Toward direct numerical simulation of high speed droplet impact.

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Abstract When a liquid drop impacts a solid surface or a liquid film, several outcomes are possible. In particular, splashing phenomena can exhibit complex behaviors, like the formation of very thin crowns and emission of small droplets. Underlying mechanisms are hard to elucidate, partly due to the difficulty for current experimental devices to access to the very small length scales involved. Here, we use direct numerical simulation to explore low and high velocity drop impact phenomena. We show that classical incompressible two-phase methods can be sufficient to address low energy impacts and take into account wetting phenomena. However, dedicated robust and conservative methods are needed to simulate splashing phenomenon at higher velocities. In our test cases, we show that an impact on a thick liquid film exhibits thick crown formation and delayed splashing. On a dry wall, on the other hand, splashing phenomenon can be difficult to reproduce even with high velocity impacts. We show however how a higher value of the surrounding air density may trigger splashing. The presence of a even very thin liquid film on the wall strongly modifies impact outcome, forcing the ejection of a thin crown and subsequent secondary droplet emission.

Keywords Multiphase flow · Drop impact · Splashing phenomenon · Direct Numerical Simulation

1 Introduction

Drop impact phenomenon can be encountered in everyday situations. From the energetic raindrop splashing on the windshield to the gentle cascading from a leaf to another, this phenomenon has always attracted curiosity. Today various industrial applications as sprinkling irrigation, inkjet droplets, combustion or icing in aviation are interested in the deep understanding of drop impact phenomenon.

If the problem have been studied for more than a century [1], the last decades have seen a sharp rise of interest in this topic. On one hand, the improvement of temporal and spatial resolution of the visual acquisition devices enables the access to microscopic phenomena with an acquisition frequency able to reach over a million frames per second [2]. On the other hand, the development of new computational clusters and numerical methods allow the community to investigate fully 3D cases, and access to physical quantities hardly measurable by experimental means.

This active research resulted in a lot of progresses with still many open questions, especially about splash mechanism which could involve sub-micronic effects. For an updated state-of-the-art, the reader is strongly encouraged to read the insightful reviews proposed by Josserand and Thoroddsen [3] and Liang and Mudawar [4]. The outcome of a drop impact can be classified in three regimes, mainly depending on the impact velocity. A low energy impact leads to deposition or rebound of impacting droplets, driven by a competition between inertia and capillary forces. At higher energy,

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a liquid crown is formed, enhanced by the presence of a liquid film. This crown might be unstable : secondary droplets may be formed by jetting phenomena during crown ascend, which is designated as delayed splashing. Finally, high energy impacts lead to small liquid structures formation in the early stages of the impact (prompt splashing). Splashing might in this case result in a flow seeded with hundreds of secondary droplets, which can eventually impact the wall again.

It should be noticed that an overwhelming majority of works concerns the fall of millimeter-sized droplets under gravity, with a velocity between one to ten meters per second, but very few on high velocity and micrometric droplets. However, these high-energy regimes are involved in many key industrial applications such as in the aviation context. Moreover, scaling laws based on Reynolds and Weber number only are not sufficient to predict splashing phenomenon[5], which encourages works to be in the same dimensional configuration to perform comparisons with other papers.

In this study, we explore drop impact phenomenon by using fully three-dimensional direct numerical simulation, and show that highly precise and conservative methods are required to properly reproduce splashing phenomenon. In the first part, the code DYJEAT we used and numerical methods will be described. Then, a low energy impact on a solid surface will be presented as a validation case. In a third part, a delayed splashing case is tested and crown formation is studied. Finally a high-energy impact configuration is explored. A particular effort has been made to discuss the results obtained in exploratory configurations.

