly transition a millimeter-sized droplet to a liquid film on the surface only about 100 µm thick. The subsequent rapid transfer of heat form the surface across the film to the interface, results in rapid evaporation and a very high heat transfer coefficient over the footprint of the droplet.

Recent studies by Rahman, et al. [7] and Kim, et al [8] have used a wickability parameter to quantify the tendency for superhydrophilic micro- or nano-structured surfaces to exhibit rapid spreading of liquid over an initially dry surface. Rahman, et al. [7] proposed a simple way of measuring an appropriately defined wickability for micro and nano structured surfaces. The results of these investigations [7,8] indicate that augmentation of critical heat flux in boiling processes

correlates with the magnitude of the wicking parameter for a variety of micro and nano structured surface morphologies.

The prior work described above has demonstrated that use of hydrophilic, strongly-wicking, nanostructured surfaces can enhance water vaporization heat transfer processes. However, this raises the question: how should nanostructured surfaces be designed to maximize the benefits of a high wickablity surface layer? In the study summarized here, we explored this question using a droplet spreading model developed in tandem with our experimental studies of droplet spreading on nanostructured surfaces. The model is used here as a means to predict how changes in the morphology of the nanoporous layer affect the spreading mechanisms and heat transfer process during water droplet evaporation.

As will be discussed below, the model used here was specifically developed for droplet spreading in ultra-thin nanostructured layers on metal substrates that generate high capillary forces and exhibit low to moderate permeability. In this regard, this investigation differs from earlier studies that have considered liquid spreading on deep porous layers or microstructured surface morphologies larger (e.g., [7,20,21,22]). In addition, we specifically focused on nonordered, nanostructured surfaces that can be thermally grown on metal substrates because this type of process is scalable and adaptable to complex substrates, making it an ideal approach to putting nanostructured, superhydrophilic coatings on heat exchanger surfaces.

In the next two sections, the theoretical framework of the droplet spreading model is described and its predictions are compared with experimental observations and data. The discussion in those sections demonstrates the connection between the nanoporous layer morphology and the speed and extent of liquid spreading, which strongly impact evaporation heat transfer. A subsequent section of this paper explores the predicted parametric effects of nanostructure morphology changes on wickability, spreading, and associated phase-change heat transfer processes.

#### MODEL FORMULATION

Previous studies have developed models for spreading of droplets on flat solid surfaces [23] and on the surface of a thick porous medium [22,24-26]. Here we are specifically interested in low Weber number deposition and spreading of a droplet on a specific category of ultrathin, nanostructured, superhydrophilic layers on a metal substrate which exhibits the following key features that cause the spreading to differ from droplet spreading on either a solid flat surface or a thick porous medium:

(1) The nanostructure has large capillary pressure difference across the interface at the ultra small pores of the structure.

(2) The thickness of the nanostructured layer is very small, and therefore transport across the structure is very fast compared to radial transport of liquid.

(3) The superhydrophilic nature of these surfaces make hemispreading [27] possible (hemi-spreading being a phenomenon in which the leading edge of liquid infusion into the porous nanostructure separates and proceeds beyond the contact line of the upper droplet).

The nanostructure surface features listed above are of central interest here because they were characteristics observed experimentally for superhydrophilic ZnO nanostructured surfaces studied by Ruiz, et al. [17] and Padilla and Carey [18], and they are expected to be representative of the behavior for other similar superhydrophilic nanostructured surfaces. Previous studies of droplet spread on surfaces mentioned above have not considered this specific type of surface (e.g., [7,20,21,22]).

#### Early Time Synchronous Spreading Process

Figure 1a depicts the initial contact of a droplet deposited on a thin nanostructured surface at time t = 0. Because the layer is thin, the time required for the liquid to wick across the thin nanoporous layer  $t_p$  is very small (see Fig. 1b). Liquid then wicks radially outward (Fig. 1c) in the nanostructured layer while the droplet above spreads radially. During this first stage of the spreading process, the droplet contact line is postulated to stay within the leading edge of the nanoporous layer filled with liquid. This postulated synchronized spreading of the upper droplet and the liquid wicking in the porous layer appears justifiable for two reasons:

(1) Transfer of the contact line to a higher contact angle dry region would force the interface to at least temporarily become more convex near the contact line, which is expected to increase the pressure in the liquid there (due to capillary effects across the interface), moving liquid away from that location and thus slowing the spread.

(2) Observation of experiments for these conditions indicates that the contact line does tend to stay within the liquid filled portion of the nanoporous layer for conditions of interest here.

As indicated in Figures 1d and 1e, spreading of the liquid droplet continues until the contact angle and interface radius of curvature of the droplet adjusts to be consistent with the total volume of liquid in the droplet and to minimize the free energy of the system. The surface under the droplet is effectively a composite surface comprised of solid fraction  $\phi_s$ , wetted at intrinsic contact angle  $\theta_E$ , and liquid regions (fraction  $1-\phi_s$ ), effectively wetted at zero contact angle. The Cassie-Baxter [28] composite surface wetting model suggests that the resulting equilibrium apparent contact angle  $\theta_{aop}$  is given by

$$\cos\theta_{app} = \phi_s \cos\theta_E - (1 - \phi_s) \tag{1}$$

Since departure from this equilibrium increases system free energy, it is expected that the droplet resists leaving that state one it has achieved it. The model analysis developed here adopts the hypothesis that in the synchronous stage of droplet





Figure 1. Droplet spreading process.

spreading, the upper droplet responds as if it is spreading on a composite surface, a mosaic of dry solid surface and fullywetted liquid surface. The upper droplet stops expanding when it reaches the footprint radius  $R_s$  that corresponds to a spherical cap having the volume of the original deposited droplet and the apparent contact angle  $\theta_{app}$  for the composite liquid and solid surface. For a droplet with initial volume  $V_{d0}$ , the spherical cap droplet geometry with apparent contact angle  $\theta_{app}$  dictates that the equilibrium footprint radius, which corresponds to  $R_s$ in our model, must equal

$$R_{s} = \left[\frac{3V_{d0}}{\pi(2 - 3\cos\theta_{app} + \cos^{3}\theta_{app})}\right]^{1/3} \sin\theta_{app}$$
(2)

If the nanoporous layer is permeable enough and the capillary pressure for the layer is high enough, the region of the porous layer that is filled with liquid will continue to expand beyond the contact line of the droplet. As discussed above, this circumstance, depicted in Fig. 1e, is referred to as hemispreading [27].

