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External convective jumping-droplet condensation on a flat plate



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A R T I C L E I N F O

ABSTRACT

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Keywords: Convective condensation Forced convection Jumping droplet Superhydrophobic Condensation Flat plate Boundary layer Suction

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 ($\sim 1 \mu m$) 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 ($1 < R_d < 100 \mu m$), condensation heat flux $(0 < q < 10 \text{ W/cm}^2)$, initial jumping location along the plate $(10 \text{ cm} < x_0 < 5 \text{ m})$, free stream velocity $(1 < U_f < 30 \text{ m/s})$, and plate inclination $(0-360^\circ)$, 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.

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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 grav-

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ity at millimetric length scales or spontaneously jump away from the surface at micrometric length scales [5], respectively. Specifically, jumping-droplet condensation, whereby microdroplets (\sim 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 selfcleaning [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

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v_{μ} kinematic viscosity of water vapor Re_{c} Reynolds number at $x = l$ μ_{μ} dynamic viscosity of water vapor Re_{c} Reynolds number at $x = l$ $h_{h_{c}}$ latent heat of vaporization of waterBobond number T_{c} sufface tension of water (liquid-vapor interface)MaMach number T_{c} gravitational field O CaCapillary number T_{st} saturation temperature of the vapor η non dimensional stream function T_{w} walt temperature at a given location q dimensional stream function m_{w} walt temperature at a given location q distance travels walt shear stress ψ angle of inclination of plate T_{w} wall shear stress ψ_{cnt} critical angle of inclination (CCW) T average wall shear stress ψ_{cnt} critical coordinate axis (fixed) F_{p} force on the plate from laminar filmwise convective x horizontal coordinate axis (fixed) F_{r} gravitational force χ^{1}_{s1} coordinate axis negendicular to the plate ϕ_{s} Saffman Inif force χ^{1}_{s1} coordinate axis perpendicular to surface ϕ_{s} Saffman force χ^{1}_{s1} velocity vector of the vapor flow and droplet π_{s} veconponent of Saffman force χ^{1}_{s1} velocity vector of the vapor flow K_{s} initial position of droplet in the χ^{1} direction κ velocity vector of the vapor flow K_{s} initial position of droplet in the χ^{1	$ ho_1$	density of liquid water	<i>Re_x</i>	Reynolds number based on <i>x</i>
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$ \begin{array}{c} V_{\rm rel} & {\rm distance traveled by the droplet} \\ h & {\rm maximum jumping height of the droplet (horizontal plate)} \\ x & {\rm horizontal coordinate axis (fixed)} \\ y' & {\rm vertical coordinate axis (fixed)} \\ x^{\rm l} & {\rm coordinate axis (fixed)} \\ x^{\rm l} & {\rm coordinate axis (fixed)} \\ y' & {\rm vertical coordinate axis perpendicular to the plate} \\ y' & {\rm velocity of the vapor at the wall, perpendicular to surface} \\ face \\ V_w & {\rm velocity of the vapor at the wall, perpendicular to surface} \\ V_{\rm rel} & {\rm relative velocity vector between vapor flow and droplet} \\ V_{\rm r} & {\rm velocity vector of the vapor flow} \\ V_{\rm d} & {\rm velocity vector of the vapor flow} \\ V_{\rm d} & {\rm velocity vector of the vapor flow} \\ v & {\rm velocity of the vapor flow} \\ v & {\rm velocity of the vapor flow} \\ u' & {\rm for velocity of the vapor flow} \\ v' & {\rm velocity of the vapor flow} \\ u' & {\rm for velocity of the vapor flow} \\ v' & {\rm velocity of the vapor flow} \\ u' & {\rm for velocity of the vapor flow} \\ v' & {\rm velocity of the vapor flow} \\ u' & {\rm for velocity of the droplet in the y^{\rm direction} \\ v'_{\rm d} & {\rm velocity of the droplet in the y^{\rm direction} \\ v'_{\rm d} & {\rm velocity of the droplet in the y^{\rm direction} \\ v'_{\rm d} & {\rm velocity of the droplet in the y^{\rm direction} \\ v'_{\rm d} & {\rm velocity of the droplet in the y^{\rm direction} \\ v'_{\rm d} & {\rm velocity of the droplet in the x^{\rm direction} \\ v'_{\rm d} & {\rm mitial velocity of the droplet in the y^{\rm direction} \\ v'_{\rm d} & {\rm velocity of the droplet in the x^{\rm direction} \\ v'_{\rm d} & {\rm oplet in the x^{\rm direction} \\ v'_{\rm d} & {\rm oplet in the x^{\rm direction} \\ v'_{\rm d} & {\rm mitial velocity of the droplet in t$	ψ			