2 Problem Description

In the following, the impact of a single drop is considered. This drop of diameter D impacts a target with velocity U_D . This target is either a liquid film of thickness h_{film} or a solid surface assumed smooth and exempt from impurities. Density and dynamic viscosity are respectively designated by ρ_l and μ_l for the liquid phase, and by ρ_g and μ_g for the gas. Surface tension is noted σ . Once the drop contacts the solid surface, a triple line is formed, defined as the common frontier of the gas, the liquid and the solid phase. This contact line moves with velocity U_{CL} . Dimensionless numbers can be constructed using these parameters, such as the Reynolds, Weber and Capillary number or the adimensional film thickness.

$$Re_l = \frac{\rho_l U_D D}{\mu_l} \quad We = \frac{\rho_l U_D^2 D}{\sigma}$$

$$Ca = \frac{\mu_l U_{CL}}{\sigma} \quad h^* = \frac{h_{film}}{D}$$

Each fluid phase is considered as incompressible. Mass conservation (1) under the incompressible assumption, is equivalent to a divergence free velocity vector (2):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0 \quad (1)$$

$$\nabla \cdot \mathbf{U} = 0 \quad (2)$$

where $\mathbf{U}$ is the velocity vector, t is the time, ρ the density. Momentum equation can be written under conservative form (3a) or non conservative form (3b). The use of one of these two forms in the numerical treatment will be explicated in the next section.

$$\frac{\partial(\rho \mathbf{U})}{\partial t} + \nabla \cdot (\rho \mathbf{U} \otimes \mathbf{U}) = \nabla \cdot (-p \mathbf{I} + \mathbf{D}) + \mathbf{f} \quad (3a)$$

$$\rho \left(\frac{\partial \mathbf{U}}{\partial t} + (\mathbf{U} \cdot \nabla) \mathbf{U} \right) = \nabla \cdot (-p \mathbf{I} + \mathbf{D}) + \mathbf{f} \quad (3b)$$

where p is the pressure, $\mathbf{f}$ a volumetric force (such as gravity) and $\mathbf{D}$ the viscous stress tensor. While crossing the interface, viscous stress tensor and pressure follow the jump condition (4):

$$[(-p \mathbf{I} + \mathbf{D}) \cdot \mathbf{n}] = \sigma \kappa \mathbf{n} \quad (4)$$

where σ is the surface tension, κ is the local curvature, $\mathbf{n}$ the unit vector normal to the interface.

3 Numerical code Dyjeat

In this paper, the numerical code DYJEAT [6] is employed. This code, in development at ONERA-Toulouse since 2004 has been used on various configurations related to atomization, including challenging high-density ratio cases such as water/air liquid sheet or cross-flow jet atomization [7][8].

In this paper, two numerical methods related to the discretization of mass and momentum equations are used and compared on the drop impact case : a Level-Set/Velocity Advection [6] and a CLSVOF/Conservative Momentum [12] schemes. Some terms, as the viscous and capillary terms, are treated in the same way in both methods. More details about the following section may be found in [9] and [12].

3.1 Level-Set (LS) - Velocity based advection

Mass and momentum equations are written using the velocity formulation stated in (2) (3b), and are solved by means of the projection algorithm of Chorin [14] on Cartesian Staggered meshes (MAC). In a first step, a predicted velocity field $\mathbf{U}^*$ is obtained by solving the

momentum equation without taking into account the pressure gradient term (5). The divergence free property of the velocity field is then ensured by the projection step (7) where P^{n+1} must be obtained beforehand by solving the Poisson equation (6):

$$\mathbf{U}^* = \mathbf{U}^n + \Delta t^n \left(-(\mathbf{U}^n \cdot \nabla) \mathbf{U}^n + \frac{\mu}{\rho} \nabla \cdot (\nabla \mathbf{U}^n + (\nabla \mathbf{U}^n)^T) \right) \quad (5)$$

$$\nabla \cdot \left(\frac{1}{\rho} \nabla P^{n+1} \right) = \frac{\nabla \cdot \mathbf{U}^*}{\Delta t^n} \quad (6)$$

$$\mathbf{U}^{n+1} = \mathbf{U}^* - \frac{\Delta t^n}{\rho} \nabla P^{n+1} \quad (7)$$

The interface is described implicitly by the use of the Level-Set function ϕ , defined as the signed distance from the interface. This scalar field is passively advected by solving a transport equation (8).

$$\frac{\partial \phi}{\partial t} + \mathbf{U} \cdot \nabla(\phi) = 0 \quad (8)$$

In the previous equations, advection term are discretized using WENO5 schemes, viscous and pressure terms with a centered second order scheme, while temporal discretization is following a Runge-Kutta 2 scheme.