The spreading sequence depicted in Fig. 1 is consistent with that observed on thin nanostructured layers on metal substrates we tested. Postulated behavior for the model developed here is based on such experimental observations. A basic premise adopted here is that the flow in the nanoporous layer is driven by a pressure field that is determined from a basic transport equation. The proposed model postulates that:

(i) The droplet exhibits axisymmetric spreading, although spreading of real droplets may deviate significantly from such symmetry. Spreading in our experimental studies typically is close to radially symmetric, with stronger deviation in the later stages. Also, the transport is idealized as being quasi-steady in the following sense: It is postulated that at a given spread radius, a pressure field is established which is equivalent to that for steady transport of liquid to the outer perimeter of the liquid filled region of the porous layer. As the spread radius increases, the pressure field is presumed to adjust rapidly to velocity and mass flow changes to sustain the equilibrium pressure field, and once the pressure field is known, the resulting flow quantities and motion of the liquid can be computed from it.

(ii) When the droplet first touches the structured surface, the capillary pressure difference draws liquid first across the thickness of the thin nanoporous layer, which takes a very short time,  $t_p$ .

(iii) Capillary pressure in the layer then drives liquid flow radially in the porous layer.

(iv) The upper droplet spreads over the portion of the layer already filled with liquid. The apparent contact angle on this composite surface is less than that for the liquid on the dry surface. The contact angle would have to increase for droplet contact line to move beyond the radial extent of the liquidoccupied portion of the nanoporous layer. The resulting change in curvature would produce a local rise in liquid pressure that would drive liquid away from the contact line. This tends to resist the contact line extending beyond the leading edge of the liquid filled nanostructured layer. It is expected, however, that the contact line could move beyond it if the droplet fluid momentum and/or stagnation pressure are large enough.

(v) Based on the argument in (iv), the upper droplet can be expected initially to spread within the confines of the liquid saturated portion of the nanostructured layer below, for low impingement velocities and Weber numbers.

To model the spreading liquid within the nanostructured layer, we considered it to be flow in a porous medium that obeys Darcy's Law, indicating that the Darcy velocities in the r and z direction are

$$v_r = -\frac{\kappa}{\mu_l} \left( \frac{\partial P}{\partial r} \right), \quad v_z = -\frac{\kappa}{\mu_l} \left( \frac{\partial P}{\partial z} \right)$$
(3)

and for radial flow in a porous nanostructured layer of thickness *b*:

$$\dot{m}_{r} = -\frac{(2\pi rb)\kappa}{v_{l}} \left(\frac{\partial P}{\partial r}\right)$$
(4)

Here, we do not invoke modifications similar to Brinkman's [29] model to account for possible inertia term effects because we are specifically interested in nanoporous low-permeability structures in which inertia effects are expected to be negligible. The flow under the droplet can be modeled as 2-D flow in the porous layer with appropriate pressure boundary conditions. However, for reasons discussed below, a 1-D model was adopted here, which is consistent with the physics and is more straightforward to handle mathematically.

For an annular control volume of liquid completely filling the nanostructured layer under the droplet, if the pressure field is unchanging with time, the conservation of mass requirement in the control volume can be stated as

$$\frac{1}{r}\frac{d}{dr}\left(r\left(\frac{d\bar{P}}{dr}\right)\right) - \frac{2}{b^2}\left(\bar{P} - P_d\right) = 0$$
(5)

In this 1-D model,  $\overline{P}$  is the mean pressure in the porous layer at location r, and the first term on the left represents the difference in radial Darcy flow across the control volume. The second term on the left represents Darcy flow from the upper droplet into the porous medium driven by the difference between the local pressure in the medium  $\overline{P}$  and the droplet internal pressure  $P_d$ . This flow travels a mean difference b/2into the porous nanostructured layer. The left side of Eq. (5) can be reorganized by executing the differentiation to yield

$$\frac{d^2\overline{P}}{dr^2} + \left(\frac{1}{r}\right)\frac{d\overline{P}}{dr} - \frac{2}{b^2}\left(\overline{P} - P_d\right) = 0 \tag{6}$$

To predict the pressure distribution, this equation must be solved with appropriate boundary conditions. Physically, it is clear that the following conditions must hold:

$$\frac{dP}{dr} = 0 \text{ at } r = 0, \tag{7a}$$

$$\overline{P} = P_a - \Delta P_{cap} \text{ at } r = R \tag{7b}$$

In a typical situation of interest here, r values and R (the spread extent of the droplet) are on the order of a centimeter or two (~0.02 m), whereas the thickness of the nanostructured layer is several orders of magnitude thinner, with  $b \sim 1 \mu m$ . Because the nanostructured layer is so thin, the mass transport due to pressure differences between the droplet and the layer pores will be very fast, and the liquid in the pores will quickly establish pressure equilibrium with the droplet interior. This indicates that two different solutions of the above equation exist in two different region of the porous layer. In the equilibrium layer far from the contact line of the upper droplet (r << R), the solution is simply  $\overline{P} = P_d$ . In the region close to r = R,  $\overline{P}$  will vary between  $\overline{P} = P_d$  and the value specified by condition (7b):  $\overline{P} = P_a - \Delta P_{cap}$  at r = R. This is depicted in Fig. 2.



Figure 2. Synchronous spreading regions.

Note that this implies that the new fluid added to the nanostructured layer comes primarily from the region of the upper droplet near the contact line.

To solve for the pressure field in the outer near-contactline region, we define

$$\vec{P} = P_d - \vec{P} . \tag{8}$$

$$\vec{r} = \frac{R - r}{b} \tag{9}$$

Using the above relations and the basic rules of differentiation to reorganize in terms of  $\breve{P}$  and  $\breve{r}$ , Eq. (6) converts to

$$\frac{d^{2}\breve{P}}{d\breve{r}^{2}} - \left(\frac{b/R}{1 - b\breve{r}/R}\right)\frac{d\breve{P}}{d\breve{r}} - 2\breve{P} = 0$$
(10)

Since here  $b/R \ll 1$ , the second term is neglected, reducing the equation to

$$\frac{d^2 P}{d\tilde{r}^2} - 2\tilde{P} = 0 \tag{11}$$

The boundary conditions are dictated by matching the inner solution ( $\breve{P} = P_d - \overline{P} = 0$ ) as  $\hat{r} \rightarrow \infty$ , and matching boundary condition (7b). In terms of  $\hat{r}$  and  $\breve{P}$  these become:

at 
$$\breve{r} = 0$$
:  $\breve{P} = P_d + \Delta P_{cap} - P_a$  (12a)

as 
$$\breve{r} \to \infty$$
:  $\breve{P} = 0$  (12b)

