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Simulation of flow and heat transfer in a liquid drop sliding underneath a hydrophobic surface

Basant Singh Sikarwar, Sameer Khandekar *, K. Muralidhar

Department of Mechanical Engineering, Indian Institute of Technology Kanpur, Kanpur 208016, India

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ABSTRACT

Clusters of liquid drops growing and moving on physically or chemically textured surfaces are encountered in dropwise mode of vapor condensation. This process can be sustained only if the surface integrity is maintained over a long period of time. Surface features are altered when sliding drops leach away the promoter layer. In the absence of chemical reactions between the promoter and the condensing liquid, the wall shear stress is the primary parameter controlling the physical leaching. In turn, wall shear stress depends on the relative speed between the drop and the substrate surface and the shape of the drop. Given a wall shear stress distribution for individual drops, the net effect of an ensemble of them during continuous quasi-steady state dropwise condensation can be determined using the population density of drops.

Wall shear stress and local heat fluxes have been determined in the present work by solving the Navier–Stokes and energy equations in three-dimensions on an unstructured tetrahedral grid that represents an individual droplet. The drop size and relative velocity are parameterized by the Reynolds number (Re = 10–1000), apparent contact angle (90–120°) and its shape. The simulations presented here are for a wide range of Prandtl numbers, i.e., 0.005–30. The wall shear stress and wall heat flux are expressed in terms of the skin friction coefficient and the Nusselt number, respectively. While these two quantities show an increase with Reynolds number, they decrease at higher values of the drop contact angle on/underneath hydrophobic surface. At low Prandtl numbers, heat transfer is mainly diffusional and the wall Nusselt number is practically independent of Reynolds number at any given Pr. The maximum wall shear stress as well as heat flux occurs at the corners of the drop close of the three-phase contact line. The surface averaged shear stress and heat flux are expressed in terms of appropriate correlations that include Reynolds number, Prandtl number, and the apparent contact angle. The wall shear stress in the relatively inactive central region at the drop base is smaller than the overall base average by a factor of 6, while that for heat transfer, the corresponding factor is in the range of 1.3–1.8. The figure of merit function, represented by the ratio of average Nusselt number to the friction coefficient, increases with contact angle, indicating an advantage to be gained from hydrophobic surfaces. The information presented in this paper is vital for further improvement of the available models of dropwise condensation on textured surfaces.

1. Introduction

The sliding of liquid drops over and underneath textured surfaces has been a subject of extensive research in the context of many engineering applications. These include examples such as dropwise condensation, microfluidics, lab-on-chip devices, ink jet printing systems, spraying of insecticide on crops and several biochemical processes [1–3]. It is known that dynamic steady-state of condensing vapor on a cold substrate involves a large population of drops of varying sizes, involving various generations [4,5]. The drops increase in size by a combination of direct condensation and/or coalescence with neighboring drops [6]. As drops grow, the body forces eventually exceed the drop retention force due to surface tension, leading to sliding of drops and fall off thereafter [7]. This step exposes virgin substrate for condensation, where a new generation of drops begins to grow [6,8]. The effective heat transfer coefficient during dropwise condensation is considerably greater than that for a liquid film condensation mode, making the former ideal from a heat transfer enhancement and energy conservation perspective [9].

The long term sustainability of dropwise condensation on a given substrate depends on the shear interaction of sliding drops with the hydrophobicity promoter layer [10]. The phenomenon of removal of this promoter layers, or surface damage due to sliding of drop, leads to surface leaching. It arises primarily from

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* Corresponding author. Tel.: +91 512 259 7038; fax: +91 512 259 7408.
E-mail address: samkhan@iitk.ac.in (S. Khandekar).

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Nomenclature

C	Cell center of tetrahedron
C_p	specific heat of liquid (J/kg K)
d	base diameter of the drop measured on the solid substrate (m)
f	face center of tetrahedron
g	gravitational acceleration (m/s^2)
H	height of cavity (m)
h	local heat transfer coefficient (W/m^2 K)
$\bar{h}$	average heat transfer coefficient (W/m^2 K)
$\hat{i}, \hat{j}$ and $\hat{k}$	unit vectors in x, y and z directions
k	thermal conductivity (W/m K)
n	unit normal vector drawn on the drop surface (–)
P	vertices of the grid cell (–)
p	pressure (Pa)
q	heat flux (W/m^2)
t	time (s)
t_1 and t_2	unit tangent vectors over the surface of the drop (–)
T	temperature (°C)
ΔT	temperature difference between the substrate and the drop boundary (°C)
u	velocity component in x direction (m/s)
v	velocity component in y direction (m/s)
w	velocity component in z direction (m/s)
U	sliding velocity of substrate (m/s)
V	volume of drop (m^3)
α	thermal diffusivity (m^2/s)
β	volumetric expansion coefficient (K^{-1})
μ	dynamic viscosity of liquid (Pa s)
θ	apparent contact angle (° or radians)
ρ	fluid density (kg/m^3)
τ	shear stress (N/m^2)
ϕ	general flow variable (–)