During the advection process, the Level-Set field can be distorted and no longer represents the distance from the interface. To minimize this effect, the reinitialization equation presented in equation (9) from [15] is used at each time step. A Runge-Kutta 3 is used for advancing the fictive time τ and Godunov fluxes for the Hamiltonian discretization.

$$\frac{\partial \phi}{\partial \tau} = \text{sign}(\phi_{\tau=0})(1 - \|\nabla \phi\|) \quad (9)$$

Performing reinitialization can shift interface position and is generally not convergent in time. For this reason, only three time steps are performed, which was empirically found as a good compromise to ensure field correction and minimize interface displacement.

Pressure and stress tensor jumps, including surface tension, are taken into account by using a Ghost-Fluid method [16]. In this method, the jumps are directly incorporated in the numerical discretization, by extending the continuous solution behind the interface, and adding a source term to take in account the discontinuity: this ensures proper discretization on both sides of the interface and a sharp jump representation. In Fig. 1, we consider a simple 1D case : in this example, the studied function is piecewise constant, with a jump at the interface between points x_i and x_{i+1} . The derivative is zero in each domain. To approximate the derivative

Fig. 1: A jump across the interface taken into account with Ghost fluid formulation

at the right of point x_i , the monophasic version would simply be :

$$\left(\frac{dF}{dx} \right)_{i+1/2} = \frac{F_{i+1} - F_i}{x_{i+1} - x_i}$$

which is here obviously non zero. The idea of the ghost fluid method is to substitute value at the point F_{i+1} by its ghost value defined by

$$F_{ghost,i+1} = F_{i+1} - a_\Gamma$$

where a_Γ is the jump of F while crossing the interface. Calculating the jump a_Γ is made possible by explicitly locating the interface with the help of the surrounding Level-Set values. The discretization then results in the single-phase formulation corrected by a jump term. The Level-Set function is used to compute the interface normal vector and the curvature.

The Level-Set formulation does not ensure mass conservation, as no conservation equation for liquid mass is solved. Any error in the position of the zero-contour directly translates in mass loss or gain. The same applies to momentum equation: in the solution of equation (3b), conservation is ensured by the zero-divergence constraint in the single-phase case, but individual phases ($\rho \mathbf{U}$) momentum conservation is not explicitly enforced. Moreover, there is no consistency between the mass and the momentum evolution which are evolved almost independently. These reasons have driven the development of the new algorithm described in the following section.

It has to be stated however that, for cases in which weak interface deformations occur, the Level-Set formulation may still perform reasonably well. A small shifting of the whole Level-set function can be imposed at each time-step to ensure global, but not local, mass conservation [6].

3.2 Conservative momentum (CMOM) algorithm

The Level-Set formulation, as stated before, presents difficulties for ensuring mass conservation. For this reason, we use a second method designated as conservative

Fig. 2: (a) : Interface is approximated by a plane - PLIC reconstruction [10]. (b) : geometric computation of mass flux through east face of a velocity cell using PLIC reconstruction.

from now on, which brings two differences to the LS formulation.

First, the interface is described by both Level-Set and Volume-of-Fluid (VOF) variables. The VOF variable represents the liquid fraction contained in each computational cell. Coupling these two variables allows us to benefit from the mass conservation of VOF method and good precision in geometrical properties calculation thanks to LS use. In each mixed cells, the interface is approximated by a plane (PLIC reconstruction - Fig. 2a). The plane is oriented by the use of the surrounding LS values, and shifted to ensure mass conservation using VOF variable. From the reconstructed plane, mass fluxes can be geometrically computed as described in [11]. It is indeed possible to geometrically locate the volume entering or leaving a computational cell during time step Δt using the normal velocity. In this volume, PLIC reconstruction provides liquid and mass fraction and thus mass fluxes can be accurately computed. (Fig. 2b) This treatment is applied in each direction using a splitting algorithm.

