Proceedings of the First Pacific Rim Thermal Engineering Conference, PRTEC
March 13-17, 2016, Hawaii's Big Island, USA

PRTEC-15163

METRICS FOR QUANTIFYING SURFACE WETTING EFFECTS ON BOILING AND EVAPORATION AT NANOSTRUCTURED HYDROPHILIC SURFACES

Claire M. Kunkle[1*], Van P. Carey[1]

[1]University of California, Berkeley, CA, 94720, USA

ABSTRACT

Static contact angle is most often used as a means of quantifying the wetting characteristics of the liquid phase in vaporization processes. This metric is often convenient to measure and it is intuitive in its interpretation, but its usefulness is questionable in some cases. For highly wetting, nanostructured surfaces, the use of a static contact angle to quantify wetting has two key disadvantages. One is that it can be difficult to measure from photographs of sessile droplet profiles or contact line regions when the contact angle is very small. A second disadvantage is that the relationship of the macroscopic contact angle to the nanoscale interaction of the liquid and vapor contact line with the nanostructured surface is unclear. In this study, the advantages and disadvantages of different wetting metrics were explored and evaluated for hydrophilic surfaces. Alternate choices of wetting metric suggested in earlier studies such as dynamic advancing and receding contact angles, and spreading coefficients, are explored here as alternatives to static contact angle. A new wetting metric based on spreading characteristics of sessile droplets is also proposed that has the advantage of being easily measured for hydrophilic surfaces. Use of this new metric is then explored for evaporation and boiling applications with superhydrophilic surfaces. The results of our study indicate that this new metric can be particularly useful for characterizing the effects of variable wetting on vaporization processes at highly wetted surfaces.

KEYWORDS: Hydrophilic, wetting, contact angle, CHF, boiling, and evaporation.

1. INTRODUCTION

There has been significant interest in recent years in the development of hydrophilic and superhydrophilic surfaces for the purpose of enhancing boiling and evaporation. Such surfaces have been shown to have a distinct relation between high wetting characteristics and enhanced boiling and evaporation compared to uncoated surfaces [1]. These surfaces are produced in a variety of ways from laser etching to coatings of oxides and nanoparticles. When these coatings are added, the surfaces become so wetting, they can exhibit apparent contact angles of zero. Yet these same surfaces often exhibit a range of boiling characteristics. So if a relation is to be discovered for these surfaces, the contact angle does not show enough sensitivity to be the metric for this comparison. Previous studies have shown a correlation between this apparent contact angle and enhanced boiling characteristics, but they often avoid the most enhanced wetting surfaces. Forrest [2] observed an increase in the critical heat flux and the boiling heat transfer coefficient for nanoparticle thin-film coatings. Similarly, Padilla [3], related contact angles to the Leidenfrost temperature, where lower angles related to higher to temperatures. Yet both of their data sets have a number of surfaces that exhibit a range of critical heat flux and Leidenfrost temperatures, respectively, yet have the virtually same measured contact angle. Currently, contact angles are the most commonly used metric to quantify the wettability of surfaces. Yet, as surfaces become more advanced, it is important that the metric used is highly sensitive and able to measure minute differences in surface wettability, especially at low contact angles.

One alternative method of categorizing surfaces is with receding and advancing contact angles, as discussed by Gao [4]. Gao [4] explains contact angle hysteresis as the difference between receding and advancing

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*Corresponding Author: ckunkle@berkeley.edu

contact angles as liquid is either removed or added from a droplet. This hysteresis effects water molecules at the three-phase contact line, which is of particular interest for hydrophilic surfaces which exhibit adhesion forces as fluid droplets are drawn into the nanoscale roughness at this contact line. This hysteresis metric, while employing two, rather than one, contact angle measurement, has the same issue as apparent contact angle measurement when surfaces are superhydrophilic. That is, the three phase contact line is difficult to image and accurately measure. Another alternative method is quantifying wettability with spreading coefficients. The spreading coefficient calculates wetting based on a relation between surface energies, employing equations developed by Young and Dupré. However, for measurement purposes, this metric still relies on a contact angle measurement, which leads to the same occurring issue of calculating wetting for superhydrophilic surfaces without the ability to accurately measure contact angle.

