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Impact dynamics of egg-shaped drops on a solid surface for suppression of the bounce magnitude

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ABSTRACT

Enhancement of drop deposition is advantageous in various fields, such as painting, cooling, and agricultural spraying. We present a method to suppress the bounce magnitude of a drop on nonwetting solid surfaces via asymmetrical shaping. Numerical results show that the asymmetrical drop shape can substantially alter the hydrodynamics, thereby leading to a reduction in bounce height by nearly 55% on hydrophobic surfaces compared with the spherical shape. To elucidate how the shape affects the bounce magnitude, we scrutinize the asymmetrical hydrodynamic features in spreading and retraction and the quantitative analysis of momentum for varying geometric parameters, revealing that enhancement of asymmetry in the horizontal momentum plays a vital role in suppressing bounce magnitude. The asymmetrical drop impact can provide implications for exploiting dynamic scenarios of drops, such as fusion of sprayed drops in unequal size and drop manipulation in microfluidics.

1. Introduction

Drop deposition is widely used in diverse applications, including inkjet printing [1], cooling [2,3], and agricultural spraying [4]. In these applications, several physical outcomes may arise during drop impact on a solid surface, such as deposition, rebound, and splashing [5–7]. The drop rebound is generally accelerated by high impact velocity, high surface tension, and low viscosity of fluid and high receding angle on solid surfaces. In agriculture, drop rebound suppression is needed because sprayed liquids often contain pesticides [8]. The fraction that bounces off waxy plant leaves leads not only to environmental pollutions of the soil and groundwater but also to increased costs that compensate for loss [9,10]. Thus, low retention of drops on surfaces should be improved through advanced methods for efficient drop deposition.

Current approaches to improve drop deposition depend on modifying the fluid properties and the solid surface. Drop rebound was prevented by adding a small amount of polymer additives to utilize the rheological properties of the fluid [11–13], adding surfactants to reduce the surface tension of the fluid [14,15], and charging microdrops electrically to adhere them on conductive surfaces [2,16]. Another methods of enhancing drop deposition was to pin the contact line of sprayed drops on hydrophobic surfaces through *in-situ* precipitation of polyelectrolytes on the surface [17]. Oscillating target solids horizontally or vertically caused rebound suppression by exerting mechanical forces on drop hydrodynamics [18,19]. In addition, an eletcrowetting can increase drop deposition by controllable wettability of drops [20,21].

As an alternate approach, shape-dependent impact dynamics was proposed by our group [22–25]. The non-axisymmetrical drop impact on hydrophobic surfaces (HP) exhibited the feasibility of controlling of drop deposition with the initially deformed shape [22]. The ellipticity of the drop shape at the impact moment alters the spreading and retraction dynamics considerably, thereby increasing the critical impact velocity that causes rebound. Analysis of the kinetic energy exchange between the horizontal axes accounted for the anti-rebound mechanism [23]. Shape-dependent method is an economical and eco-friendly technique because it does not require surface modification of the target solid or chemical transition of liquid. The elliptical drop not only reduces its bounce magnitude but also promotes fast detachment from surfaces with high water-repellent properties [24,25].

The previous works reporting the elliptical footprint drop impact on solid surfaces showed the rebound suppression on hydrophobic surfaces [22,23] and a substantial reduction in the maximum height of bouncing drops on heated [24] and superhydrophobic surfaces [25]. The works investigated the effects of the ellipsoidal shapes on the bouncing dynamics and the contact time with the solid. The ellipsoidal shapes used in the previous works were non-axisymmetric with respect to the normal vector of the solid plane. However, the shapes were far from asymmetrical shapes because the ellipsoids were still axisymmetric with respect to the principal axes [23].

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To further understand the shape-dependent impact dynamics and extend the capability to enhance drop deposition, we introduce asymmetrical drop shapes, such as egg shape, and hypothesize that the shapes may show distinct hydrodynamics, compared with the typical spherical shape. We demonstrate the effect of shape on impact dynamics through the experiment and simulation, which reveals that the asymmetry and ellipticity of the asymmetrical shape play a crucial role in reducing the bounce height on nonwetting surfaces. The asymmetrical shape is motivated by the collision of drops with unequal sizes in a natural phenomenon, such as rain drops. This scenario would be potentially applicable to merging of unequal-size drops in the phenomena of nature [26], drop interaction in dual spray ionization [27], and drop manipulation, including dispensing and splitting in microfluidics [28].

In this study, we focused mainly on the effect of the asymmetrical drop shape on the suppression of the bounce magnitude by performing a parametric study in the volume of fluid (VOF) simulation. The simple geometric model of the drop shape was introduced, and diverse asymmetrical shapes were derived by using geometry parameters of asymmetry and ellipticity. We elucidated how shape affects symmetry breaking in the horizontal momentum and the consequent suppression of bounce magnitude.

