

Study of the Impact of Drops onto Solid Surfaces

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Abstract

In this paper, we report experimental results on the collision dynamics of a water droplet impinging on a rigid surface. The rigid surfaces considered cover a wide range of roughness' and porosities from stainless steel to paper.

The experimental method used is based on a high-speed cinematography technique combined with advanced image processing means. The observations are made at ambient pressure, ambient temperature, with an initial droplet diameter of 2 mm.

The measurements are performed on a large range of variation of relevant dimensionless parameters in order to determine different thresholds. We show that whatever the operating conditions, the drop spreads and retracts under the action of inertia and capillarity respectively. In the initial stages of impact, the transient evolution of wetted area and spreading rate for a given impact Weber number, appear to be independent of the surface on which the droplet impinges. These results are discussed within the framework of possible physical mechanisms.

Introduction

Liquid drop impact with a solid surface is a topic of interest in many engineering applications. Some of these include nuclear reactor cooling where heat transfer is affected by the drop dynamics upon impact of the drop with a solid surface, or the deleterious effect of high velocity rain drops on airplane wings. Detailed knowledge of droplet impingement on solid materials is also critical for overall process development and advancement of engineering operations such as spray cooling and/or spray coating.

The fluid flow associated with impinging drops is rather complicated because of the extreme deformation of the droplet surface occurring within very short time scales and is not really understood in detail. In the case of low impact velocities, the spreading phenomenon is probably controlled by the surface tension. When impact velocities become important, it has been shown that compressibility effects play a major role.

The studies of drop impact on solid and liquid surfaces were initiated by Worthington[1] who investigated the pattern left by drops of various liquids after their impact onto glass plates. More recently Chandra and Avedisian[2], Prunet-Foch et al[3] and Mähönen et al[4] have performed experiments varying the operating conditions and the solid targets and using much more sophisticated visualization techniques than Worthington[1]. Nevertheless, except the work by Chandra and Avedisian[2] who performed experiments on steel and ceramic surfaces, there are not many attempts in the literature of direct comparison of the droplet impact dynamics on porous and impervious surfaces. This aspect presents of course an interest in industrial printing.

The work, which is presented here, is connected to ink-jet printing where drop impact onto solid surfaces is a frequent occurrence to say the least. The emphasis is on the different phenomena related to low speed impacts on a variety of solid surfaces which possess essentially different wetting characteristics. Indeed in view of the low droplet velocities at which the experiments are performed the elastic response of the surfaces can be considered to be insignificant. In this work we report results of the collision and deformation dynamics of droplets impacting on targets of stainless steel and various grades of paper. The objectives are to:

1. detail the impact of a droplet on the surfaces for different values of droplet velocity.
2. measure the evolution of droplet shape (spreading diameter, droplet height) during impact.
3. compare results obtained on porous and impervious surfaces and their eventual agreement when possible with relevant theoretical analyses.

Therefore the impact of single drops is studied using a high speed camera which takes photographs at successive stages of the impact process of one single droplet. A wide range of flow régimes are covered in this work like spreading, retraction, oscillation and splashing and the results obtained are compared with existing data. The particular impacts we present here are for Weber numbers of interest in ink-jet printing and may be characterized as the interplay between inertial effects which are shown to dominate the early spreading of the fluid, and the viscous and surface tension forces which arrest the spreading and eventually bring the fluid to an equilibrium configuration. This latter aspect is shown to depend greatly on the substrate used.

Experimental

In this section, we present the device for forming the droplets, the measurement methods as well as the substrates which are used.

The experimental set-up is shown in figure 1. The droplet exits from the needle of a hypodermic syringe having a diameter of 0.3 mm. The motorized translation table situated above the syringe helps in dispensing well formed drops of diameter 2 mm with an accuracy of about 3.5%. This simple arrangement replaces the syringe pump, that is ordinarily used in this type of experiment. The velocity of the drops is varied by one order of magnitude (0.3 to 3 m/s) by simply changing the height of fall (distance between needle and the substrate). The velocity is measured from the distance of travel between two images taken with the high-speed camera at a given frequency.