It is straightforward to show that the solution of Eq. (11) with boundary conditions (12a&b) is

$$\vec{P} = (P_d + \Delta P_{cap} - P_a)e^{-\sqrt{2}\bar{r}}$$
(13)

For water droplets on the order of 1 mm in radius, the capillary pressure difference across the interface is small compared to atmospheric pressure so  $P_d \cong P_a$ . Neglecting the difference and taking  $P_d = P_a$ , and reorganizing in terms of physical variables, Eq. (13) reduces to

$$P_d - \overline{P} = \Delta P_{cap} e^{-\sqrt{2}(R-r)/b}$$
(14)

Using the mean pressure distribution predicted for the nanoporous layer, the mass flow rate delivered to the outer edge of the liquid-filled layer is computed from the Darcy relations (3) for 1-D flow evaluated at r = R:

$$\dot{m}_{R} = -\left[\frac{(2\pi rb)\kappa}{\nu_{l}} \left(\frac{d\bar{P}}{dr}\right)\right]_{r=R}$$
(15)

Differentiating (14) to get the pressure derivative, substituting into (15) and setting r = R yields

$$\dot{m}_{R} = \frac{2\pi\sqrt{2}R\kappa\Delta P_{cap}}{v_{l}}$$
(16)

The rate of mass delivery to r = R must equal the mass growth rate of the liquid in the nanostructured layer:

$$\dot{m}_{R} = \frac{d}{dt} \left( \pi R^{2} b \varepsilon \rho_{l} \right) = 2 \pi R b \varepsilon \rho_{l} \frac{dR}{dt}$$
(17)

where  $\varepsilon$  is the porosity of the layer. Equating the right sides of Eqs. (16) and (17) and solving for dR/dt yields

$$\frac{dR}{dt} = \frac{\sqrt{2\kappa\Delta P_{cap}}}{b\epsilon\rho_{i}\nu_{i}}$$
(18)

Integrating the above equation yields

$$\int_{b}^{R} dR = \int_{t_{p}}^{t} \frac{\sqrt{2\kappa\Delta P_{cap}}}{b\varepsilon\rho_{l}v_{l}} dt$$

$$R = b + \frac{\sqrt{2\kappa\Delta P_{cap}}}{b\varepsilon\rho_{l}v_{l}} \left(t - t_{p}\right)$$
(19)

Since  $b \ll R$  and  $t \gg t_p$  for most conditions of interest, the result can be simplified by neglecting *b* and  $t_p$ :

$$R = \frac{\sqrt{2\kappa\Delta P_{cap}}}{b\epsilon\rho_l v_l} t \tag{20}$$

Thus, the model predicts a linear variation of R with t for the initial synchronous stage of the spreading process with the droplet contact line closely following the edge of the liquid filled nanoporous layer under the droplet.

This model also predicts the variation of the mass flux from the droplet to the nanostructured layer. Considering an annular differential surface with area  $2\pi r dr$  at the top of the nanostructured layer (z = b), Darcy's law, as used here, requires that the radial mass flow rate at any r location is given by

$$\dot{m}_r = -\frac{(2\pi rb)\kappa}{\nu_l} \left(\frac{d\overline{P}}{dr}\right)$$
(21)

Using Eq. (14) to evaluate  $d\overline{P}/dr$  yields

$$\dot{m}_r = -\frac{2\pi\sqrt{2\kappa}}{v_l} r e^{-\sqrt{2}(R-r)/b}$$
(22)

If  $m_{z=b}''$  is the mass flux of liquid through the annular differential surface at radial location *r* through area  $2\pi r dr$ , conservation of mass in the layer requires that

$$\dot{m}_{z=b}^{\prime\prime}(2\pi r dr) = (d\dot{m}_r / dr)dr$$
<sup>(23)</sup>

which simplifies to

$$\dot{m}_{z=b}'' = \frac{1}{2\pi r} \left( \frac{d\dot{m}_r}{dr} \right) \tag{24}$$

Differentiating Eq. (22) to evaluate the derivative in (24), and neglecting terms of order b/R compared to terms of order r/R, Eq. (24) converts to the form

$$\dot{m}_{z=b}^{\prime\prime} = -\frac{2\kappa\Delta P_{cap}}{v_l b} e^{-\sqrt{2}(R-r)/b}$$
(25)

This 1-D relation, plotted in dimensionless form in Fig. 3, predicts that the flux of liquid into the layer is zero except in the region close to the contact line (R-r < 3b).

As noted above, the flow in the nanoporous layer can also be modeled as 2-D Darcy flow by solving the Laplace equation for the pressure field with pressure boundary conditions  $P = P_a - \Delta P_{cap}$  at r = R,  $P = P_d$  at z = b, and  $\partial P / \partial r = 0$  at r =0, and at z = 0. The solution for the pressure field can be obtained using separation of variables. Taking  $P_d \cong P_a$ , and using Darcy's law with the resulting pressure field relation, the variation of the mass flux at the interface between the upper droplet and the nanoporous layer (z = b) is determined to be

$$\dot{m}_{z=b}'' = -\left(\frac{2\Delta P_{cap}\kappa}{\nu_{b}b}\right) \frac{e^{-\pi(R-r)/2b}}{1 - e^{-\pi(R-r)/b}}$$
(26)

This predicted variation of the mass flux into the layer is also plotted in Fig. 3. It can be seen in Fig. 3 that the 2-D Darcy flow model and the 1-D model are virtually identical away from the contact line region. However, the 2-D Darcy solution predicts that the mass flux from the droplet into the layer increases without bound as  $r \rightarrow R$ . This singularity is a consequence of the discontinuity in the pressure boundary condition at the contact line location (r,z) = (R,b) and can be similarly seen in the analogous heat transfer problem (see the discussion in Gebhart [30]). Here, the discontinuous boundary pressure and the resulting infinite mass flux are not expected to be accurate predictions for a real system. The 1-D model therefore appears to be a better representation of the physics for this system, predicting a linear variation of R with time for the initial synchronous stage of the spreading process.



