THE DYNAMIC BEHAVIOUR OF SINGLE DROPLETS IMPACTING ONTO A FLAT SURFACE

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Abstract

This paper presents part of an experimental study on the impingement of liquid droplets onto flat surfaces. The experiments presented here consider the effects of droplet diameter and velocity at the instant of impact and the effects of surface roughness and wettability. Comparison of the results with a simple theoretical model based on energy conservation arguments, show that the dynamic behavior of droplet deformation upon the surface cannot be described by non-dimensional numbers which only consider the physical properties of the droplets. For the range of Weber and Reynolds number considered here, the effect of increasing surface roughness was observed to correspond to a shift for smaller values of Weber and Reynolds numbers.

Nomenclature

D_0	Droplet diameter before impact
D_{max}	Maximum spread diameter
Re	Impact Reynods number
U_0	Droplet impact velocity
We	Impact Weber number
$\beta(t)$	Dimensionless height
$\xi(t)$	Spread factor

Introduction

The dynamic behaviour of an individual droplet impacting onto a solid surface includes several individual phenomena, such as deformation, fingering, splashing and rebound. The onset and physical description of those phenomena are usually characterized based on dynamic similarity arguments making use of dimensionless numbers characterizing the relative magnitude of the forces acting upon the surface of the droplet (Reynolds, Weber and Ohnesorge numbers), e. g., Chandra and Avedisian [1], Marmanis and Thoroddsen [2], Thoroddsen and Sakakibara [3]. Estimative of these numbers are, in turn, obtained by scaling the forces (surface tension, shear and gravity) with physical properties of the liquid (density, viscosity and surface tension) and considering all lengths and velocities proportional to the diameter and velocity at the instant of impact, respectively. However, the physical properties of the impacting surface such as temperature, roughness or inclination alter the boundaries of the problem and similarity arguments cannot be applied (e.g., Stow and Hadfield, [4], Karl *et al.* [5]; Bernardin *et al*., [6]; Riboo *et al*. [7], [8]; Kang *et al.* [9], Sikalo *et al.*[10]).

This is the reason why it appears, from the reviewed literature that it is not possible to correlate the several phenomena occurring during droplet deformation with proper non-dimensionlal numbers. The complexity introduced by the non-scaled variables requires more experimental information to account for the influence of those parameters and it is the main objective of this study.

Experimental Method

Droplets are generated at the tip of a hypodermic needle and impact by gravity onto a tilting flat surface. The time history of droplet deformation is recorded by a high speed camera triggered by the passage of the droplet through a laser beam hitting onto a photodiode. A function generator allows to introduce an adjustable delay in the signal that triggers the camera. The camera has a frame rate from 30fps up to 10000fps and an exposure time between 0.1ms and 1.0ms.

The influence of several parameters in the droplet behavior during impact was taken into account. Namely, impact velocity, diameter and surface roughness. The impact velocity was varied between 0.2m/s and 5.05m/s, by changing the distance between the needle tip and the impact surface; droplet diameter was varied between

