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Numerical analysis on air entrapment during a droplet impacts on a dry flat surface

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ABSTRACT

When a droplet impacts on a dry flat surface, air is generally entrapped. The formation of air bubbles into the liquid during drop impact processes has drawn extensive attention. Air entrapment during droplet-surface impaction is numerical analyzed. According to numerical results, pressure difference between gas and liquid is the main reason leading to phase interface topology changes, which is the cause of trapped air film formation. Trapped air film presents contraction, coalescence and detachment after formation. Wall heat flux distribution is closely related to dynamic feature of trapped air. At the very initial stage of impaction, trapped air largely hinders heat transfer from droplet to surface. The effective of impact velocity on bubble detachment suggesting a feasible way to eliminate bubbles in droplet impact applications.

1. Introduction

The droplet impingement on a solid surface is a common phenomenon, such as rain drops falling on the ground, ink-jet printing, spray cooling of hot surfaces, spray painting and coating, plasma spraying, fuel spray in combustion chamber, catalytic processing in fixed bed reactors and more recently in microfabrication and micro-channels [1]. Therefore, research on droplets impacting on a solid surface attracts great interest from researchers. In particular, the formation of air bubbles into the liquid during drop impact processes has drawn extensive attention.

There are two distinctive types that bubbles enclosed into a droplet during the process of droplet impacting onto a solid surface [2]. The first kind is labeled as entrapped bubble has been deeply investigated [2–13]. The second kind of entrapped bubble named impact bubble evolved from the air film between the impinging drop and solid surface right after the impaction [14]. Experimental and theoretical investigations have been performed to study the impact bubbles since the early 1990s. Chandra and Avedisian [15] provided the earliest report for the impact bubbles in droplet-surface collision experiments, a bubble has been beautifully photographed at the point of impact. Then, a new visualization technique was developed to observe the evolution of the fingering instability of an impacting drop, the formation of a small bubble under the center of the drop is captured and the size of the bubble can be roughly estimated from the photographs [16]. A flash photographic method was used to investigate the time evolution of liquid and solid contact area of impacting drop on a solid surface [17], it was observed that air is entrapped between the liquid and solid surface, the noncontact area depends on the Weber number. Van Dam and Clerc [14] reports on an experimental study of the impact of water droplets on a solid substrate, a small bubble inside the droplet was observed and the size of the bubble was explained based on air entrapment in the early stages of impact. The evolution of the disk of air as it contracts into a bubble under the center of the drop was captured by imaging the impact through an acrylic plate with an ultra-high-speed video camera [18]. The initial size and contraction speed of the air disk were measured with a range of impact Weber and Reynolds numbers. A novel imaging modality was used by Kolinski et al. [19] to visualize the falling drop from below rather than from the side, it was identified a thin film of air is trapped between the impacting drop and the surface so that the dynamics of impacting drops are much more complex than previously thought, the time evolution of the liquid-air interface before liquid-solid contact was firstly analyzed by Jolet de Ruiter et al. [20]. Lee et al. [21] directly visualized the evolution process of an air film to a bubble during drop impact onto a solid surface, three stages were identified. According to the theoretical and experimental investigation by Bouwhuis et al.

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Nomenclature

General symbols

a	thickness of transition region for phase interface
A	area of trapped air film
c_p	specific heat capacity
C	scale factor
D_0	initial diameter of droplet
D_c	diameter of the air-film covered area
D_{max}	maximum spreading diameter of droplet
f_{max}	maximum spread factor
$\vec{F}$	source term of surface tension
$\vec{g}$	gravity vector
h	minimum size of computational cell
H	distance between bottom of droplet and wall
H_e	thickness of trapped air film
$H(\phi)$	Heaviside function
$\hat{n}_w$	unit vector normal to the wall
p	pressure
r_q^*	the dimensional radius distance for q_w>0
r_s^*	dimensional wetting radius
$R_b(t)$	radius of trapped air film
q_c	heat exchange amount of droplet
q_w	wall heat flux
q_w'	average wall heat flux
r	radius coordinate
R_j	initial radius of trapped air film
S_{max}	maximum spread area of droplet
t	time
t_e	time for system achieving thermal equilibrium
T	temperature
U_a	contracted velocity of trapped air film
$\kappa(\phi)$	curvature for liquid surface
Ω	volume of trapped air film
θ	equilibrium contact angle
λ	thermal conductivity
μ	viscosity
ρ	density
σ	surface tension coefficient
$\hat{\tau}_w$	unit vector tangential to the wall
ϕ	level set function

