CFD MODELLING OF IMPACT AND SPREADING OF DROPLETS ON A SMOOTH SURFACE

M. Garbero, M. Vanni and G. Baldi.
e-mail: garbero@polito.it
Dip. Scienza dei Materiali e Ingegneria Chimica, Politecnico di Torino,
C.so Duca degli Abruzzi 24 10129, Torino, Italy.

Abstract

The impact of droplets of water, ink and paint has been analysed by means of a CFD technique using the VOF model. Particular attention has been paid to the study of the spreading phase and on the prediction of the maximum diameter reached by the liquid lamella after spread. Such a diameter is of great importance when paint droplet are considered, since it is very close to the final diameter of the paint spot.

The role of the dynamics of the contact angle between liquid and solid has also been considered, in order to evaluate its influence on the modelling. This parameter is not very important during the spreading phase, but become significant during the recoiling phase, above all for liquids with low viscosity.

Simulations concerning the impact of water have shown that CFD codes may fail in predicting very small droplets. Fortunately the problem disappears for liquids with higher viscosity and smaller surface tension than those of water, as shown by analysing the behaviour of ink and paint. The high viscosity of paint is also the reason why the paint droplets have never shown any splash phenomena, always spreading all the liquid on the surface.

Introduction

The impact of single droplets on a solid surface is a widespread phenomenon in many natural and industrial processes such as herbicides spraying, ink jet printing, spray cooling of hot surfaces, fuel injection of diesel engines and paint coatings.

The prediction of the impingement of a droplet is rather complex due to the large number of influencing factors. The outcome depends on the diameter and the impact velocity of the droplet, on the properties of the liquid and of the target surface and it may result in deposition on the surface, reatomisation into smaller secondary droplets or in a complete rebound. A comprehensive review of the research in this area has been done by Rein [1]. So far, many researchers have focused on the developing of models able to distinguish when splash or spread occurs [2-5], on the study of the recoiling phase [6-9], on the surface instability that leads to the reatomisation process [10-12], and on the discussion of the spreading process, from the beginning of the impact up to the time at which the droplet reaches its maximum base diameter [13-16].

The maximum diameter is one of the parameters of major interest in processes such as coating and ink jet printing, because it is in strict relation with the prediction of the final aspect of the target surface. In a coating process the high viscosity and the small surface tension of the paint, in conjunction with its shear-thinning behaviour prevents droplet reatomisation and rebound and, above all, makes the recoiling phase occurring after spreading negligible. Therefore the final diameter of the lamella formed after the impact of the drop is nearly the same as the diameter at the maximum spread.

Most of the works concerning spreading have been addressed towards the two extreme conditions: impact at high Weber and Reynolds numbers, where spreading is driven by impact velocity [1], or slow spreading of highly viscous liquids, at very low Reynolds numbers, driven by capillarity effect at the contact line [17].

Hatta *et al.* [18] made computational studies for different Reynolds number at moderate value of Weber number, neglecting entirely the effect of the Young force at the contact line. They obtained good agreement with experiments in the early stages of the spreading phase, in which the phenomenon is governed by inertial effects. In order to predict accurately also the subsequent stages, in which the Young force is important, Bussmann *et al.* [19] showed that detailed information on the dynamics of the contact angle as a function of the contact line velocity is required.

In this work the deposition onto smooth surfaces of droplets of ink and paint is analysed, focusing on the prediction of the maximum diameter reached after the spreading phase and on the influence of contact angle, in order to predict correctly the outcome of the impingement.

Spreading dynamics

The dynamics of spreading are mainly characterised by Weber and Ohnesorge numbers [3] and, in the final part of the spread, by the contact angle. The Weber number takes into account inertia and elastic force due to surface tension. At high We inertia predominates over surface tension ones and the lamella quickly expands till reaching a large diameter and a thin thickness, before starting the retraction phase. At small We it is surface tension that predominates and thus a shorter spreading phase occurs, followed by an accelerated recoiling. The Ohnesorge number scales viscous dissipation with elastic forces, that is, the two forces that contrast spreading. Viscosity is mainly responsible for the resistance at high values of the Oh, while surface tension effect is predominant at low Oh.