2. THE WETTING NUMBER

While both contact angle hysteresis and spreading coefficients have unique characteristics as wetting metrics, neither of them allow for complete departure from contact angle measurement for superhydrophilic surfaces. We propose another metric that uses the wetted footprint of a droplet on a surface to quantify wettability. The wetting number, N_w, we propose is a dimensionless ratio relating the wetted footprint of a fixed volume droplet to that of an equal volume droplet with 90° contact angle. If the droplet of interest is a spherical cap, it can easily be shown as this ratio, a function of the droplet's contact angle, shown in Eq. (1).

$$N_w = \frac{A_{sl}}{A_{sl,90}} = \frac{2^{2/3}(1-\cos^2\theta)}{(2-3cos\theta+\cos^3\theta)^{2/3}} \tag{1}$$

For any sessile droplet geometry, this wetting number can be directly determined by analyzing images to calculate wetted (footprint) area for a droplet of known volume on a hydrophilic surface. The spherical cap model is an idealization for a liquid droplet on a solid surface that can be used to calculate the contact angle based on a known spread area and vice-versa. This method is widely accepted and was used by Padilla [3] for the contact angle calculations in Fig. 2. To better visualize the unique benefit of the wetting number for low contact angles, a range of contact angles from 0° to 180° were plotted in Fig. 1 with their corresponding wetting numbers.

As the contact angle approaches zero, a spherical cap model predicts that the footprint of a droplet on the surface will become increasingly large. So, as the contact angle approaches zero, a small change in contact angle produces an increasingly large change in droplet footprint area. Changes in the wetting number, defined here, thus reflect more accurately the changes in wetted area for a droplet on a highly wetted surface. This increases sensitivity for surface types that consistently produce near-zero contact angles. Unlike small contact angle measurements, which require a high performance camera, enhanced lighting, and careful calibration, and still have a high degree of inaccuracy, the wetted area for a droplet on a surface can be easily measured to a great degree of accuracy with a camera and simple, accessible imaging software. Use of the wetting number effectively takes out the inaccuracy of measuring wetting for conditions that correspond to low degree contact angles.

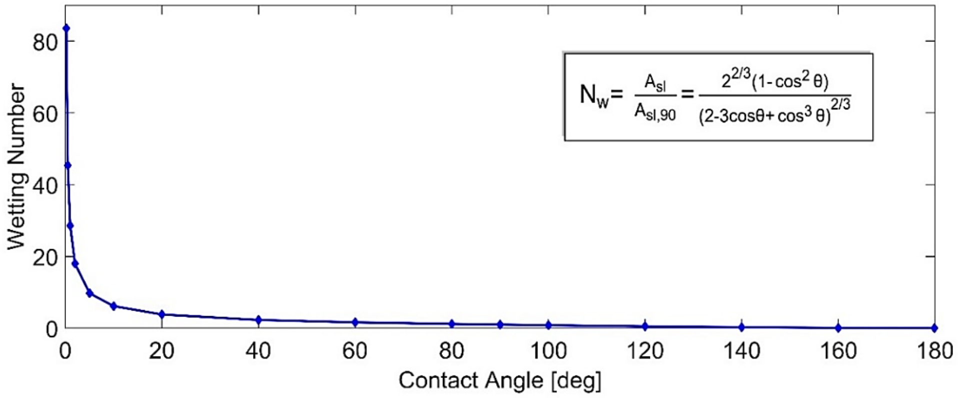

Fig. 1 Wetting number as a function of contact angle

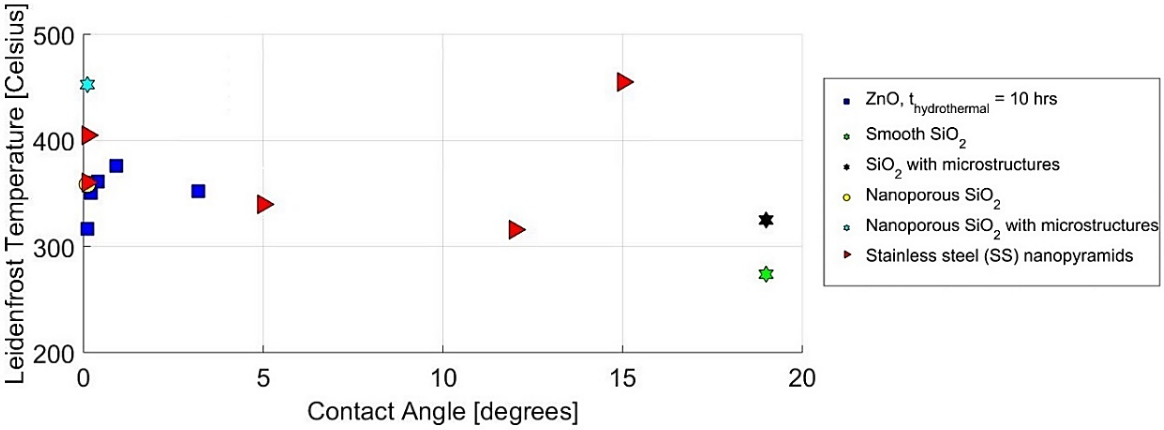

Fig. 2 Leidenfrost temperature variation for a range of surfaces and contact angles – data shown are from multiple sources summarized by Padilla [3]

Additionally, the integration of a wetted area, the physical contact of liquid and solid, is a logical direction for applying this metric to evaporation and boiling data. As droplets spread out very thin on heated surfaces, evaporation is enhanced by increased surface contact as well as the potential development of thin film evaporation. This correlation between surface area contact and enhanced heat transfer is at the heart of this new wetting number metric, and therefore allows for particular application in boiling and evaporation. Especially for superhydrophilic surfaces, this metric shows how a small contact angle change can lead to dramatic changes in wetting number.

