MULTI-DROPLET IMPACT ONTO SOLID WALLS: DROPLET-DROPLET INTERACTION AND COLLISION OF KINEMATIC DISCONTINUITIES

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ABSTRACT

Multi-droplet impact onto initially dry solid walls is investigated numerically using a commercially available implementation of the volume-of-fluid method. For verification purposes, the code is applied to binary drop collisions. Single-drop impact is studied in some detail, considering the influence of shear-thinning effects of the fluid, in particular. Comparison of numerical results with available experiments yields very good agreement. Droplet-droplet interaction is studied for the case of binary drop impact. The calculation scheme is extended to idealised multi-drop impacts and further to model real sprays. Finally, the behaviour of splashing coronae under collision and under reflection at a solid obstacle is tackled; findings suggest that the coronae do not interfere or reflect as waves do in other circumstances.

INTRODUCTION

Impact of liquid sprays onto walls and films is of importance in a variety of fields such as combustion engines, where fuel sprays may hit the wall of the combustion chamber, or painting facilities, where a target is coated by paint from a spray. In the former, the typical impact speed of the spray (expressed by a single-drop Reynolds number or Weber number, which relates the impact inertia effects to viscous effects or capillary effects) is rather high, whereas in the latter it is generally low. Similarly, the spray can be "dense" (average liquid fraction high) or "dilute" (average liquid fraction low).

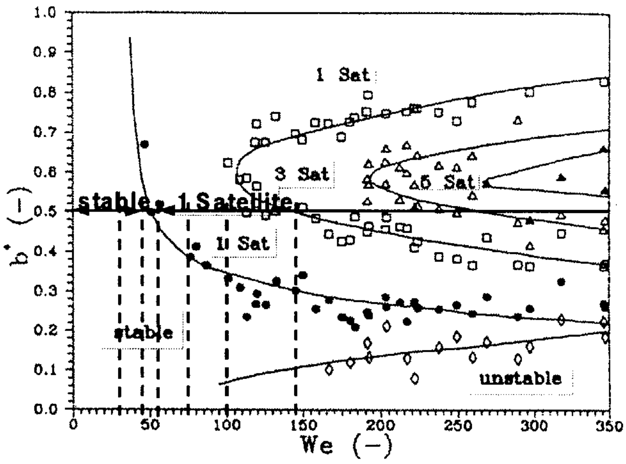
Numerical and experimental investigation of spray impact on walls and films is often performed by looking at the impact of single drops first and then superimposing the results to describe a spray. Interactions between drops are initially neglected; yet they may be considered in a subsequent step. Their importance is frequently believed to be significant, although quantitative statements are missing.

In this work, a numerical simulation of a multi-drop impact onto walls and films mainly at moderate drop impact velocities is presented. The numerical method is outlined first, it is verified by application to the case of binary droplet collisions. We then proceed to the case of single-drop impact onto dry walls, where we also include shear-thinning effects of the fluid. Multi-drop impact is considered in two steps, i. e. two drops impinging to a dry wall next to each other, and model set-ups of 14 or 22 drops, impinging to an initially dry wall. Based on the treatment of multi-drop impact, the procedure for real sprays is outlined. Interaction of kinematic discontinuities is considered. The paper is concluded with an outlook to future studies.