**Figure 3.** Dimensionless mass flux variation at the droplet/layer boundary.

#### Modeling of Hemi-Spreading

As discussed above, thermodynamic analysis of the upper droplet suggests that the linear variation of R with t will continue until the upper droplet contact line reaches the spread radius and apparent contact angle that minimizes its free energy. Further spreading of the upper droplet beyond that point is not thermodynamically favored. We therefore model the upper droplet as stopping its spread at the radius where it minimizes its free energy and achieves its equilibrium apparent contact angle. However, growth of the liquid-filled region of the porous layer can continue beyond that point, leading to a hemi-spreading process.

Here, the wicking spread of liquid in the porous layer beyond the upper droplet contact line is modeled in the same quasi-static manner as for the porous region flow under the droplet. As depicted in Fig. 4, flow in the porous layer beyond the droplet is driven by the difference in pressure between the edge of the upper droplet and the capillary reduced pressure at the edge of the growing liquid filled porous layer. Liquid enters the extended portion of the liquid filled layer near the droplet contact line and as additional mass is added to the extended region of liquid-filled nanoporous layer, the extended region grows. The governing equation for this process is the Darcy transport equation discussed above with only the term that represents Darcy transport in the radial direction.



Figure 4. Droplet feeding hemi-spreading.

Equation (27) is solved in the extended region of the nanoporous layer filled with liquid from the contact line of the droplet to the furthest extent of the liquid filled region in the nanoporous layer (from  $R_s$  to R in Fig. 4). The pressure boundary conditions are:

at 
$$r = R_s$$
:  $P = P_d$  (28a)

at 
$$r = R$$
:  $P = P_a - \Delta P_{cap}$  (28b)

Here again we take  $P_a \cong P_d$ . The solution to Eq. (27) for the pressure field satisfying the boundary conditions (28a&b) is

$$P - P_d = -\Delta P_{cap} \frac{\ln(r/R_s)}{\ln(R/R_s)}$$
(29)

Darcy's law (3) dictates that, given this pressure field, the mass flow rate at r = R is

$$\dot{m}_{R} = \left(\frac{(2\pi b)\kappa}{\nu_{l}}\right) \frac{\Delta P_{cap}}{\ln(R/R_{s})}$$
(30)

and since the rate of mass delivery to r = R must equal the mass growth rate of the liquid in the nanostructured layer as specified from the conservation of mass relation (17), equating the rights sides of Eqs. (30) and (17) yields

$$2\pi Rb\varepsilon\rho_l \frac{dR}{dt} = \left(\frac{2\pi b\kappa}{\nu_l}\right) \frac{\Delta P_{cap}}{\ln(R/R_s)}$$
(31)

Separating variables, and integrating this differential equation from  $(t_s, R_s)$  to (t, R) yields the following implicit relation for R(t) in the hemi-spreading regime

$$\frac{R^2}{2}\ln(R/R_s) - \frac{1}{4}\left(R^2 - R_s^2\right) = \left[\frac{\kappa\Delta P_{cap}}{\varepsilon\rho_l v_l}\right](t - t_s)$$
(32)

The net outcome of this model analysis is the prediction that there are two regimes in the spreading process:

$$R = \left(\frac{\sqrt{2}\kappa\Delta P_{cap}}{b\epsilon\rho_l v_l}\right)t \qquad \text{for } R \le R_s \quad (33a)$$

$$\frac{R^2}{2}\ln(R/R_s) - \frac{1}{4}\left(R^2 - R_s^2\right) = \left[\frac{\kappa\Delta P_{cap}}{\varepsilon\rho_l v_l}\right](t - t_s) \text{ for } R > R_s \quad (33b)$$

Note that in Eq. (33a), factor in parentheses multiplying t is the characteristic velocity associated with the spread of the upper droplet liquid over the surface. In that sense it can be defined as the wickability  $\omega^*$  for this process

$$\omega^* = \frac{\sqrt{2\kappa\Delta P_{cap}}}{b\varepsilon\rho_i v_i} \tag{34}$$

Note here that the transition occurs at  $R = R_s$ , where  $R_s$  is the equilibrium radius for a spherical cap with contact angle  $\theta_{app}$  (on the liquid filled nanostructured layer) having the same volume as the spherical deposited droplet. As argued above, separation of the surface layer liquid penetration from the upper droplet contact line is postulated to occur approximately at  $R = R_s$ . The spreading curve relations (33a&b) can also be cast in non-dimensional form by normalizing R and t with  $R_s$  and  $t_s$ 

$$\hat{t} = t/t_s, \quad \hat{R} = R/R_s \tag{35}$$

Substituting into Eqs. (33a&b) and using the fact that Eq. (33a) requires that  $R_s = (\sqrt{2}\kappa\Delta P_{cap} / b\epsilon \rho_i v_i) t_s$ , yields

$$\hat{R} = \hat{t} \quad \text{for } \hat{R} \le 1$$
(36a)  
$$\frac{\hat{R}^2}{2} \ln(\hat{R}) - \frac{1}{4} \left( \hat{R}^2 - 1 \right) = \left( \frac{b}{R_s} \right) \frac{\hat{t} - 1}{\sqrt{2}} \quad \text{for } \hat{R} > 1$$
(36b)

Note that this condenses the spreading relations into a universal curve for the synchronous early spreading regime and a collection of curves for different  $b/R_s$  ratios in the hemispreading regime. An obvious question at this point is: does spreading of water droplets on a thin, nanostructured, superhydrophilic layer on a solid substrate exhibit behavior consistent with this predicted two-regime model? Results of spreading experiments are used to explore this question in the next section.

# COMPARISON OF MODEL PREDICTIONS WITH EXPERIMENTAL DATA

To assess the model described in the previous section, we conducted droplet deposition experiments in which a water droplet was deposited on a thin ZnO nanostructured surface on a copper substrate. The development of this surface uses a process known as hydrothermal synthesis. This process is described below and in more detail in Padilla [31] and Padilla and Carey [18]:

(i) Surface preparation involves: polishing the copper surface to achieve near-uniformity in surface smoothness and cleaning the copper surface using a sonication bath.

(ii) ZnO nanoparticles measuring 6nm in diameter are evenly

deposited on the clean surface and this is annealed in a dry oven at 150-160°C.

(iii) Once annealed, the surface is cooled and submerged, coated side facing down, in a liquid growth solution (details in [18,31]) and placed in a 90°C oven for 8 hours.

(iv) Once removed and cooled, the surface is desorbed on a heating plate at 275°C for an hour to get rid of any liquid or substances adsorbed on to the surface.

