SPREADING BEHAVIOR OF SINGLE AND MULTIPLE DROPS

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Summary This paper describes experimental and numerical work relevant to the impact of single and multiple drops onto various solid substrates. The experimental methods are based on visualization techniques and the single drop spreading transients are obtained using the variational principle and a commercial numerical code. The collision of two drops is then considered and the results lead to a simple model able to describe the axisymmetric collision of drops. The extension of the model to other forms of coalescence is also discussed.

INTRODUCTION

Impact and spreading of single and multiple liquid drops onto a solid substrate is a widely encountered and often critical process. Indeed detailed knowledge of droplet impingement on solid materials is required for the overall process development and improvement of many engineering operations.

The work reported here is connected in many aspects to ink-jet printing where drop impact onto solid surfaces is a ubiquitous phenomenon. The emphasis is first on the characterization of phenomena related to impacts of single drops of fluids having different surface tensions on a variety of impervious surfaces. Not only the effects of the dynamic impact conditions but also the wetting behavior are investigated. For this purpose, drop velocity, shape and size at various steps of the spreading phase [1-3] are recorded. The impact of the drops is simulated numerically using the variational principle [3,4] and a commercial code [5] based on a volume-of-fluid (VOF) method. Some remarks are given on the work which still needs to be done for improving the agreement with experimental results.

Finally this study focuses on the fate of an incoming droplet impinging on an other at rest on the substrate. This situation happens quite often in ink-jet printing where a variety of drop onto drop impacts can be observed [6]. The discussion is limited to the axisymmetric situation for which the transient interaction phenomena between the two drops are detailed and comparison with the case of a single drop given.

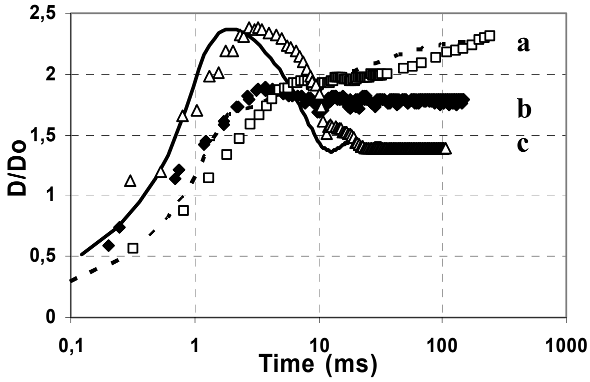
IMPACT OF A SINGLE DROP

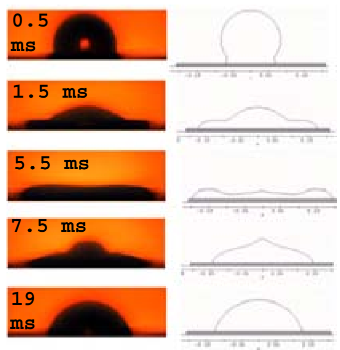
The experimental devices, single drop impact experiments on dry substrates and modeling aspects are detailed in this section. Impacts on wetted surfaces may present a host of other peculiarities [7-8] and are not discussed here.

Drop ejectors and visualization devices

The experimental set-up includes a precision syringe pump for forming millimeter sized drops and ink-jet print-heads for ejecting drops which are less than 100 µm in diameter. The size of the big drops can be tuned by changing the needle and those used in this work allowed forming drops between 1.7 and 2.3 mm. The velocity of the drops can be varied by almost an order of magnitude by simply changing the height of fall [1-3]. The manipulation of the drive waveform allows ejecting small sized drops with velocities varying between 1 and 7 m/s [6].

The camera used to capture the impact spreading and eventual collision processes of large drops is a high speed Kodak camera allowing a frame rate of 2000 images/s. In the case of small drops, a PCO SensiCam fast shutter (100 ns) video capturing system is used. Multiple exposure shot experiments give access to the velocity of the impinging drop and permit checking of the reproducibility of different experiments.