Changing the liquid properties, the drop diameter and the impact velocity, four regions can be distinguished as a function of We and Oh [8]. At small We and Oh the impact occurs at relatively small velocities and surface forces govern the spread phenomenon. As a consequence, the contact angle between liquid and surface becomes important. Here the dissipation due to viscous forces can be neglected since the velocity is low. At high values of We and small Oh the spread mainly depends on the impact dynamic pressure. Viscous dissipation can be neglected in the first phase of the spread, where impact velocity and drop size are the controlling parameters, while it becomes significant when the lamella approaches its maximum size. At high values of Oh and small We the velocities are low, the spread is controlled by the surface forces and the high viscosity quickly damps all the velocities. In the last region, high We and high Oh, the drop impacts the surface with high velocity and the liquid has a high viscosity and a small surface tension. The spread is controlled by the inertia and the dissipation by the viscous force is remarkable.

Maximum diameter

A droplet impacting onto a smooth surface normally forms a liquid disk, called lamella, which expands very quickly and reaches a maximum diameter d_m. Subsequently the lamella tends to shrink due to surface tension and to reach its final shape. The maximum extent to which a droplet spreads is a crucial parameter not only in those processes, described above, in which the whole impact phenomenon is reduced to the spreading phase, but also in other applications where splash, rebound or reatomisation may happen. The prediction of the final area covered by a droplet is in strict connection with that of its maximum diameter, since the lamella at this point has its maximum elastic energy and zero velocity. A change of the shape of the lamella can lead to large velocity variations during the recoiling phase and, as a consequence, modify strongly the outcome of the impingement.

An approach for the prediction of the maximum spread is based on the application of energy conservation. The total energy owned by the drop before impact is equal to that of the lamella at its maximum diameter minus the energy dissipated by friction:

$$\underbrace{E_k + E_p + E_s}_{\text{Before impact}} = \underbrace{E_k + E_p + E_s + E_{diss}}_{\text{After impact}} \tag{1}$$

where subscripts *k*, *p*, *s* and *diss*. refer to kinetic, potential, surface and dissipated energy, respectively. By prescribing simplified shapes for the deforming drop and expressions for the velocity distributions, the terms of the equation can be written as a function of the diameter reached by the lamella at a specific time [1,13-15] and the maximum diameter can be calculated.

An example of the results of such an approach is the expression proposed by Moo *et al.* [20], that correlates the maximum spreading ratio B_m, that is, the diameter of the lamella at its maximum spread scaled by the droplet diameter, with Re, We and contact angle:

$$\left[\frac{1}{4}(1-\cos\theta)+0.35\frac{\mathrm{We}}{\sqrt{\mathrm{Re}}}\right](B_m)^3-\left(\frac{\mathrm{We}}{12}+1\right)(B_m)+\frac{2}{3}=0 \tag{2}$$

Another example is the relationship by Chandra and Avedisian [14]:

$$\frac{2\,\mathrm{We}}{3\,\mathrm{Re}}(B_m)^4+(1-\cos\theta)(B_m)^2-\left(\frac{\mathrm{We}}{3}+4\right)=0 \tag{3}$$

A different approach, which is the one used in this work, consists of solving the Navier-Stokes equations for the air and the liquid phase by means of a Computational Fluid Dynamics (CFD) and predicting in detail the transient flow field. By using models like the Volume of Fluid (VOF) [21-22] the size of the liquid lamella is computed and the interface between liquid and air is traced.

Results

The impact of droplets of water, ink and paint has been simulated by means of the CFD code FLUENT, version 6.0, by using the VOF model. The liquid has been assumed as incompressible, with constant viscosity and surface tension. The flow has been considered as Newtonian and laminar. Neglecting the possible instability at the rim of the lamella, axisymmetric conditions have usually been prescribed and a 2D grid made of square cells has been adopted. For the paint droplets a 3D configuration has been used as well. The simulations have been carried out with a constant time step, that ranged from 10^{-7}s to 10^{-9}s and that was set proportionally to the impact time scale *D/V*. Boundary conditions for fluid along solid surface impose no slip and no penetration. The contact angle has been prescribed as well. Its value depends not only on the wettability of the solid surface, but also on the velocity of the contact line. To take into account this effect, some simulations have been performed using a model for the dynamics of the contact angle similar to that adopted by Bussmann *et al.* [19]. Practically, the equilibrium angle has been considered for small contact line velocities, whereas in the other cases the asymptotic values associated with rapidly advancing and receding contact lines have been used.

The study of water droplets has shown the difficulty of simulating liquids with high surface tension and droplets of small size (less than approximately 200 μm). The high surface force arising from the combination of these two factors (proportional to σ/D) tends to destabilise the CFD simulation. The situation improves considering high impact velocities or liquids with viscosity higher than water, probably because the increased inertia or viscous forces are now able to balance the destabilising effects of the surface force.