The second main difference with the LS-version concerns the momentum advection treatment. Recently, a new method has been developed and implemented by Orazzo & al. [12] hereinafter referred as Conservative MOMentum (CMOM), inspired by [13]. The momentum equation is written in the conservative form (3a) and treated with finite volume formulation. In the same way as for mass transport, momentum fluxes can be geometrically computed. The term $\rho\mathbf{U}$ is set equal to the mass fluxes calculated before since it appears in both advection terms: this treatment ensures consistency between mass and momentum conservation, and in that way provides the code with good robustness, even for high density ratio cases. This translates numerically to the solution of conservative forms for both equations, (10) and (11), in which consistency is ensured by the

use of the same mass fluxes ($\rho\mathbf{U}$) in both equations:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho\mathbf{U}) = 0 \quad (10)$$

$$\frac{\partial (\rho\mathbf{U})}{\partial t} + \nabla \cdot ((\rho\mathbf{U}) \otimes \mathbf{U}) = \nabla \cdot (-p\mathbf{I} + \mathbf{D}) + \mathbf{f} \quad (11)$$

4 Study of a low energy impact on dry wall

When addressing drop impact phenomenon, a major part of literature is focused on low energy impacts, such as millimeter-sized droplets falling at a velocity of a few meters per second. These impacts may lead to deposition, rebound or secondary droplets formation (splash). For a long time, the segregation between these regimes has mainly been imputed to the droplet properties, with splash predicting models based on a combination of Reynolds and Weber number only [17]. However, it is now well known that target nature strongly influences the outcome of the impact. Concerning impact on solid surface, wettability or surface geometry (ie. rugosity or pattern) can promote one of these impact topologies [3]. The effect of wettability on smooth surface has remarkably been demonstrated by Yokoi et al. in 2009 [18] by experiments and axisymmetric simulation. In this section, we reproduce the results obtained by Yokoi et al [18] with 3D simulations by implementing contact angle model in the code DYJEAT.

4.1 Contact Angle Implementation

When a drop impacts a solid surface, a triple line is formed, and thus a contact angle is defined as the angle between the solid and the liquid/gas interface, as shown in Fig. 3. Without movement, this angle arises to satisfy a local equilibrium between the different molecular forces exerted on the triple point region. This contact angle is called the equilibrium contact angle θ_e and might be difficult to observe experimentally, since this equilibrium takes place on microscopic scale. Another contact angle can be defined at a macroscopic scale and called apparent contact angle. This last angle can take different values depending on contact line velocity (dynamic contact angle): its behavior is generally measured experimentally and fitted by a Tanner law [19], particularly relevant at a low Capillary number. Hysteresis comes to complicate the matter, as in a certain range of contact angles the triple line is fixed to the wall, while exceeding this range extrema makes the triple line to move again. This behaviour is generally explained by the presence of wall roughness or impurities, and thus difficult to be modelled in numerical simulations.

Fig. 3: Contact angle is defined as the angle in the liquid phase between the solid surface and the triple line. Its value depends of the contact line velocity U_{CL} [19].

In Yokoi experiment [18], a water drop of 2.28 mm diameter is considered, impacting with a velocity of 1 m.s^{-1} on a hydrophobic surface. Contact angle was measured and a correlation was proposed by Yokoi (12): this law consists in a Tanner law for high capillary number and degenerates to equilibrium contact angle as velocity tends to zero. A different behaviour is represented whether the contact line is advancing or receding. This law is adjusted to experimental data with the use of maximum advancing and receding dynamic contact angle $[\theta_{mda}, \theta_{mdr}]$ and parameters $[k_r, k_a]$ described as specific to solid properties. Images showing depositing process are shown in Fig. 4.

$$\theta_D = \begin{cases} \min \left[\theta_e + \left(\frac{Ca}{k_a} \right)^{1/3}, \theta_{mda} \right] & \text{if } U_{CL} \geq 0, \\ \max \left[\theta_e + \left(\frac{Ca}{k_r} \right)^{1/3}, \theta_{mdr} \right] & \text{if } U_{CL} < 0, \end{cases} \quad (12)$$

Contact angle effect practically results in a capillary force on the contact line acting as a spring to bring it back to equilibrium. To take this effect into account, one might directly implement a local force in momentum balance [20] or modify the interface geometry [21]. This second approach is in our opinion easier to implement in a solver using LS function. LS boundary condition under the solid surface is written as stated in (13) and take into account the contact angle. The VOF condition stay unchanged, since VOF ghost cells under the wall are not needed due to its impermeability.

$$\forall (x, y_{wall}, z), \partial_y \phi = -\sqrt{(\partial_x \phi)^2 + (\partial_z \phi)^2} \cot(\theta_D) \quad (13)$$

