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Study of jumping water droplets on superhydrophobic surfaces with electric fields

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ABSTRACT

Macro-sized droplets adhering to non-wetting surfaces, a phenomenon referred to as progressive flooding, is one of the major problematic issues found on a superhydrophobic condenser, which reduces the heat and mass transfer performance. Utilization of an electric field on superhydrophobic surfaces can potentially address this problem. In this study, a water droplet is placed on a superhydrophobic plate which is in parallel to another plate. A positive electrode and a ground line are connected to the bottom plate and the top plate, respectively. The droplet motion is recorded by a high-speed camera and analyzed in sequential frames. This work aims to investigate the electrical voltage threshold, the electric field threshold and the droplet charge required to remove a macro-sized droplet from a superhydrophobic surface. The results show that with an increase in gap width, both the electrical voltage threshold and the electric field threshold increase, while the droplet charge decreases. Additionally, the results of this study also reveal a constant electrostatic force acting on droplets in the air and the maximum electrostatic force acting on droplets on the superhydrophobic surface regardless of the gap width and of applied electric field intensity. This work can offer a platform for improving the performance of self-cleaning surfaces, thermal diodes/switches and anti-icing surfaces.

1. Introduction

Condensation heat transfer processes can be found in thermal management systems [1,2], power generation systems [3] and water harvesting systems [4]. 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 [5–7]. 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 [13,14], enhancing heat transfer by 30% compared to the normal dropwise condensation [15,16]. However, gravitational force and vapor flow around the surface can cause jumping droplets to return to the surface [17]. These returning droplets can either coalesce with other neighboring droplets on the surface and jump again, or adhere to the surface. As time progresses, the size of these adhering droplets become larger, leading to progressive flooding. As a result, condensation heat transfer will be degraded [18]. Electric fields applied between two parallel plates to remove droplets adhering to the surface is one potential method to solve this problem. A number of studies are carried out to investigate the electrostatic-induced jumping water droplets in both horizontal and vertical directions with various electric fields and gap widths.

In the study by Takeda et al. [19], a DC high voltage power supply connected to the glass-coated superhydrophobic surface was used to create a strong vertical electric field between two parallel plates with a gap width of 10 mm. The results showed that a 2-mm diameter droplet can jump to the top plate when a 9 kV voltage was applied. Roux et al. [20] also investigated saturated NaCl solution droplets and 0.5 M NaCl solution droplets on a non-wetting surface in a light-mineral-oil condenser with applied electric fields. Droplets were placed on the surface with the gap width of 33 mm. Mineral oil has the specific density of 0.84, the relative permittivity (ε_r) of 2.11 and the electrical conductivity (σ) of 396×10^{-15} S/m. The electric field thresholds of four different droplet sizes were revealed. The results showed that a saturated NaCl solution droplet with a maximum diameter of 1.5 mm required at least 175 V/mm to depart from the surface, while only 125 V/mm was required to induce the jumping of the less condensed 0.5 M NaCl solution

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Nomenclature

A	droplet cross-sectional area [m^2]
C_D	drag coefficient [–]
E	electric field [V/m]
F_{AD}	maximum adhesion force [N]
F_W	gravitational force [N]
F_D	drag force [N]
F_E	electrostatic force [N]
F_B	buoyancy force [N]
$F_{E,S}$	maximum electrostatic force [N]
g	gravitational acceleration [m/s^2]
L	gap width between two plates [m]
Q	droplet average charge [C]
Re	Reynolds number [–]
r_o	droplet radius [m]
r_c	contact radius [m]
t	time duration [s]
V	electrical voltage [V]
V_d	droplet volume [m^3]
v_d	droplet velocity [m/s]
We	Weber number [–]
ε	medium fluid permittivity [F/m]
ε_r	relative permittivity [–]
θ	contact angle [°]
θ_{cr}	critical contact angle [°]
μ	air viscosity [kg/ms]
ρ_a	air density [kg/m^3]
ρ_w	water density [kg/m^3]
γ	water-air surface tension [N/m]
σ	medium fluid conductivity [S/m]
τ	relaxation time [s]