Another problem, regarding fluids with small viscosity as water, is their tendency to form a lamella extremely thin during the spreading phase, before the liquid start to retract. As a consequence, a very high mesh density near the impact wall may be required in order to maintain the continuity of the liquid film, with a huge increase of the computational effort.

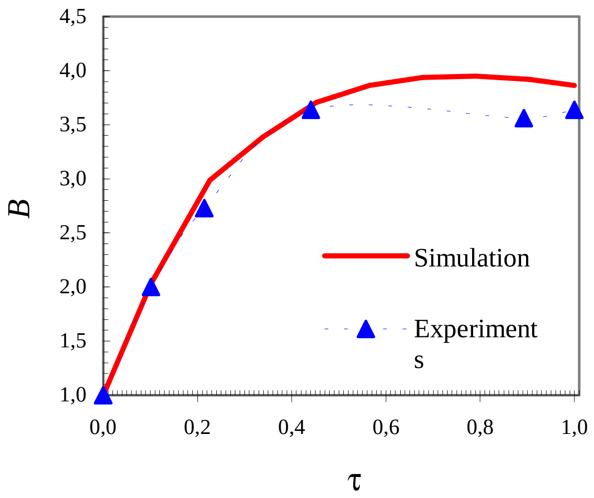

Figure 1. Spreading factor as a function of dimensionless time during the impact of an ink drop with a diameter of 3.2 mm and a velocity of 1.75 m/s. Experiments by Kim and Chun [6].

For liquids more viscous than water the afore-mentioned problems disappear and the code is able to describe the impact of small droplets colliding the surface with high velocity. Figure 1 reports the spreading factor as a function of dimensionless time τ during the impact of an ink droplet with a diameter of 3.2 mm and an impact velocity of 1.75 m/s. The simulation has been performed assuming a constant contact angle θ = 70°. The figure shows a good agreement with the results found experimentally by Kim and Chun [6] in the early phase of spreading, whereas there is a little discrepancy in the prediction of the maximum spread factor, which results 3.97 from the simulation against an experimental value of 3.86. Considering a variable angle a prediction even closer to the experimental one can be obtained. Nevertheless the value calculated with a constant contact angle is already more precise than those obtained by applying the relationship by Chandra and Avedisan [14] or the semi-empirical correlation by Scheller [23], which give 3.44 and 5.4, respectively.

The simplification of a constant contact angle, although acceptable for the spreading phase, leads to large errors if maintained also when the liquid retracts. An example is the simulation of the aforementioned droplet, which predicts wrongly the rebound of the liquid if the constant equilibrium contact angle is adopted, while simulates correctly the actual spreading-recoiling dynamics if the dynamic value of θ is used, as shown in Fig. 2.

After the first part of study concerning water and ink droplets, mainly aimed to test the reliability of the CFD code, simulations of impact of droplets of paint with a viscosity of 40 cP and a surface tension of 0.03 N/m have been performed. The drop diameter has been varied from 25 to 200 μm, whereas the drop velocity from 5 to 20 m/s. Both normal and oblique impacts have been studied, with inclination of 30°, 45° and 60°.

Differently from water and ink, for the case of paint the lamella does not retract significantly after having reached its maximum diameter, but shows only some small oscillations before assuming its final shape. This is due to the high viscosity and small surface tension of the system: the high viscosity dissipates rapidly the inertia of the liquid and the small surface tension is not able to provide the elastic energy needed by the recoiling phase. The consequence is that the final size is very close to the maximum diameter reached after spreading. In addition, due to the small extent of the recoiling phase, the role of contact angle is less important than before and the simulations can be performed reliably even by adopting the constant equilibrium value of this parameter. The difference in the prediction of B_m between simulations performed considering the dynamic behaviour of θ and considering the constant equilibrium value has always been below 5%.

