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Three-dimensional numerical investigation of a droplet impinging normally onto a wall film

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Abstract

The paper presents a three-dimensional numerical investigation of a droplet impinging normally onto a wall film. The numerical method is based on the finite volume solution of the Navier–Stokes equations coupled with the volume of fluid method (VOF) and utilizing an adaptive local grid refinement technique for tracking more accurately the liquid–gas interface. The results are compared with available experimental data for integral quantities such as the lamella temporal development. Two mechanisms are identified leading to secondary droplet formation; in the initial and intermediate stages of splashing secondary droplet formation is according to Rayleigh instability while at later times surface tension effects contribute further to secondary atomization. Moreover, the influence of Weber number on the impingement process is investigated and correlations for the diameter and number of secondary droplets are proposed.

Keywords: Deposition; Splashing; Lamella; Liquid film; Volume of fluid method

1. Introduction

The normal impact of a droplet onto a liquid film is a process occurring in many cases of engineering interest, such as fuel direct injection into internal combustion engines, surface cooling by water sprays, inkjet printing, as well as in a number of other physical processes realized in nature, for example the impact of raindrop onto the ground, which enhances soil erosion and produces secondary droplets that can act as carriers of spores and bacteria.

This complicated fluid mechanics phenomenon, is characterized by non-dimensional parameters as the droplet Weber number (We), the Reynolds number (Re), the Froude number (Fr) and the non-dimensional film thickness (H). Finally, a non-dimensional time (T) is also introduced. These parameters are defined as

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$$We = \frac{\rho_2 D_o U_o^2}{\sigma}, \quad Re = \frac{\rho_2 D_o U_o}{\mu_2}, \quad Fr = \frac{U_o^2}{g \cdot h}, \quad H = \frac{h}{D_o}, \quad T = \frac{tU_o}{D_o} \tag{1}$$

where D_o and U_o are the diameter and mean impact velocity of the droplet, σ is the coefficient of surface tension, ρ_2, μ_2 are the density and dynamic viscosity of the liquid phase, g is the acceleration of gravity, h is the film height and t is time.

During the droplet impact onto a wall liquid film, the normal to the wall velocity component changes within a very short distance from that of the impinging droplet U_o (almost at the surface of the liquid film) to zero. This almost step-like jump in velocity in an incompressible liquid with a free surface, inevitably results in a liquid sheet out flowing normally to the free surface called lamella. During the lamella development, two main driving opposing forces influence its evolution, the inertia forces, which tend to stretch out the lamella and the surface tension forces, which tend to shrink the lamella. Accordingly, dominance of the surface tension effects over the inertial ones precludes the formation of three-dimensional structures, as fingering on the crown. Moreover inertial forces are damped by the viscous ones.

Weiss and Yarin [1] indicate that fingering occurs at the tip of the lamella formed at the limit of relatively weak surface tension (relative to the inertial effects, high *We* number), whereas sufficiently strong surface tension is able to suppress it (low *We* number).

The formation of the liquid sheet and its velocity were theoretically analyzed in the case of impact on a wetted solid surface by Yarin and Weiss [2]. In their analysis the evolution of the liquid sheet crown diameter generated by the impact of a drop on a liquid film, is expressed as

$$D(T) = C \cdot D_o \cdot (T - T_o)^n, \; n = 0.5, \quad C = \left(\frac{2}{3H}\right)^{0.25}, \tag{2}$$

where $D(T)$ is the crown diameter and n is a constant. The value of the constant C mainly depends on film thickness but the experiments reported by Cossali et al. [3] suggest a dependence also on the drop impact Weber number. The value of T_o can be also evaluated by a best fit procedure after n and C have been derived and ranges between 0 and 1.5. Fig. 1(a) and (b) show a typical form of a droplet during impingement and some basic global quantities concerning the lamella's dimensions; these quantities have been the subject of numerous investigations in the open literature.

The lamella temporal development depends on the parameters of the impact. Liquid jets may protrude from the crown, a process known as fingering, which subsequently may break-up to form secondary droplets. This is the well-known splashing regime realized with high impact *We* numbers, as reported by Levin and Hobbs [4], Macklin and Metaxas [5], Cossali, Coghe and Marengo [6], Wang and Chen [7]. For low impact

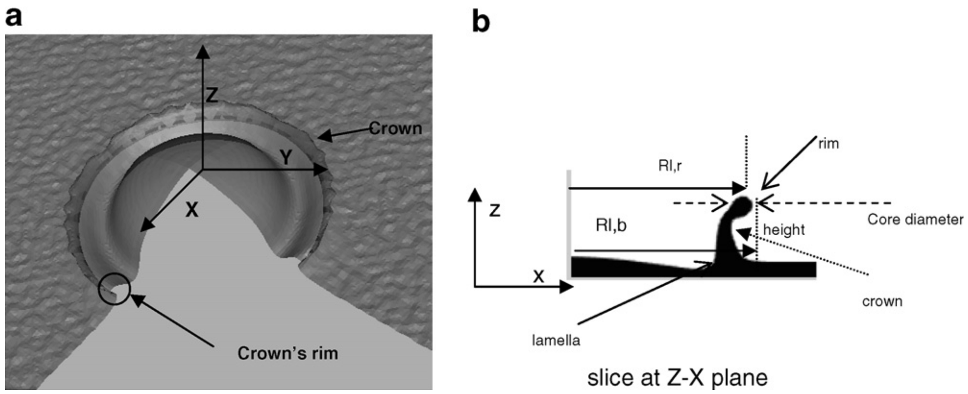

Fig. 1. Definition of impingement characteristics (droplet moves along the Z-axis, impinging onto the film on the XY plane): (a) Crown and crown's rim (perspective view); (b) some global quantities concerning the crown and lamella dimensions.