An electron microscope image of the resulting surface morphology is shown in Fig. 5. The desorption process was repeated prior to all experimental tests in order desorb any adsorbed molecular species on the surface between experiments. Each time we do this pre-experiment prep, the resulting surface's intrinsic wetting can vary slightly, so we treat the surface after being prepped this way as a distinct surface. In our results we refer to a "prep 1" and "prep 2" surfaces, which designate two surfaces with the same nanomorphology, but slightly different intrinsic wetting. When comparing parametric changes in the spreading process, we only compare experiments done on an identical morphology from the same prep process. The specific surface prep is noted on the experimental data presented in the next section.

In the spreading experiments, a measured volume of liquid was deposited on a nominally horizontal nanostructured surface of this type and the resulting spreading process was recorded using a high-speed video camera. Frames from a high-speed video of a droplet spreading experiment are shown in Fig. 6.

Figure 7 shows two frames of a digital video of the spreading process for a 2  $\mu$ l droplet (1.6 mm diameter before



**Figure 5.** Tightly packed pillar structure on copper surface enhanced with ZnO nanostructures (6nm seeding particles, grown in solution for 8 hours) imaged with SEM microscope.

deposition) spreading at room temperature. These frames illustrate the appearance of the droplet before (a) and after (b) reaching the separation point  $(t_s, R_s)$  where the upper droplet stops spreading and the liquid continues to penetrate radially within the nanostructured layer. This illustrates the behavior

leading to the onset of hemi-spreading that leads to the two different regimes in the model analysis.



**Figure 6.** High-speed video frames for a  $2\mu$ l water droplet spreading on copper surface with a ZnO nanostructured layer.



**Figure 7.** Spreading of a  $2\mu$ l water droplet on copper surface with a ZnO nanostructured layer. (a) initial spreading at t = 0.014 sec (b) hemi-spreading at t = 4 sec.

The image processing software ImagJ was used to extract contact line and nanolayer liquid front position data from frames of the digital video. To determine the variation of the mean radius of the spread droplet with time, the wetted area was divided by  $\pi$  and the square root of the result was taken to be the mean radius of the spread droplet at that point in the spreading process. The corresponding time was computed from the frame number relative to the start, and the known frame rate of the video camera. The frame rate for these videos was 1000 frames per second, leading to an uncertainty of roughly ±0.0005 seconds, as movement between frames wasn't captured. While this time interval is very small, it does lead to more uncertainty in the early stage data when movement is occurring on a much smaller time scale. The fast, synchronous stage spreading can lead to  $\pm 10\%$  uncertainty in determination of the time, while later stage spreading causes roughly  $\pm 1\%$ uncertainty. Therefore, as the droplet spreading slows, the uncertainty decreases. Uncertainty in radius is a result of image processing. Wetted area from photos was measured with a known scale ratio of 30 pixels/mm. The contact line and wicking limit radius measurements were determined to ±2-3

pixels, which translates to  $\pm 2\%$ -3% uncertainty in the radius measurements. An example of the resulting R(t) data is shown in Fig. 8 for spreading of a 2 µl droplet deposited on an unheated ZnO nanostructured surface like that shown in Fig. 5 at room temperature.



**Figure 8.** Experimentally determined variation of liquid front radius with time as a 2  $\mu$ l droplet spreads on a nanostructured ZnO surface.

Figure 8 is a log-log plot to clearly depict the very early time variation during which the droplet rapidly spreads to the radius of a few millimeters in less than 0.02 seconds. It should be noted that the R(t) variation of the data in this figure clearly reflect the two regimes represented in the model described above. At early times, the variation of R with t is close to linear, corresponding to the synchronous solution for which the droplet contact line expands radially in tandem with the liquid front in the nanoporous layer. The data in Fig. 8 also show a clear transition to the slower expansion of the liquid front beyond the contact line of the upper droplet after the upper droplet stops expanding. This transition, at about t = 0.011 s, corresponds approximately to the time when the upper droplet visually is observed to stop expanding.

If the mean permeability, capillary pressure characteristics, porosity and layer thickness of the nanostructured layer are known, they, together with water properties, can be used to compute a prediction of R(t) by the model developed in this study. Determining accurate values of all the morphology parameters in the model equations would require an extensive micrographic analysis for the random nanostructure used in our experiments. However, here we took a more direct approach to evaluating the model. The transition point  $(t_s, R_s)$  is a unique point in the R(t) variation at the end of the linear first stage that we can determine directly from our experimental results. It is clear from the model solution that if  $t_s$  and  $R_s$  are known, the wickability  $\omega^*$  defined by Eq. (34) can be computed from Eq. (33a) as

$$\omega^* = \frac{\sqrt{2\kappa\Delta P_{cap}}}{b\varepsilon\rho_l v_l} = \frac{R_s}{t_s}$$
(37)

To determine this key transition point  $(t_s, R_s)$ , we iteratively determined the pair of  $R_s$  and  $t_s$  values that provided the best fit of the normalized  $R/R_s$  and  $t/t_s$  video frame data to the linear universal curve and transition point predicted by equations (36a&b). As shown in Fig. 9, for the data shown in Fig. 8 (using surface prep 1),  $R_s = 3.06$  mm and  $t_s = 0.0090$ s provide a best fit. Note that once this is done, the value of  $b/R_s$  that provides the best fit of Eq. (36b) to the data in the hemi-spreading region indicates the  $b/R_s$  ratio that characterizes this nanostructured surface. Since  $R_s = 3.06$  mm, the best fit for  $b/R_s = 0.0016$  implies that the mean surface layer thickness b is 4.9 microns. We also found that the  $t_s$  values determined by the model fitting method agreed well with the time in our video recording where hemi-spreading was observed to begin.



**Figure 9.** Comparison of droplet spread data with the model predicted variation of  $\hat{R} = R/R_s$  with  $\hat{t} = t/t_s$  for surface prep. 1: (a) linear plot, (b) log-log-plot.

The fitting process to determine  $(t_s, R_s)$  was also applied to droplet spread data obtained for another experiment, using data from surface prep 2, in which both 2 µl and 4 µl droplets were deposited on the surface. These data are shown in Fig. 10. For the 2  $\mu$ l droplet on this surface, a best fit implied an  $R_{\rm s}$ value of 2.37 mm, whereas for the 3 µl droplet, the results indicate an  $R_s$  value of 2.73 mm. Note that the postulated variation of  $R_s$  proportional to  $V_{d0}^{1/3}$  indicates that  $R_s$  for this 3 µl droplet case should be about 14% higher than for the 2 µl droplet experiment. The determined  $R_{\rm s}$  value of 2.7 is about 15% higher, which is consistent with the model prediction. Overall our comparisons indicate that with appropriately specified  $(t_a, R_a)$  values, the model predictions agree well with the nanostructured surface spreading data in both the regimes considered in the model analysis, and the model and data exhibit trends that are consistent with the postulated behavior in our model.