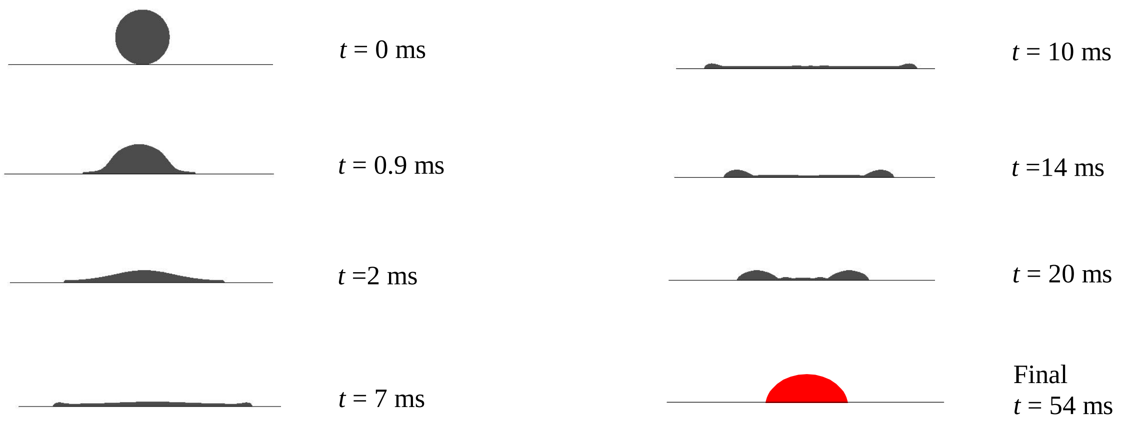

Figure 2. Impact of an ink drop with a diameter of 3.2 mm colliding the target surface at a velocity of 1.75 m/s.

Figure 3 shows the maximum spread factor calculated with constant contact angle of 70° at different values of Reynolds and Ohnesorge numbers. The graph reports also the results of the empirical correlation proposed by Scheller [23]:

$$B_m = 0.61\,(Re^2\,Oh)^{0.166} \tag{3}$$

and shows that the correlation is in good agreement with our simulation. Increasing Re a larger lamella is obtained due to the greater inertia.

The high viscosity of the system is the reason why we have never observed any splashing, even considering oblique impact. This is confirmed by the splashing criterion based on parameter K=We$^{0.5}$Re$^{0.25}$, which, for our system, is always smaller than its critical value for smooth surfaces [2-3]. Figure 4 shows two sequence of images referring to an impact normal to the wall (Fig. 4.a) and with a inclination of 30° (Fig. 4.b). Obviously the lamella formed after an oblique impact assumes a nearly elliptic shape. Considering a droplet of a diameter of 100 μm colliding the surface at 100 m/s, the major axis of the lamella become of 250 μm, 200 μm, 190 μm and 176 μm for inclinations of 30°, 45°, 60° and 90°, respectively, whereas the minor axis correspondingly changes from 135 μm, to 140 μm, 160 μm up to 176 μm for the axisymmetrical case of normal impact.

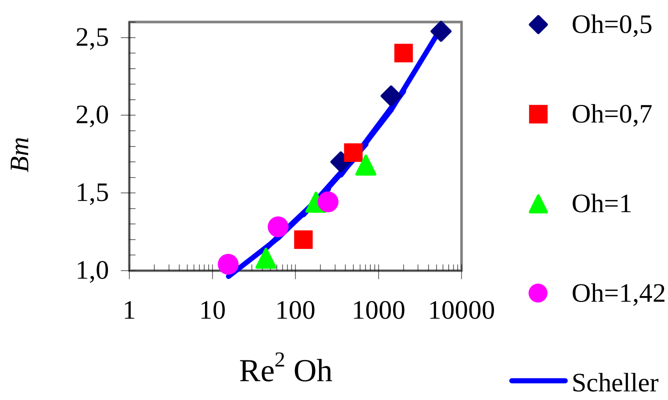

Figure 3. Maximum spreading factor predicted by CFD simulations at different values of Re and Oh. The continuous line is the correlation by Scheller [23].

Conclusions

The impact of droplets of water, ink and paint on a smooth and flat surface has been examined by means of simulations performed with the CFD code FLUENT.

The spreading phase after the droplet collision with the target surface has been analysed in detail and the maximum diameter reached before the liquid lamella starts to retract has been evaluated. A simple model able to take into account the dynamics of the contact angle during the spreading and recoiling phase has been adopted. The model has evidenced that the dynamics of the contact angle is significant only in the simulation of the recoiling phase.

This work has underlined that CFD codes can be powerful tools in the description of impact and can be helpful in those applications such as coating process in which the final aspect of the treated surface is extremely important.