NUMERICAL METHOD

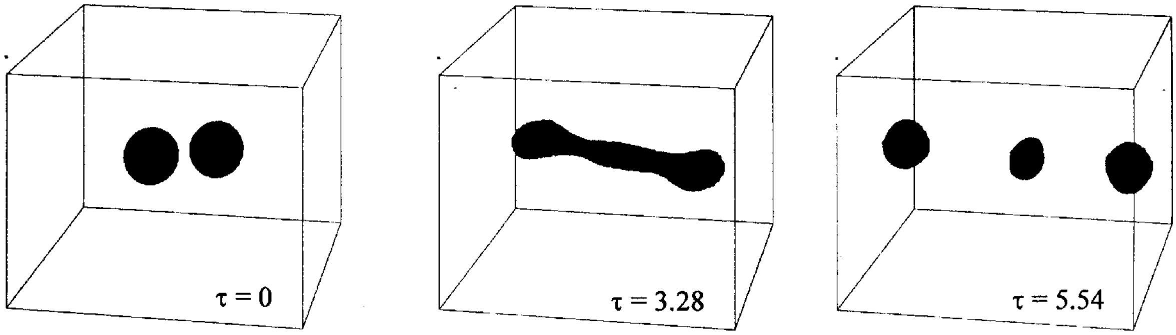
Our objective is to simulate numerically the impact of drops of a Newtonian or shear-thinning fluid (density ρ) onto initially dry solid walls. In the Newtonian case, the fluid is described by its (kinematic) viscosity ν, which allows for definition of a single-drop Reynolds number $Re = U{\cdot}D/\nu$, where U and D denote the initial drop velocity and diameter, respectively; in the shear-thinning case, we will have to assume explicit flow curves. Free surfaces are subject to the surface tension σ, its effect is measured by the Weber number $We = \rho\, D{\cdot}U^2/\sigma$. The wetting behaviour of the even, smooth solid wall by the fluid is described by the (constant) contact angle $\theta = \theta_{stat}$. Gravity is assumed to be weak (expressed in terms of the inverse Froude number $Fr^{-1} = g{\cdot}D/U^2$) and the force is perpendicular to the wall.

The model outlined is implemented in a commercially available code (Flow3D®), which is based on the volume-of-fluid method. For calculation of drop impact, we assume a rectangular box in three dimensions; at the solid wall, i. e. at $z = 0$; a no-slip boundary condition is assumed, whereas periodic boundary conditions are assumed in the x- and y-direction. At the top of the box, a rigid wall is assumed.



DROP COLLISIONS

The code has been verified by applying it to the problem of (binary) drop collisions. Fig. 1, taken from literature, shows the stability diagram determined experimentally for collisions of drops of propanol-2 drops of equal size [1]. The diagram is supplemented by the numerical results of the present work. The calculations have been performed for b* = 0.5, where $b^* = 2b / (D_{p1}+D_{p2})$, and for different Weber numbers $We = U^2 \rho(D_{p1} + D_{p2})/(2\sigma)$. As dimensionless time we use $\tau = Ut/(D_{p1}+D_{p2})$. D_{p1} and D_{p2} denote the drop diameters of the two drops, respectively, b is the distance between the two initially parallel trajectories and U is here the relative velocity. Up to $We = 45$, stable results with merging or coalescence of the drops have been found. The stability limit obtained from the present numerical simulations is $We = 50 \pm 5$. In particular for $We = 75$, we observe disintegration into two larger drops with one smaller satellite, see Fig 2. Thus, the results are in good quantitative agreement with available experimental results.