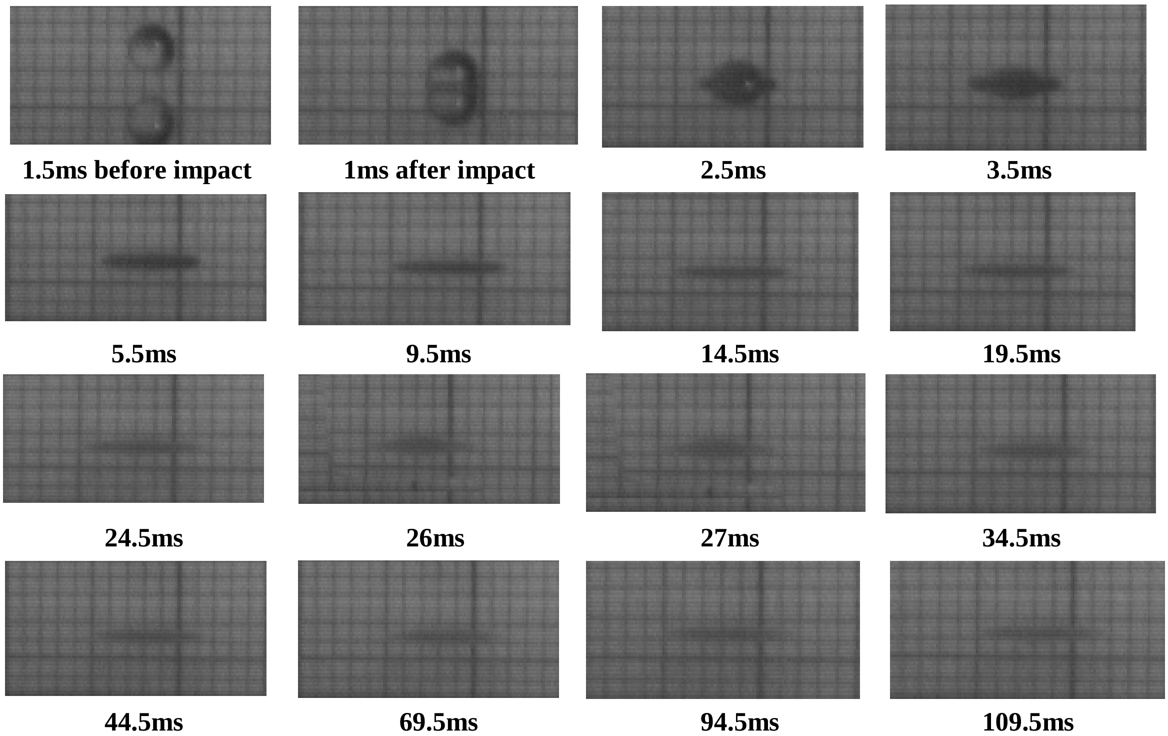
1.69 mm and 3.67 mm and several impact surfaces were used, with different wettabilities and roughness. Also, several liquids were used in order to vary the physical properties of droplets.

The droplet diameter and height above the surface, contact angles, number of fingers and several other quantities relevant to characterize droplet dynamic behaviour, were measured directly, using the recorded images. The impact velocity was obtained from the distance, in pixels, traveled by the drop between the two last frames before impact. The instant of impact (t=0s) was taken from the recorded sequences of images. This procedure provides a velocity and a lenght scales for dimensionless analisys.

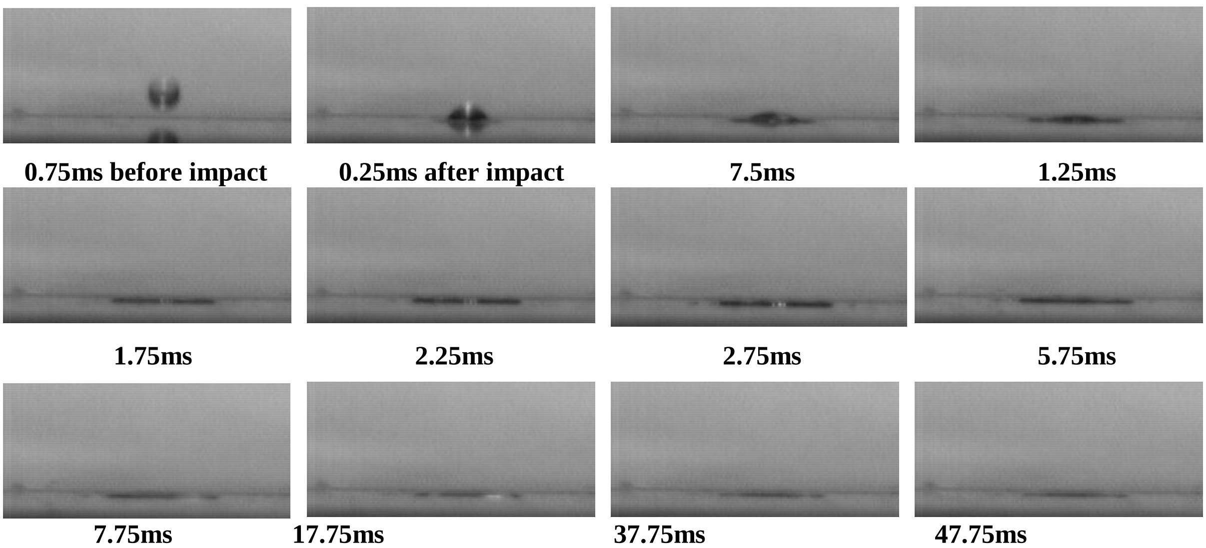
The droplets were not always perfectly spherical at impact, particularly for large release height. Therefore, both horizontal and vertical diameters were measured and an equivalent droplet diameter was considered, as in Sikalo *et al.* [10], to be $D = (D_h^2 D_v)^{1/3}$, where D_h is the horizontal diameter and D_v is the vertical diameter.

