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Drop impact on small targets with different target-to-drop diameters ratio

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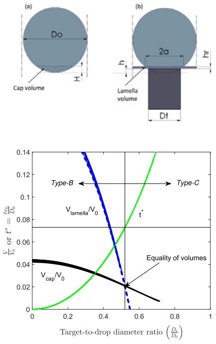
HIGHLIGHTS

- Three different types of responses to an impact of droplet onto a small target, with respect to different target-to-drop ratios are identified and classified.
- ***Type***-A was observed for $1 < \beta_t \leqslant \beta_{max}$ and demonstrated mainly a radial spread. ***Type-B*** $(1/2 < \beta_t \leqslant 1)$ demonstrated two directional spread; radial and vertical, and ***type-C*** for $\beta_t \leqslant 1/2$, a very small obstacle which barely affects the drop flow.
- The particular response of each type group was analyzed to define the specific spreading characteristics, and different expressions for the maximal spreading of each type were developed.
- The experimental results focus on low values of target to drop ratio, ranging from $\beta_t = 0.32$ to 0.79, where the experimental data in the literature is scarce.
- An illustrative map of the experimental work with regard to a drop impact on small cylindrical targets is presented. The map demonstrates, amongst other things, the lack of experimental results for type-A and type-C, mainly for high Weber numbers.

GRAPHICAL ABSTRACT



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ABSTRACT

Drop impact on small cylindrical targets has been experimentally studied. Special attention has been drawn to the effect of the different target-to-drop diameters ratio on the evolution of the drop spreading after colliding with the surface. Three distinct regions have been identified as related to the ratio of the target-to-drop diameters ($\beta_t \equiv D_t/D_0$), and the maximum spreading to drop diameters $\beta_{max} \equiv D_{ma}/D_0$. The

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particular response of each type group was analyzed to define the specific spreading characteristics. The small target is an obstacle on the drop way, yet it does not stop its vertical velocity completely, as for the larger surfaces. A drop that impacts a small target continues to flow, not only radially but with some vertical velocity, in accordance with an appropriate energy balance. The analysis yielded expressions for the maximal spread of each impact type. ***Type-A*** was observed for $(1 < \beta_t \leqslant \beta_{max})$ and demonstrated mainly a radial spread, ***type-B*** $(1/2 < \beta_t \leqslant 1)$ with two directional spread; radial and vertical, and ***type-C*** for $(\beta_t \leqslant 1/2)$ a very small obstacle which barely affects the drop flow. The present analysis yielded expressions for the maximal spread of each impact type.

1. Introduction

The time evolution of a drop colliding with a small area surface and the final form of the target coating depends on the fluid properties and the target surface characteristics (wetness, smoothness, curvature, temperature, contact angle, etc.). The present study considers a single, spherical drop impact on a dry, smooth, flat disc-shape surface, under atmospheric conditions, having a diameter that ranges from values that are slightly smaller than the maximal spread diameter that pertains to a large flat surface or smaller than the initial drop diameter.

Owing to the process complexity and the practical implications in a variety of applications, the dynamics of the drop spreading attracted the attention of many researchers (Josserand and Thoroddsen, 2016; Yarin, 2006; Rein, 1993). Impact of droplets onto solid surfaces are extensively being studied, due to their grave importance on practical processes such as spraying, deposition or encapsulation, whether for combustion, printing, agriculture, coating, cleaning, filtration, medical applications, etc. (Yarin et al., 2017; Sher et al., 2013; Juarez et al., 2012; Rozhkov et al., 2002). As Different applications involve different surface texture and roughness, it is important to characterize the effect of the target-to-drop ratio on the impact process. The present research aims to study its effect on the maximal spreading diameter. A comprehensive review can be found in the recently published book by Yarin et al. (2017). The drop impact is followed by the generation of a lamella which has been found a major subject of a large number of studies, where the diameter of the lamella (Vadillo et al., 2009; Roisman et al., 2009; Clanet et al., 2004) and its height (Wang and Bourouiba, 2017; Vernay et al., 2015; Lagubeau et al., 2012) are examined. The prediction of maximal spreading has been intensively studied in an attempt to define the delicate balance between the inertial, surface tension, and viscosity forces. Different prediction methods are in use, with the most common ones based on energy and mass balances (Ukiwe and Kwok, 2005; Clanet et al., 2004; Pasandideh-Fard et al., 1996; Chandra and Avedisian, 1991). The dynamic of the drop has also been modeled with semi-empirical models based on an energy balance (Attané et al., 2007; Erickson et al., 2001; Gu and Li, 2000). Other different approaches include a dynamic model with a viscous boundary layer (Eggers et al., 2010; Roisman et al., 2009), and naturally experimental studies and numerical simulations (Arogeti et al., 2017; Attané et al., 2007; Pasandideh-Fard et al., 1996).