SINGLE-DROP IMPACT

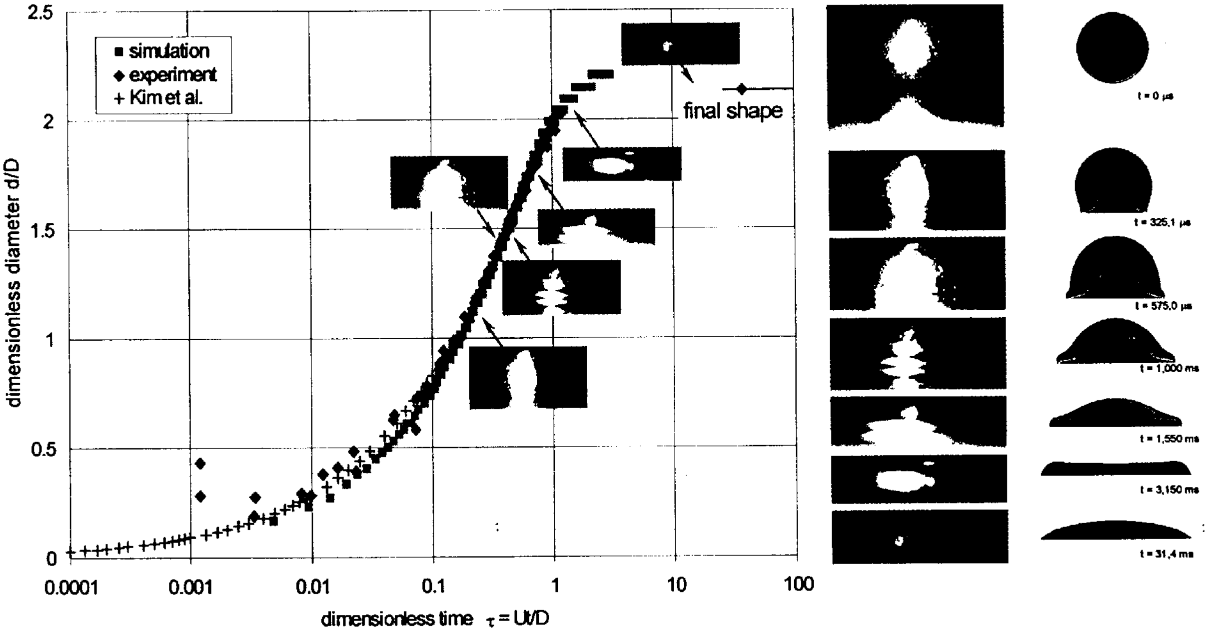
The code is applied to single-drop impact processes onto dry solid walls, where azimuthal symmetry is assumed. An experimental set-up used in previous studies [2] is employed to perform experiments to verify the numerical results. The evolution of the wetted surface underneath the droplet with time, a quantity that can easily be observed in experiments, is considered in some detail.

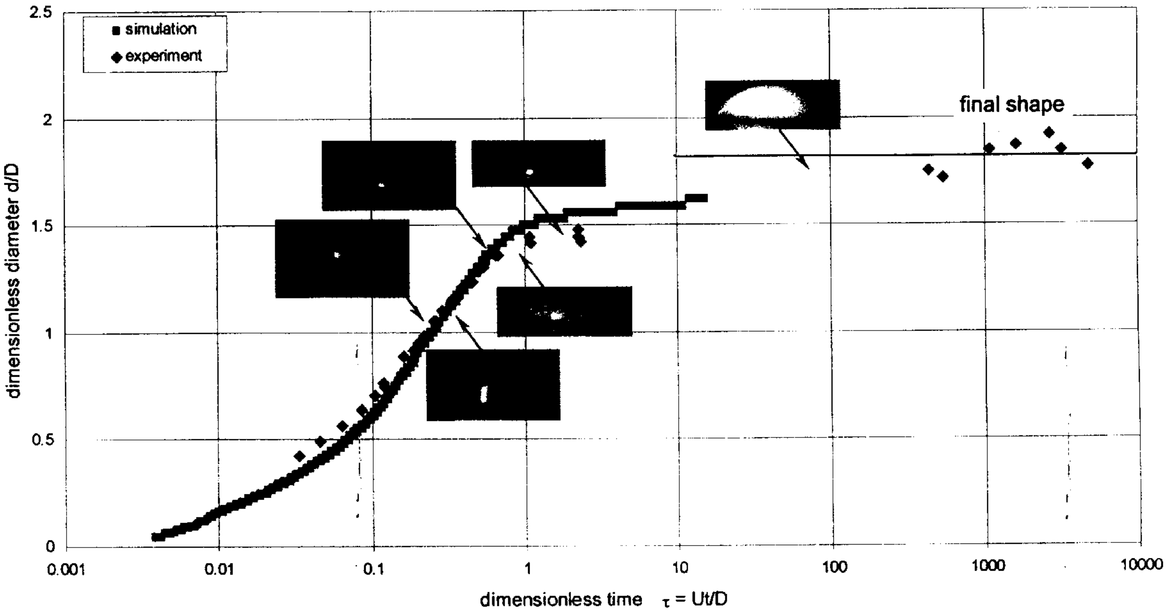
For drop impact of a Newtonian fluid at moderate impact velocity ($We = 54$, $Re = 59$, $\theta_{stat} = 23°$), experimentally and numerically obtained drop shapes for several (dimensional) times after impact are compared in Fig 3 (right). Excellent agreement can be observed. Evolution of the diameter d of the wetted surface underneath the droplet, scaled by the initial drop diameter D, is plotted in Fig. 3 (left). Very good agreement between experiment and numerics is seen from comparison of the dimensionless diameters. In addition, we compare the curves with the model recently provided by Kim *et al.* [3], i. e. their Eq. 27:

