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Bouncing characteristics of an elliptical footprint drop on a solid surface

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ABSTRACT

Bouncing dynamics of drops on solid surfaces have gained increasing importance in a wide range of practical applications, such as surface cooling, coating, and agricultural spray. Here, we investigate the bouncing characteristics of elliptical footprint drops on nonwetting surfaces through numerical simulation. The bouncing dynamics are investigated as a function of the geometric aspect ratio (AR), impact velocity, and effective interfacial tension. During bouncing, drop splashing occurs at high AR, high impact velocity, and low interfacial tension because the conditions enable liquid to be highly elongated and well-aligned along one horizontal axis before bouncing. We determine a splash regime for varying ARs and Weber numbers. Momentum analyses in horizontal axes reveal that the underlying mechanism of splashing can be interpreted as retarded retraction and low retraction momentum during bouncing at high AR and Weber number. This work can offer potential implications for the control of bouncing dynamics with drop shape and broaden our fundamental understanding of elliptical drop dynamics after the impact.

1. Introduction

Bouncing dynamics of drops on solid surfaces is ubiquitous in nature and can be observed in a wide range of practical situations, such as rain drops colliding on an umbrella and splashing drops onto target solids in surface cleaning and spray cooling [1–6]. The characteristics of dynamics have made a considerable progress since Worthington initiated pioneering works about impact patterns [7–9]. Various studies have revealed that bouncing behavior is highly affected by several factors, including surface wettability and roughness, impact velocity, and material properties of fluids [2,10]. In particular case of impact on high-temperature surfaces, drops can bounce off quickly because of a stable vapor layer between liquid and solid, which is known as the dynamic Leidenfrost phenomenon [11–13]. Leidenfrost drops that are produced by the phenomenon can have a high mobility and levitate on a continuously formed vapor layer without any contact with solid, which is analogous to drops bouncing on highly hydrophobic surfaces [14–18]. Depending on boiling regimes [15,19], drop bouncing can be accompanied by the formation of small drops, such as satellite drops due to destabilization of the moving edge of the drop (called as splash) [2,19], liquid fragmentation due to hole-opening mechanism [20], and secondary drops with extremely small size like mists [21–23]. Such drop bouncing and the ejection of small drops can result in the reduction in the efficiency of spray cooling. Several works have suggested methods to change the bounce characteristics. Bertola et al. reported that dilute polymer solution drops suppressed the formation of splashing and secondary atomization [23,24]. Celestini and Kirstetter investigated the effect of an electric field applied between Leidenfrost drops and solids on the bouncing [25]. Deng and Gomez studied the effect of electric charge in microdrops on conducing surfaces and demonstrated that drop rebound at the Leidenfrost temperature could be suppressed in spray cooling [6]. The emphases of current studies mainly focus on controlling the bouncing behavior of impinging drops.

Recently, we suggested an efficient approach for suppressing the bounce magnitude of drops and improving deposition by electrically deforming drops into elliptical shapes at the moment of impact [26–29]. The drops hitting nonwetting solid surfaces altered the impact dynamics considerably, thereby resulting in anti-rebound. The geometric aspect ratio (AR) of the drop, which ranged from 1.0 to 2.0, dominantly affected the impact dynamics and the outcomes. In addition, the bounce magnitude of elliptical Leidenfrost drop on the surfaces was suppressed compared with the spherical drop, and the contact time with the surface was reduced below the theoretical limit [28]. The suppression of the bounce magnitude could be achieved by avoiding convergence of kinetic energy (KE) on symmetric axis and converting the axial KE into the non-axial KE. In other words, the reduction in the bounce magnitude was basically due to symmetry breaking in liquid mass and momentum, thereby resulting in exceptional spreading and retracting dynamics. The distinctive features of

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shape-dependent impact dynamics do not require modification of either solid surface or the chemical composition of liquid.

Our previous study demonstrated that the splashing of elliptical Leidenfrost drops with high AR occurred during bouncing [29]. The study reported that the drop bounced off the surface and then divided itself into three parts in the experiment. The phenomena might be triggered by effects of the initial symmetry breakup in dynamics and effects of fluid properties. The former effects could be related to extremely elongated and aligned liquid on one horizontal axis caused by asymmetric spreading and retraction dynamics, which is a typical feature of elliptical drop impact [27]. The latter effects can be related to a reduced effective interfacial tension due to high temperature of the solid surface or electric charging of the impinging drop. The effective interfacial tension can reduce to 0.058 N/m at boiling temperature of 100 °C in water [13,14], based on the thermal effect. Moreover, the interfacial tension can reduce to 0.040 N/m at the amount of charge of 0.42 nC in 2-mm drops, based on the effect of electric charge [30,31]. In dynamic situations of drop impact, the interfacial tension would vary spatially at the interface.

Thus, the occurrence of splashing during bouncing of elliptical drops is highly affected by asymmetry in mass and momentum and the variation in the interfacial tension. The effects of the relevant parameters on the bouncing behavior should be scrutinized. However, the hydrodynamics of bouncing drops have not been profoundly investigated in previous works. Systematical considerations on key parameters that control splash, including AR, impact velocity (U), and liquid–vapor effective interfacial tension (σ), should be addressed to understand bouncing characteristics.

