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Local heat transfer to an evaporating superhydrophobic droplet

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ABSTRACT

The heat flux distribution beneath a superhydrophobic evaporating droplet has been explored. High speed, high resolution infrared thermography was employed to measure the heat transfer characteristics of the evaporating droplet. Optical imaging and analytical techniques were used the capture droplet dynamics over the course of its evaporation. The droplet evaporated with a receding contact line predominantly in the constant contact angle regime. The peak local convective heat transfer was located at the triple contact line over the entire evaporation period. Peak and average heat fluxes were shown to increase as the evaporation proceeded due to the increasing contact line length density and liquid-gas interface temperature. The total thermal power across the solid-liquid interface decreased due to the decreasing solid-liquid surface area. The average heat flux to the evaporating droplet was shown to vary linearly with contact line length density.

1. Introduction

Evaporation of sessile drops is of significant scientific and engineering interest. It represents a common natural phenomena that is not fully understood while at the same time is used in many industrial fields, ranging from DNA mapping to evaporative spray cooling [1–13].

Droplet evaporation dynamics depends on many factors, including though not limited to wettability, the evaporation flux at the interface and the triple line, the substrate temperature, external fields and thermocapillarity, and these have been researched extensively over the past decade [12,14–28]. From a thermal transport standpoint, the process is a complex interaction of diffusion within the substrate, buoyant convection in the gas and liquid phases, contact line evaporation, vapour diffusion, evaporative cooling at the liquid-gas interface and possible Marangoni effects [12,14–29]. The droplet evaporation process is clearly very complex and even though considerable progress has been made with regard to understanding the thermal and fluid transport processes, they are still not fully understood, in particular with regard to the conjugate heat transfer near the triple contact line [29].

The contact line or triple line is defined as the region where the gas, liquid and solid phases intersect. Droplet evaporation can occur in four primary modes: constant contact angle (CCA), constant contact radius (CCR), a mixed mode, and a stick slip mode. Both CCA and CCR were first introduced by Picknett and Bexon [14]. In CCA mode, the droplet's contact angle remains fixed with a decreasing base radius r_b, whereas for CCR mode, the droplet's radius is fixed (pinned) and droplet evaporation occurs with a decreasing contact angle. In mixed mode evaporation both the contact angle and radius decreases as the evaporation proceeds [30]. Finally in the stick-slip mode the contact line fluctuates between pinning and unpinning [31]. Which mode occurs is dependent on the droplet and substrate properties [24].

Conjugate heat transfer near the contact line during droplet evaporation on a heated substrate is a topic that still requires significant research. For a hydrophilic droplet, it is known that the adsorbed layer forms due to the strong adhesion forces between the liquid and the solid. As depicted in Fig. 1a, these strong adhesion forces results in a contact line region that has multiple length scales, ranging from nanometer at the adsorbed film region to millimeter in the bulk droplet. The adsorbed film region is characterised by long range intermolecular forces. This disjoining pressure establishes a flat liquid-vapour interface that is tens of nanometers thick (10–20 nm) [32] and prevents evaporation occurring in this region [33]. The transition region is defined by a growing film thickness which results in a reduction in the long range intermolecular forces. This region experiences the highest heat fluxes across the droplet as a result of the low thermal resistance due to the thin film thickness (1–3 μm) [32]. The total length of the adsorbed film and transition region varies from 0.5 μm to 10–20 μm [32]. As the film thickness increases from the transition region into the intrinsic meniscus and micro-convection regions, so

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Nomenclature

A	area [mm^2]
C	curvature [mm^{-1}]
C_p	specific heat capacity [J]
E	energy [W m^{-1} K^{-1}]
H	height [mm]
I	current [A]
k	thermal conductivity [W m^{-1} K^{-1}]
q''	heat flux [W m^{-2}]
r	radius [mm]
R	thermal resistance [KW^{-1}]
S	coordinate [mm]
T	temperature [K]
t	time [min]
V	voltage [V]

Dimensionless numbers

Bi	$Bi = hL/k$ [–]

Greek symbols

δ	thickness [µm]
γ	surface tension [N m^{-1}]
ρ	density [kg m^{-2}]
σ	Stefan-Boltzmann constant [W m^{-2} K^{-4}]
θ	contact angle [°]
ε	emissivity [–]

