



Thermal transport to droplets on heated superhydrophobic substrates



R. Hays, D. Maynes, J. Crockett*

Brigham Young University, Department of Mechanical Engineering, Provo, UT 84602, USA

ARTICLE INFO

Article history:

Received 9 June 2015

Received in revised form 29 February 2016

Accepted 1 March 2016

Keywords:

Superhydrophobic
Droplet evaporation
Heat transfer
Structured substrate

ABSTRACT

This paper reports on measurements of thermal transport to solitary sessile water droplets placed on heated superhydrophobic substrates maintained at constant temperature. A single water droplet of nominally 3 mm diameter is placed on a preheated substrate and allowed to evaporate completely while being imaged from two angles with video cameras and an infrared camera. Substrate temperatures are varied from 60 °C to 230 °C and total evaporation time and heat transfer rate are determined. Three different rib-patterned superhydrophobic substrates are investigated of 0.5, 0.8, and 0.95 cavity fraction (relative projected cavity area of substrate to total projected surface area). The rib features range in width from 2 to 30 μm and in height from 15 to 20 μm. Results are also obtained for a smooth hydrophobic substrate for comparison. Droplet evaporation times increase with substrate cavity fraction while overall heat transfer rates decrease. At subcritical substrate temperatures the Nusselt number is larger for lower cavity fraction substrates. For supercritical substrate temperatures, as the cavity fraction increases nucleate boiling is delayed to higher substrate temperatures and the Leidenfrost point occurs at lower temperature. At the highest cavity fraction explored nucleate boiling does not occur at any substrate temperature. At temperatures above the Leidenfrost point the influence of cavity fraction is negligible.

© 2016 Elsevier Ltd. All rights reserved.

1. Introduction

Evaporation of a water droplet is a common, natural occurrence, yet it is a complex process where both heat and mass transfer occur as the water evaporates into the surrounding unsaturated air. Droplet evaporation from substrates is a regularly studied phenomenon due to its multiple applications including ink-jet printing [1,2], micro/nano fabrication [3,4], thin film coatings [5], and spray cooling [6]. Recently, droplet evaporation on superhydrophobic (SH) substrates has captured interest due to the significant alteration of heat transfer dynamics on these substrates caused by very high contact angles and micro/nanoscale surface structuring [7–12].

Superhydrophobic (SH) surfaces exhibit internal static contact angles with water in excess of 120° and contact angles up to 177° have been reported [13]. This non-wetting behavior occurs in nature with such examples as the lotus leaf [14]. Artificial SH surfaces are manufactured by combining micro and/or nanoscale surface roughness with a non-wetting surface coating such as Teflon. Manufacturing methods include, among others, deep reactive ion etching, wax film growth, alumina gel film preparation, and vapor deposition of fluoroalkyl silanes [15]. The left panel of

Fig. 1 is a scanning electron microscope (SEM) image of a rib/cavity structured surface created using common photolithographic techniques. If the distance between roughness features is minimal, and the Laplace pressure is not exceeded, liquid above the cavities will form menisci between roughness features and rest above the cavities (Cassie–Baxter state [16]), significantly increasing the contact angle and altering the fluid flow and heat transfer behavior of liquids on the surface. SH surfaces can be characterized by the cavity fraction, defined as the ratio of the projected area of the cavities to the overall projected area of the surface. Significant research has been focused on the hydrodynamics of fluid interactions with SH surfaces (channel flow [17–22], jet impingement [23–26], and droplet motion [27–30]). More recent research has explored heat transfer dynamics (channel flow [31,32], condensation [33–35] and ice formation [36,37]). However, much less research has been published regarding the heat transfer behavior associated with droplet evaporation dynamics on a heated SH substrate [12,38].

Droplet evaporation rate is a function of the relative humidity of the surrounding air, the surface area in contact with the air (a function of the liquid–solid contact angle), the substrate temperature and the thermal conductivity of the material [39,40]. During evaporation, two distinct modes can occur; constant contact angle and constant contact line, where in the latter the surface area of the droplet in contact with the substrate remains nominally constant [7,8,41,42]. During evaporation of droplets from most hydrophilic

* Corresponding author.

E-mail address: crockettj@byu.edu (J. Crockett).

