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# A numerical analysis of drop impact on liquid film by using a level set method †

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**Abstract**

Splashing and spreading of a liquid by drop impact on liquid film depends on the impact velocity, drop size, drop properties and liquid film thickness. These parameters can be summarized by three main dimensionless parameters: Weber number, Ohnesorge number and non-dimensional film thickness. Upon impact of a drop on liquid film, these parameters influence the shape of the splash and the formation and propagation of the crown. In the present study, the splashing and spreading resulting from drop impact on liquid film has been numerically investigated by using a Level Set method for the interface tracking of the two-phase flow simulation. For various dimensionless parameters, characteristics of the crown formation and spreading were predicted, and the results were found to show good agreement with available experimental data in the earlier stage of crown formation and show some discrepancies in the later stage of crown spreading due to the present 2D axi-symmetric computation, which cannot predict the secondary drops.

*Keywords*: Computational fluid dynamics; Crown propagation; Drop dynamics; Drop impact; Level set method; Liquid film

## 1. Introduction

Drop impact phenomena on a surface widely occurs in practical engineering fields, which include spray cooling [1], spray coating [2], jet printing [3] and fuel injection in an internal combustion engine [4], among others. Drop behavior differs upon impact on a dry or wet surface. Many studies in this subject can be found in the literature. Rioboo et al. [5] and Chen et al. [6] reported drop behaviors such as deposition, splashing and rebound by drop impact on a dry surface through experimental study. Rein [7] investigated the behavior of drop impact on a wetted surface through experimental study. Cossali et al. [8] showed that a drop impacting liquid film generates phenomena such as prompt splash, crown formation and jets formation. Yarin and Weiss [9] and Cossali et al. [10] characterized drop splashing and spreading by proposing empirical formulas for the crown diameter and height.

Many attempts have also been made to simulate drop impact on a dry or wet surface. Since the simulation requires solutions of the two distinct phases, a form of liquid-gas interface tracking has to be considered. Various interface tracking methods such as BIM (Boundary Integral Method) [11], LBM (Lattice Boltzmann Method) [12], LCRM (Level Contour Reconstruction Method) [13] and VOF (Volume-of-Fluid) method [14, 15] were used for the simulation of splashing by a liquid drop. Most previous studies were focused on the validation of the interfacial tracking method with the experimental data at the specific condition of drop impact. However, the drop impact phenomena is determined by drop impact conditions such as the impact velocity, drop size and liquid film thickness, liquid properties such as the density, viscosity and surface tension. For an accurate prediction of drop splashing and spreading due to drop impact, the effect of drop impact conditions and properties of liquids must be considered.

In the present study, a 2D axi-symmetric simulation of drop impact on liquid film was performed by using a Level Set method. For the validation of the present numerical simulation, the drop splashing and spreading were compared with the empirical correlation. With the validated numerical method, the characteristics of drop splashing and spreading were predicted with various Weber numbers, Ohnesorge numbers and film thicknesses.

## 2. Numerical analysis

To analyze drop impact on liquid film, a two-phase flow with a sharp interface between air and water has to be considered. Most interface tracking methods in a numerical simulation with a finite volume method can be categorized into a VOF (Volume-of-Fluid) method and a LS (Level Set) method. A VOF method proposed by Hirt and Nichols [16] in 1981, in which the interface is tracked with the volume fraction of a particular phase in each cell, has been widely used with the

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advantage of mass conservation for the two-phase flow simulation. Although it is relatively easy to implement the VOF method in the program, it suffers from the diffusive nature of the results. On the other hand, an LS method proposed by Sussman et al. [17] in 1994, in which the interface is tracked by the signed distance from the interface, maintains sharp interfaces. It has been successfully used in a problem with sharp interfaces such as in simulations of a two-phase flow and a combustion problem. This LS method, however, also has drawbacks in maintaining mass conservation, for which many numerical methodologies are being developed (Son and Hur [18]). In the present study, the numerical analysis of drop impact on liquid film was performed by implementing the LS method for interface tracking into the in-house program NUFLEX, which is a FVM based program adopting a collocated grid system with a non-orthogonal grid capability (Hur et al. [19]).

### *2.1 Governing equations*

To analyze the two-phase flow of immiscible gas and liquid, the following conservation of mass and momentum equations were used:

$$\nabla \cdot \mathbf{u} = 0 \tag{1}$$

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u}\right) = -\nabla p + \nabla \cdot \mu\left[(\nabla \mathbf{u}) + (\nabla \mathbf{u})^T\right] + \rho \mathbf{g} - \sigma\kappa\nabla\alpha . \tag{2}$$

In these governing equations, fluid properties such as the density and viscosity must be computed using the volume fraction of each phase in the computational cell. For the surface tension in the last term of Eq. (2), the curvature of the interface and the gradient of the volume fraction are also needed. Therefore, the interface between the gas and liquid must be tracked for predicting drop impact phenomena.

### *2.2 Interface tracking method*

Since the crown behavior due to the drop impact on the liquid film has a sharp gas-liquid interface, the information of this interface shape has an important role on the prediction of drop splashing and spreading. Therefore, the interfacial flow simulations in the present study were performed by using the LS method, which has an advantage in handling a sharp interface over the VOF method. To track the interface between the gas and liquid, the LS method uses an LS function $\phi$ defined as the distance from the interface. In the LS formulation, the interface is described as the regions with $\phi = 0$. The governing equation for the advection of the LS function is:

$$\frac{\partial \phi}{\partial t} + \nabla \cdot \mathbf{u}\phi = 0 . \tag{3}$$

The solution of Eq. (3) may not satisfy the condition of the distance function, $|\nabla \phi| = 1$. Therefore, the LS function $\phi_0$ obtained from Eq. (3) is reinitialized to a distance function from the interface by using the following equation:

$$\frac{\partial \phi}{\partial t_a} = S(\phi_0)(1 - |\nabla \phi|) . \tag{4}$$

With the reinitialized LS function, the volume fraction and interface curvature can be calculated as follows:

$$\alpha = \min\left\{1, \max\left[0, \frac{1}{2} + \frac{\phi}{3h_n} + \frac{\sin(2\pi\phi/3h_n)}{2\pi}\right]\right\} \tag{5}$$

$$\kappa = \nabla \cdot \frac{\nabla \phi}{|\nabla \phi|} . \tag{6}$$

In governing equations for the two-phase flow, the density and viscosity are obtained by using the volume fraction of each computational grid as follows:

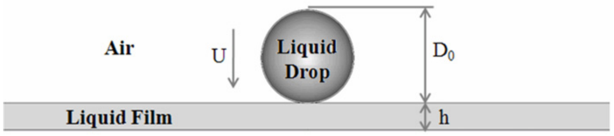
$$\rho = \rho_g + (\rho_l - \rho_g)H \tag{7}$$

$$\mu = \mu_g + (\mu_l - \mu_g)H . \tag{8}$$

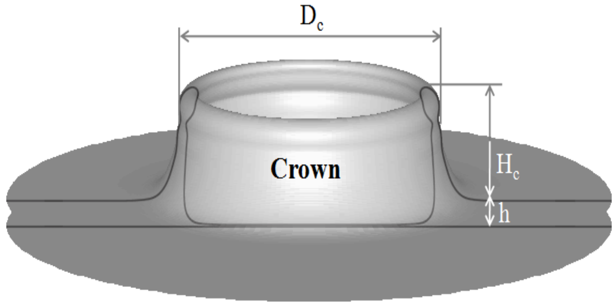
### *2.3 Simulation conditions*

When a drop impacts liquid film, drop splashing and spreading exhibit 3D characteristics with formation of secondary drops due to the effect of flow instability. However, the drop behavior in the early stage of drop impact shows axi-symmetric 2D characteristics. The drop impact phenomena with the propagation of small secondary drops also can be treated as 2D physics. In the late stage of drop impact, and when the crown propagates with larger secondary drops, the drop impact is truly 3D physics, which is quite a different situation from the present 2D axi-symmetric simulation. In the present study, 2D axi-symmetric simulation was performed with a focus on the prediction of drop behavior in the early stage of the drop impact phenomena.

To simulate drop spreading and splashing, the computational domain of $3.6D_0 \times 4.0D_0$ was used to avoid the effect of the domain size on crown behavior. In the computational domain, computational meshes were generated with various grid densities of 50, 100, 150 and 175 computational cells in the diameter of the initial liquid drop. By examining sensitivity to the mesh density, a computational mesh of $150 cells / D_0$ was adopted throughout the present computation, and the total number of computational cells was 324,000. The no-slip wall boundary condition was applied at the bottom wall, whereas the slip wall boundary condition was applied at outer and upper boundaries located sufficiently far from the region of the drop impact in order to minimize the effect of the boundary condition on the results near the region of interest. The symmetric boundary condition was used in the




(a) A liquid drop just before the impact ($\tau = 0$)




(b) Drop splashing and spreading

Fig. 1. Schematic of a drop impact on the liquid film.

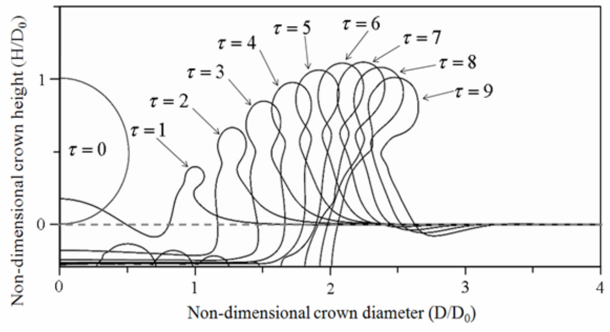



Fig. 2. Drop splashing and spreading ($We = 297$, $\delta = 0.29$, $Oh = 2.156 \times 10^{-3}$).

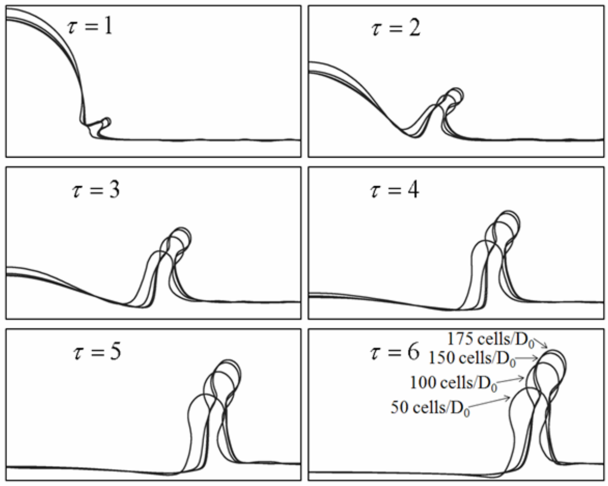



Fig. 3. Sensitivity to mesh density ($We = 250$, $\delta = 0.116$, $Oh = 2.156 \times 10^{-3}$).

azimuthal faces for the 2D axi-symmetric simulation. With these simulation conditions, it took about 4 days to complete a computation on 1 CPU of a Linux server with a 2.4 GHz AMD Opteron 64 bit processor.

## 3. Results and discussion

A schematic of drop impact on liquid film is shown in Fig. 1. When a spherical drop with the velocity $U$ impacts liquid film of thickness $h$, drop splashing with the formation of a crown occurs and is followed by the spreading of the crown. Secondary droplets may be generated at the crown rim due to flow instability, which is not considered in the present study since a 2D axi-symmetric computation is performed. The dimensionless parameters that affect the behavior of the drop impact are the Weber number, Ohnesorge number and non-dimensional film thickness:

$$We = \frac{\rho_l U^2 D_0}{\sigma}, \quad Oh = \frac{\mu_l}{\sqrt{\rho_l \sigma D_0}}, \quad \delta = \frac{h}{D_0}. \tag{9}$$

The time is non-dimensionalized by the diameter and the impact velocity of the drop ( $\tau = D_0 / U$ ) for the presented results.

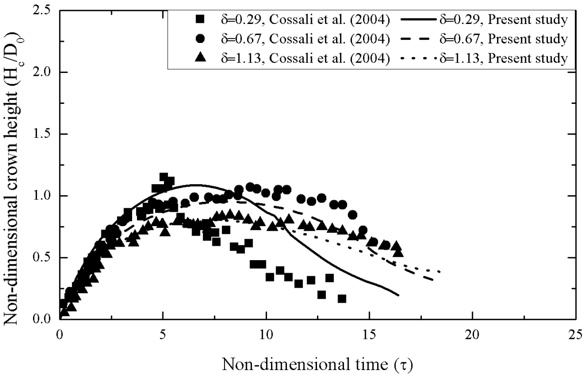
### 3.1 Drop splashing and spreading

Since the kinetic energy of the impacting drop is reflected by the static liquid film, the crown is formed in the contact area between the drop and the liquid film. This crown is then spread out due to the radial momentum generated by the drop impact, as shown in Fig. 2. In the figure, it is also shown that the crown height reaches its maximum and drops down due to the effect of gravity.

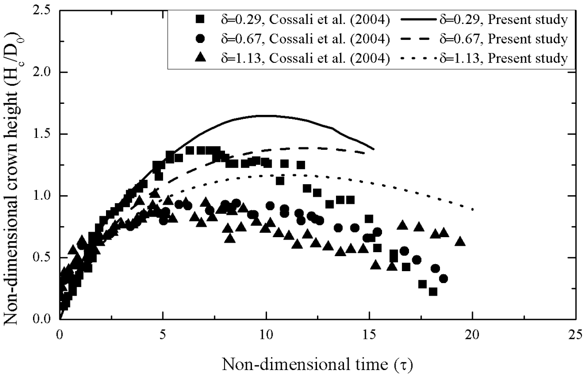
Fig. 3 shows crown behavior from simulations with various grid densities. In the early stage of the crown formation phenomena, accurate information of the interface between the gas and liquid is important for predicting crown formation and spreading. As shown in Fig. 3, the results with coarser meshes depict a lower crown height, thicker crown rim and slower spreading speed compared to those with denser meshes. Therefore, a sufficiently resolved mesh must be used for accurate prediction of the crown behavior.

### 3.2 Effect of the dimensionless parameters

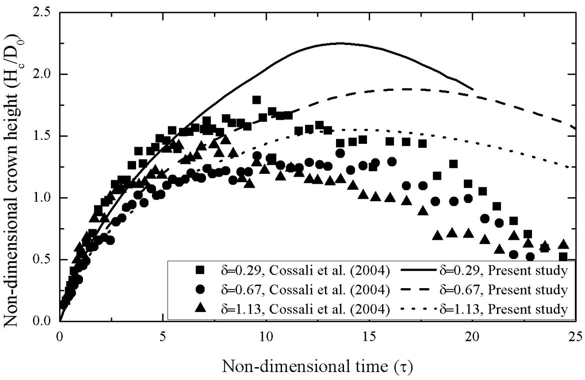
The evolution of the crown after the drop impact for various Weber numbers and film thicknesses is shown in Fig. 4. These results were compared to the experimental data by Cossali et al. [9]. The figure shows that the present numerical results agree quite well with the experimental data in the early stage of the crown formation and growth. Discrepancies, however, between the prediction and the experimental data are quite large at a later stage of crown spreading. It is believed that these larger discrepancies are due to the nature of the present 2D axi-symmetric computation, which cannot predict the splashing with the secondary drops as seen in the experiment. As the Weber number increases, the crown height increases due to the higher momentum of the impacting drop since the




(a) We = 297

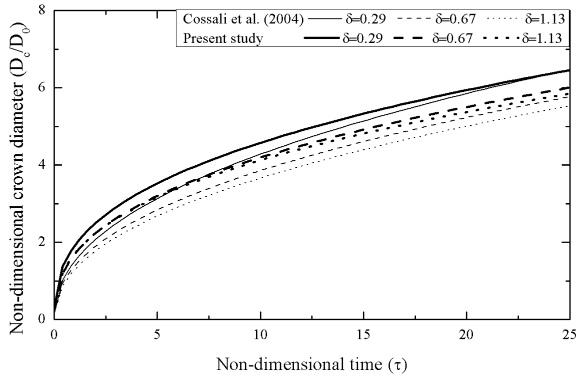



(b) We = 485

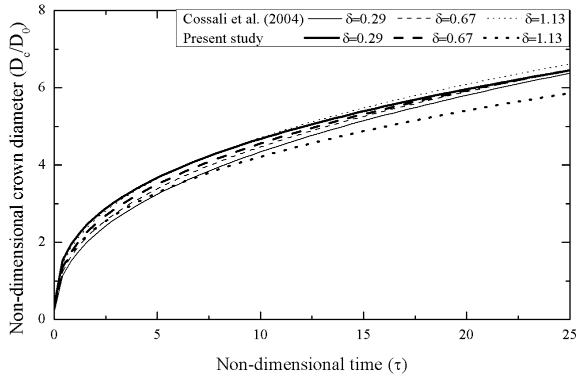



(c) We = 667

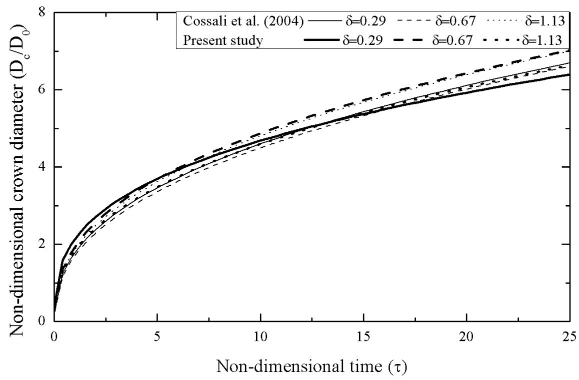
Fig. 4. Crown heights evolution for various Weber numbers with $Oh = 2.156 \times 10^{-3}$.




(a) We = 297




(b) We = 485




(c) We = 667

Fig. 5. Crown diameter evolution for various Weber numbers with $Oh = 2.156 \times 10^{-3}$.

Weber number is defined as the ratio of the inertia force to the surface tension force.

The spreading of the crown is also shown in Fig. 5, where the crown diameter is defined by the outer diameter of the neck below the crown rim. The crown diameter shows a similar trend to the crown height in the fact that the agreement with the experimental data is good only in the early stage of the crown formation. As the drop impact velocity increases, the crown spreads more strongly because the drop impact velocity is related to the kinetic energy of the crown behavior. When the film thickness decreases, the evolution of the crown diameter slows due to the effect of wall friction, which is not clearly visible in the previous experiment. However, the overall trend is that evolution of the crown diameter has a weak dependence on the drop impact velocity and film thickness. This observation is consistent with the empirical correlation proposed by Cossali et al. [9]. Yarin and Weiss [8] also proposed a correlation for the evolution of the crown diameter from their experiment. Their correlation, however, does not include the effect of the Weber number and film thickness, and is not included in the present comparison.

Fig. 6 shows the evolution of the crown height with various

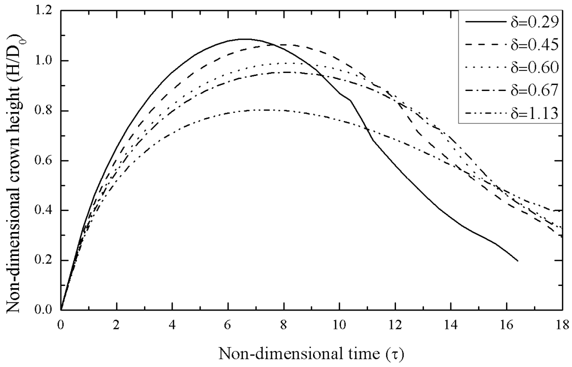



Fig. 6. Crown heights with various film thicknesses $(We = 297, Oh = 2.156\times10^{-3})$.

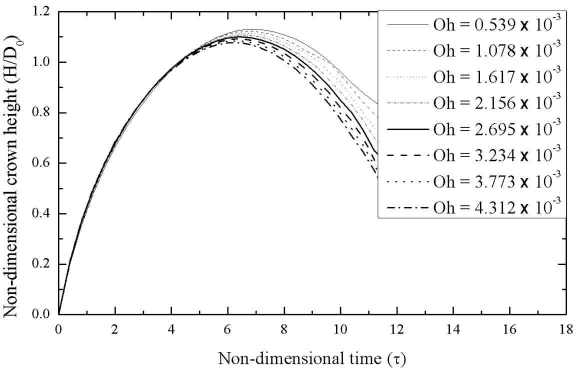



Fig. 7. Crown heights with various Ohnesorge numbers $(We = 297, \delta = 0.29)$.

film thicknesses. It is also shown from the figure that, at a fixed Weber and Ohnesorge number, the effect of an increased film thickness is to lower the maximum crown height and to maintain its height longer as the crown spreads out. This is due to the fact that more impact momentum is absorbed by the thicker liquid film upon impact and more spreading energy is dissipated by the viscous action in the shallower film.

The observed crown heights with various Ohnesorge numbers are shown in Fig. 7. The Ohnesorge number denotes the ratio of the viscous force over square root of the inertia force multiplied by the surface tension force. By varying the Oh number, one can examine the effect of the viscosity on a drop impact. From the figure, it is shown that the effect of the viscosity is minimal in the stage of crown formation. With a higher viscosity, the crown height is lower and the crown dies out faster.

## 4. Concluding remarks

In the present study, crown splashing and spreading due to drop impact on liquid film were numerically investigated by using a Level Set (LS) method for tracking the interface. A 2D axi-symmetric simulation of the two-phase flow predicted the drop behavior after impact on the film. The numerical results of the crown diameter and height were compared with the available experimental data and empirical correlations. Good agreements between the numerical prediction and the experimental data were obtained in the early stage of the drop impact up to the formation of the crown. Discrepancies, however, were observed in the later stage of crown spreading due to the nature of the present 2D axi-symmetric computation, which cannot predict the splashing with the secondary drops observed in the experiment.

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## Nomenclature

$D_0$ : Initial drop diameter
$D_c$ : External upper diameter of crown
$\mathbf{g}$ : Acceleration vector of the gravity
$H_c$ : Crown height
$h$ : Liquid film thickness
$h_n$ : Grid spacing normal to the interface
$Oh$ : Ohnesorge number
$p$ : Pressure
$S$ : Smoothed sign function.
$t$ : Time
$U$ : Impact velocity
$\mathbf{u}$ : Velocity vector in Cartesian coordinates
$We$ : Weber number
$\alpha$ : Step function for gas-liquid phases
$\delta$ : Non-dimensional film thickness
$\tau$ : Non-dimensional time
$\phi$ : Distance function
$\sigma$ : Surface tension coefficient
$\kappa$ : Interface curvature
$\rho$ : Density
$\mu$ : Dynamic viscosity

### *Subscripts*

$a$ : Artificial
$g$ : Gas
$l$ : Liquid

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