Figures 1a and 1b: Experimental and simulated diameters and profiles of the spreading drop

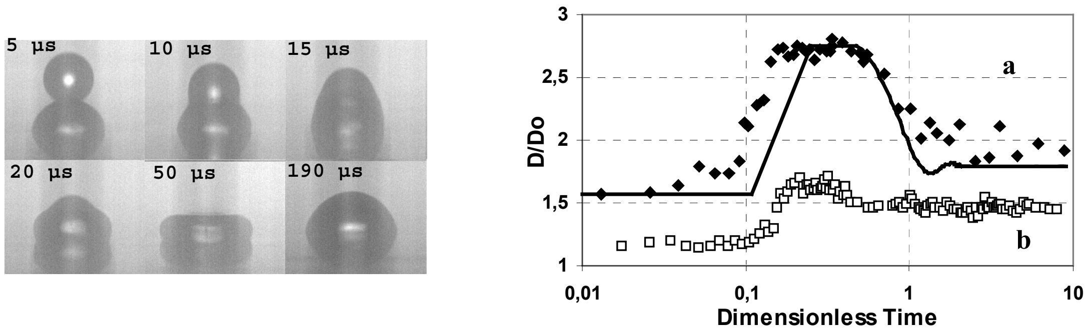
Experiments and modeling

Figure 1a gives the transient spreading diameter of different fluids on a variety of substrates. Almost 4 decades of time scales are covered and allow emphasizing the different regimes [2,3]. Curve (a) shows the transient diameter for a drop of surfactant based fluid ejected at 0.3 m/s having a final equilibrium angle of about 20° with the substrate whilst curve (c) represents that of a water drop ejected at a higher velocity (1.1 m/s) on a polyesterterephtalate surface with a final equilibrium angle of 75°. As demonstrated elsewhere [2,3], the transients in the kinematic phase are independent of the

nature of components and essentially governed by the dynamic parameters and geometrical considerations whilst the physico-chemical characteristics of the fluid and substrate become predominant in the late stages of spreading.
For modeling the impact behavior, Lagrangian methods are used together with an assumed flow field and the drop shape approximated by a truncated sphere [4]. The maximum diameter attained during the inertial spreading phase is controlled by the dissipation factor and is found from various relationships reported elsewhere [3]. This model fits rather well the diameters as demonstrated by the dotted and solid curves shown in figure 1a but is unable to render the transient deformations of figure 1b obtained at high Reynolds number. The use of Flow3D, which employs specific algorithms to circumvent the problem of deforming surfaces, allows to obtain the profiles with relative success as show in figure 1b.

MULTIPLE DROP COLLISION

It has been stated that all works about impact can be classified into two groups: impact on dry surfaces or impact into liquid pools where the pool can be either deep or shallow. During the past few years, significant progress in the understanding of the impact of a single drop onto a liquid film of uniform thickness has been made [8]. Nevertheless the above literature is not directly related to our applications since droplet splashing and disintegration do very seldom occur in the case of small impact energy processes such as ink-jet printing and most importantly single drop impacts onto a liquid film do not consider the interaction effects between drops.
In figure 2a the axisymmetric collision of two drops of the same size is shown. Note the sharpness of the photographs and the very small times related to the interaction of drops of 80µm in diameter with all variations died out in less than 200 µs. In figure 2b the data obtained for collisions between millimeter sized drops (diamonds) and micrometer sized drops (blank squares) are given. The Weber number formed with the impinging drop is rather similar for both experiments with however a large variation in the Reynolds numbers. It can be noted that for both cases there is a latency time during which there is no movement of the contact line before the second drop has completely immersed into the first one and has hit the substrate. From then on the liquid mass begins to swell in a similar manner for both sizes of drops followed by a more vigorous retraction and slight oscillations for the most energetic impact.



Figures 2a and 2b: Snap shots of the multiple drop collision process and transient evolution of diameter

Also give in figure 2b are the results obtained with a simple model (solid line) which considers the incoming drop as a solid mass penetrating the first drop. Upon hitting the substrate, the maximum diameter is found from a balance of energies taking into account the surface energy of the static drop and the change of total liquid volume. The evolution from the maximum is found using the variational model with the diameter taken to be that of two merged drops. The overall model is quite satisfactory compared to published results [9] and is amenable to off-centred collisions as well.

CONCLUSIONS

In this paper, the collision dynamics of single and multiple drops impinging on a variety of substrates have been detailed and modeled. In the case of single drop impacts occurring at small dimensionless numbers the shape of the drop is essentially a truncated sphere and the transients are well rendered using a variational model. More sophisticated numerical simulation is necessary for impacts at high Reynolds numbers where the profiles are quite intricate and further work is still needed in that area. Low velocity drop onto drop axisymmetric collisions can be split into three phases: a latency period during which the drop stays pinned on the substrate, a spreading phase with the maximum diameter given by energetic considerations and finally the recoiling phase well predicted by the variational model for different experiments.

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