**Figure 10.** Comparison of droplet spread data with the model predicted variation of  $\hat{R} = R/R_s$  with  $\hat{t} = t/t_s$  for surface prep 2 with 2 µl droplet and surface prep 2 with 3 µl droplet.

#### IMPLICATIONS FOR ENHANCING DROPLET VAPORIZATION OR BOILING

The generally good agreement between the experimentally determined R(t) spreading data and the model prediction suggests that the idealizations in the model may be appropriate for this type of process. Our motivation in developing the model is to better understand how the morphology and material of the nanostructured layer can be chosen to maximize the heat transfer performance associated with droplet spread and evaporation on the surface.

For vaporizing of spreading droplets, two strategies tend to enhance heat transfer. One is to spread the droplet faster. The model solution indicates that faster spreading of the upper droplet results when the wickability  $\omega^* = \sqrt{2\kappa} \Delta P_{cap} / (b\epsilon \rho_l v_l)$  is larger. The definition of wickability here indicates that, if other factors are held constant, spreading speed is enhanced when:

- (1) the permeability  $\kappa$  is increased
- (2) the porosity  $\varepsilon$  is decreased
- (3) the capillary pressure difference  $\Delta P_{cap}$  across the interface in the pores of the nanostructured layer is increased.
- (4) the viscosity of the liquid  $\mu_i = \rho_i v_i$  is lower

Note that changing the geometry of the nanoporous layer may change more than one of these parameters. And, although water is usually the fluid of interest, its liquid viscosity varies substantially with temperature, and, therefore, changing the temperature can strongly affect the wickability. The key prediction of the model analysis presented here is that some of the parameters affecting wickability may be interdependent, but the overall strategy to enhance spreading speed must be to maximize the combination of these parameters in  $\omega^* = \sqrt{2\kappa}\Delta P_{con} / (b\epsilon\rho_i v_i)$ .

The second strategy to enhance droplet evaporation heat transfer is to enhance the footprint area of the spread droplet. For the thin nanostructred layers considered in this study, the high wickability spreads a droplet over an extensive area in a time that is very short compared to the evaporation time. In effect, the upper droplet spreads first to it maximum extent  $R_s$ , followed by evaporation of the resulting thin upper droplet. Furthermore, the extremely thin nanoporous layers considered here will evaporate very little liquid compared to the content of the upper droplet, and virtually all the liquid evaporation occurs at the upper droplet liquid-vapor interface.

Use of a nanoporous layer to increase the maximum footprint area of the spread droplet increases the area of direct contact heat transfer between the spread droplet and the heated surface, and, for fixed droplet volume, it reduces the heat conduction path length from the surface to the liquid-vapor interface. The net result is that droplet evaporation time  $t_e$  is a very strong function of maximum spread area  $A_{st,0} = \pi R_s^2$ , or equivalently, maximum mean spread radius  $R_s$ . This is reflected, for example, in the droplet evaporation model prediction of Kunkle and Carey [32]:

$$t_{e} = \frac{3\gamma V_{d0}^{2}}{2A_{sl,0}^{2}} \left[ \frac{\rho_{l} h_{lv}}{k_{l}(T_{w} - T_{i})} \right] = \frac{3\gamma V_{d0}^{2}}{2\pi^{2} R_{s}^{4}} \left[ \frac{\rho_{l} h_{lv}}{k_{l}(T_{w} - T_{i})} \right]$$
(38)

which indicates that for a given initial droplet volume  $V_{d0}$ , evaporation time for a spherical cap droplet with fixed contact angle is inversely proportional to maximum droplet footprint area squared ( $A_{sl,0}^2$ ), or equivalently, inversely proportional to  $R_s^4$ . Experimental data were found to agree well with predications of this relation with the shape-factor-related constant  $\gamma$  set to one [32]. These parametric trends clearly indicate that even surface modifications that moderately enhance the upper droplet maximum spread area can dramatically reduce the droplet evaporation time. For spray cooling, reducing droplet evaporation time  $t_e$  can be attractive because it allows delivery and evaporation of more droplets per unit time to the surface, resulting in a higher rate of evaporative cooling.

The model analysis developed here also indicates that for any specified droplet volume, smaller contact angle for the spread droplet results in greater spread area. The Cassie-Baxter model in Eq. (1) can be used to predict the apparent contact angle for the upper droplet if the intrinsic contact angle for the nanoporous layer solid material,  $\theta_E$  and the fraction of the top surface of the layer that is solid,  $\phi_s$ , are known. If we accept this as a model for the apparent contact angle, Eq. (1) dictates that minimizing  $\theta_{app}$  requires making  $\phi_s$  as large as possible and making  $\theta_F$  as close to zero as possible.



Figure 11. Wicked flow from a capillary tube onto a nanoporous layer.

Our analysis of enhanced droplet spreading on nanostructured surfaces also connects to the heat transfer issues associated with pool boiling critical heat flux (CHF) conditions. In a recent experimental study, Rahman, et al. [6] presented results indicating that enhancement of pool boiling CHF on heated micro and nano porous surfaces correlates with the magnitude of a wickability parameter. The study done by Rahman, et al. [6] relates wickability to a volume flux,  $\dot{V}_0''$ , which is experimentally determined in their study wherein they initiated deposition of water onto a hydrophilic microstructured surface from a tube by raising a surface until it contacted a pendent liquid at the bottom of the tube. The experimental setup for this study is shown in Fig. 11. Video recordings of these experiments were analyzed to measure the volume rate,  $(dV/dt)_0$ , at which liquid spreads over the surface per unit area at the beginning of the process. Rahman, et al. [6] define their wickability metric as the volume flux per unit area:

$$\dot{V}_0'' = (1 / A_w) (dV / dt)_{t=0}$$
(39)

where  $A_w = \pi R^2$ , the wetted area of the droplet, and V is the volume of liquid present in the space between the bottom of the tube and the top of the microstructure layer (shown in Fig. 11). For the initial spreading stage under the end of the capillary tube, this volume is represented by:

$$V = \pi R^2 h_{gap} \tag{40}$$

Using Eq. (40), we can differentiate to solve for dV/dt,

$$dV / dt = 2\pi R h_{sam} (dR / dt)$$
(41)