$$d/D = \xi_1 = \left[\frac{3}{2} - \frac{9}{8}s^2 - \frac{1}{2}\left(\frac{81}{16}s^4 - \frac{27}{2}s^2 + 12s - 3\right)^{1/2}\right]^{1/2}$$

where $s = 1 - 2\tau$. The agreement is found to be good.

Numerical calculations are extended to liquids that show a simplified shear-thinning behaviour and a thixotropic characteristic. Again, the numerical procedure is checked by comparison with experimental results. Fig. 4 illustrates the comparison for a fluid showing shear thinning behaviour, leaving out any viscoelastic or thixotropic behaviour of the fluid. Also, *d/D* is seen to behave in a qualitatively similar way.





A problem arises when shear-thinning liquids are used in practice. The dynamic viscosity can be measured at finite shear rates only. However, this does not yet enable determination of the overall behaviour. The evolution of *d/D* with time after impact is calculated for several flow curves, each in agreement with measurement of viscosity in a finite range of shear rate, see Fig. 5 . From the different cases, it can be concluded that the

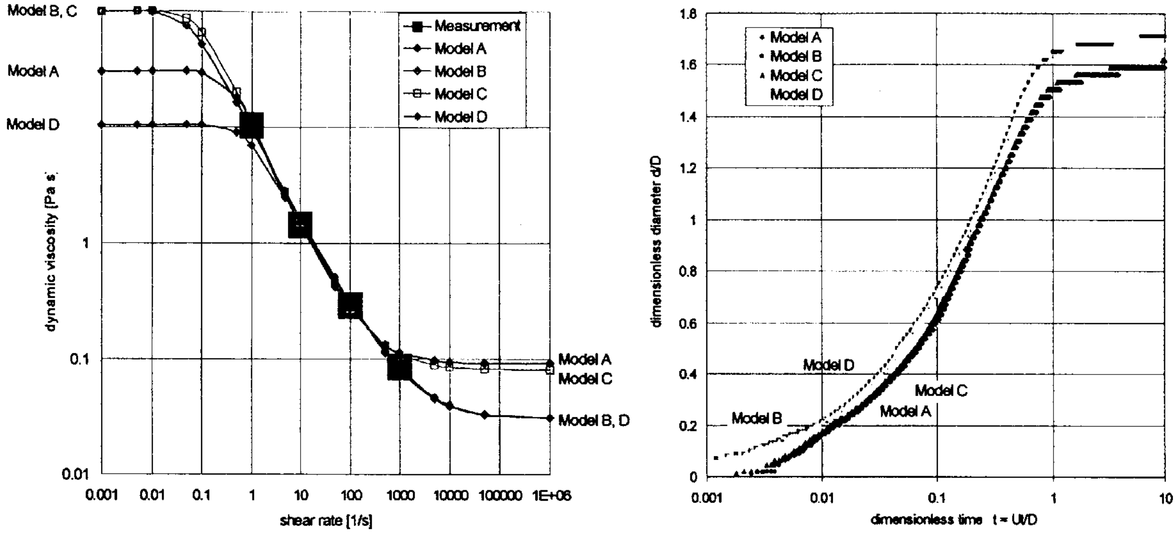


Fig. 5: On the influence of the flow curve details on the evolution of d/D. Several model curves are investigated (left, cases A to D), all in agreement with the experimentally measured flow curve. The resulting evolution of *d/D* is shown on the right; the details are governed by the flow curve at high shear rates.

evolution of *d/D* is governed mainly by the flow behaviour at very high shear rates. In practice, viscosity can frequently be measured up to shear rates up to some 10^4 to $10^5 s^{-1}$.

