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Oblique impact of two successive droplets on a flat surface

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ABSTRACT

Using the lattice Boltzmann method, a numerical study was conducted to investigate the oblique impact of two successive droplets on a flat surface. The focus was placed on the effects of surface inclination, lateral/longitudinal offset, the impact dynamics of the two droplets and the subsequent dynamics of the combined droplet. The evolution of the topology, contact lines and spread factor of the two droplets under various conditions was compared and analyzed. It was found that, compared to single droplet impact, the impact of successive droplets shows quite different dynamics due to the involved coalescence process. The surface inclination causes asymmetric spreading of the droplets. The increase in surface inclination leads to faster downward spreading and reduced lateral spreading. The non-zero offset between the two droplets further enhances this asymmetry. Furthermore, the intermixing between the two droplets during the oblique impact was also examined. It was observed that the surface inclination changes the mass distribution of the combined droplet.

1. Introduction

Impact of droplets on solid surfaces is a commonly observed phenomenon both in nature and in industrial applications, such as ink-jet printing [1,2], plasma spraying, spray cooling [3], droplet fuel mixtures in internal combustion engines and microfluidics [4], and hence it is of fundamental and practical importance. In the past century the dynamics of droplet normally impacting on surfaces has been extensively investigated [5–13], which has been well reviewed by Yarin [14]. Apart from normal impact, works are also available in which oblique impact of single droplet is studied. Šikalo et al. [15] investigated droplet impact and spreading on dry walls and liquid films with low impact angles by looking at the effects of impact angle, Weber number and surface properties on the occurrence of droplet rebound. Lunkad et al. [16] studied the effects of surface inclination, surface properties, liquid properties and impact velocity on the dynamics in different regimes of droplet spreading: spreading and sliding, splash, and rebound and deformation. Particularly, they focused on surface wetting characteristics by using the static contact angle (SCA) and dynamic contact angle (DCA) models. They found that the DCA model performed better in predicting the spreading behavior. Shen et al. [17] used the lattice Boltzmann method (LBM) to study complex asymmetric spreading on slanted surfaces by investigating droplet spreading, contact line motion and topological evolution.

Impact of successive droplets further encompasses the dynamics of collision and coalescence of one droplet with another that is stationary or has hit the surface slightly earlier. The coalescence of a moving droplet with a stationary droplet on a surface has been studied both experimentally and numerically [18–20]. Li et al. [18] focused on the spread length and identified three different coalescence mechanisms. Graham et al. [19] carried out a combined experimental and numerical study on coalescence of two droplets with various wettability and offsets. It was found that the maximum spread length decreased with increasing the hydrophobicity and offset, but increased with the droplet inertia. The dynamics and intermixing of two similar-sized droplets normally impacting on a flat surface were studied by Castrejón-Pita et al. [20]. They did not see the occurrence of mixing during the impact and coalescence. Roisman et al. [21] experimentally and theoretically studied the velocity, thickness and height of the uprising liquid sheet formed from the impact of two droplets. Raman et al. [22] reported the formation of crown and central uprising jet during the impact and subsequent coalescence of two droplets simultaneously impinging on a liquid film. Air bubbles entrapment and segment detachment from the surface depending on the Bond number and Weber number for two droplets impacting on a dry surface was investigated by Wu et al. [23]. Zhou et al. [24] applied an improved lattice Boltzmann method to investigate multiple droplet impact and subsequent interactions. Fujimoto et al. [25] also experimentally investigated the normal impact of two successive droplets, and looked at the influence of impact interval between the droplets on the evolution

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of the diameter of resulting liquid film. It was shown that, although the non-dimensional diameter of the liquid film is larger than that in the single droplet case, they share a similar variation trend. Tong et al. [26] observed two modes of interaction, namely in-phase and out-of-phase, depending on the interdroplet spacing. Their results indicated an increase in maximum spread factor with increasing trailing droplet velocity. Recently, Raman et al. [27] also studied the modes of droplet impact depending on the velocity ratio of the leading and trailing droplets. In addition, they investigated the droplet offset and observed asymmetric coalescence. By fixing the offset between two droplets, the same group [28] also studied simultaneous impact of the two droplets on a surface with one droplet having an oblique velocity, and observed the formation of asymmetric ridge.

Different from all the previous studies, in the present study we aim to investigate the dynamics of two successive droplets obliquely impacting on a flat surface, including both the impact process and the subsequent coalescence. The focus is placed on the effects of impact obliqueness (equivalently the surface inclination if the droplet velocity is fixed) and lateral/longitudinal offset between the two droplets. This study is directly motivated by fog harvesting, in which tiny fog droplets successively impinge on an inclined mesh, coalesce, grow in size, and roll off the mesh surface due to gravity [29]. Recently, bio-inspired meshes are being prepared for efficient fog collection. Such mesh wires can have a diameter (or width in case of flat ribbons) of micrometers [30], where the role of droplet offset also becomes important for determining minimum mesh wire diameter (or ribbon width). This study is also important for the understanding of some natural phenomena, such as rain droplets impacting on car windscreen, spray coating where the droplet impact angle is a key for uniform deposition, and spray on plant leaves in agriculture herbicide applications [31].