Subscripts

∞	bulk or infinity
ag	air gap
b	base
cap	capacitive or storage
$cond$	conduction
d	droplet
f	foil
gen	generated
lc	lateral conduction
lg	liquid-gas
p	paint
rad	radiation
s	heated substrate
sl	solid-liquid
T	apex
wf	working fluid
x, y, z	coordinate direction

Acronyms

CAH	contact angle hysteresis
CCA	constant contact angle
CCR	constant contact radius
CLD	contact line length density
DC	direct current
IR	infrared
PEEK	polyether ether ketone
PU	percentage uncertainty

too does the thermal resistance resulting in a decrease in the local heat flux. Both the intrinsic meniscus and micro-convection regions are characterised by surface tension and inertial forces [21]. The net thermal boundary resistance R_{net} is the sum of the solid-liquid R_{sl} and the liquid-gas R_{lg} thermal resistance, with R_{lg} typically 10–100 times greater in magnitude than R_{sl} [24]. If the evaporating vapour is lighter than the surround medium (air) convection may occur [23]. Vapour concentration gradients at the

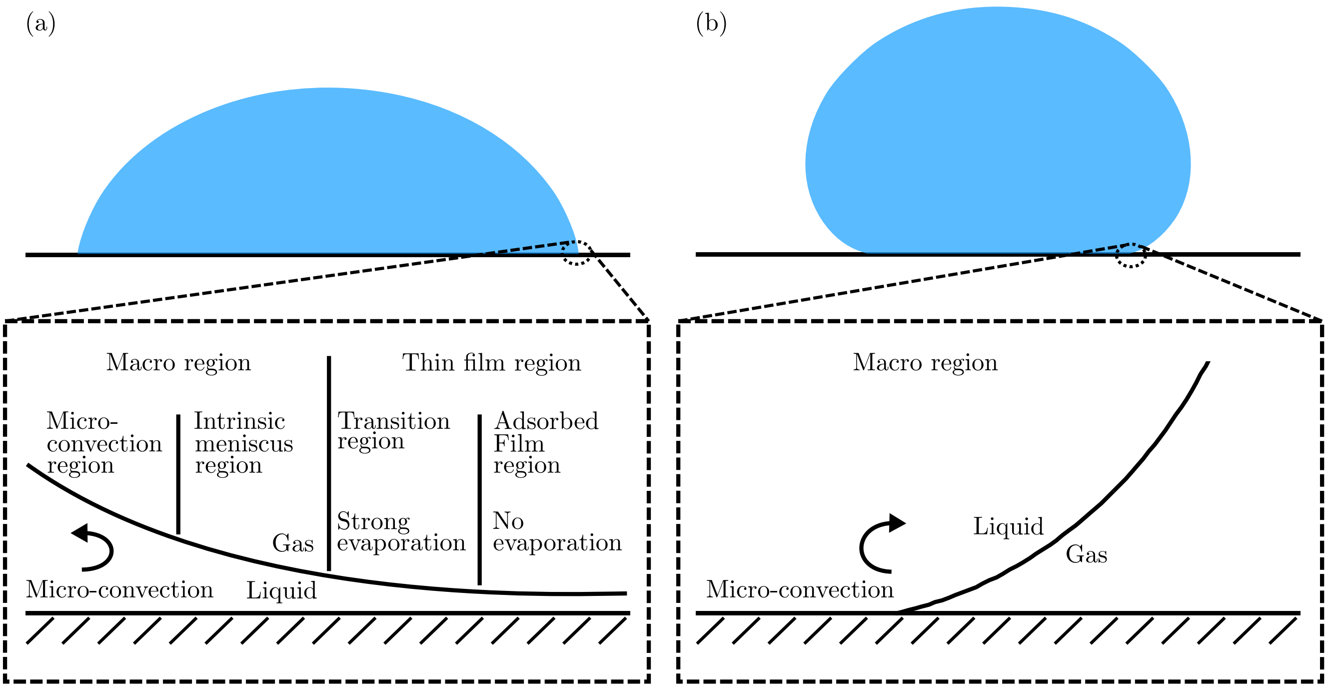

Fig. 1. Droplet evaporation at the contact line. (a) Hydrophilic droplet [21] and (b) hydrophobic droplet.