MULTI-DROP IMPACT

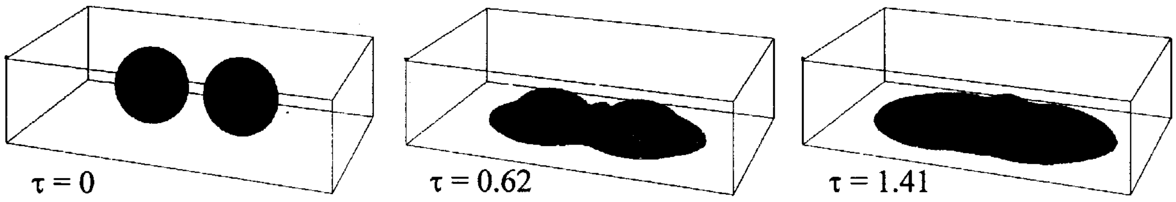


Fig. 6: Parallel impact of two identical drops of a Newtonian fluid with $We = 54$, $Re = 60$, $\theta_{stat} = 23°$, the drop centers are initially separated by $5D/4$ .The dimensionless time τ is based on the drop diameter D.

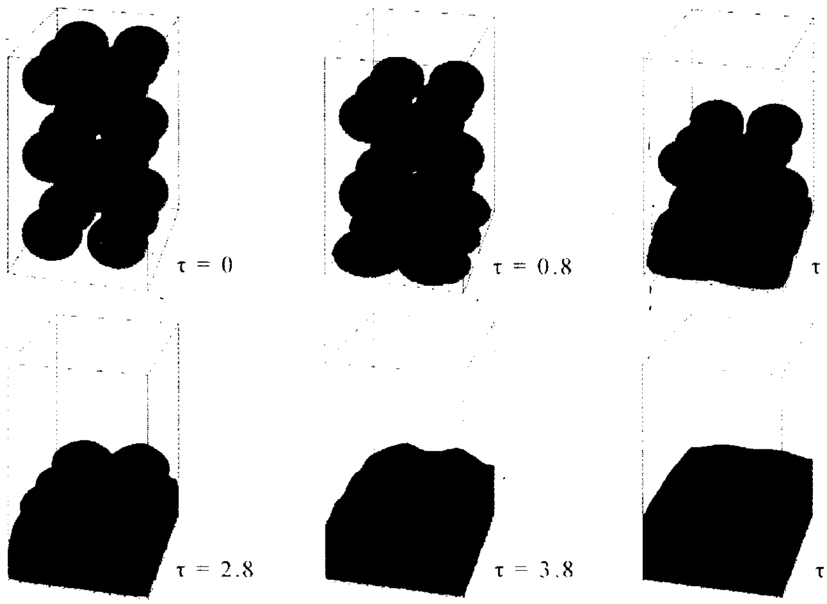


Fig. 7: Parallel impact of 22 identical drops, forming a body-centered hexahedral lattice, with $Re = 3.6$ and $We = 6.9$. The in-plane distance between neighbouring drops is $1.1 \cdot D$, the distance between equivalent planes is $1.6 \cdot D$. The dimensionless time is based on D.

Our aim is to study numerically the impact of a spray onto a film or a wall. In a first step, we investigate the impact of two drops impinging close to each other or one after the other. The outcome of two drops impinging in parallel with the same velocities as in the example before, i. e. with $We = 54$, $Re = 60$, and $\theta_{stat} = 23°$ and with the centres separated by $5D/4$, is shown in Fig. 6 . In a second step, we look at the impact of distributions of several drops in close proximity to one another. In view of calculating a segment out of a spray, we apply periodic boundary conditions in x- and y-direction here. As an example, we consider the impact of 22 drops that initially form a body-centred hexahedral lattice. The distance between equivalent planes in z-direction is $1.6 \cdot D$; within each plane, the drop centres form square lattices with a distance of $1.1 \cdot D$. The drops initially move with a homogeneous velocity field, corresponding to single-drop Weber and Reynolds number of $We = 6.9$ and $Re = 3.6$, respectively. The result is shown in Fig. 7; the drops form a closed film on the solid wall after some time units, the free surface of which is only slightly wavy.