We then evaluate the derivative at t = 0, substitute into Eq. (39) and rearrange to get an equation for volume flux in terms of the rate of change of the radius:

$$\dot{V}_0'' = \left[ (2\pi R h_{gap} / \pi R^2) (dR / dt) \right]_{t=0} = (2h_{gap} / R_{ti}) (dR / dt)_{t=0} \quad (42)$$

where  $R_{ii}$  is the inner tube radius, which we take to be the radius R when t = 0. As Fig. 11 suggests, the gap height  $h_{sap}$  is primarily dictated by the extent to which the pendent liquid extends below the end of the tube. This is expected to scale linearly with the inside radius of the tube, which suggests that  $h_{gap} = aR_{ti}$ , where *a* is an order-one constant. Using this relation allows Eq. (42) to simplify to:

$$\dot{V}_0'' = 2a(dR/dt)_{t=0} = 2a\omega^*$$
 (43)

where we have set  $(dR/dt)_{t=0} = \omega^*$  based on the hypothesis that we have synchronous spreading of the upper liquid front at early times. This relation, derived in a previous section for droplet spreading, also applies here. By rearranging Eq. (43), we can directly relate the velocity flux rate  $\dot{V}_0''$  in the study of Rahman, et al. [6] to the wickability,  $\omega^*$  determined for our surfaces as

$$\omega^* = \dot{V}_0'' / 2a \tag{44}$$

Based on images in the study [6], we estimate a to be in the range of 1-2. For comparison, if a value of a = 1 is chosen to relate the gap height shown in Fig. 1 to the inner tube radius, the reported values from the study of Rahman, et al. [6] (for nanostructured and microstructured surfaces) would result in  $\omega^*$  values of around 1-3 mm/s. For the ultra-thin, nanostructured, superhydrophilic surfaces considered in our study, our data indicate wicking rates ( $\omega^*$  values) were on the order of 200-300 mm/s, implying that they have a substantially stronger capability to enhance droplet spreading and liquid wicking transport in boiling processes.

This model analysis suggests that  $\dot{V}_0''$  and  $\omega^*$  are proportional, and the proportionality constant (1/2*a*) is of order one. This result is significant because, given the definition of  $\omega^*$  from our droplet spreading model, we can write Eq. (44) as

$$\frac{\dot{V}_0''}{2a} = \omega^* = \frac{\sqrt{2\kappa\Delta P_{cap}}}{b\varepsilon\rho_l v_l} \tag{45}$$

which links  $\dot{V}_{0}^{"}$  and  $\omega^{*}$  to the properties of the porous wicking structure. With this relation it is possible to explore how changes in permeability, porosity, capillary pressure, and fluid properties modify  $\dot{V}_0''$ . Additionally, by using the empirical relations developed by Rahman, et al. [6], it is possible to determine how the changes affect critical heat flux (CHF). This connection can provide an understanding of how parametric changes in the nanoporous structure may affect CHF, and it can provide a means to develop nanoporous layer designs that improve CHF performance.

#### **CONCLUDING REMARKS**

Our experimental data and observations, together with the model framework described here, support the conclusion that droplet spreading on our highly-wicking, nanostructured surfaces is characterized by two regimes. Early in the process, the very rapid, synchronized spreading of liquid in the upper droplet and in the porous layer is facilitated by localized liquid flow from the upper droplet into the porous layer near the upper droplet contact line. At a specific mean footprint radius, dictated by the apparent contact angle of the upper droplet and the volume of the deposited droplet, the upper droplet spreading essentially halts, and hemi-spreading continues the flow of liquid from the upper droplet contact line into the porous layer.

The predictions of the model framework discussed here agree well with these trends in the observed spreading behavior. In particular, the model provides insight into the mechanism of very rapid spreading early in the process, and we have demonstrated how a wickability parameter can be determined from measurement of the time and mean spread radius at the regime transition point. The model also indicates that for the surfaces tested in this study, the high wickability associated with this early stage is a consequence of the extremely thin nanoporous layer and the high capillary pressure difference generated in its very small interstitial spaces. The early rapid, synchronous spreading process can quickly spread the droplet to a large footprint area, which can strongly enhance the subsequent droplet evaporation heat transfer rate.

It should be noted, that the model analysis described here and our experiments correspond to low Weber number droplet spreading dominated by capillary and viscous forces on an ultrathin, nanostructured, hydrophilic layer on a solid substrate. The model is not designed to apply to vaporization on thicker porous layers, low permeability, low capillary pressure porous layers, or for deposition and spreading at higher impact Weber numbers.

As discussed in the previous section, the model suggests specific strategies for increasing surface wickability and the extent of liquid spreading on a solid surface as means of enhancing droplet evaporation heat transfer. Our results, together with those from other studies of wickability boiling enhancement, suggest that these same nanostructure parameter strategies also are likely to enhance boiling heat transfer.

#### ACKNOWLEDGMENTS

Support for this research was provided by the US-China Clean-Energy Research Center's CERC-WET Grant DE-IA0000018, and the National Science Foundation Graduate Research Fellowship Program.

#### REFERENCES

[1] Li, C., Wang, Z., Wang, P. I., Peles, Y., Koratkar, N., and Peterson, G. P. Nanostructured copper interfaces for enhanced boiling, Small, 4, pp. 1084-1088, 2008.