Non-dimensional parameters

C_f	local Skin friction coefficient, $\tau_{wall}/(2\rho U^2)$
$\overline{C}_f$	average Skin friction coefficient, $\overline{\tau_{wall}}/(2\rho U^2)$
Nu	local Nusselt Number, hd/k
$\overline{\text{Nu}}$	average Nusselt number, $\bar{h}d/k$
Pr	Prandtl number, $\mu C_p/k$
Re	Reynolds number, $\rho Ud/\mu$
Ra	Rayleigh number, $g\beta\,(T_h - T_c)H^3/\nu\alpha$

Dimensionless quantities

u/U	dimensionless velocity in x direction
v/U	dimensionless velocity in y direction
w/U	dimensionless velocity in z direction
$p/(\frac{1}{2}\rho U^2)$	dimensionless pressure
$(T - T_w)/\Delta T$	dimensionless temperature

Subscripts

adv	advancing angle
b	base of the drop
C	cell center of tetrahedron
Cb	cell center of boundary tetrahedron
f	face center of tetrahedron
fb	face center of boundary face
f_{123}	face of cell which have node P_1, P_2 and P_3
$free$	free surface of the drop
h, c	hot and cold surfaces
i	free indices
j	repeated indices
rcd	receding angle
x, y, z	component in the x, y, or z direction, respectively
xy	x–y plane
yz	y–z plane
n	component in the normal direction, curvilinear coordinates
t_1, t_2	component in the tangential direction, curvilinear coordinates
$wall$	condensing wall surface

viscous forces at the contact surface and chemical reactions between the condensing liquid and the promoter. Heat transfer rates and temperature fluctuations affect these interactions [11]. A detailed analysis of viscous forces that lead to substrate leaching is sparse and forms the motivation of the present work.

Literature on surface leaching due to drop motion is limited. Most of the existing work [12–17] have considered the critical state of a static sessile drop on an inclined surface and focused on the apparent contact angle hysteresis, drop shape, and drop retention with tiltable surfaces, for various combinations of the hydrophobic substrates and liquids. Elsherbine and Jacobi [16–17] performed experiments on an isolated sessile drop and reported that the drop is deformed at the critical state over an inclined substrate. The geometric parameters necessary to describe the shape of the deformed drop at the critical state over an inclined substrate, and corresponding retention forces, were investigated. Though a large volume of work exists on predicting the drop shape under static conditions, only a few researchers have reported the sliding behavior of the drop on an inclined surface [18–28]. Kim et al. [18] performed experiments for measuring the steady sliding velocity of liquid drops on an inclined surface and reported a scaling law to determine the sliding velocity of a liquid drop of known wetting characteristics. Huang et al. [19] used a front tracking method to determine the motion of two-dimensional drops and bubbles on a partially wetting surface exposed to shear flow. Gao and McCarthy [20] postulated two mechanisms for drop moving down an inclined plane. Drops can move by sliding, where the particles near the solid-liquid interface exchange their position with those at the gas-liquid interface while the bulk of the fluid remains unaffected. The particle movement along the gas- liquid and solid-liquid interfaces is compared to the motion of a tread of a chain-driven tank. On the other hand, there could be rolling motion, where the entire fluid mass undergoes a circulatory movement. Suzuki et al. [21] studied the sliding behavior of water drops on various chemically textured surfaces at a fixed inclination of 35° and reported sliding displacement of the advancing edge of the drop. Sakai et al. [22] studied rolling versus sliding behavior of drops on various chemically textured surfaces. In their theoretical analysis, Grand et al. [23] scaled the viscous force as $\mu UV^{1/3}$ for a drop of volume V moving with a speed U and reported that the sliding velocity along an inclined plane is a linear function of the Bond number. Yoshida et al. [24] did not consider viscous forces in their study of sliding behavior of water drops on a flat polymer surface. The authors reported that the sliding motion changes from constant velocity to one of constant acceleration with an increase in the apparent contact angle. Daniel et al. [25] reported the maximum velocity of the condensing sessile drop on a chemically textured horizontal substrate having a wettability gradient. Sakai