SPRAY

To model and simulate a spray, the procedure of the preceding section is further generalised. Data from a real spray for sizes and velocities of drops (probability-density functions), as well as for their mutual positions, are used to produce a spray-like configuration. This is done by collecting, together with their time delay, drops encountered in a tube around the trajectory that crosses the site of impact studied. The drops are injected at realistic times during the calculation.

COLLISION OF KINEMATIC DISCONTINUITIES

As is well known, higher impact velocities of drops lead, in practical situations, to splashing, i. e. the formation of a rim at the edge of the spreading lamella, followed by the ejection of small secondary droplets. This rim was identified as a kinematic discontinuity, showing several features of a shock wave [4]. One might ask now what happens if such a kinematic discontinuity hits an obstacle or if two such kinematic discontinuities are to collide; to investigate the latter, similar calculations, as shown in Fig. 6, are performed for higher impact velocities.

In experiment, the former case had been considered earlier, i.e. whether such a kinematic discontinuity would be reflected when hitting a solid obstacle. To this aim, single drops were observed when impinging perpendicularly to a solid wall. The arising crown hit an obstacle, a block of plexiglass, which had been put on the solid wall at a place separated by one or two initial drop diameters from the site of impact. The experimental set-up used is standard and has been described at several places in literature so far. The drop impact process was observed from below the plate by means of a CCD camera, whereas it was illuminated from above by a light-emitting diode (LED). The outcome of the experiment is shown in Fig. 8, a reproduction from [5]. As can be seen, the rim remained stuck at the solid obstacle and was not reflected at all.

The numerical results plotted in Fig. 6 and obtained for moderate impact velocities suggest, when extrapolated, a similar behaviour for colliding kinematic discontinuities. As shown for both investigations the kinematic discontinuities collide without an obvious reflection or interference, respectively.

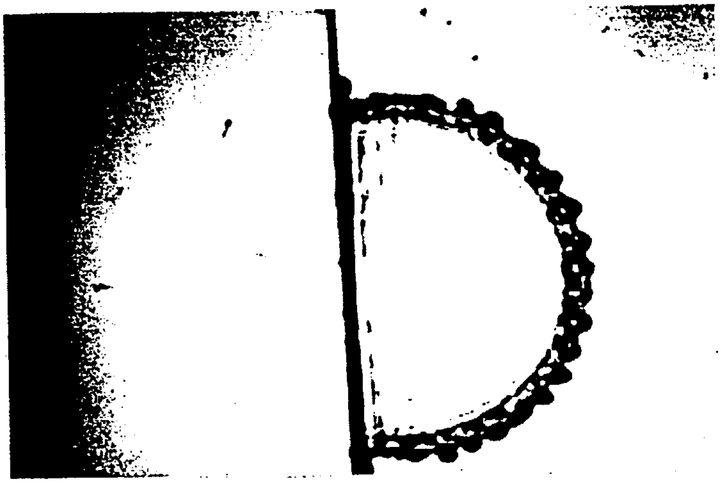


Fig. 8: Interaction of a splashing corona with a solid obstacle upon single drop impact, observed from below the wall (reproduced from [5]). The splashing corona, arising at the rim of the lamella (circular arc), hits an obstacle (left part) and remains stuck at the wall without being reflected.

CONCLUSION AND OUTLOOK

A commercial implementation of the volume-of-fluid method has been used to investigate single- and multiple-drop impact onto initially dry walls. The code has first been checked with experimental results available for drop collisions. Results for single-drop impacts are compared with experiments done for verification and with a model from literature; the agreement is found to be very good. The calculations have been extended to describe idealised multi-drop configurations. Further generalisation to sprays is made with special consideration of droplet-droplet interaction through the film. Interaction or reflection, respectively, of splashing coronae is found to be somewhat different from what one would expect from wave theory, giving thus some limit to the interpretation as a kinematic discontinuity.

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