- [2] Chen, R., Lu, M.-C., Srinivasan, V., Wang, Z., Cho, H. H., and Majumdar, A., Nanowires for Enhanced Boiling Heat Transfer, *Nano Lett.* 9, pp. 548–553, 2009.
- [3] Sathyamurthi, V., Ahn, H. S., Banerjee, D., Lau, S. C., Subcooled Pool Boiling Experiments on Horizontal Heaters Coated With Carbon Nanotubes, *J. Heat Transfer*, **131**, p. 071501, 2009.
- [4] Lu, M.-C., Chen, R., Srinivasan, V., Carey, V. P., Majumdar, A., Critical heat flux of pool boiling on Si Nanowire Array-Coated Surfaces, *Int. J. Heat Mass Transfer*, 54, pp. 5359–5367, 2011.
- [5] Yao, Z., Lu, Y. W., Kandlikar, S. G., Effects of nanowire height on pool boiling performance of water on silicon chips, *Int. J. Therm. Sci.*, **50**, 2084–2090, 2011.
- [6] Rahman, M.M., Ölceroğlu, E., and McCarthy, M., Scalable Nanomanufacturing of Virus-Templated Coatings for Enhanced Boiling, *Adv. Mater. Interfaces*, 1, p. 1300107, 2014.
- [7] Rahman, M.M., Ölceroglu, E., and McCarthy, M., Role of Wickability on the Critical Heat Flux of Structured Superhydrophilic Surfaces, *Langmuir*, **30**, pp. 11225-11234, 2014.
- [8] Kim, B.S., Lee, H., Shin, S., Choi, G. and Cho, H.H., Interfacial wicking dynamics and its impact on critical heat flux of boiling heat transfer, *Appl. Phys. Letters*, 105, pp. 191671-1 to 191671-4, 2014.
- [9] Ahn, H. S., Park, G., Kim, J. M., Kim, J., Kim, M. H., The effect of water absorption on critical heat flux enhancement during pool boiling, *Exp. Therm Fluid Sci.*, 42, pp. 187–195, 2012.
- [10] Chu, K.-H., Soo Joung, Y., Enright, R., Buie, C. R., Wang, E. N., Hierarchically structured surfaces for boiling critical heat flux enhancement, *Appl. Phys. Lett.*, **102**, p. 151602, 2013.
- [11] Kim, S., Kim, H. D., Kim, H., Ahn, H. S., Jo, H., Kim, J. Kim, M. H., Effects of nano-fluid and surfaces with nano structure on the increase of CHF, *Exp. Therm Fluid Sci.*, 34, pp. 487–495, 2010.
- [12] Yao, Z., Lu, Y.-W., Kandlikar, S. G., Pool Boiling Heat Transfer Enhancement Through Nanostructures on Silicon Microchannels, *J. Nanotechnol. Eng. Med.*, 3, pp. 031002, 2012.
- [13] Bon, B. K., J, F., McKenna, E., The Hoodoo: A New Surface Structure for Enhanced Boiling Heat Transfer, J. *Thermal Sci. Eng. Appl.*, 5, p. 011003, 2013.
- [14] Chu, K.-H., Enright, R., Wang, E. N., Structured surfaces for enhanced pool boiling heat transfer, *Appl. Phys. Lett.*, **100**, p. 241603, 2012.
- [15] O'Hanley, H., Coyle, C., Buongiorno, J., McKrell, T., Hu, L.- W., Rubner, M., Cohen, R., Separate effects of surface roughness, wettability, and porosity on the boiling critical heat flux, *Appl. Phys. Lett.*, **103**, p. 024102, 2013.
- [16] Zou, A., Maroo, S. C., Critical height of micro/nano structures for pool boiling heat transfer enhancement, *Appl. Phys. Lett.*, **103**, p. 221602, 2013.
- [17] Ruiz, M., Kunkle, C.M., Padilla, J. Jr., Carey, V.P., Boiling heat transfer performance in a spiraling radial

inflow microchannel cold plate, *Heat Transfer Engineering*, **38**, pp. 1247-1259, 2017.

- [18] Padilla, J. and Carey, V.P., Water droplet vaporization on superhydrophilic nanostructured surfaces at high and low superheat, paper IMECE2014-39957, Proc. ASME 2014 Inter. Mechanical Engineering Congress & Exposition IMECE2014, Nov. 14-20, 2014, Montreal, Canada.
- [19] Kunkle, C.M., Mizerak, J.P., and Carey, V.P., The effects of wettability and surface morphology on heat transfer for zinc oxide nanostructured aluminum surfaces, paper HT2017-4847, Proc. ASME 2017 Summer Heat Transfer Conf. HT2017, July 10-14, 2017, Bellevue, WA, USA.
- [20] Xiao, R., Enright, R., and Wang, E.N., Prediction and optimization of liquid propagation in micropillar arrays, *Langmuir Letter*, 26, pp. 15070-15075, 2010.
- [21] Zhu, Y., DiAntao, D.S., Lu, Z., Somasundaram, S., Zhang, T., and Wang, E.N., Prediction and characterization of dry-out heat flux in micropillar wick structures, *Langmuir*, **32**, pp 1920–1927, 2016.
- [22] Joung, Y.S. and Buie, C.R., Scaling laws for drop impingement on porous films and papers, *Phys. Review E*, 89, p. 013015, 2014.
- [23] Mitra, S. and Mitra, S.K., Understanding the Early Regime of Drop Spreading, DOI: 10.1021/acs.langmuir.6b02189, *Langmuir*, 32, pp. 8843–8848, 2016.
- [24] Navaz, H.K., Markicevic, B., Zand, A.R., Sikorski, Y., Chan, E., Sanders, M., D'Onofrio, T.G., Sessile droplet spread into porous substrates—Determination of capillary pressure using a continuum approach, *Journal* of Colloid and Interface Science, **325**, pp. 440–446, 2008.
- [25] Reis, N.C. Jr., Griffiths, R.F., Me'ri Santos, J., Parametric study of liquid droplets impinging on porous surfaces, *Applied Mathematical Modelling*, **32**, pp. 341– 361, 2008
- [26] Clarke, A., Blake, T.D., Carruthers, K., and Woodward, A., Spreading and Imbibition of Liquid Droplets on Porous Surfaces, *Langmuir*, 18, pp. 2980-2984, 2002.
- [27] Quéré, D., Wetting and roughness, *Annual Rev. Mater. Res.*, **38**, pp. 71–99, 2008.
- [28] Cassie, A.D.B., and Baxter, S., Wettabiity of porous surfaces, *Trans. Faraday Soc.*, **40**, p. 546, 1944.
- [29] Brinkman, H.C., A calculation of the viscous force exerted by flowing fluid on a dense swarm of particles, *Appl. Sci. Res.*, A1, pp 27-34, 1947.
- [30] Gebhart, B., *Heat Conduction and Mass Diffusion*, Section 3.1.1, McGraw-Hill, New York, NY, 1993.
- [31] Padilla, J., "Experimental Study of Water Droplet Vaporization on Nanostructured Surfaces," PhD Dissertation, University of California at Berkeley, 2014.
- [32] Kunkle, C.M. and Carey, V.P., Metrics for quantifying surface wetting effects on vaporization processes at nanostructured hydrophilic surfaces, paper HT2016-7203, Proc. ASME 2016 Summer Heat Transfer Conf. HT2016, July 10-14, 2016, Washington, DC, USA.