This boundary condition implies however the use of a local contact angle defined everywhere on the solid surface (even far from the contact line). Moreover, the level set field must be consistent with this boundary condition. To ensure these properties, the redistancing algorithm is rewritten as proposed by Xu et al [22]. Briefly resumed, dynamic contact angle is first calculated on each cell containing a contact line. Then, contact angle

is extended following the LS normal projected on the solid plane, by solving eq (14). This algorithm is processed during the reinitialization algorithm to directly propagate the information from the boundary condition to the nearby LS cells.

$$\forall (x, y = y_{wall}, z), \lambda \frac{\partial \theta}{\partial \tau} + \text{sign}(\phi) \mathbf{n}_s(\phi) \cdot \nabla_s \theta = 0 \quad (14)$$

where ∇_s is the surface gradient on the wall, $\mathbf{n}_s$ the associated normal vector, and λ a parameter controlling the propagation speed of θ , typically set to the unity.

4.2 Results

In Yokoi et al [18], the impact has been experimentally recorded using high-speed camera and profiles have been compared to axisymmetric simulation. Here, 3D direct numerical simulation results are shown. As stated by the authors, a wrong estimation of the contact angle law produces an incorrect behaviour. A simulation with a constant static angle $\theta_e = 90^\circ$ leads indeed to a dramatic overestimation of capillary forces during the retraction phase which can even produce a drop rebound (Fig. 5).

However, a good spreading dynamic can be qualitatively and quantitatively obtained after Yokoi law implementation. Using LS algorithm with the moderate resolution of 58 cells per diameter ($\Delta^* = 58$), one can obtain a good visual agreement to Yokoi's images : spreading dynamic, rim formation and retraction behavior are all good indicators of code capabilities and validation criteria (Fig. 6).

Indeed, during spreading, contact angle tends to form an angle greater than θ_e due to the competition between inertia and viscous effects. If the contact angle obtained with contact angle law is smaller than this "natural" one, then the arising capillary forces will tend to accelerate the contact line. Here, the contact angle obtained from (12) is greater than θ_e which means that the spring force is less important, allowing the drop to deposit on the substrate without bouncing.

A further and more quantitative comparison has been carried out by measuring spreading diameter during the simulation, as it has been provided by Yokoi in his experiment. Diameter measured for three different grid sizes shows that even a coarse grid is sufficient to accurately capture the spreading dynamic (Fig. 7).

It is interesting to add a few remarks to the previous conclusion about present results. First of all, readers may notice that, at long time, axisymmetry is broken on Yokoi visualization, which may be due to initial droplet non-sphericity, or imperfection on the solid surface. Capillary waves are therefore travelling differently

Fig. 4: Drop deposition process recorded by Yokoi [18]. $D = 2.28 \text{ mm}$, $U_D = 1 \text{ m.s}^{-1}$, $We = 32$, $Re = 2280$, $Ca = 0.01$
Reproduced with kind permission of Yokoi.

Fig. 5: Rebound obtained by using a static contact angle $\theta_{eq} = 90^\circ$, $\Delta = 39 \mu\text{m}$, $\Delta^* = \Delta/D = 58$

Fig. 6: Deposition obtained by using the dynamic contact angle law (12), $\Delta = 39 \mu\text{m}$, $\Delta^* = \Delta/D = 58$
Dynamic law parameters : $\theta_{eq} = 90^\circ$, $\theta_{mda} = 114^\circ$, $\theta_{mdr} = 52^\circ$, $k_a = 9.10^{-9}$, $k_r = 9.10^{-8}$

Fig. 7: Drop diameter obtained in simulation with different mesh sizes compared to Yokoi's measure.

in numerical simulation where the surface is perfect (smooth and impurity-free). This can explain the asynchronicity developed at long physical times between experiment and simulation and, in part, the difference in the diameter measurement. It is also interesting to notice that the law for dynamic contact angle includes two adjustment parameter k_r , k_a , which has been shown to be of primary importance on spreading dynamics in [18]. These parameters have been fitted by Yokoi so that axisymmetric simulations present good agreement to experimental data ; conducting the same calibration on 3D simulation would necessarily lead to slightly different results.

