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Dynamics and heat transfer of a hollow droplet impact on a wetted solid surface

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A B S T R A C T

A numerical model based on the coupled level set and volume of fraction (CLSVOF) method is developed to investigate dynamics of a hollow droplet impacting on a wetted solid surface and the associated heat transfer process. Numerical results show different impact behaviors of the hollow droplet as compared to a continuous dense droplet. One of the distinctive flow features of the hollow droplet is a central counter jet, which is not present in continuous dense droplets. Analysis of pressure distribution indicates that the central counter jet is mainly due to the pressure gradient inside the hollow droplet during the impact and spreading. Simulation results also show that the impact velocity of the hollow droplet determines its spread factor, dimensionless spreading edge-jet height and central counter-jet height, all with positive relations. The complicated transient heat transfer between the impacting droplet and the surface was analyzed. The average heat flux increases with higher impact velocity. Overall heat transfer during hollow droplet impact is found to be lower than that during continuous dense droplet impact. These results provide better understanding of hollow droplet impingement and heat transfer on wetted surfaces.

1. Introduction

Droplet impact on a solid surface is a phenomenon widely appearing in both nature and industry. Examples include raining and icing on surfaces, dynamics of liquid fuels in combustion systems, ink-jet printing, and material casting [1,2]. Understanding droplet dynamics and associated heat transfer in the impingement process helps better design of these systems for higher efficiency and reliability. Great research progress has been made in this area. Depending on different impacting targets, droplet impact can be categorized into three types: (1) dry-surface impact, (2) wetted-surface impact and (c) liquid-pool impact. The underlying mechanisms of these processes are fundamentally different. Droplet impact on a wetted surface involves far more complex droplet-liquid-solid interactions than the other two types of impacts [3,4].

Many experimental studies have been conducted to understand dynamics of liquid droplet impacting on dry or wetted surfaces. Rioboo et al. [5] observed six different conditions of droplet impact: deposition, prompt splash, corona splash, receding break-up, partial rebound, and complete rebound and later summarized four stages of a droplet impact process, i.e., kinematic phase, spreading phase, relaxation phase and equilibrium phase [6]. Based on different impact conditions, liquid properties, and surface wettability, to experimentally analyze droplet dynamics, high speed camera is commonly used to capture detailed images during droplet impact and spreading process [7–10], while the droplet impact speed can be controlled by the height of droplet generation system. Guo et al. [8] applied high speed imaging to study the flow phenomenon such as spray, splash and especially the interesting bell-like spray that appears after a droplet impacts on the liquid film. They investigated the relationships between the flow phenomenon and diameter and speed of the droplet, as well as the effects of viscosity, surface tension and thickness of the film. Liang [9] conducted a review on mass and momentum interactions during droplet impact on a liquid film and described different behaviors of droplet impact including spread, ejecta sheet, crown sheet and splash. Recently Pan et al. [10] used a high speed camera to study water droplet dynamics on stainless surfaces with different wettability conditions. With a statistical design of experiments method, they investigated the effects of surface temperature, impact speed, droplet temperature and surface wettability. It was found that the impact speed and surface wettability are significant

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Nomenclature

a	minimum size of computational cell, mm
c_p	specific heat capacity, J/kg K
D_0	initial diameter of continuous dense droplet, mm
D_p	initial diameter of hollow droplet, mm
$D_{p,s}$	spreading diameter of hollow droplet, mm
f	spread factor
$\vec{F}$	source term of surface tension
$\vec{g}$	gravity vector
h_0	initial thickness of the liquid film, mm
h_j	edge-jet height, mm
H	Heaviside function
L_j	height of counter jet, mm
$\hat{n}_w$	unit vector normal to the wall
p	pressure, Pa
q_w	wall heat flux, kW m^{-2}
R	radius coordinate, mm
r	radial distance, mm
t	time, ms
U_p	impact velocity, m s^{-1}
$\vec{V}$	velocity vector, m s^{-1}
Greek	
δ_p	shell thickness, mm
δ_{tr}	thickness of transition region for phase interface, μm
θ	equilibrium contact angle, °
$\kappa(\phi)$	curvature for liquid surface
λ	thermal conductivity, W/(m^2 K)
μ	viscosity, Pa s^{-1}
ρ	density, kg m^{-3}
σ	surface tension coefficient, N m^{-1}
$\hat{\tau}_w$	unit vector tangential to the wall
ϕ	level set function
Superscript	
$*$	dimensionless
$'$	average
Subscripts	
g	gas phase
l	liquid phase
Mathematical operators	
∂	partial differential operator
∇	del operator
Δ	difference between two quantities of a variable

factors. The oscillation time increased significantly on hydrophobic surfaces.