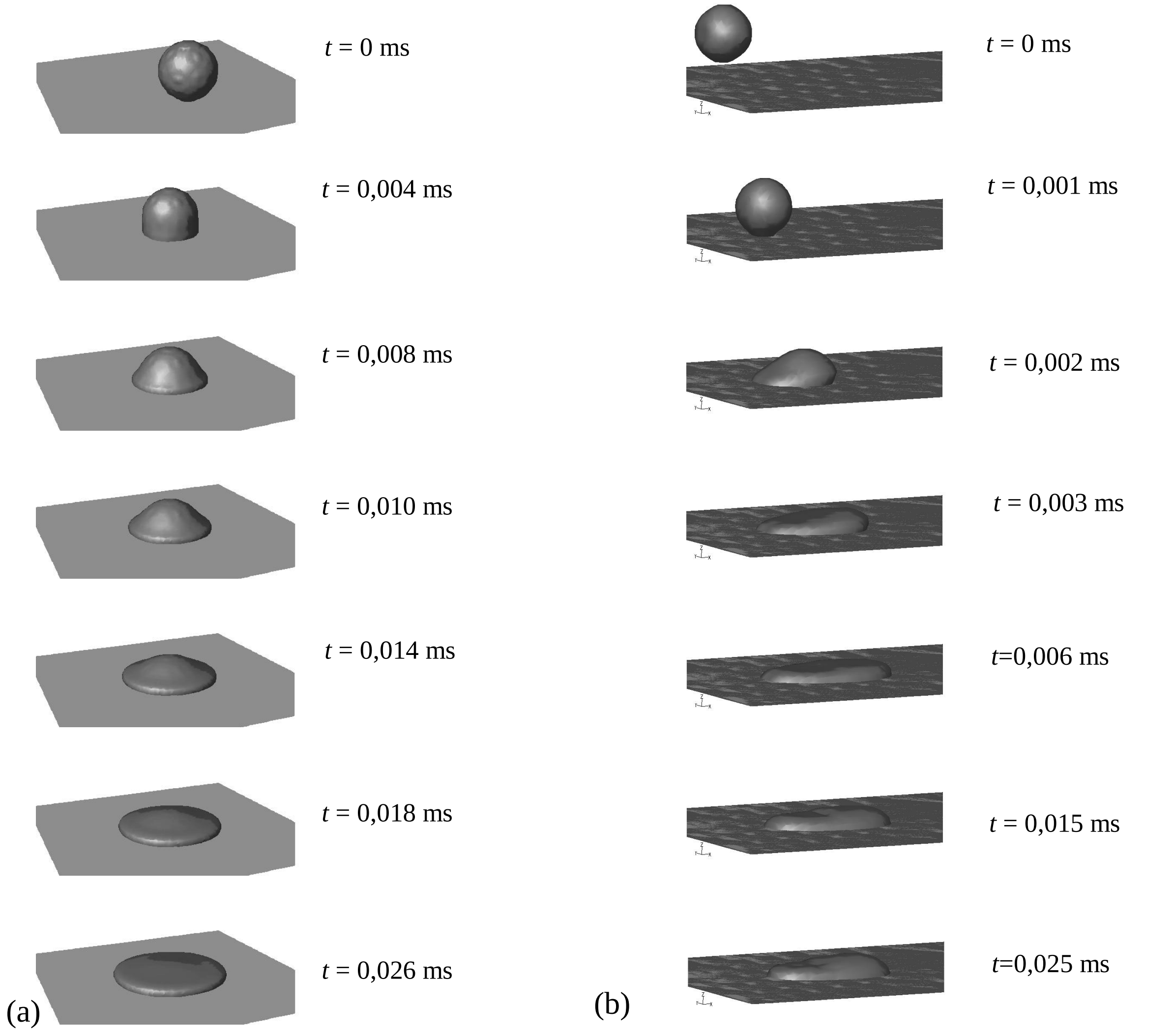

Figure 4. (a) Normal impact of a paint droplet with a diameter of 200 μm colliding the surface at 10 m/s. (b) Impact of a 100 μm diameter droplet colliding the surface with a velocity of 10 m/s and a inclination of 30°.

Nomenclature

ρ	density
σ	surface tension
μ	viscosity
D	droplet diameter before impact
Re	Reynolds number, $\rho DV / \mu$
V	droplet velocity before impact
We	Weber number, $\rho DV^2 / \sigma$
Oh	Ohnesorge number, $\mu / \sqrt{D\sigma\rho}$
d	diameter of the liquid lamella
d_m	maximum diameter of the liquid lamella

$B = d/D$	spreading factor
$B_m = d_m/D$	maximum spreading factor
θ	liquid-solid contact angle
t	time
τ	dimensionless time, $t\sqrt{\dfrac{\sigma}{\rho R^3}}$

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