In 2002, Rozhkov et al. (2002) presented a pioneering study on the phenomena associated with the impact of water drops on small targets. They studied the phenomena in depth and characterized the development of the lamella and the expansion dynamics of the liquid drops after the impaction (Rozhkov et al., 2006). Later, the analysis was broadened to examine the influence of both Newtonian and non-Newtonian liquids with various properties (Rozhkov et al., 2010, 2006, 2004, 2003, 2002). Other studies observed different aspects of the influence of small targets. Yarin et al. (2017) state clearly that the evolution of drop height, and therefore of its diameter, depends mainly on the ratio of the drop and target radii.

Villermaux and Bossa (2011) described a drop sequence that forms fragments after impacting a target with the same diameter as the drop. Juarez et al. (2012) focused on the instability of the lamella following a drop impact on targets with different polygon cross sections. They found an interesting symmetric response: the number of fingers developed after the impact is compatible with the polygon vertex and are located half-way between each two vertex.

Rozhkov et al. (2003) analyzed aqueous solutions of polyethylene oxide drops on stainless steel disks with target-to-drop ratios of $\beta_t \equiv D_t/D_0 = 0.67–0.97$; i.e. pertaining to type-B, as defined in the present study. Vernay et al. (2015) studied water drops with target-to-drop ratio of $\beta_t = 0.6$. Based on experimental results, simple expressions for the maximal lamella diameter have been proposed on the literature (Eq. (1) (Rozhkov et al., 2003) and Eq. (2) (Vernay et al., 2015)).

$$\beta_{max} = \sqrt{\frac{We}{20}} \tag{1}$$

$$\beta_{max} = 1 + \frac{4}{27}\sqrt{\frac{2}{3}We} \tag{2}$$

Recall that $\beta_{max} \equiv \frac{D_{max}}{D_0}$.

The Weber $We \equiv (\rho D_0 v_0^2)/\sigma$ represents the ratio between the inertial forces and the surface forces ρ, D_0, v_0 and σ are the drop density, diameter, velocity, and surface tension, respectively). Neglecting the viscous forces in the above expressions can be justified by either having a low impact number ($P = We/Re^{4/5} < 1$, Clanet et al., 2004) or by the very fact that when considering small targets, the viscous friction long the substrate is drastically reduced compared to other forces (Rozhkov et al., 2003). Low impact numbers are often the case when water droplets are considered, as water and its low concentration solutions are considered low viscosity fluids. For these cases, the maximum drop diameter is determined exclusively by the capillary number, and the maximum diameter is correlated exclusively to the *We* number (§4.4 Yarin et al., 2017).

Arora et al. (2016) investigated the viscosity effect of freely expanding liquid lamella. They defined an expression for the maximal extension while using energy balance and effective velocity. Their experiments were conducted for $\beta_t = 0.6$. This expression considers the fluid viscosity and the influence of the target-to-drop diameter ratio by defining an additional parameter, β $\left(\beta \approx \frac{2}{2\sqrt{2}}\frac{1}{\sqrt{Re}}\left(\frac{D_t}{D_0}\right)^{5/2}, 0.03 < \beta < 0.96\right)$. Their expression (Eq. (3)) indicates that for low *Re* numbers and high *We* numbers, viscous forces may play a significant role ($Oh \equiv \sqrt{We}/Re > 0.1$).

$$\beta_{max} = \sqrt{\frac{We}{6}\frac{1}{1+\beta}} \tag{3}$$