International Journal of Heat and Mass Transfer 128 (2019) 550–561

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Electrostatic-induced coalescing-jumping droplets on nanostructured superhydrophobic surfaces

B. Traipattanakul [a], C.Y. Tso [a,b,c], Christopher Y.H. Chao [d,*]

[a] Department of Mechanical and Aerospace Engineering, The Hong Kong University of Science and Technology (HKUST), Clear Water Bay, Kowloon, Hong Kong, China
[b] HKUST Jockey Club Institute for Advanced Study, The Hong Kong University of Science and Technology (HKUST), Clear Water Bay, Kowloon, Hong Kong, China
[c] School of Energy and Environment, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong, China
[d] Department of Mechanical Engineering, The University of Hong Kong, Hong Kong, China

A R T I C L E I N F O

Article history:
Received 5 June 2018
Received in revised form 13 August 2018
Accepted 31 August 2018

Keywords:
Condensation heat transfer
Electrostatic
Jumping droplets
Jumping height
Superhydrophobic surface

A B S T R A C T

Coalescing-jumping droplets from the condensation of water vapor on a non-wetting surface return to the substrate due to resistance forces. While some can coalesce with neighboring droplets and jump again, some adhere to the surface and become larger, leading to progressive flooding, limiting heat transfer performance. To address these issues, an electric field is utilized. This study investigates the jumping height, the droplet charge, the jumping angle, the gravitational force, the drag force, the inertia force and the electrostatic force of coalescing-jumping droplets in electric fields through experiment and mathematical models. The results show that an electric field can enhance the jumping height due to a significant increase in the electrostatic force. With the applied electric field, the maximum jumping height is over three times higher than those without. Additionally, the study reports the intersection point at the jumping droplet radius of 35 μm separating jumping droplet motion into two regimes; the drag-force-dominated regime where the small-sized droplets can jump and reach the top plate, and the gravitational-force-dominated regime where the larger droplets can jump, but return to the substrate. The other intersection point is between the gravitational force and the inertia force showing a decrease in the influence of the inertia force with a greater applied electric field. Moreover, it is also found that the average charge of the droplets is relatively constant in all pressure conditions and applied electric fields. The results of these findings can further advance knowledge on the enhancement of heat transfer and can be applied to several applications including self-cleaning, smart windows, thermal diodes and condensation heat transfer enhancement.

1. Introduction

Condensation heat transfer processes can be found in thermal management systems [1,2], power generation systems [3] and water harvesting systems [4,5]. On a non-wetting surface, small spherical condensates, the result of dropwise condensation, have the potential to enhance heat transfer much more than filmwise condensation [6,7]. When droplets coalesce on the surface, excess surface energy converts to kinetic energy leading to a jumping phenomenon of coalescing droplets [8–12]. These departing droplets leave new spaces on the surface which can be exposed to the continuing water droplet condensation process [13], enhancing heat transfer by 30% compared to the normal dropwise condensation [14,15]. Over the past decade, the coalescing-jumping droplets have been investigated in several aspects to provide more insights to the self-propelled jumping droplet mechanism. The self-jumping of the coalescing-jumping droplets on a superhydrophobic surface due to dropwise condensation was first discovered by Boreyko and Chen [8], who reported that the phenomenon of coalescing-jumping droplets was caused by the conversion of excess surface energy to kinetic energy. They also indicated that the droplet velocity is approximately 20% of the capillary-inertial velocity. Nam et al. [9] numerically investigated the hydrodynamic analyses of coalescing-jumping droplets on superhydrophobic surfaces with a full 3D unsteady model based on the level contour reconstruction method. They found that a quick increase in kinetic energy of the merging droplets at the initial state of the evolution was caused by low pressure at the neck due to the high negative curvature of the liquid bridge [9]. Liu et al. [10] investigated the phenomenon of coalescing-jumping droplets using a 2D lattice Boltzmann simulation based on the pseudo-potential lattice Boltzmann model with the real gas equation of state. Their results showed that when the

---

* Corresponding author at: Department of Mechanical Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong. Tel.: +852 3917 2800.

E-mail address: cyhchao@hku.hk (C.Y.H. Chao).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.08.134
0017-9310/

