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Dynamic performance of a static or throwing droplet impact onto a solid substrate with different properties

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HIGHLIGHTS

- Dynamic performance of a droplet impact onto a solid substrate is studied.
- The droplet is either released or thrown out above the substrate.
- The substrate is either hydrophilic/hydrophobic or inhomogeneous.
- Droplet breakup may occur under some specific conditions.

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ABSTRACT

The dynamic performance of a static or throwing droplet impact onto a solid substrate with different properties is numerically studied in this work. After being released or horizontally thrown out, a two-dimensional droplet can fall freely under gravity. The substrate, which is below the droplet, is either hydrophilic/hydrophobic or inhomogeneous. To conduct numerical simulations, a hybrid method is adopted, in which the flow field is solved by using the lattice Boltzmann method and the interface is captured by solving the Cahn–Hilliard equation directly. Given a fixed distance between the droplet and the substrate (H^*), the effects of Bond number (Bo), Weber number (We), and surface property on the performance of droplet impingement are investigated in detail. With the increase of Bond number, the surface coverage area of a static droplet also increases. A hydrophilic surface or an inhomogeneous surface with small advancing/receding angle difference can lead to the breakup of droplet rim due to the bubble entrapment. Moreover, dependent on the Weber number and the surface property, the leading edge rim of a throwing droplet developing on an inhomogeneous surface may break up before or after it contacts the substrate. As a result, compared to the case of static droplet, the surface coverage area will be reduced due to the diffusion of small droplet segment.

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1. Introduction

In practical applications, droplet impact is a frequently observed phenomenon, which is always related to various dynamic processes, such as spray cooling [1], raindrop erosion on soil [2], coating operation in food systems [3], and so on. After the pioneering work of Worthington more than one century ago [4], the studies on the dynamics of droplet impact onto a surface have attracted more and more attention.

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There exist different impact patterns depending on whether the impacted surface is wet or not. If the surface is covered by a liquid film, prompt splashes and subsequent crown structures are observed for high impact velocity, whilst only a lamellae-like shape is generated for low impact velocity [5,6]. If the surface is dry, on the other hand, six possible impact patterns are produced [7]. They are deposition, prompt splash, corona splash, receding breakup, partial rebound, and complete rebound. Since there are important fluid mechanics in the process of droplet impact, both experimental and numerical investigations have been performed in recent years that can assist in understanding the transport processes in engineering applications.

In the aspect of experimental study, great efforts have been made. Roisman et al. [8] explained the formation of secondary spray generated by a single droplet impact. It is caused by the bending instability of a rim, which can form a free liquid sheet. Bird et al. [9] demonstrated that the contact time could be reduced below the conventional theoretical limit. By utilizing superhydrophobic surfaces, the liquid mass is redistributed, and thereby the droplet hydrodynamics can be altered. Kompinsky and Sher [10] found three different regimes when a single cold water droplet falls onto a hot horizontal flat solid surface. Depending on the Weber number and surface temperature, complete rebound, small secondary droplet rebound and leap can be observed. Roisman et al. [11] reported that the interaction of two droplets impact might produce cylindrical jets, which is different from the situation of a single droplet impact under the same conditions. Farhangi et al. [12] investigated the coalescence of a falling droplet with a stationary droplet on a superhydrophobic surface. As the impinging droplet carries very small amount of kinetic energy, the coalesced droplets can detach from the surface.

Besides experiments, numerical simulations on droplet impact have also been conducted. Bussmann et al. [13] applied the volume-of-fluid (VOF) method to simulate the fingering and splashing of droplet impact. The obtained results indicate that the contact angle plays an important role in the development of finger and splash. Ge and Fan [14] employed the level-set method to analyze the hydrodynamics and heat transfer phenomena of a liquid droplet impacting upon a hot flat surface. Compared to the saturated impacts, the subcooled impact yields a thinner vapor layer and a higher heat transfer rate. Tasoglu et al. [15] simulated the impact of a compound droplet by using the front-tracking method. They demonstrated that the deformation of inner droplet increases with the Reynolds number, diameter ratio of inner droplet to encapsulating droplet, and surface tension ratio of air to droplet. Bang et al. [16] applied the boundary element method to investigate the physics of a liquid drop impacting onto a solid and dry plate. The air entrainment induced by the displaced gas seems to be an important contributor to corona formation, which always precedes any instability, fingering, or splashing of the liquid.

On the other hand, as an alternative to Navier–Stokes equations based solvers, the lattice Boltzmann method (LBM) has also been adopted for simulating droplet impact problems in recent years. Gupta and Kumar [17] presented the numerical results of droplet impingement by taking the pseudo-potential method. At a given Ohnesorge number, the droplet spreading behavior is seen to be a function of Weber number and Reynolds number. Later, Shen et al. [18] also applied the pseudo-potential method to study the droplet impact onto a pipe surface. Dependent on the impact velocity and surface wettability, four typical deformation processes are found. More recently, Zhang et al. [19] developed a pseudo-potential-based multi-relaxation time LBM to model the drop impact on a dry surface at large density ratio. It is noted that the surface wettability plays an important role in the process of drop impact. By using the free energy method, Tanaka et al. [20] simulated the impingement of a single droplet upon a horizontal wall as well as the collision of a falling droplet with a stationary droplet on a solid surface. Both the dynamic behavior of a droplet and the mixing process of two droplets are sensitive to the Weber number. In addition, the LBM has further been applied to simulate the motion of droplet on a solid surface. For example, Son et al. [21] adopted the color method to analyze the behavior of a droplet on a heterogeneous surface. Based on the phase field method, Zheng et al. [22] developed a lattice Boltzmann model for high-density-ratio immiscible fluids flow with gravity. Then the contact line motion of a droplet attached on a substrate in shear flow was investigated. Shortly after that, the contact angle hysteresis of a droplet on striped textured surfaces was also examined by them [23].

Although a great deal of research has been done for investigation of droplet impact onto a dry surface, some issues have not been addressed yet. For instance, the droplet falls with prescribed velocity, which occurs in practical applications, is not explored. Moreover, the contact angle hysteresis, which is usually employed to represent the rough and chemically inhomogeneous solid walls [24], is not involved in the droplet development after impingement. Therefore, this paper continues to cope with the performance of a static or throwing droplet impact onto a solid substrate with different properties. To implement numerical simulations, a hybrid method is employed. To solve the flow field, a phase-field-based incompressible LBM [25] is utilized. In addition, to capture the interface between the droplet and the ambient fluid, the Cahn–Hilliard equation in the phase-field framework is directly solved [26]. At a fixed distance between the droplet and the substrate (H^*), the effects of Bond number (Bo, ratio of gravity to surface tension of droplet), Weber number (We, ratio of inertial force to surface tension), and surface property (hydrophilic, hydrophobic or inhomogeneous) on the dynamic performance of droplet impact are systematically examined. Based on the numerical results established, different impact structures are illustrated.

2. Problem description

After being released or horizontally thrown out with a given velocity, a two-dimensional (2D) droplet above a solid substrate can fall freely under gravity, as shown in Fig. 1. The upper, left and right sides are open boundaries. The radius of the droplet is R, the distance between the droplet and the substrate is H, and the throwing velocity of the droplet is U_0. Using the droplet radius, the distance can be normalized as H^*, which is fixed at 5 in the current study.

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