As a conclusion for this part, the numerical code DYJEAT produced good results in a full deposition situation. These results are extremely dependent on the contact law formulation and implementation, so that reaching very accurate results on contact line dynamics may lead to a very careful study of the contact angle law. A LS formulation is sufficient to explore this configuration, since low interface deformation and very low convective velocities are involved. In the next part, a higher energy impact will be considered in which the LS method alone shows its limits, while the dedicated CMOM formulation leads to very promising results.

5 Impact on a liquid film : crown and delayed splashing

Deposition is a possible outcome of a drop impact on a liquid film, it is however far less frequently encountered than on a solid surface. Indeed, the impact leads to a crater formation while liquid is ejected in a crown

shape. This crown can either be axisymmetric on low energy impact, or present regularly distributed instabilities leading to secondary droplets, or even take a more irregular form. Secondary droplets may be produced at the early stage of the impact (prompt splash) or by the jetting phenomenon at the top of the crown (delayed splash).

In this section, numerical simulations are conducted on one particular configuration experimentally explored by Cossali [23]: we focus on the impact of a 3.82 mm diameter water droplet on a water film of 2.57 mm with a velocity of 3.94 m.s^{-1} . In [23], impact is recorded by a CCD camera from both the bottom and the side of the impact area to provide access to crown characteristics. As a comparison, the Reynolds and Weber numbers are respectively 6 and 25 time greater than the case studied in the previous section, resulting in a more difficult configuration for numerical simulation.

We compare the simulated liquid shape to the images recorded during experiment. In particular, we focus on the crown expansion dynamic through diameter measurement. We found a very good qualitative and quantitative agreement by using the CMOM algorithm. The crown shape and jet instabilities are close to those observed on the picture taken by Cossali (Fig. 8) while crown diameter measurements follow closely the experimental points (Fig. 9). Error bars have been added by present authors on Cossali results from error margins estimated in [23]. Our numerical results are also subjected to measurement error, which has been evaluated at less than 3%. Error bars associated with this uncertainty have been displayed on the most refined case.

The widespread model of Yarin & Weiss [24] has been plotted and, as remarked by Cossali, do not fit the experimental data, even if used in its presumed validity domain. This arises as a warning signal and remind such model or correlation should be used as a predictive tool in exploratory configuration with extra caution [25].

If on the previous case, LS algorithm was sufficient to capture spreading dynamic, it is not the case for splashing. As the reader may notice, LS calculation results in significant errors on crown diameter (Fig. 9), due to aberrations in the early stage of the impact, when high velocities are involved due to impact pressure. Outside of this consideration, one can observe that the crown remains quite stable at the resolution explored and do not produce secondary droplet during crown elevation (Fig.10).

The last discussion of this section concerns grid convergence. Two grid sizes have been tested with the CMOM algorithm : no difference is shown on drop diameter (Fig.9). This is consistent with the results obtained by Guo and Lian [25], who showed a weak varia-

Fig. 8: Impact of water droplet on a liquid film and. Crown formation and delayed splashing. Left : Image recorded by Cossali [23], reproduced with his kind permission. Right : result from CMOM simulation. $\Delta = 30\mu m - \Delta^* = 127$ cells per drop diameter. $D = 3.82\text{ mm} - U_D = 3.94\text{ m.s}^{-1} - h_{film} = 2.57\text{ mm} - Re_l = 8400 - We = 8200$

Fig. 9: Crown diameter measured at the base of the rim. Data measured by Cossali [23], results from present 3D simulations (CMOM and LS methods), results obtained by Guo & Lian [25], Yarin & Weiss model [24].

tion on this variable with resolution higher than 62 cells per diameter, and concluded on a converged simulation. However, some clear differences appear when looking at crown profile: on the fine grid, jetting is observed during crown elevation and a myriad of secondary droplets are produced, while on the coarse grid instabilities occur only when the crown is well developed (Fig. 11). When looking at the secondary droplets distribution in Fig.12, it may be noted that a fair amount of secondary droplets are found at $t = 2.5\text{ ms}$ in a diameter distribution centred around $130\text{ }\mu m$. Practical experience with

code DYJEAT shows that, with the CMOM algorithm, droplets with at least 2 mesh points in the diameter may be tracked for long physical times. A large part of the droplets present in the fine grid simulation may therefore be tracked by the coarser grid. It seems in consequence that the coarser grid simulation is not able to capture the mechanisms underlying the formation of these droplets: instabilities leading to these secondary droplets have been totally smoothed due to insufficient mesh, even if the same mesh is sufficient to obtain a converged crown diameter.