Nomenclature

a_y	droplet acceleration in the vertical direction [m/s^2]
Bo	Bond number [–]
Ca	Capillary number [–]
C_D	drag coefficient [–]
E	applied electric field [V/m]
F_D	drag force [N]
F''_D	drag force per droplet cross-sectional area [N/m^2]
F_E	electrostatic force [N]
F''_E	electrostatic force per droplet cross-sectional area [N/m^2]
F_I	inertia force [N]
F''_I	inertia force per droplet cross-sectional area [N/m^2]
F_W	gravitational force [N]
F''_W	gravitational force per droplet cross-sectional area [N/m^2]
g	gravitational acceleration [m/s^2]
H	jumping height of the jumping droplets [m]
L	gap width between two copper plates [m]
m	mass of the droplet [kg]
Oh	Ohnesorge number [–]
Q	droplet charge [C]
q	droplet charge per surface area of the droplets on the substrate [C/m^2]
R	jumping droplet radius [m]
R_0	droplet radius on the superhydrophobic substrate [m]
t	the initial time when a jumping droplet departs from the substrate [s]
v_a	air velocity [m/s]
v_0	initial velocity of the coalescing-jumping droplets [m/s]
$v_{0,y}$	initial velocity of the coalescing-jumping droplets in the vertical direction [m/s]
v_y	velocity of the coalescing-jumping droplets in the vertical direction [m/s]
V	applied electrical voltage [V]
We	Weber number [–]
Δt	time duration of the jumping droplets [s]
Δv_y	the change in the droplet's velocity in the vertical direction [m/s]
Δy	the change in the droplet position in the y direction [m]
θ	jumping angle with respect to x axis [°]
μ_a	air viscosity [Pa s]
μ_w	water droplet viscosity [Pa s]
ρ_a	air density [kg/m^3]
ρ_w	water droplet density [kg/m^3]
σ	surface tension [N/m]

droplet radius was smaller than 50 μm, the jumping velocity increased with an increase in the droplet radius. However, the jumping velocity decreased with an increase in the droplet size when the droplet radius was larger than 50 μm [10]. These results obtained by Liu et al. [10] were in line with experimental results reported in Ref. [8]. Liu et al. [10] further indicated that the maximum jumping height of the classical coalescing-jumping droplets was about 1.5 mm above the substrate. Liu et al. [11] conducted 3D numerical simulations on the coalescing mechanism with the assumed 180-degree contact angle. They found that the non-dimensional jumping velocity in the capillary-inertial regime is 0.2, the same as reported in Ref. [8]. They also mentioned that the capillary-inertial regime was defined with the ohnesorge number of less than 0.1 [11]. Enright et al. [12] experimentally and numerically studied the coalescing droplet velocity and the internal flow momentum during the jumping mechanism. They found that only 6% of excess surface energy was converted to kinetic energy [12].

However, resistance forces and vapor flow around the surface can limit the jumping height and cause coalescing-jumping droplets to return to the surface regardless of the jumping orientation [16,17]. These returning droplets can either coalesce with other neighboring droplets on the surface and jump again, or adhere to the surface. Miljkovic et al. [16] showed that after 10 min of condensation, the maximum droplet radius on the substrate increased by almost 15 times to 140 μm. These large droplets on the surface cause progressive flooding leading to heat transfer degradation [16,17]. Utilization of an electric field has been proven to be one of the effective methods to address the condensation heat transfer degradation issue caused by the progressive flooding [17–19]. Traipattanakul et al. [18] utilized a high parallel electric field intensity to remove 2 mm droplets from a flat superhydrophobic copper substrate. They found that the voltage threshold applied to parallel plates linearly increased with an increase in the gap width between the two plates [18]. Apart from the removal of the large-sized droplets adhering to the surface, the electric field can also be applied to increase the jumping height of the coalescing-jumping droplets and to prevent the growth of the droplet size on a non-wetting surface, resulting in the enhancement of the condensation heat transfer [16,17,19]. Miljkovic et al. [19] first revealed the electrical charge of droplets condensed on a superhydrophobic surface. They investigated [19] the electrostatic-induced jumping droplet behavior on a copper tube which was coated with copper oxide nanostructures. It was discovered that jumping droplets' trajectories move in the same direction as the electric field, and the amount of charge did not depend on the electric field intensity, but the droplet surface area as well as types of hydrophobic coatings [19]. Due to the electric-double-layer charge separation at the hydrophobic coating and the droplet interface [20], jumping droplets gained a positive charge, implying that droplets from dropwise condensation on a non-wetting surface could move along an electric field [19]. Additionally, the findings from another experimental study conducted by Miljkovic et al. [16] showed that when the applied electric field increased, the number of droplets returning to the condensing substrate significantly reduced. The findings [16] also showed that electric-field-enhanced condensation could minimize the droplet size and increase the number of small droplets on a superhydrophobic surface. As a result, when the applied electric fields were 10 V/mm and 20 V/mm, the overall heat transfer coefficient increased by 50% compared with the classical coalescing-jumping droplets without an applied electric field [16]. A theoretically comprehensive model was also developed by Birbarah et al. [17], revealing the relationship of the drag force, the gravitational force and the electrostatic force acting on jumping droplets in the anti-gravitational orientation. However, it should be noted that the inertia force was neglected in the Ref. [17], and they reported that when the droplet radius was larger than 20 μm, the gravitational force dominates the drag force, and vice versa, based on their developed model [17].

Although previous studies investigated the coalescing-jumping droplets on a superhydrophobic surface in electric fields in some aspects, there is a lack of understanding of several physical parameters affecting the jumping height and the jumping physics of the coalescing-jumping droplets including the gap width between the superhydrophobic copper plate and the normal copper plate, the applied electric field, and the pressure condition. Therefore, the current study aims to investigate the effects of applied electrical potential differences on the jumping height of coalescing-jumping droplets with respect to the droplet size and