Results and Discussion

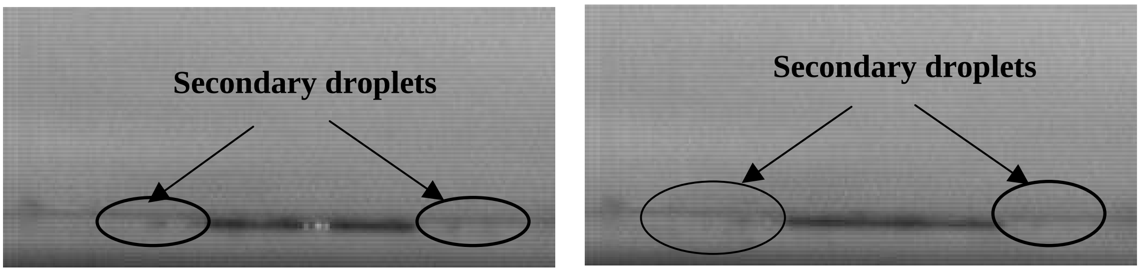
Figure 1 shows the sequence of images recorded with the CCD camera of a Diesel oil droplet impacting onto a smooth perspex surface, at a lower (U_o = 0,4 m/s) and a higher velocity (U_o = 2.47 m/s), respectively.



(a)



(b)

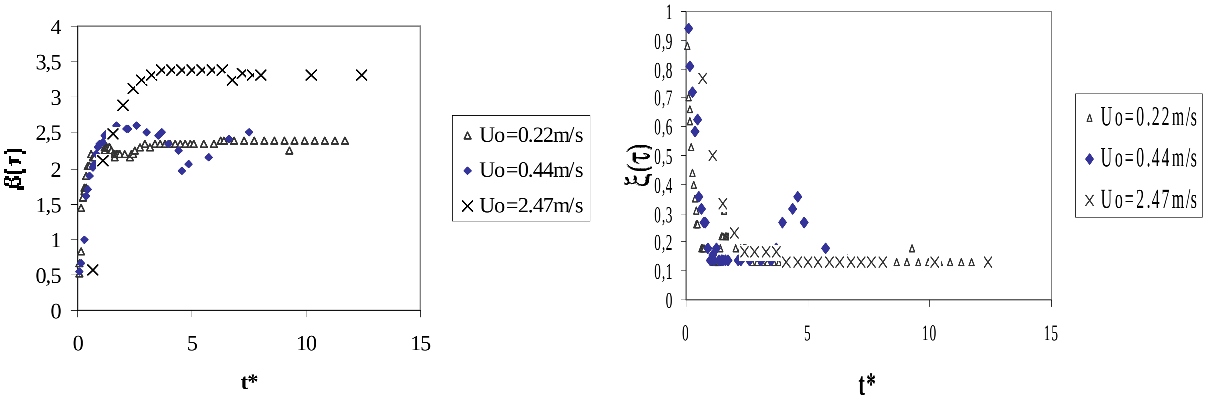


2.75ms **5.75ms**

(b_1)

Figure 1. Diesel oil droplet impacting onto a smooth perspex surface. Droplet diameter Do = 2.5mm. **(a)** U_0= 0.4m/s**; (b)** U_0 = 2.47m/s; **(b_1)** Detail of secondary droplets in prompt splash for U_0 = 2.47m/s.