Superscript

$*$	dimensionless number
$'$	average number

Subscripts

a	trapped air film
d	droplet
g	gas phase
l	liquid phase

Mathematical operators

∂	partial differential operator
∇	del operator
Δ	difference between two quantities of a variable

[22], two competing effects minimize the size of entrapped air bubble were shown, it has pointed that there is an optimum leading to maximal air bubble entrapment. Recently, the reflection interference microscopy was used to detect the thickness of an air film between the impact droplet and the solid surface [23]. Then, this technique was exploited to reveal the complex spatial and temporal evolution of the air layer [24].

Comparing with experimental and theoretical investigations, very limited numerical research on the impact bubble. Mehdi et al. [25] developed a numerical model to simulate impact of water, n-heptane, and molten nickel droplets on a solid surface, the one-field volume-of-fluid method was used to track the droplet surface. It was found that the different behavior of entrapped air bubble was attributed to the contact angle. The droplet deformation occurring before surface impact occurs was reported by a theoretical and numerical study [26]. Then, a three dimensions numerical model was derived to describe the evolution of the free surface and pressure field during a droplet impact on to a fixed bed with an air cushioning [27]. It was revealed the presence of the cushioning air layer and the topography of fixed bed have a significant effect on the impact process. Two competing effects minimize the size of the entrained air bubble during impact of liquid drop on a solid surface was theoretically and numerically investigated [28]. It was found that there is an optimum between inertial of the liquid and capillary forces, leading to maximal air bubble entrapment. Hendrix et al. investigated air entrapment during liquid drop and rigid sphere impact onto a deep liquid pool with numerical method [29]. Three impact configurations-a drop onto a solid, a solid sphere onto a pool, and a drop onto pool were unified.

The above studies have proved a comparatively deep exploration on dynamic behaviors of entrapped air layer, while study about the effects of air layer on heat transfer during impaction is rarely limited. Also, experimental visualization system was commonly used in present study. Due to its technical constraints, experimental method is difficult to reveal the imperceptible phenomenon like velocity distribution, pressure distribution, temperature distribution and heat flux distribution. Therefore, major concentration of present study is macroscopic morphologies of the trapped air layer and the impacting droplet. Numerical modelling has become an important tool for process control and optimization in droplet-impaction applications. A well-developed model can provide insight into the underlying physics of the process by overcoming the technical constraints imposed by experiments. However, the numerical investigation on the impact bubble is severely insufficient.

In current study, the process of air entrapment during droplet impaction was numerical analyzed. The underlying formation mechanism and dynamic behavior of trapped air film are discussed according to numerical analysis. Also, the influence of trapped air on heat transfer characteristics during impaction is heighted.

2. Summary of numerical method

In this study, a diesel droplet with an initial diameter D_0 = 2 mm at 345 K is simulated to vertically impacts on a dry, flat steel surface. The ambient pressure is 1 atm. The impacting velocity of the droplet U_0 increases from 1 ms^{-1} to 10 ms^{-1}, from which the dimensionless number of Weber number (We), Reynolds number (Re) and Ohnesorge number (Oh) are calculated. The model-based quantitative parameters are: droplet density ρ_d = 835 kg m^{-3}, air density ρ_g = 1.225 kg m^{-3}, surface tension coefficient σ = 0.039 N m^{-1}, droplet viscosity $\mu_d = 2.745 \times 10^{-3}$ Pa s^{-1}, air viscosity $\mu_g = 1.789 \times 10^{-5}$ Pa s^{-1}, equilibrium contact angle $\theta = 30°$, gravity 9.8 ms^{-2}. The schematic of the computational domain and boundary conditions can be shown in Fig. 1.

In CLSVOF method, the following continuity equation, Naiver Stokes equation and energy equation are solved throughout the domain: