Numerical Simulations of Droplet Splashing

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We perfumed numerical simulations of droplet splashing (single droplet impacting, multiple droplets impacting, and droplet-droplet collisions). The numerical framework is based on a CLSVOF (coupled level set and volume-of-fluid) method, the THINC/WLIC (tangent of hyperbola for interface capturing/weighed line interface calculation) method, the CIP-CSL (constrained interpolation profile-conservative semi-Lagrangian) method, VSIAM3 (volume/surface integrated average based multi moment method) and CSF (continuum surface force) model. Our numerical framework can reproduce a prompt splash with satellite droplets and spikes at least qualitatively. The framework can also qualitatively reproduce droplet coalescence and separation of Weber number 30. We also conducted numerical simulations of five droplets splashing and collision of two droplets of Weber number 1000.

Keywords: droplet, splash, coalescence, CLSVOF, THINC/WLIC, CIP-CSL, VSIAM3

1. Introduction

Droplet splashes have been investigated for more than a century (Worthington 1908). Although droplet splashing is a historical and common research topic, it has not fully been understood. This is because droplet splashing is quite complex and appears as a result of complex interactions among all the physical effects such as the inertia, viscosity, surface tension, gravity, contact angle and roughness. Droplet impacts onto dry surfaces as well as splashes play important roles in many industrial applications such as internal combustion engines (fuel droplets), inkjet printing and spray cooling. Many others have been indicated for example in a review article (Yarin 2005). We aim to study the fundamental of droplet splashing using numerical simulations and to contribute to a wide range of industrial applications through the fundamental study and numerical simulations.

2. Numerical method

We employ an approach using a regular Cartesian grid and use the coupled level set and volume-of-fluid (CLSVOF) formulation (Sussman & Puckett 2000), which uses both the level set method (Other & Sethian 1988) and the VOF method (Hirt & Nichols 1981). In this formulation, the VOF method deals with interface motion and the level set method is used for surface tension and wettability computations. In this paper, the tangent of hyperbola for interface capturing/weighed line interface calculation (THINC/WLIC) method (Xiao et al., 2005, Yokoi 2007) is used instead of the VOF/piecewise linear interface calculation (PLIC) method. Although the THINC/WLIC method is a type of VOF method and satisfies volume conservation, it is easy to implement and the numerical results from the THINC/WLIC method appear to be similar to the results from the VOF/PLIC method. For the flow calculation, we employ a finite volume framework. The constrained interpolation profile-conservative semi-Lagrangian (CIP-CSL) method (Yabe et al., 2001) is used as the conservation equation solver. Although finite volume methods usually deal with only the cell average as the variable, the CIP-CSL method uses both the cell average and the boundary value as variables. By using both values (moments), a parabolic interpolation function is constructed in a cell, and the boundary value and the cell average are updated based on the parabolic function. For multidimensional cases, dimensional splitting is used (Xiao et al., 2002). The volume/surface integrated average based multi moment method (VSIAM3) (Xiao et al., 2005, 2006) is a fluid solver which can be combined with the CIP-CSL methods. For the surface tension force, we use the CSF (continuum surface model) model (Brackbill 1992). For more detail see (Yokoi 2008, Yokoi et al., 2009).

3. Governing equation

We use a finite volume formulation so that we use the following governing equation of an integral form:

$$\int_{\Gamma} \mathrm{u}\cdot\mathrm{n_c} dS = 0 \tag{1}$$

$$\frac{\partial}{\partial \mathrm{t}}\int_{\Omega}\mathrm{u}dV+\int_{\Gamma}\mathrm{u}(\mathrm{u}\cdot\mathrm{n_c})dS=-\frac{1}{\rho}\int_{\Gamma}pn_c dS+\frac{1}{\rho}\int_{\Gamma}(2\mu\mathrm{D})\cdot n_c dS+\frac{1}{\rho}\mathrm{F_{sf}}+\mathrm{g} \tag{2}$$

Where u is the velocity, n_c the outgoing normal vector for the control volume Ω with its interface denoted by Γ, ρ the density, μ the viscosity coefficient, $D \equiv 0.5(\nabla u + (\nabla u)^T)$, F_{sf} surface

tension force, g the gravity acceleration. Equations (1) and (2) are solved by a multi moment method based on the CIP-CSL method and VSIAM3.

4. Numerical results

4.1 Droplet splashing on dry surfaces

We conducted three dimensional numerical simulations of droplet splashing on super hydrophobic substrates. As a validation, we compare a numerical result with the experiment

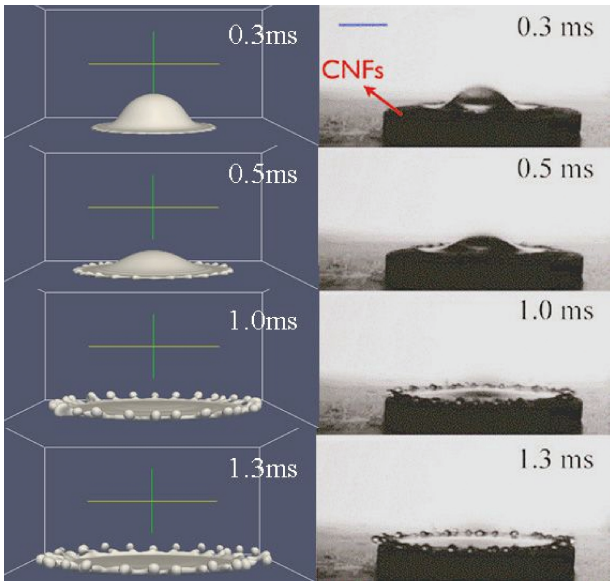

Fig. 1 A comparison between a numerical result of droplet splashing and the experiment (Tsai et al., 2009).

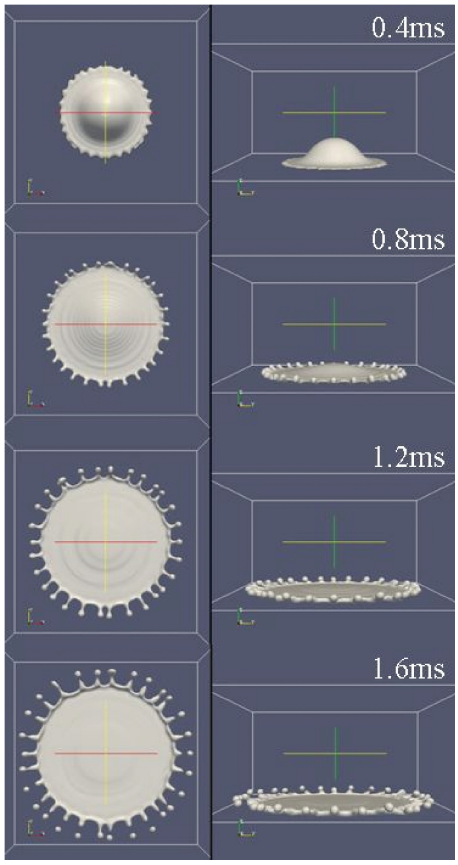

Fig. 2 A numerical result of single droplet splashing.

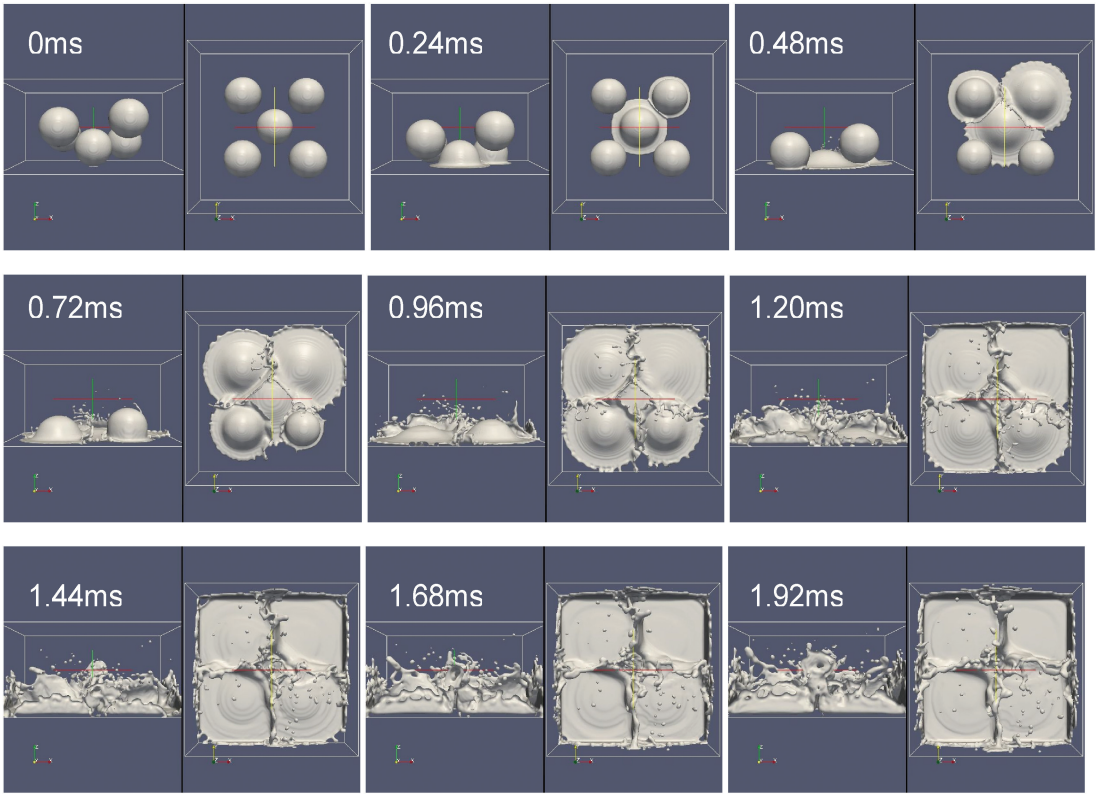

Fig. 3 Five droplets impacting onto a dry surface.

(Tsai et al., 2009) in which a distilled water droplet impacts onto a super hydrophobic substrate. In the comparison, quantitative parameters, ρ_{liquid} = 1000kg/m^3, ρ_{air} = 1.25kg/m^3, μ_{liquid} = 1.0 × 10^{-3} Pa·s, μ_{air} = 1.82 × 10^{-5} Pa·s, σ =7.2 × 10^{-2}N/m , g9.8m/s^2, the initial droplet diameter 1.86 mm, the impact speed 2.98 m/s, the equilibrium contact angle 163° are used. In this simulation, we do not explicitly give any perturbation. Some numerical errors (tiny random noises) such as the tolerance of the pressure Poisson equation solver must play as the perturbations. 200 × 200 × 100 grids are used. Figure 1 shows the result of the comparison. The numerical result has shown at least qualitative agreement with the experiment. Figure 2 shows another numerical result of a distilled water droplet impact. The diameter of the droplet is 2.28 mm and the impact speed is 3 m/s. The simulation well captured the physics of droplet splashing including satellite droplets and spikes. In this study, we found that the contact angle plays a very important role in droplet splashing behaviour. Please see (Yokoi 2011) for more detail.

Figure 3 shows five droplets impacting onto a dry surface. The numerical simulation well capture lamella structures between droplets as observed in experiments. The numerical framework can robustly simulate multiple as well as single droplet impacting behaviours.

4.2 Droplet-droplet collision

Droplet coalescences play very important roles in many paractical applications such as rain droplet formation and fuel atomization (combustion efficiency). We conducted preliminary numerical simulations of droplet coalescences. As a validation, we compare a numerical result with the experiment (Ashgriz & Poo 1990). In this numerical simulation, 128×128×128 grids are used. The initial diameter of the water droplet is 1mm. Figure 4 is the result of Weber number 30. It shows at least qualitative agreement. Figure 5 shows a numerical result of Weber number 1000. The grid resolution is 256×256×256. Although we are not considering that the grid resolution is enough for Weber number

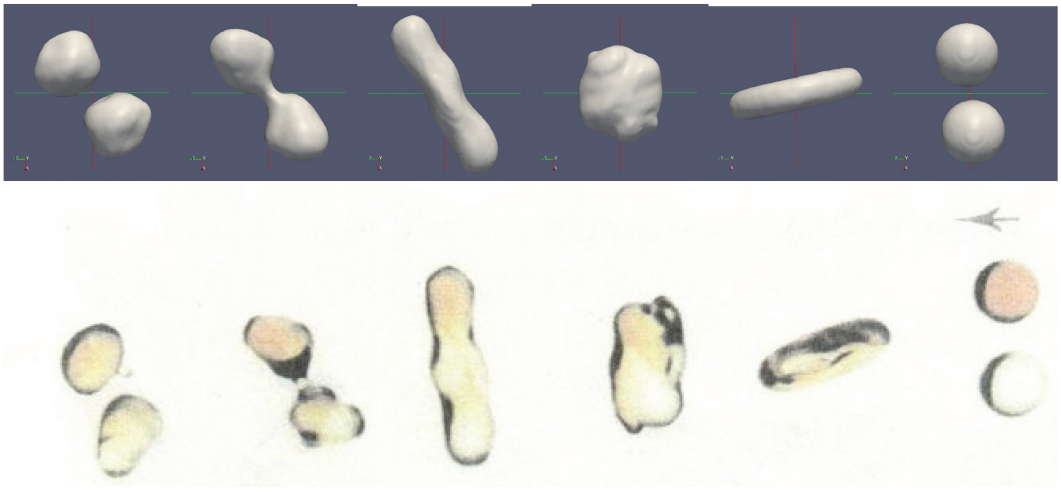

Fig. 4 Comparison between a numerical result (top) and the experiment of We=40 (bottom, Fig. 10 in Ashgriz & Poo 1990). The time evolution is from right to left.

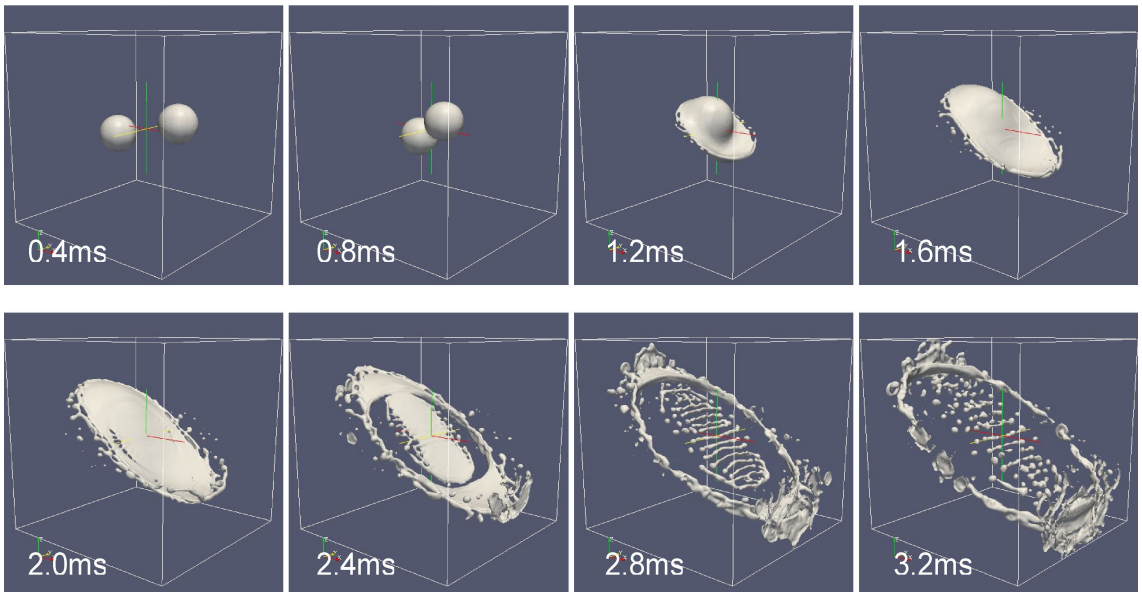

Fig. 5 Collision of two droplets. We = 1000. 256x256x256 grids are used.

1000, if the numerical resolution is greatly increased on high-end super computers such as ES2, the droplet behaviour would be quantitatively reproduced.

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水滴衝突（スプラッシュ）の数値的研究

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水滴衝突（スプラッシュ）に関する数値シミュレーションを行った。計算手法には、CLSVOF (coupled level set and volume-of-fluid) 法、THINC/WLIC (tangent of hyperbola for interface capturing/weighed line interface calculation) 法、CIP-CSL (constrained interpolation profile-conservative semi-Lagrangian) 法、VSIAM3 (volume/surface integrated average based multi moment method)、CSF (continuum surface force) モデルを用いた。本計算は、スプラッシュを伴う水滴衝突の実験を少なくとも定性的に再現することが出来る。また、Weber 数 30 の水滴の衝突（結合と分離を含む）の実験を定性的に再現することが出来る。また、5 つの水滴の固体壁面への衝突及び Weber 数 1000 の水滴同士の衝突の計算も行った。

キーワード: 水滴, スプラッシュ , 接触, CLSVOF, THINC/WLIC, CIP-CSL, VSIAM3