Droplet spreading is usually characterized by the diameter of the wetted area, *d* and the droplet height above the surface, *h* , made dimensionless by the initial droplet diameter, D_0, which yields the spread factor, $\beta(t)=d/Do$ and the dimensionless height, $\xi(t)=h(t)/Do$. Figure 2 shows the variation of $\beta(t)$ and $\xi(t)$ with the dimensionless time (time normalized by the impact velocity and by the initial droplet diameter) for a Diesel droplet impacting onto a smooth perpex surface, at different velocities.



a) **b)**

Figure 2. Variation of $\beta(t)$ and $\xi(t)$ with the dimensionless time for a Diesel oil droplet impacting onto a smooth perpex surface, at different velocities.

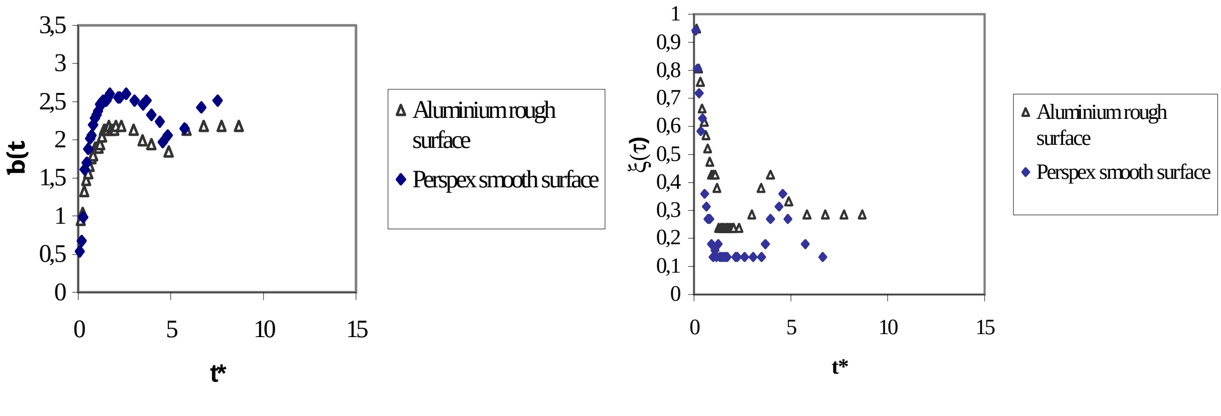
The results in Figure 2 show the influence of the impact velocity on droplet deformation during impact. It is clear that at the lowest velocity the droplet moves periodically, spreading and recoiling twice (see also Figure 1 a)) without splash or break-up. At the largest velocity of impact the droplet spreads almost without recoiling and a prompt splash is observed when the droplet impacts onto the surface (see Figure 1(b) and (b_1)) as also reported by Sikalo *et al.*, [10] with water drops impacting on wax.

The maximum value of the spread factor clearly increases with the impact velocity, varying from about 2.2 for the lowest velocity to about 3.5 for the highest impact velocity. This indicates the importance of the inertial forces during the spreading: as the impact velocity increases, the velocity of the film liquid propagating on the surface also increases and the inertial forces overcome the surface tension and shear forces for a longer period. Furthermore, increasing the velocity the dimensionless time corresponding to the maximum spread also increases. Therefore, the dimensionless time alone is not enough to lead to similarity in the spread factor evolution as it has been suggested by Pasandideh-Fard *et al.* [11], based on a simple energy conservation analysis. At low impact velocities, when the droplets present a periodic motion, the droplet at higher impact velocity has a larger spreading and consequently recoils later, so there is a difference between the maximum values of the spread factor and dimensionless height, for the curves correspondent to the drops at lower velocities.