In Fig. 2 and Fig. 3, data was taken from sources that were previously summarized by Padilla [3]. Padilla's Leidenfrost data summary includes ZnO hydrophilic surfaces, silicon dioxide enhanced surfaces, and stainless steel enhanced surfaces, all of which have contact angles below 20º. In Fig. 2, the Leidenfrost transition temperature is plotted against the individual surface contact angles. Leidenfrost points range from ~270 to 450ºC, and most of this range is for contact angles reported to be well below 3º. As previously discussed, achieving accuracy for contact angle measurements for such highly wetting surfaces is difficult and there is no clear trend from the bundle of points on the left-most part of Fig. 2. However, in Fig. 3, when the same data is plotted against the wetting number, the lower contact angles are more sensitively represented with wetting numbers spreading the points out.

For Fig. 3, the lowest contact angle surfaces (five of which reported contact angles of 0, but were calculated as 0.1 when plugged into Eq. (1)) are shown on the right hand side of Fig. 3. In Fig. 3, the variation of Leidenfrost transition temperature with changing surface wetting can be seen more clearly, despite some scatter in the data.

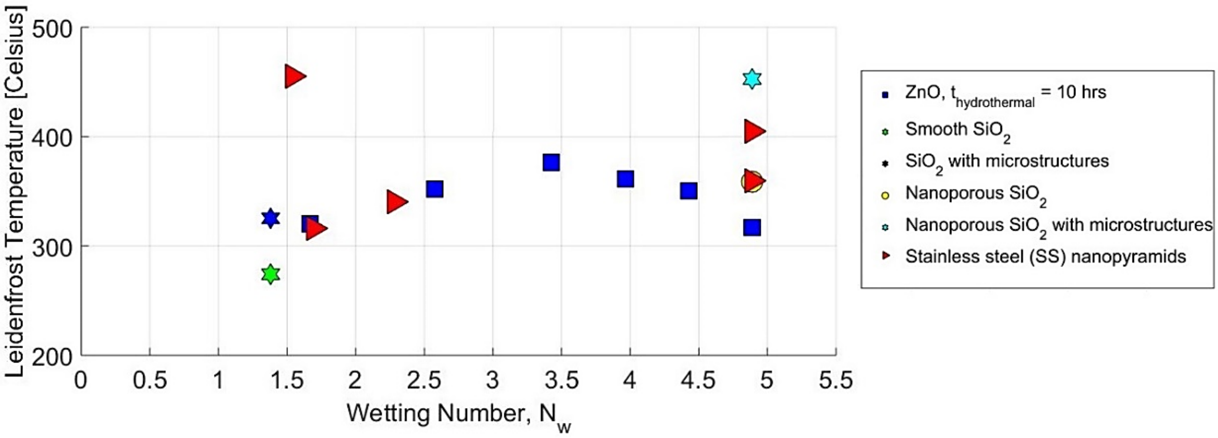

Fig. 3 Leidenfrost temperature variation with N_w – data shown are from multiple sources summarized by Padilla [3]

If the experiments for the data shown in Fig. 3 were collected as areas rather than contact angles it is possible that there would be a more robust, visible trend. There is also less room for error in the calculation of a wetting number from area rather than contact angle. This increased accuracy lends itself to more than just creating relations between key boiling points like Leidenfrost transition and critical heat flux. It can also be an advantage to establish the link between evaporation heat transfer and wetting in a droplet evaporation model.

3. DROPLET EVAPORATION MODEL

A simplistic model is proposed here to calculate the time for complete evaporation of a droplet on heated surface as a function of the wetting number. An energy balance equating the rate of latent heat consumed, as the droplet evaporates and shrinks, to the heat conducted from the solid surface to the droplet liquid-vapor interface is used to derive Eq. (2), where δ_h is the mean thickness of the droplet during the evaporation process.

$$\rho_l h_{lv} \frac{d}{dt}(V_l) = -\frac{k_l A_{sl} \Delta T}{\delta_h} \tag{2}$$

Here, we postulate that the mean thickness for computing conduction heat transfer will be proportional to droplet volume and inversely proportional to droplet footprint area at any point in time. We can therefore modify this relation by replacing δ_h with $\gamma V_l/A_{sl}$. Where γ is an order-one constant. This is consistent with shape factor treatment of conduction in bodies with complex geometries. Rearranging the resulting equation, we arrive at Eq. (3) which can then be integrated from initial wetted area to time dependent wetted area.