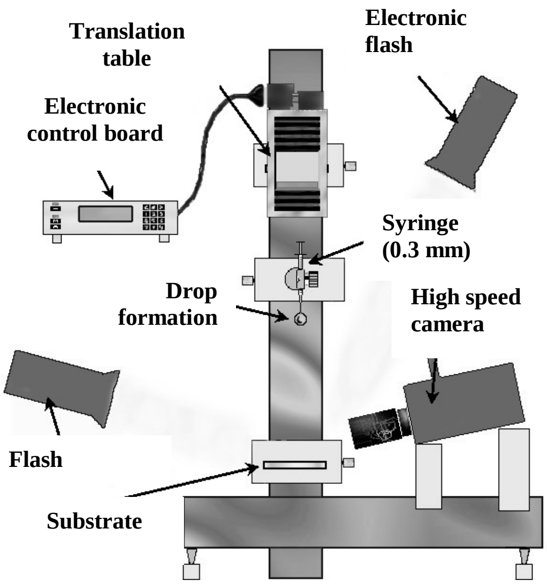

Figure 1. Schematic of the experimental set-up

When the drop arrives near the substrate, an electronic signal is sent to the system so as to begin the grabbing process. A single image (snap-shot) or a sequence (movie) may be captured. The camera is part of an acquisition system NAC high-speed video HSV-1000 allowing a frame rate of 1000 images per second. The system is built around a continuous frame grabber board which is capable of digitizing full RS-170 (NTSC) frames at VGA resolution (512 × 512 pixels). At the high framing rate of 1000 images per second, the vertical number of pixels is reduced. Nevertheless there is no distortion in the images which are acquired. The above framing rate requires intense illumination of the drop. This is taken care by two flash controller units of 200 Watts each providing 10 μs duration flash synchronized with the camera. Once the image acquisition is completed, an edge finder algorithm accurately locates an edge from a gray-scale image. After the images have been processed, data is exported to industry-standard spreadsheets and databases for further analysis.

The high speed cinematography technique does not require a perfect reproducibility from one experiment to an other. This is in contrast to the work by Chandra and Avedisian or Prunet-Foch et al[2,3] who use a stroboscopic technique and reconstruct the evolution of the drop dynamics with photographs of different droplets taken at successive stages of the impact process. Nevertheless, we have checked the aspect of reproducibility and found the phenomenon to be very repeatable within the limits of variation of the dimensionless parameters which will be given in the next section.

Top and side views of the drop are obtained independently on different series of droplets since the experimental arrangement must be changed. Top views are seldom considered in this paper because we have found that they are prone to higher uncertainty than side views. The side views give access to the spreading diameter d(t) and the flattening apex or height h(t). The accuracy in the measurements is more or less one pixel which leads to an error of about 1%.

Results and Discussion

To fulfill the objectives listed in the introduction part, we have performed drop-impinging experiments on steel and papers having different coatings and with porosities ranging from 16 to 61%. The measurements of the transient spreading diameter and the apex are taken for impact Weber numbers covering an order of magnitude of two as stated below.

Theoretical Background

As soon as there is contact between a drop and a solid surface, the liquid generally starts spreading out. In the limiting case i.e. when the drop is carefully placed onto the surface, the process of spreading is dominated by intermolecular forces. The dependence on time of the radius of the wetted spot and of the contact angle can be described by universal scaling laws as shown in detail by de Gennes[5]. This topic is out of the scope of this paper and will not be considered further.

In the case of a finite velocity, the mathematical formulation of the problem of impact of a droplet on a solid surface leads to consider the equation of continuity and the momentum equations both in the radial and in the axial directions. The non-dimensionalization process[6] gives the following dimensionless numbers (Reynolds, Weber, Froude and Mach) respectively:

$$Re = \frac{\rho\, V\, D}{\mu} \quad We = \frac{\rho\, V^2\, D}{\sigma} \quad Fr = \frac{V^2}{D\, g} \quad Ma = \frac{V}{c} \qquad (1)$$

where D is the diameter of the drop prior to impact, V its velocity, μ the dynamic viscosity of the liquid, σ the liquid-air surface tension, g the gravity acceleration and c the speed of sound in the liquid medium.