There is no evident influence of the impact velocity on the dimensionless height except for the fact that the maximum value of $\xi(t)$ occurs for a larger values of *t**, which is in agreement with the time evolution of the spread factor. However, the results in Figure 2b) for the droplet with a larger impact velocity, show that the dimensionless height remains constant after the diameter attains the maximum value. This is due to the concave form of the droplet surface, which does not allow visualization of the centre of the droplet from a side view. Similar observations can be inferred from the results reported by B. S. Kang and D. H. Lee [9] for a droplet of water impinging onto a surface heated at the temperature of nucleate boiling regime. However, the phenomenon is more noticeable in the present case, which may be associated with a larger velocity of deformation. As a consequence, changes in the height of liquid due to the influence of impact velocity may not be detected from the measurement of the height of liquid above the surface.

The aforementioned results also show that the frequency of the periodic deformation is decreased when the impact velocity decreases. In fact, at high impact velocities, the wetted area is larger and the energy dissipated against progression of the liquid film on the surface is larger. So, based on energy conservation principles it may be argued that the surface energy needed to bring the liquid back to the central region of the droplet is smaller and the drop will have significant smaller recoil. On the other hand, the contact angle is so small that it does not allow recoiling. This is particularly evident when the wettability is larger, as it is the case of Diesel oil drops impacting onto clean smooth surfaces.

Figure 3 shows the time evolution of the spread factor and dimensioless height of Diesel oil drops impacting onto a rough aluminium surface and on a smooth perspex surface. The droplets have nearly the same diameter and the same impact velocity, so changes in the behavior may be attributed to surface properties only.



a) b)

Figure 3. Variation of $\beta(t)$ and $\xi(t)$ with the dimensionless time for a Diesel oil droplet, impacting onto an aluminium rough surface (We = 18; Re = 464) and on a smooth perspex surface. (We = 13; Re = 394).

The results show similar qualitatitive trends, in the sense that both cases show the periodic deformation behavior previously reported. Quantitatively, the effects of surface roughness seems to be negligibly small in the initial stage ($t^* < 0,5$), which is in accordance with the fact that the initial rate of change depends more on the kinetic energy of the droplet at impact (e. g., Fukai *et al.*, [12]). Further, the maximum spread is larger on the smooth surface as also observed by other authors (e. g., Fukai *et al.*, [12]; Sikalo et. al., [10]) and the minimum non-dimensional height is larger on the smooth surface, in accordance with the requirement of mass conservation. However, other authors observed that the surface only affects the height of the droplet on the recoil phase. The difference may stem from the much smaller value of the Reynolds number considered in the present work (about 400 compared 3264). It may be so, since the increased dissipation due to roughness takes more time to act when the kinetic energy at impact is larger. Also, a larger dissipation of the initial energy at the surface will decrease the period of the deformation, as also observed in Figure 3. Therefore, the results presented here suggest that, as the kinetic energy at impact increases, the effect of surface roughness may be delayed for later stages of the deformation process.

It is worth discussing at this point the physical meaning of these results based on the model proposed by Pasandideh-Fard *et al.* [11], wich is an improvement of the model presented by Chandra and Avedisian [1]. In this model, it is assumed that the droplet spreads into a liquid film with the shape of a disk with a diameter $D(t)$ and a height $h(t)$ expanding radially on the surface with velocity V_R given by conservation of mass:

$$\frac{V_R}{U_o} = \frac{d(t)^2}{4D(t)h} \qquad \textbf{(1)}$$

where U_0 and D_0 are, respectively, the droplet velocity and diameter before impact. Manipulation of eq. (1) considering that when the disk (liquid film) reaches its maximum diameter, D_{max}, the liquid volume within the disk equals the volume of the initial droplet, gives:

$$V_R = \frac{3}{8}\frac{U_o D_{max}^2}{D(t) D_o^2} d(t)^2 \qquad \textbf{(2)}$$

Assuming, as Pasandideh-Fard *et al.* [11], an average value $d(t)$~$D_0/2$ and knowing that $V_R=\delta D(t)/2\delta t$, the evolution of splat diameter ($D(t)$) is given by integration of eq. (1) and maximum diameter occurs when

$$t^* = t\frac{U_o}{D_o} = \frac{8}{3} \qquad \textbf{(3)}$$

Therefore, the dimensionless time, t^*, required for the droplet to reach its maximum extent, is a constant.

Table 1 compares the values of t^* obtained from our experimental results with those estimated from the theoretical model of Pasandideh-Fard *et al.* [11].