Numerical approach was also widely used in study of droplet dynamics where transient flow field during droplet impact is simulated with Computational Fluid Dynamics (CFD) tools [11–16] or more recently Lattice Boltzmann Method (LBM) [17–21]. In modeling the droplet dynamics, the impact velocity is usually assumed as an input; then mass and energy conservation laws are applied to solve for the maximum spread diameter and flow field of the droplet. In terms of energy, it's essentially the conversion between kinetic energy and surface energy, as pointed out by Mao [22]. In CFD modeling, different interface tracking methods have been applied. Harlow [23] used the Marker and Cell (MAC) method to numerically simulated droplet impact on a liquid film. Damir [13] simulated the three-dimensional impact of a droplet onto a solid surface using the level contour reconstruction method. Lee [24] applied level set method and numerically investigated the splashing and spreading resulting from drop impact on liquid film. Rocco [25] applied the VOF method to numerically simulate a drop impact on liquid film. To improve the calculating accuracy of interface tracking, coupled level set and VOF (CLSVOF) method [26,27] was proposed by combing the advantages of level set and VOF methods. Li [28] developed a numerical model using CLSVOF method to simulate air entrapment during a droplet impacting on a wetted surface. The mechanisms of deformation of the phase interface and formation of entrapped air were explored. Liu [29] used the CLSVOF method to investigate droplet impact on a hydrophobic tube. The effects of impact velocity and contact angle on the dynamic characteristics of droplets were obtained. Liang [30] established a numerical model using the CLSVOF method to simulate flow and heat transfer characteristics during a single liquid drop impinging onto a liquid film. Results indicate that liquid inside the film can be classified as three zones: the impact zone, the transition zone, and the static zone. Average surface heat flux can be increased by increasing impact velocity, while effects of film thickness and drop diameter are minor. Gumulya [31] developed a numerical model based on the CLSVOF method to study droplet impact on a heated solid sphere. The flow dynamics were found to be dependent on droplet initial diameter. The rate of evaporation of the droplet was found to be highly dependent on the capillary length of the fluid and the stability of the vapour layer formation underneath the droplet.

Compared with these experimental and numerical investigations on impact of continuous dense droplet, only limited research can be found on impact of droplets with cavitation bubbles, or hollow droplets, which often appear in thermal spray of coatings and high pressure spray combustion [32–37]. Due to the effects of cavitation bubbles, hollow droplets tend to obtain relatively high initial impact velocity compared to continuous dense droplets, as a hollow droplet has less liquid mass with the same initial diameter. Upon impingement, cavitation bubbles have more complex effects on liquid flow and heat transfer on the surface than a continuous dense droplet. Existing research on hollow droplets is very limited and only focus on dry-surface impact. For example, Gulyaev [33] experimentally studied a glycerin hollow droplet impact on a flat surface, where a central counter jet of the liquid was observed. Then they investigated the formation of a counter-jet in a wide range of Reynolds and Weber numbers [38]. Kumar [34] developed an impingement model using the VOF method to simulate the hydrodynamic behavior of a hollow glycerin droplet. It is found that the impact and spreading of the hollow droplet on a flat surface is distinctly different from the conventional continuous droplet. The central counter jet was also predicted. They also investigated the effects of void fractions and void distribution droplet within droplets [39] and compared the impingement behavior of a metal hollow droplet and an analogous continuous droplet onto a substrate [35]. In an earlier study, Zheng [40] numerically investigated a hollow droplet impact on a flat surface using the CLSVOF method and analyzed the flow and heat transfer behaviors. To the best of the authors' knowledge, there is currently no study on hollow droplet impact on wetted surface. With the complex impact mechanisms and wide applications of hollow droplet impact on wetted surfaces, it is important to develop better understanding of the process. This is the objective of the present study.