In the case of a finite impact velocity, the drop spreads into a “pancake” shape. The rate of spreading is driven by the inertia of the drop and it is slowed by viscous and surface tension effects. When the inertial energy is dissipated, the drop reaches its maximum diameter. A rough model for the prediction of this maximum diameter has been worked out from a simple energy balance equation[2] and reads:

$$\beta_{max} = \left(\frac{-(1-\cos\theta) + \sqrt{(1-\cos\theta)^2 + 4\,Ca\left(\frac{We}{2}+6\right)}}{3\,Ca} \right)^{1/2} \qquad (2)$$

where β_{max} equal to d_{max} /D is the maximum spreading factor, θ is the contact angle and Ca is the capillary number equal to the ratio of viscous forces over surface tension forces or We/Re.

Following the rules of similarity,[7] experiments conducted with our model (droplet diameter = 2 mm) can be compared to those performed with an actual print head prototype (droplet diameter = 50 µm) if the above cited dimensionless numbers remain the same between the two sets of experiments. Given the low impact velocity of ink droplets, the Mach number is probably irrelevant in the problem at hand. As for the Froude number, it is hard to keep it the same for the two sets of experiments but its influence has been shown elsewhere to be negligible. In fact, a number of preliminary experiments have pinpointed out that the main controlling parameter is the Weber number, so the different experiments will be performed by varying this dimensionless number.

Results

All the experiments given in this paper have been carried out with distilled water as the impacting fluid. Figure 2 shows an 18 frame movie for an experiment performed at a Weber number of 2.1. For the sake of comparison, this would correspond to the case of an ink droplet impinging on the substrate at a velocity of about 2 m/s.

The substrate used in this experiment is a thin stainless steel foil having an average roughness of about 0.7 µm. The first frame is taken precisely at the time of contact and the frame interval for the successive photos is 1 ms. As soon as the droplet contacts the solid surface, there is a sideways flow which tends to flatten the droplet. In the first stages of the phenomenon, the upper part of the droplet which is not yet in contact with the surface does not seem to be influenced by the sideways flow (frames # 3 and # 4). Then when the apex of the drop comes closer to the substrate, the upper part collapses inside the crater and this corresponds to the largest spreading diameter (frame # 6). From that time, the drop begins to recoil and the attains the largest height at about the tenth frame. Finally from the 13[th] frame, it can be noted that the drop is subject to very small variations around an equilibrium configuration.

In figure 3, we have plotted the spreading factor β and the flattening factor ζ = h(t)/D versus time for the experiment described above. The largest spreading occurs at time t_1 equal to 5 ms and the value for the diameter attained at that time is 1.6 times the initial one. Conversely the time t_1 also corresponds to the lowest value in terms of height with $h(t_1)$ less than 0.4 D. One can also note that from time t_2 equal to about 13 ms the drop diameter stabilizes around a value equal to 1.3 D. The height first evolves slowly with no particular period and then from 30 ms it has a given oscillation frequency.

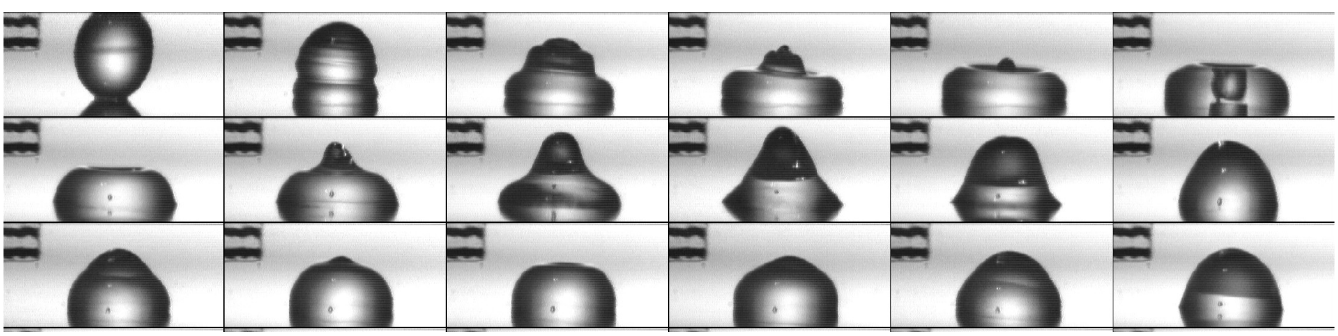

Figure 2. Impact of water drops on a stainless steel substrate (We = 2.1)