Diesel oil droplet	t^* (experimental)	t^* (Pasandideh-Fard *et al.*)	Difference [%]
We=487, Re=2558 (smooth surface)	4.25	8/3	36.5
We=4, Re=198 (smooth surface)	1.3	8/3	51.8
We=13, Re=390 (smooth surface)	1.61	8/3	39.3
We=18, Re=464 (rough surface)	1.66	8/3	38.5

Table 1. Comparison between experimental values of t^* and the theoretical value presented by Pasandideh-Fard *et al.* [11].

The results show that the experimental values of t^* systematically exceed the theoretical value of 8/3, suggesting that the major cause for discrepancies may be due to overestimation of the spreading velocity in the model, besides the uncertainty in the determination of the instant of impact. Moreover, larger discrepancies occur for the case with the lowest Weber and the Reynolds number (We = 4, Re = 198), which is far from the conditions tested by the authors of the model.

The maximum spread diameter may also be predicted by applying the energy conservation condition to the model of Pasandideh-Fard *et al*. [11]. According to this condition, droplet kinetic energy, KE_D, plus the energy required to keep the spherical shape of the droplet, SE_1, must equal the final surface energy, SE_2, plus the work done in deforming the droplet against viscosity, W, i. e: $KE_D + SE_1 = SE_2 + W$. The authors found a relation for W, based on an appropriate length scale, and achieved an equation for the maximum spread:

$$\frac{D_{max}}{D_o} = \sqrt{\frac{We+12}{3(1-\cos\theta_a)+4\left(We/\sqrt{Re}\right)}} \qquad \textbf{(4)}$$

where θ_a is the contact angle between the liquid and the impact surface.

Table 2 compares the experimental values of (D_{max}/D_0) with those obtained from the model of Pasandideh-Fard *et al*. [11].

Diesel oil droplet	(D_{max}/D_0) (experimental)	(D_{max}/D_0) (Pasandideh-Fard *et al.*)	Difference [%]
We=487, Re=2558 (smooth perpex surface)	3.4	3.59	5.3
We=4, Re=198 (smooth perpex surface)	2.29	1.76	30.1
We=13, Re=390 (smooth perpex surface)	2.6	2.75	5.8
We=18, Re=464 (rough aluminium surface)	2.18	3.1	30.3

Table 2. Comparison between experimental values of (D_{max}/D_0) and those predicted by Pasandideh-Fard *et al.* [11].

The results show that the model overestimates the maximum spread for the presented cases except, again, for the Diesel oil droplet with the lowest Weber number (We=4, Re=198). For all the other droplets impacting onto a smooth prespex surface the experimental values of (D_{max}/D_0) agree well with those obtained using the model of Pasandideh-Fard *et al.* [11] with differences smaller than 6%.

However for the droplet impacting onto the aluminium rough surface, the difference between the experimental value of the maximum spread factor and that predicted by model is larger than 30%, as if it impinges onto a smooth surface with a smaller impact velocity. In fact, it is expected that the physical effect of surface roughness on droplet deformation is to increase the energy lost to viscous dissipation at the wall and, hence, it would be similar to a decrease of the Reynolds number. Besides, it was observed that the rough surface promotes splash, which is known to be associated with higher impact velocities for a smooth surface. This analysis thus suggests that Reynolds and Weber numbers must be both used when taking into account the effect of surface roughness.

Summary

The experiments presented here are part of major work aimed at studying the effect of non-scalable parameters on the impinging of individual droplets onto flat surfaces. The results reported in this paper consider only the effect of surface roughness, which effect is to increase the energy lost to viscous dissipation at the wall. Comparison of the results with a simple theoretical model based on energy conservation arguments, show that the dynamic behavior of droplet deformation upon the surface cannot be described by non-dimensional numbers which only consider the physical properties of the droplets. For the range of Weber and Reynolds numbers considered here, the effect of increasing surface roughness was observed to correspond to a shift for smaller values of Weber and Reynolds numbers. More detailed experiments will be pursuit in order to find the appropriate dimensionless numbers and correlations to describe those effects quantitatively.

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