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u^1 flow velocity in the x^1 direction C proportionality constant u^1_d droplet velocity in the x^1 direction $\Delta \theta^{app}$ apparent contact angle hysteresis v_d velocity of the droplet in the y direction ∂_{e}^{app} apparent contact angle hysteresis v_{rel} relative velocity in the x direction ∂_{e}^{app} apparent receding contact angle $u^1_{d,0}$ initial velocity of the droplet in the x^1 direction ∂_{a}^{app} apparent advancing contact angle $u^1_{d,0}$ final velocity of the droplet in the x^1 direction u^a_{a} paparent advancing contact angle $v^1_{d,0}$ initial velocity of the droplet in the y^1 direction v_c vertical coordinate of the midpoint of the sessile droplet's vertical projection $v^1_{d,end}$ final velocity of the droplet in the y^1 direction y_c vertical coordinate of the midpoint of the sessile droplet's vertical projection $v^1_{d,end}$ final velocity of the droplet in the y^1 direction y_c vertical projection $v^1_{d,end}$ final velocity of the droplet in the y^1 direction y_c vertical coordinate of the midpoint of the sessile droplet's vertical projection $v^1_{d,end}$ final velocity of the droplet in the y^1 direction A_p projected face area of the sessile droplet v_1 angle formed by the vertical and horizontal relative A_p projected face area of the sessile droplet v_1 v_2 v_1 v_2 v_2				
$ \begin{array}{cccc} u_{d}^{1} & \text{droplet velocity in the } x^{1} \text{ direction} & & & & & & & & & & & & & & & & & & &$				
$ \begin{array}{cccc} 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} & initial velocity of the droplet in the x^1 direction & & & \\ u_{d,end}^1 & & & \\ v_{d,0}^1 & & &$				
$ \begin{array}{cccc} v_{rel} & \text{relative velocity in the y direction} & & & & \\ u_{rel} & \text{relative velocity in the x direction} & & & & \\ u_{d,0} & \text{initial velocity of the droplet in the } x^1 \text{ direction} & & & \\ u_{d,end}^1 & \text{final velocity of the droplet in the } x^1 \text{ direction} & & & \\ u_{d,end}^1 & \text{initial velocity of the droplet in the } x^1 \text{ direction} & & \\ u_{d,end}^1 & \text{initial velocity of the droplet in the } y^1 \text{ direction} & & \\ v_{d,0}^1 & \text{initial velocity of the droplet in the } y^1 \text{ direction} & & \\ v_{d,0}^1 & \text{initial velocity of the droplet in the } y^1 \text{ direction} & & \\ v_{d,end}^1 & \text{final velocity of the droplet in the } y^1 \text{ direction} & & \\ v_{d,end}^1 & \text{final velocity of the droplet in the } y^1 \text{ direction} & & \\ u_{c} & & \\ v_{d,end}^1 & \text{final velocity of the droplet in the } y^1 \text{ direction} & & \\ u_{c} & & \\ v_{d,end}^1 & \text{final velocity of the droplet in the } y^1 \text{ direction} & & \\ u_{c} & & \\ u_{c} & & \\ v_{d,end} & & \\ u_{c} & & \\ u_{c} & & \\ u_{c} & & \\ v_{d,end} & & \\ u_{c} & & \\ u_{c} & & \\ u_{c} & & \\ v_{c} &$	$v_{\rm d}$		θ_{app}^{app}	
$ \begin{array}{c} u_{rel}^{1} & \text{initial velocity in the x direction} \\ u_{d,0}^{1} & \text{initial velocity of the droplet in the } x^{1} \text{ direction} \\ u_{d,0}^{1} & \text{final velocity of the droplet in the } x^{1} \text{ direction} \\ v_{d,0}^{1} & \text{initial velocity of the droplet in the } y^{1} \text{ direction} \\ v_{d,0}^{1} & \text{initial velocity of the droplet in the } y^{1} \text{ direction} \\ v_{d,0}^{1} & \text{initial velocity of the droplet in the } y^{1} \text{ direction} \\ v_{d,0}^{1} & \text{initial velocity of the droplet in the } y^{1} \text{ direction} \\ v_{d,0}^{1} & \text{initial velocity of the droplet in the } y^{1} \text{ direction} \\ v_{d,0}^{1} & \text{initial velocity of the droplet in the } y^{1} \text{ direction} \\ u_{d,0}^{2} & \text{vertical coordinate of the midpoint of the sessile droplet} \\ v_{d,0}^{2} & \text{initial velocity of the droplet in the } y^{1} \text{ direction} \\ v_{d,0}^{2} & \text{velocities } (u \text{ and } v) \\ \end{array}$				
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θ^{opthal} angle formed by the vertical and horizontal relative A_{p} projected face area of the sessile droplet arbitrary index of a jump in a multihop process			y _c	vertical coordinate of the midpoint of the sessile dro-
θ angle formed by the vertical and horizontal relative A_p projected face area of the sessile droplet velocities (u and v) i arbitrary index of a jump in a multihop process	$v_{d,end}^{I}$		٨	
	θ			
C _D arag coefficient	C		1	arditrary index of a jump in a multihop process
	c_D	drag coefficient		

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 (\sim +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. Download English Version:

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