Fig. 10: Crown profile obtained 6.6 ms after impact with mesh size $\Delta = 30\mu m$. Left : Smooth crown obtained with Level Set calculation. Right : Jetting phenomenon and delayed splashing obtained with Conservative MOMentum algorithm.

Fig. 11: Influence of grid resolution on splashing process with CMOM algorithm. Crown profile at $t = 2.5ms$ On the fine grid, droplets are emitted earlier in the process and in a larger number.

Fig. 12: Secondary droplets distribution at $t = 2.5 ms$ reported for two grids. Count made in the numerical domain (1/4 of the main drop simulated). Initial droplet diameter $D = 3.82 mm$.

Although a grid convergence should be regularly verified in a numerical simulation, this is particularly relevant for drop impact study due to the particular mechanisms underlying the secondary liquid structures.

To conclude this part, CMOM algorithm produces good results in both crown dynamic evolution and secondary droplets formation. LS method, however, failed on both due to weaker robustness and precision. Mesh convergence may be obtained for crown macroscopic quantities but not necessarily for instability growth. Cutting frequency associated with mesh size may not only avoid the survive of small secondary droplets, but also significantly restrain mechanisms leading to bigger droplets generation.

6 High velocity impact simulation

Drop impact on a solid surface may lead to deposition as we have seen in Section 4, but also to splash on higher velocity. Detailed comprehension of splashing mechanisms has known a renewed interest in the past decade, due to the possibility for camera to reach very high recording frequency up to 1M frames per second in a recent study [2]. However, splashing phenomenon has only been barely addressed using 3D direct numerical simulation due to high costs involved in such calculation. In 2018, Guo & Lian [25] proposed some high-velocities impact calculations, showing that current hardware resources now enable the community to address this problem.

At the same time, high-energy drop impacts have drawn the attention of the aviation community. Indeed, interaction between cloud droplets and plane wings or instrumentation belongs to this category: impact dynamic is there associated with icing, which is often involved in plane crashes. In this context, experimental studies have been conducted in ONERA : conclusions and experimental setup have been presented in [26]. These experiments provides a rare reference for numerical investigation on high velocity impact. Here, we focus on a impact of a 420 μm diameter water droplet on a smooth solid target, with an impact velocity of 20 m.s^{-1} . The associated Reynolds number and Weber number are respectively 4700 and 2300, so that the Reynolds number is the same order of magnitude as in previous case whereas the Weber number is 5 times larger. This configuration belongs to the splashing regime, as it may be seen on Fig.13.

A very thin and unstable crown is formed and secondary droplets are created all along the process. On the first and second image, we can distinguish micrometric droplets produced on the first microseconds after the contact, a clear manifestation of prompt splash-

ing. Jetting phenomenon is also visible during the early stages of the impact. Numerical simulation is conducted with a resolution of 900 nm , which is equivalent to a resolution of 470 cells per drop diameter.

A quarter of drop has been simulated to reduce mesh costs down to 500 M degrees of freedom. Full drop may be shown to improve figures readability. LS method has been used but systematically resulted in drop deposition : this confirms previous conclusions describing LS method as unsuitable to cope with this configuration. All the results discussed hereafter have so been obtained using CMOM algorithm.

With this algorithm, a prompt splash is obtained, generating about 50 secondary droplets (200 secondary droplets considering the full drop) in the first 3 microseconds. However, no crown is observed and a deposition occurs after the prompt splash phase. From this observation, several explanations may arise and are discussed hereafter.

It has been shown by experimental means that liquid lamella radially ejected during the impact lifts off and skates on a film of air [27]. This film of air may be of a few tens of nanometers thick only, and the interaction with the liquid lamella is yet to precise. Since such distance is of the same order of magnitude than the mean free path of air molecule, the associated effects fall in the scope of non-continuum mechanics [28]. It is obvious that such distance and effects are not resolved by present solver and mesh resolution. Lowering mesh size to this distance while keeping the full drop geometry would imply equivalent resolution hundreds of billions of computing cells, which is hardly accessible today, even with adaptive mesh refinement technologies.