2. Numerical and experimental method

In the simulation, we used VOF method to predict the asymmetrical drop impact on the solid surface. Our numerical schemes were based on previous works that simulated drop impact on a solid surface [23,29,30]. Operating liquid and gas were employed as water and air at room temperature, respectively. In the two-phase system, the phases were indicated by the subscripts 1 and 2, and the volume fraction was represented by φ. The unsteady and three-dimensional mass and momentum equations were solved in the computational domain as

$$\frac{\partial}{\partial t}(\rho) + \nabla \cdot (\rho \vec{v}) = 0, \quad (1)$$

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v}\vec{v}) = -\nabla p + \nabla \cdot [\mu(\nabla \vec{v} + (\nabla \vec{v})^T)] + \rho \vec{g} + 2\sigma\rho\kappa\nabla\varphi_2/(\rho_1 + \rho_2), \quad (2)$$

where $\rho = \varphi_2\rho_2 + (1-\varphi_2)\rho_1$, $\mu = \varphi_2\mu_2 + (1-\varphi_2)\mu_1$, and κ is the surface curvature [$\kappa = -(\nabla \cdot \vec{n})$, where $\vec{n}$ is the unit normal to the surface]. The surface tension force for VOF calculation was employed in a source term of the momentum equation [31]. The advection equation for the volume fraction was used as $\partial\varphi/\partial t + \vec{v} \cdot \nabla\varphi = 0$. The volume tracking of interfaces was solved using the VOF algorithm described by Rider and Kothe [32]. In the model equations given above, the temporal derivatives were discretized using a first-order implicit method, and the spatial derivatives were discretized using the convective modeling described by Leonard [33]. The egg-like asymmetrical shapes were derived from the asymmetry and ellipticity according to the simple geometry model. We patched the shape as the initial drop shape in a computational domain. The domain presented a mesh resolution of nearly 50 cells per drop diameter. The maximum internal iteration and time step were selected to 30 per time step and 1 μs, respectively. To investigate the mechanism behind the rebound suppression, we introduced temporal variation in the volume integral of the horizontal and vertical momentum. In the inertia-capillary regime of drop impact, the hydrodynamics can be governed by Weber number (We = $\rho DU^2/\sigma$) representing a ratio of the inertial force to the surface tension and Ohnesorge number (Oh = $\mu/(\rho D\sigma)^{1/2}$) denoting a ratio of the viscous force to the inertial force and surface tension, where ρ is the density, D is the equilibrium diameter, U is the impact velocity, σ is the liquid–gas interfacial tension, and μ is the viscosity of the drop. In this work, the water drop impact yielded We = 10–24 and Oh = 0.0026, which indicated extremely weak viscous force. Thus, the inertia-capillary force balance can represent the impact dynamics. A contact angle of 100° was set to reasonably reproduce impact dynamics that is comparable with the experimental results on hydrophobic surfaces, based on the previous study [23]. In addition, a contact angle of 155° was set to represent impact dynamics on superhydrophobic surfaces. Details of the contact angle model are described in Figs. S1 and S2 of the Supplementary materials.

In the experiment, asymmetrical drops were generated using a conventional nozzle-ring electrospray device. We used a stainless-steel nozzle (Hamilton 27 gauge), and a water drop hanging from the nozzle with a volume of 4 μL was made by using a syringe pump. The modified ring was fabricated from copper. The inner shape of the ring included three teeth toward the ring center, based on the previous work [22]. Distinct from the ring used in the work, we set the location of the nozzle to be slightly off-center toward one tooth or set the length of one tooth to be slightly more elongated than those of the other teeth to generate an asymmetrical electric field in the device. We applied a pulse signal of 6–7 kV to the electrodes for 7–10 ms to pinch the drop off at the end of the nozzle. The drop deformed into asymmetrical shapes when passing through the ring. We chose egg-shaped drops of which the *x*-axis was parallel to the bottom wall surface. Overall shape evolutions from the shape oscillation to the impact dynamics were recorded using a high-speed camera (Photron, Fastcam SA3). Teflon-coated hydrophobic (HP) surfaces (AF1600) and methyltrichlorosilane-treated transparent superhydrophobic surfaces (SHP) were used. We measured the apparent contact angle of the water drop on the surfaces as 116 ± 3° (HP) and 155 ± 3° (SHP) by using the sessile drop method. The advancing and receding contact angles for HP were measured as 119 ± 3° and 110 ± 3° by expanding or contracting the sessile drop, respectively. In addition, the advancing and receding contact angles for SHP were measured as 157 ± 3° and 153 ± 3° in the same manner. The details of asymmetrical drop generation and shape oscillation are described in Fig. S3 of the Supplementary materials.

3. Results and discussions

Fig. 1 shows the impact dynamics of spherical and asymmetrical drops on a hydrophobic surface in the simulation and experiment. The spherical drop maintains circular hydrodynamics throughout the impact and bounces off the surface, as shown in Fig. 1a. Experimental results revealed that drop detachment from the surface occurred at We > 7. The BV and SV represent the bottom and side-views in the experiment, respectively. The asymmetrical drop, similar to an egg shape, shows peculiar spreading and retracting dynamics, allowing liquid to be aligned along the alignment axes (dashed line) inclined at an angle (θ) to the *x*-axis, as described at 5.5 ms in Fig. 1b. The aligned liquid is released along the *y*-axis by capillary retraction and then forms the second alignment with the *x*-axis at 12 ms, thereby suppressing bounce. The impact dynamics of the asymmetrical drops might resemble those of elliptical footprint drops because the liquid alignment occurring during retraction induces symmetry-breaking in mass and momentum. However, the geometric characteristics of the asymmetrical drop considerably alter the drop hydrodynamics in spreading and retraction, resulting in an alignment angle of less than π/2. In contrast to the elliptical drop, the egg-shaped drop is asymmetrical with respect to the *y*-axis because of its smaller radius at one end compared with the other end (that is, $r < R$).