Nomenclature

A_c	projected droplet-substrate contact area	\dot{q}_{rad}	radiative heat transfer rate at external droplet-air interface
\bar{A}_p	average projected area of droplet surface intercepting radiation from substrate	\dot{q}_s	heat transfer rate at droplet-substrate interface
A_u	exposed upper-surface area of droplet	\dot{q}_{sens}	rate of sensible heat change within droplet
C	constant coefficient for Nu power-law relation with Ra	$\bar{q}_{s,rad}$	average radiative heat transfer rate at droplet-substrate interface
C_0	constant coefficient for Nu power-law relation with Ra for smooth hydrophobic substrate	Ra	Rayleigh number
c_p	specific heat capacity of water	t	time
D	instantaneous equivalent droplet diameter	t_e	time at point of critical heat flux
d_i	diameter of a single-pixel thick droplet slice from CCD images	T_d	droplet temperature
d_l	width of droplet at droplet-substrate interface longitudinal to ribs	T_s	substrate temperature
d_t	width of droplet at droplet-substrate interface transverse to ribs	T_{sat}	local saturation temperature of water
F_c	substrate cavity fraction	T_∞	ambient air temperature
g	acceleration due to gravity	V	droplet volume
h_{conv}	convective heat transfer coefficient for external water-air interface	V_0	volume of spherical droplet with 3 mm diameter
h_{fg}	latent heat of vaporization of water	w_c	substrate cavity width
h_p	height of one pixel in CCD images	w_r	substrate rib width
h_s	heat transfer coefficient representing all modes of heat transfer from the substrate to the droplet	α	thermal diffusivity of water
k	thermal conductivity of water	β	volumetric thermal expansion coefficient of water
Ma	Marangoni number	ϵ	emissivity of water
Nu	Nusselt number	ϵ_s	emissivity of solid substrate
\dot{q}_{conv}	convective heat transfer rate at external droplet-air interface	γ	surface tension of air–water interface
\dot{q}_{evap}	evaporative heat transfer rate at external droplet-air interface	μ	dynamic viscosity of water
		ν	kinematic viscosity of water
		θ	contact angle
		ρ	density of water
		σ	Stefan–Boltzmann constant

surfaces the constant contact line mode prevails due to the droplet being pinned to the surface. Pinning may also occur for some hydrophobic and SH surfaces [8,10]. However, more commonly hydrophobic and SH surfaces exhibit the constant contact angle mode which is characterized by a retreat of the liquid–solid contact line accompanied by the maintenance of the liquid–solid interior contact angle.

For a sessile droplet on a smooth hydrophobic surface it has been shown that the evaporation rate is linearly proportional to the radius of the liquid–solid contact area between the droplet and the hydrophobic surface [43,44]. As hydrophobicity or superhydrophoicity increases, the evaporation rate decreases due to

water vapor being trapped near the contact line of the droplet between the sides of the droplet and the substrate [11,45–47].

When the substrate is heated the evaporation process is enhanced on both hydrophobic and hydrophilic surfaces. Convection exists in the drop, driven by buoyancy or surface tension gradients due to temperature gradients within the droplet, which alter the evaporation dynamics. The evaporation rate on hydrophilic surfaces is underestimated when a diffusion-only model is applied [48,49]. At surface temperatures greater than the saturation temperature, the dynamics in the liquid change dramatically as nucleate boiling begins to occur. Above the Leidenfrost temperature the vapor layer between the droplet and substrate acts as a

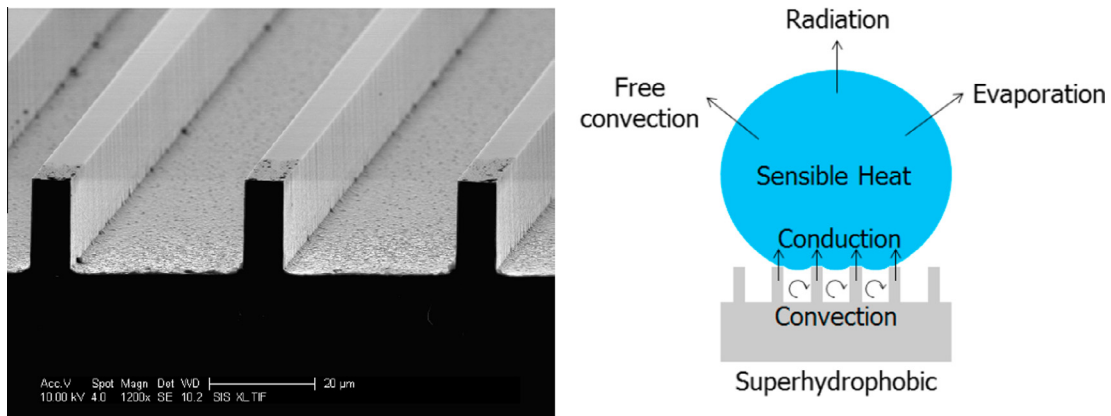


Fig. 1. Left panel: SEM image of an $F_c = 0.8$ SH surface. Right panel: Sessile droplet placed on a heated SH surface (note the ribs are not to scale as the droplet with a 3 mm diameter would be in contact with hundreds of ribs). Convection, conduction, and radiation (not shown) occur at the base of the droplet, while free convection, radiation, and evaporative cooling occur at the upper surface of the droplet.

Download English Version:

<https://daneshyari.com/en/article/7055461>

Download Persian Version:

<https://daneshyari.com/article/7055461>

[Daneshyari.com](https://daneshyari.com)