The paper is organized as follows. In Section 2 the problem is defined and a dimensionless analysis is conducted. Section 3 introduces the numerical methodology with mesh specification and code validation. Section 4 presents the results and discussion on three selected parameters: surface inclination, lateral offset and longitudinal offset. Finally, conclusions are drawn from the present work.

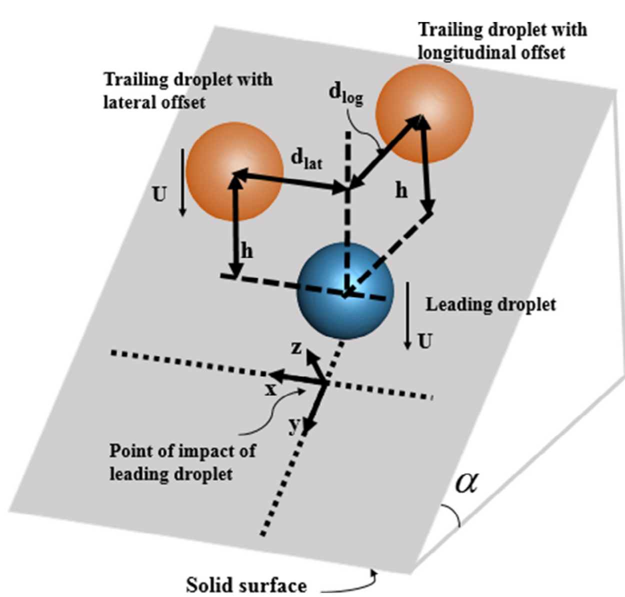

Fig. 1. Schematic of two successive droplets impacting on an inclined surface.

2. Problem definition and dimensional analysis

Fig. 1 shows a schematic of the present problem. With the same velocities two identical droplets make successive impact on a slanted surface along the vertical direction. The two droplets are separated with a vertical distance and, in some cases, a lateral/longitudinal distance during the impact. To help facilitate the study, a Cartesian coordinate system is defined in such a way that its origin is located at the impact point of the leading droplet on the surface, and its x and y axes point to the lateral and longitudinal (slope) directions over the slanted surface, respectively.

Assume there is no gravitational force. The dynamics of the two droplets are determined by twelve key parameters: the surface inclination angle α, the surrounding gas density ρ_g and viscosity μ_g, the liquid droplet diameter D, density ρ, viscosity μ, surface tension σ, contact angle θ and impact velocity U, and the center-to-center distance of the two droplets in the lateral direction d_{lat}, in the longitudinal direction d_{long}, and in the vertical direction h (see Fig. 1). According to the Buckingham-Pi theorem, these parameters can be condensed into following nine independent non-dimensional parameters:

$$\alpha, \rho/\rho_g, \mu/\mu_g, Re = \rho UD/\mu, We = \rho U^2 D/\sigma, \theta, \lambda_x = d_{lat}/D, \lambda_y = d_{long}/D, h/D \quad (1)$$

where ρ/ρ_g and μ/μ_g are liquid-to-gas density ratio and viscosity ratio, respectively. The Reynolds number Re describes the relative importance of the fluid inertia compared to the viscosity force in the droplets, the Weber number We describes the relative importance of the fluid inertia compared to the surface tension of the droplets, and λ_x, λ_y and h/D describe the offsets between the two droplets along the x (lateral), y (longitudinal) and vertical directions, respectively. In literature the Ohnesorge number $Oh = \mu/(\rho\sigma D)^{1/2}$ is also used to describe droplet dynamics [9,32], which can be related to Re and We through $Oh = (We)^{1/2}/Re$.

In the present study, the properties of the two droplets and surrounding gas are fixed. That is, the density ratio $\rho/\rho_g = 10.46$, viscosity ratio $\mu/\mu_g = 10.46$, Reynolds number $Re = 80$, and Weber number $We = 40$ are all constants. In addition, among the three offsets of the two droplets, the vertical distance is fixed at $h/D = 1.15$. The contact angle of the droplets on the slanted surface is fixed at $\theta = 90°$, a moderate value between hydrophobicity and hydrophilicity. Hence the focus is placed on the remaining three non-dimensional parameters, i.e., the inclination angle of the surface α, the lateral and longitudinal offsets between the two droplets λ_x and λ_y.

To describe the dynamics of the two successive impacting droplets, non-dimensional spread factors along the lateral and longitudinal directions are defined, respectively, as

$$S_x^* = S_x/D, S_y^* = S_y/D \quad (2)$$

where S_x and S_y are dimensional spread lengths defined as the largest distances of the contact edges of the two droplet system over the slanted surface in the x and y directions, respectively, as denoted in Fig. 2. In addition, a non-dimensional time t^* is used throughout this study to describe the temporal events

$$t^* = Ut/D \quad (3)$$

3. Methodology

In this study, the lattice-Boltzmann method (LBM) was adopted to simulate the two-phase fluid flow since handling the liquid-gas interface using this method is relatively easier [33]. The fundamentals of this method can be found in many review articles [33,34] and monographs [35,36], and hence are only briefly introduced