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External convective jumping-droplet condensation on a flat plate

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ABSTRACT

Water vapor condensation is vital to many natural and industrial processes such as building environmental control, power generation, and water desalination. Jumping-droplet condensation of water has recently been shown to have a 10X heat transfer enhancement compared to state-of-the-art filmwise condensation due to the removal of condensate at much smaller length scales (~1 μm) than what is capable with gravitational shedding (~1 mm). However, the efficient removal of jumping droplets can be limited by droplet return to the surface due to gravity, entrainment in bulk convective vapor flow, and entrainment in local condensing vapor flow. If used appropriately, convective condensation has the potential to entrain droplets, hence impeding their return to the surface. In this work, a comprehensive model of external convective jumping-droplet condensation on a superhydrophobic flat plate has been developed for constant heat flux boundary conditions. Boundary layer analysis was used to model the vapor flow over the external plate with condensation modeled as a vapor suction at the wall. The model was used to analyze the effects of jumping droplet size ($1 < R_d < 100$ μm), condensation heat flux ($0 < q < 10$ W/cm^2), initial jumping location along the plate (10 cm $< x_0 < 5$ m), free stream velocity ($1 < U_f < 30$ m/s), and plate inclination (0–360°), on droplet trajectory and overall heat transfer performance. Analysis of droplet trajectories revealed that the total distance traveled by jumping droplets along the plate ranged from millimeters to meters, while jumping heights were limited to less than a centimeter for the parameters considered. In addition, multiple-droplet coalescence, along with multi-jump droplet dynamics were analyzed, helping to explain a previously observed multi-hop process, and providing a potential pathway to generate larger effective trajectories along the plate. This work provides a comprehensive physical model of the external convective jumping-droplet condensation process, offers guidelines for the design of jumping-droplet systems to maximize heat transfer and minimize flooding, and develops a theoretical framework for the analysis of future convective jumping-droplet condensation processes important to more industrially relevant internal flow situations such as channels and tubes.

1. Introduction

Water vapor condensation, whether industrially driven or occurring in nature, is a critical process for the sustainability of ecosystems and advancement of economies. Due to the reduced energy barrier for vapor-to-liquid nucleation, condensation preferentially occurs on high surface energy substrates [1], forming a thermally-insulating liquid blanket, termed filmwise condensation [2]. In an effort to shed the liquid layer and enhance heat transfer, engineers and researchers have devised techniques for creating non-wetting surfaces to enable dropwise [3] or jumping-droplet condensation [4], whereby non-wetting droplets shed due to gravity at millimetric length scales or spontaneously jump away from the surface at micrometric length scales [5], respectively. Specifically, jumping-droplet condensation, whereby microdroplets (~10–100 μm) condensing and coalescing on suitably designed superhydrophobic surfaces undergo surface-to-kinetic energy transfer and result in the merged droplet jumping away from the surface [5–10], has recently been shown to have a 10X heat transfer enhancement compared to state-of-the-art filmwise condensing surfaces [11–20]. A number of works have since fabricated superhydrophobic nanostructured surfaces to achieve spontaneous droplet removal [21–31] for a variety of applications including self-cleaning [32–34], thermal diodes [33,35], anti-icing [36–39], vapor chambers [40], electrostatic energy harvesting [41–43], and heat transfer enhancement [44–55].

However, the efficient removal of jumping droplets along with the heat transfer enhancement can be limited by droplet return