$$\frac{dA_{sl}}{dt} = -\frac{2k_l \Delta T}{3\gamma \Gamma^2 \rho_l h_{lv}} \quad \text{and} \quad \Gamma = \frac{2-3cos\theta+\cos^3\theta}{2\pi^{1/2}\sin^3\theta} \tag{3}$$

When the value of A_{sl} the final wetting area, is set to zero, then evaporation is complete. Doing this with the equations, we obtain the following relation for evaporation time as a function of the wetting number, shown in Eq. (4).

$$t_{ce} = \gamma \frac{A_{sl},0}{N_w^3}\left[\left(\frac{2}{3\pi}\right)\left(\frac{\rho_l h_{lv}}{k_l \Delta T}\right)\right] \tag{4}$$

This model adopts the idealization that the droplet’s geometry is always a spherical cap, and that the contact angle (and thus the wetting number) remain constant throughout evaporation. For conditions at which the droplet geometry is close to a spherical cap, we expect a value of γ near one would apply. If the geometry deviates from the spherical cap model, due to distortion by gravity forces, for example, a value of $\gamma = 1$ may no longer match experiments. Additionally, bubble nucleation is not active in this model, so the wall superheats to be used in this should be low enough that there is no nucleation. Based on the droplet evaporation data collected by Padilla [3], with ZnO surfaces, the evaporation model, with $\gamma = 1$, was used to create the data comparison shown in Fig. 4, with experimental evaporation times on the vertical and calculated times using the model on the horizontal axis.

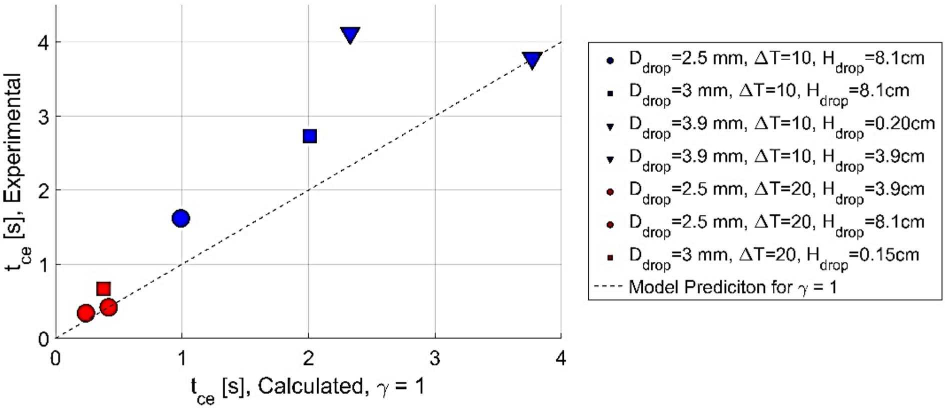

Fig. 4 Droplet evaporation times for droplet sizes of 2.5, 3.0, and 3.9mm, and superheats of ΔT = 10 and 20ºC. Experimental evaporation times compared to model evaporation times.

A linear trend with a slope of approximately one can be observed from Fig. 4, providing some confirmation of this model and the possibility of applying it to other surfaces and droplet liquids. It is noteworthy that the model predicts a very strong dependence between evaporation time and this wetting parameter, making it a very sensitive indicator of the impact that surface wetting will have on the droplet evaporation rate. This is particularly apparent when the surface is highly wetting and the wetting number value is large (see Fig. 1).

CONCLUSIONS

This paper presents a new wetting number metric that is particularly useful for quantifying wettability of highly wetting surfaces. This non-dimensional ratio can be calculated by measuring the wetting footprint of a sessile droplet on a surface, which has the advantage of being generally much easier to do with precision than measuring extremely small contact angles. This wetting number is also a more sensitive wetting metric for highly wetting surfaces, which allows, for example, a more clear definition of trends in Leidenfrost temperatures with changing wetting conditions on superhydrophilic surfaces. We have also demonstrated that formulating a droplet evaporation model in terms of this wetting number results in a predictive relation for evaporation time that directly indicates the strong dependence of evaporation time on wetting conditions, as quantified by this parameter. This wetting number appears to have the potential to better characterize the effects of superhydrophilicity on boiling and evaporation in a way that is easy to measure accurately, and sensitive to small wetting variations.

ACKNOWLEDGMENTS

The authors acknowledge the financial support of the National Science Foundation through a Graduate Research Fellowship, and the endowment for the A. Richard Newton Chair in Engineering at UC Berkeley.

NOMENCLATURE

θ	Contact Angle	(°)	ρ_l	Density of water
t_{ce}	Complete Evaporation Time	(s)	h_{lv}	Latent heat of water
A_{sl}	Solid Liquid Contact Area	(L^2)	k_l	conductivity of water
N_w	Wetting Number			

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