droplet. In addition, Khayari et al. [21] studied dynamics of a water droplet in corn oil in a vertical electric field. The density of the corn oil is 916 kg/m^3, while the permittivity (ε) and the electrical conductivity (σ) are 26.9×10^{-12} F/m and 19x10^{-12} S/m, respectively. The drop radius was 1.337 mm resting on a steel electrode, and the fixed gap width was 20 mm. Their results showed that the electric field threshold for lifting the droplet was approximately 170 V/mm. Furthermore, Khayari and Perez [22] experimentally and theoretically studied the charge acquired by a spherical ball bouncing on an electrode. Three medium fluids, namely corn oil (relative permittivity (ε_r) = 3.04–3.11, conductivity (σ) = 26.2–60.8 $\times 10^{-12}$ S/m), sunflower oil (relative permittivity (ε_r) = 3.04–3.07, conductivity (σ) = 11.0–14.3 $\times 10^{-12}$ S/m), and isopar (relative permittivity (ε_r) = 2.0, conductivity (σ) = 70–317 $\times 10^{-12}$ S/m) were used. The gap widths were 20 mm and 40 mm. The three types of spherical balls were made from a plastic covered by aluminum sheets with the radius of 4 mm, and made from aluminum sheets with the radii of 3.25 mm and 2.33 mm. The experimental results of the electric field threshold ranged between 346 V/mm and 403 V/m. Additionally, the electrical voltage threshold ranged between 7.1 kV and 16.1 kV. With the same medium fluid and the same gap width, when the droplet size increased, the voltage threshold and the electric field threshold increased. Moreover, Jung et al. [23] studied small water droplets in silicon oil in a horizontal electric field. While the density of the silicon oil is 957.24 kg/m^3, the permittivity (ε) and the electrical conductivity (σ) are 24.35×10^{-12} F/m and 1×10^{-13} S/m, respectively. The radius of the droplets ranged from 0.363 mm to 0.726 mm, and the gap width was 10 mm. The results showed that the electrical charging process depended on the electric field strength and the size of a droplet. However, due to the horizontal electric field and the horizontal motion of the droplet, the electric field threshold was not studied. Jalaal et al. [24] also investigated falling water droplets in transformer oil with an applied horizontal electric field. The density of the transformer oil is 841.9 kg/m^3. The relative permittivity (ε_r) and the electrical conductivity (σ) are 2.1 and 3.3×10^{-12} S/m, respectively. The droplet diameters ranged from 0.3 mm to 3.5 mm. They found that a high voltage electrode pulled the droplet (i.e. the droplet gained the positive charge after touching the electrode and jumped away due to the electrophoretic force) as the droplet passed through the electric field. Their results also showed that an applied voltage of 6 kV was required to move droplets of 1 mm and 2 mm in diameter between two electrodes, but an electrical voltage of 7.5 kV was needed for droplets with a diameter of 3 mm.

Although the previous studies demonstrated that the electric field can be used to move droplets in various medium fluids and at different fixed gap widths, there is still a lack of understanding of the effects of the electric field threshold and the droplet charge on droplets resting on the superhydrophobic surface with air as the medium fluid. Therefore, this study aims to investigate the effects of the electrical voltage threshold, the electric field threshold and the droplet charge required to remove a macro-sized droplet on a superhydrophobic surface at varying gap widths when air serves as the medium fluid, an area of research which has never been studied before. Moreover, this study is the first study to reveal the electrostatic forces acting on a droplet both in mid-air and on the electrode before lift-off, leading to new understanding of the droplet dynamics in the electric field. Additionally, the charge relaxation time and the lift-off mechanism are discussed and compared with other previous studies. The results of the current study not only can shed more light on the issue of progressive flooding, but also can provide further research value to the areas of self-cleaning [25], thermal diodes [26,27], anti-icing [28] and condensation heat transfer [29].

2. Review of theoretical work

In this section, previous research on coalescing jumping droplets is chronologically and briefly presented in order to provide insight of some major findings in this field. Then, the fundamental physics of the droplet dynamics in an electric field, namely forces acting on a droplet, the lift-off mechanism and charging relaxation time, from previous similar studies are illustrated for later discussion in the current work.

2.1. Background of the coalescing jumping droplets

A great deal of research has been conducted on the coalescence of droplets and the jumping mechanism over the past five years. The following are findings from some important research in this field, presented chronologically. Boreyko and Chen [8] reported that dropwise condensates can coalesce with each other and self-jump from a non-wetting surface as a result of the conversion of excess surface energy to kinetic energy. The coalescing jumping phenomena of two individual drops was observed and the inertial-capillary velocity of such jumping was developed. A study by Nam et al. [9] also showed that a quick increase in kinetic energy of the merging droplets was caused by low pressure at a