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Nomenclature

ρ_l	density of liquid water
ρ_v	density of water vapor
ν_v	kinematic viscosity of water vapor
μ_v	dynamic viscosity of water vapor
μ_l	dynamic viscosity of liquid water
h_{fg}	latent heat of vaporization of water
γ	surface tension of water (liquid–vapor interface)
$\overrightarrow{g}$	gravitational field
q	heat Flux
T_{sat}	saturation temperature of the vapor
T_w	wall temperature at a given location
$\dot{m}_c$	mass flux of condensate
w	width of the plate
ψ	angle of inclination of plate (CCW)
ψ_{crit}	critical angle of inclination (CCW)
L	distance traveled by the droplet
h	maximum jumping height of the droplet (horizontal plate)
x	horizontal coordinate axis (fixed)
y	vertical coordinate axis (fixed)
x^1	coordinate axis tangent to the plate
y^1	coordinate axis perpendicular to the plate
$\overrightarrow{j^1}$	unitary vector in the y^1 direction
R	rotation matrix
V_w	velocity of the vapor at the wall, perpendicular to surface
U_f	free stream velocity
$\overrightarrow{V_{rel}}$	relative velocity vector between vapor flow and droplet
$\overrightarrow{V_f}$	velocity vector of the vapor flow
$\overrightarrow{V_d}$	velocity vector of droplet
u	horizontal velocity of the vapor flow
v	vertical velocity of the vapor flow
u^1	flow velocity in the x^1 direction
u_d^1	droplet velocity in the x^1 direction
v_d	velocity of the droplet in the y direction
v_{rel}	relative velocity in the y direction
u_{rel}	relative velocity in the x direction
$u_{d,0}^1$	initial velocity of the droplet in the x^1 direction
$u_{d,end}^1$	final velocity of the droplet in the x^1 direction
$v_{d,0}^1$	initial velocity of the droplet in the y^1 direction
$v_{d,end}^1$	final velocity of the droplet in the y^1 direction
θ	angle formed by the vertical and horizontal relative velocities (u and v)
C_D	drag coefficient
Re_x	Reynolds number based on x
Re_d	Reynolds number based on droplet radius
Re_G	Reynolds number based on velocity gradient
Re_L	Reynolds number at $x = L$
Bo	bond number
We	Weber number
Ma	Mach number
Ca	Capillary number
δ	boundary layer thickness
η	non dimensional similarity variable
φ	dimensional stream function
f	non-dimensional stream function
τ_w	wall shear stress
$\bar{\tau}$	average wall shear stress
d	distance of interest of shear stress analysis
F_p	force on the plate per unit length
$F_{p,film}$	force on the plate from laminar filmwise convective condensation
$\overrightarrow{F_D}$	drag force
$\overrightarrow{F_G}$	gravitational force
$\overrightarrow{F_{SL}}$	Saffman lift force
ϕ_S	Saffman multiplier
F_σ	adhesion force between liquid and solid
$F_{SL,x}$	x-component of Saffman force
$F_{SL,y}$	y-component of Saffman force
g_{x^1}	projection of gravity along x^1
g_{y^1}	projection of gravity along y^1
x_0	initial position of droplet in the x direction
x_0^1	initial position of droplet in the x^1 direction
y_0^1	initial position of droplet in the y^1 direction
R_d	droplet radius
m	mass of droplet
$R_{d,0}$	initial droplet radius in a multihop process
t	time
C	proportionality constant
$\Delta\theta^{app}$	apparent contact angle hysteresis
θ_e^{app}	apparent equilibrium contact angle
θ_r^{app}	apparent receding contact angle
θ_a^{app}	apparent advancing contact angle
u_c	horizontal velocity of the flow at the midpoint of the sessile droplet's vertical projection
y_c	vertical coordinate of the midpoint of the sessile droplet's vertical projection
A_p	projected face area of the sessile droplet
i	arbitrary index of a jump in a multihop process

to the surface due to (1) gravitational force (2) entrainment in a bulk convective vapor flow, and (3) entrainment in the local condensing vapor flow toward the surface [40,56]. The first two return mechanisms (gravity and bulk vapor flow) can be mitigated with suitable geometric design of the macroscale condensing surface and vapor supply. However, the third return mechanism (local vapor flow) is more difficult to eliminate due to the need to conserve mass of the condensing vapor flowing towards the surface. Although previous studies have experimentally characterized the effects of gravitational return, [57,58] further study of local vapor flow entrainment on droplet return and methods to limit this process are needed.

One avenue to enhance droplet removal after jumping is by exploiting the fact that jumping droplets attain a positive charge (∼+10fC) after departing the superhydrophobic surface due to electric-double-layer charge separation at the coating-droplet interface [43]. This discovery has allowed for the development of electric-field-enhanced (EFE) condensation, whereby an external electric field was used to enhance the removal of jumping droplets from a radial (tube) condensing surface by counteracting the three droplet return mechanisms described above [59]. Through the elimination of droplet return, a heat transfer enhancement of 20X was experimentally demonstrated, compared to state-of-the-art filmwise condensing surfaces.

While the removal of the droplets by external electric fields offers a method remove condensate, practical difficulties exist. For example, the need for energized external electrodes presents critical safety concerns. Furthermore, the need to remove the condensate from the external electrode has not been addressed. Lastly, the added complexity associated with the design and manufacture of EFE system equates to higher probability of failure once integrated into real life applications.