In this study, we focus on elliptical drop impact on a nonwetting solid surface and study how three factors, namely, AR, impact velocity, and liquid–vapor interfacial tension, affect the bouncing dynamics by conducting numerical simulation using a volume-of-fluid (VOF) method. The dynamics is quantified by analyzing the contact diameters and horizontal widths of drops. We determine the splash regime as a function of AR and Weber number to understand the key parameters that affect the bouncing characteristics systematically. Finally, the underlying principle behind splashing during bouncing are investigated through momentum analysis.

2. Numerical method

We employed a VOF numerical method to investigate the effects of AR, impact velocity, and liquid-vapor interfacial tension on bouncing dynamics. The incompressible, unsteady, and three-dimensional numerical scheme used in this work was entirely based on previous works studying spherical or elliptical drops impacting on a solid using the VOF method [27,32,33]. Operating liquid and vapor were used as water and air at room temperature, respectively. The geometrical model of elliptical drops was represented as prolate ellipsoids with $x^2/a^2 + y^2/b^2 + z^2/a^2 = 1$, which was assigned to the initial phase condition for liquid, where a and b are the minor and major axes of the horizontal planes, respectively. The AR was determined as a ratio of the major axis to the minor axis when drops touch the surface. The computational domain had a mesh resolution of 40 cells per drop diameter (nearly 2 mm). For convergence of velocity and pressure field, we set a time step of 1 μs, maximum internal iteration of 30 per time step, and normalized residuals less than 10^{-5}. We adopted a contact angle of 180° in drop dynamics on a solid surface, which was suitable for reasonable prediction of overall bouncing dynamics including spreading and retraction behaviors. For momentum analysis, we obtained temporal variations of the volume integral of the momentum in each horizontal axis for liquid. The signs of the momentum were prescribed to correspond positive and negative signs to spreading and retracting motions, respectively.

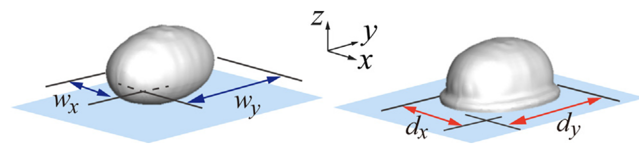

Fig. 1. Schematics of the elliptical drop impact on a solid surface and the related physical quantities. The parameters of w and d are the normalized horizontal width and normalized contact diameter by the equilibrium diameter of the initial drop (D = 1.97 mm), respectively.

To quantify bouncing dynamics, dimensionless horizontal widths (w) and contact diameters (d) in the x- and y-axes were investigated as described in Fig. 1. The dimensionless parameters of w, w_m (maximal horizontal width), d, and d_m (maximal contact diameter) are the normalized values by the equilibrium diameter of the initial drop (D = 1.97 mm).

The water drop impact can be governed by several dimensionless numbers, such as Weber number ($We = \rho DU^2/\sigma$), which indicates the relative ratio of the inertial force to surface force; Reynolds number ($Re = \rho DU/\mu$), which represents the relative ratio of the inertial force to viscous force, Ohnesorge number ($Oh = \mu/(\rho D\sigma)^{1/2}$), which denotes the relative ratio of the viscous force to inertial and surface forces, where ρ is the density, and μ is the viscosity of the drop.

This work dealt with impact conditions in ranges of AR = 1.5–2.9, U = 0.5–1.3 m/s and σ = 0.040–0.072 N/m, which yielded We = 7–85, Re = 985–2561, and Oh = 0.0026–0.0036. This result implied that drop impact corresponded to inertia-capillary regime [2,10] because the viscous force was negligible and the inertial and surface forces are dominant.

To verify the numerical model, we investigated the drop impact on a heated surface experimentally by using a high-speed camera (Photron, Fastcam SA3). The surface temperature was kept at 400–450 °C, which could produce a stable vapor layer to enable liquid to bounce on perfect non-wetting surfaces [28]. Elliptical drops were generated using a typical nozzle–ring electrospraying setup composed of a modified ring electrode, of which the inner hole had an elliptical shape [26]. A pulse signal with high voltage of 6–7 kV was applied between the nozzle and ring for 7–10 ms. The amount of charge of impinging drops was measured as 0.30–0.42 nC by using an electrometer (Keithley 6514), which depended on applied voltages.

The qualitative comparison between the experiment and simulation showed a reasonable prediction of the bouncing behavior, as shown in Fig. 2a. In addition, the contact diameters were compared between the experiment and simulation, as shown in Fig. 2b. The discrepancy in maximum spreading time of the x-axis was observed for the experimental and numerical results. The discrepancy might be related to thermodynamic effects in the experiment, such as the rupture of liquid film and the hole formation of the center on heated surfaces [19,20]. The simulation did not consider any thermodynamic effects and did not employ a vapor film model that could alter spreading and retraction dynamics [34,35]. The hole formation observed in the experiment and comparison of horizontal widths between the experiment and simulation are described in Supplementary Figs. S1 and S2.

3. Result and discussion

3.1. Variation of AR at We = 67 (U = 1.3 m/s and $\sigma = 0.70\ \sigma_0$)

First, we investigated the effects of AR on bouncing dynamics at constant conditions of U = 1.3 m/s and $\sigma = 0.70\ \sigma_0$ = 0.050 N/m,