However, interaction between the liquid lamella and this air layer is not the only effect to play a role in splashing mechanism, since suction effect on the top of it tend to promote crown formation [29]. This effect has a lower impact when considering a lower gas density, which could partly explain the results obtained by Xu & Ren [5].

Since 1980's, many studies have proposed a criterion to predict splashing transition, frequently based on the splashing parameter only proposed by Stow & Hadfield [30] (Eq. 15), but this parameter doesn't take into account the air related effect mentioned before:

$$K = We\sqrt{Re} \quad (15)$$

To study this trend qualitatively, an extreme case is tested by multiplying air density by ten, so that the liquid/gas density ratio is hundred. Effect of air density is presented in (Fig.14).

Fig. 13: Images obtained from different impacts recorded at three times. Water droplet of diameter $D = 420\mu m$ is accelerated to reach $V_D = 20m.s^{-1}$ when contacting with the wall. Prompt splash is observed at the beginning of the impact, followed by an unstable crown formation.

Fig. 14: Influence of gas density on impact topology ($t = 6.9\mu s$). $D = 420\mu m - U_D = 20m.s^{-1} - Re_l = 4700 - We = 2300$
 Left : $\rho_g = 1.2kg.m^{-3}$ - Only prompt splashing occurs. Right : $\rho_g = 12kg.m^{-3}$ - An unstable crown is formed.
 $\Delta = 900nm - \Delta^* = \Delta/D = 467$ cells per drop diameter

Lamella lifts off and a crown is obtained, which shows that a splash can be obtained without the "skating phenomenon" described before. Suction effect might so be a predominant effect in high velocity impact. In the same figure, we show that crown is very unstable and liquid sheet is broken earlier than in experiment (Fig.13), which could be reduced by increasing mesh resolution.

Until here, the assumption of a dry wall has been made. In the experimental device, a water droplet stream is generated and a lot of impacts are recorded. Even if droplets are separated by tens to hundreds of diame-

ter, and that the air used to accelerate the droplets is supposed to drive off the water from the solid surface, it is still possible that a thin residual film is present on the impact target. In order to evaluate the effect of this assumption, a $5\mu m$ -thick film is added to the simulation, so that the normalized thickness of the film h^* is $h^* = h_{film}/D_{drop} = 0.01$. Simulation result is presented in Fig.15.

A well resolved crown emerges with a remarkably axial-symmetric shape. Jetting occurs, generating a myriad of secondary droplets. In the same way as for low velocity impact, a thin liquid film does promote splash-

Fig. 15: Drop impact on a $5\mu\text{m}$ -thick film. $h^* = h/D = 0.01$ - Strong influence of the liquid film on impact topology. A crown is formed with remarkable symmetry properties. Secondary droplets are generated and mark a delayed splashing.

ing for high velocity impact. From this discussion, it emerges that a special attention must be paid to the tuning of numerical case so that it properly reflects the experimental configuration; otherwise it could result in false conclusions.

7 Conclusion and future directions

In this paper, we showed that a low velocity impact on a smooth wall can be accurately reproduced by Direct Numerical Simulation with relatively low efforts, as long as a correct law is chosen for dynamic contact angle. Obviously, detailed study focused on contact line movement requires a lot more work, but the methodology presented in this paper is relevant to study macroscopic influence of wettability on impact topology. An impact on liquid pool at higher energy has shown the importance of using conservative and accurate numerical methods, even for macroscopic characteristics as crown diameter. Capturing smaller scale phenomena like secondary droplet formation is much harder to capture and needs much finer meshes. Exploration of high velocity impact and splashing shows that a lot of numerical difficulties arise from this configuration: highly multi-scale phenomena require very small mesh sizes, well under a hundredth of the droplet diameter; non-continuum effects may also be involved in splashing mechanism. From this last remark, the commonly used term "DNS" might be questioned and be understood in this paper as "Direct discretization of incompressible Navier-Stokes equations with the finest possible mesh". A true approach of all scales would here imply a solver at a molecular scale. However, we showed that a splash may be obtained with incompressible effects only, by changing air density or assuming a slightly wetted wall, which extend the observation made on low energy impacts. These effects and associated mechanisms must

be properly studied, and the same consequences might be obtained by further increasing impact velocity.

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