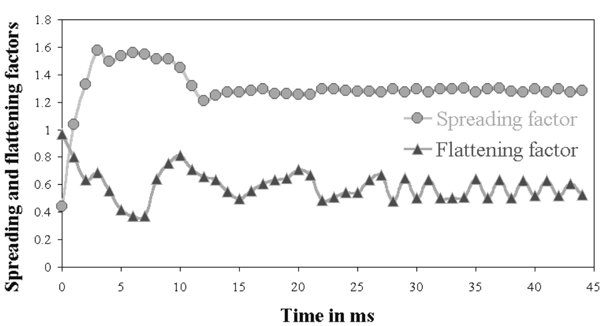

Figure 3. Evolution of β(t) and ζ(t) on steel for We = 2.1

A rough calculation shows that the value obtained (500 Hz) is consistent with the natural frequency of oscillation of a liquid droplet surrounded by a gas medium. Other experiments are on-going to confirm this tendency.

Figure 4 depicts a sequence of photographs for an experiment performed at a Weber number of 55. This value is similar to an ink droplet striking the substrate at a velocity of about 6 m/s. Again the frame interval for this experiment is 1 ms.

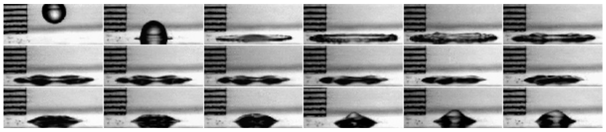

Figure 4. Impact of water drops on a steel substrate (We = 55)

We can note that in this case the inertial spreading rate is much more larger than in the previous experiment and wetting occurs almost instantaneously (frames # 3 and # 4) with a formation of a thin film.

The film diameter stretches to a significant degree (β_{max} equal to 3.5) before spreading is halted by the dominance of viscous and surface tension forces. The value of the spreading factor in the equilibrium configuration for this experiment is 1.5 which should be compared to the value of 1.3 found for the previous experiment performed at We = 2.1.

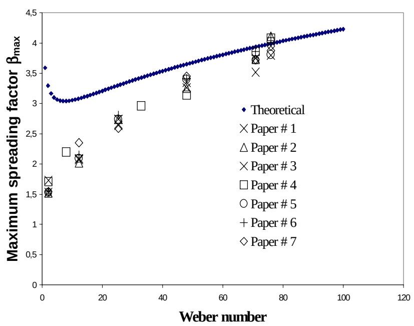

Figure 5.Maximum spreading factor for different papers

In figure 5, we report the maximum spreading factors found for drop impacts on a large variety of papers and compare them with the theoretical equation (2) given above. The contact angle θ is taken to be 60°. The porosities of the papers range from 61% for the Paper # 7 with a hydrophobic layer to less than 10% for the Paper # 3 which has a superior coating and very low roughness. The data for the different papers collapse into one single master curve and the agreement with the theoretical equation is good from Weber numbers equal to about 40. We have also found good agreement between equation (2) and experimental data for drops impinging on steel substrates. However, the validity of this equation for low values of the Weber number, is questionable and should be investigated in more detail.

Conclusions

In this paper, we have described the collision dynamics of a water droplet impinging on a variety of surfaces. Using high-speed cinematography, the emphasis has been placed upon the analysis of the whole deformation process of a liquid droplet after impact. We have demonstrated that the dominant mechanism in the early stages of impact is inertial spreading which is controlled by the Weber number. The maximum spreading factor has been shown to be independent of the type of substrate (porous or non-porous). This result is important in terms of industrial printing.

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Biography

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