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Dynamics and disintegration of drops of polymeric liquids ☆

Aleksey Rozhkov [1], Bernard Prunet-Foch, Michèle Vignes-Adler *

Laboratoire de Physique des Matériaux Divisés et des Interfaces, UMR8108 du CNRS, Université de Marne-la-Vallée, Bât. Lavoisier, 5 bd. Descartes, F-77454 Marne-la-Vallée Cedex 2, France

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Abstract

The deformation and the disintegration of drops of polymer solution upon impact with solid obstacles are investigated both experimentally and theoretically. High molecular polyethylene oxide (PEO) and polyacrylamide (PAM) solutions at concentrations 1–10,000 ppm, as well as pure water and glycerine, are used as tested liquids. A feature of this work is the use of a non-standard hydrodynamic situation, namely the collision of a spherical drop with a small disk-like solid target. In the experiments, a drop of 3 mm diameter collides with a 4 mm disk target with velocity of 3.4 m/s. If water is used, upon impact the drop is transformed into a liquid lamella (i.e. a circular film with a rather thick toroidal rim). The lamella increases in diameter and then it retracts with ejection from the rim of a set of radially directed secondary jets that, in turn, break up into secondary droplets. Typically polymeric additives do not influence much the growth and the retraction rate, but they drastically modify the disintegration process. Depending on the polymer nature and its concentration, four regimes of drop impact are observed: (i) the secondary jets are transformed into capillary thinning filaments partially retarding the detachment of secondary drops, (ii) the elastic stresses in the thinning filaments force all secondary droplets to move back to the target suppressing splashing, (iii) no rim instabilities are developed and lamella with smooth rim is formed and (iv) no lamella formation. Criteria of transition from one to another regime of drop impact are proposed.

Keywords: Drop break-up; Impact; Target; Polymer solution; Splashing

1. Introduction

The drop impact observation is far from being an esthetical curiosity. Drop impact is relevant in many industrial applications such as spray coating, ink-jet printing, pesticides spraying, etc. It may be desirable to use non-Newtonian liquids for some reason, the rheological peculiarities of the liquid being able to significantly influence the drop outcome. The understanding of the mechanisms of this influence is a powerful instrument for controlling the drop impact and the associated splash phenomena in a great variety of technological processes. The purpose of the work is to investigate theoretically and experimentally the mechanisms leading to the deformation and disintegration into separate fragments of drops of polymeric liquids upon collision with a solid target in particular to reveal the role of the rheological and surface properties of the liquids.

To understand the features of the deformation and of the splashing of a drop resulting from its collision with a solid [1–6] under high impact Reynolds number $Re_\mathrm{i} = \rho v_\mathrm{i} d_\mathrm{i}/\mu$ and impact Weber number $We_\mathrm{i} = \rho v_\mathrm{i}^2 d_\mathrm{i}/\gamma$ (where ρ is the liquid density, γ the surface tension, μ the liquid viscosity, d_i and v_i are the diameter and the impact velocity of the drop), we have used a disk-like target of approximately the same diameter as the in-flight drop instead of a large plate [7–9] (Fig. 1).

Previous experiments with water drops ([7,8], Fig. 1a) showed that, upon impact with a small disk-like target, the drop liquid is radially ejected in the shape of a thin liquid sheet, which expands and then retracts. Similar phenomenon was earlier observed for drops of water (and similar inviscid liquids) impacting on a plane plate [1–6]. In the latter case, the impacting drop behaviour would result from the competition between the inertial, capillary and viscous forces. On a small target, the influence of the viscous friction is essentially suppressed, even during the retraction phase and we mainly observe the role of the inertial and capillary forces in a "pure" view [7,8].

The liquid sheet formed upon impact is bounded by a relatively thick toroidal rim the position of which is defined by the balance between the inertial and capillary forces. The liquid rim,

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* Corresponding author. Tel.: +33 1 60 95 73 25; fax: +33 1 60 95 72 97.
E-mail address: michele.adler@univ-mlv.fr (M. Vignes-Adler).

[1] Present address: Institute for Problems in Mechanics of Russian Academy of Sciences, 101(1) Prospect Vernadskogo, Moscow 119526, Russia.

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Nomenclature

a	filament diameter
$\boldsymbol{A}$	elastic strain tensor
b	thickness of the rim
c	polymer concentration
d	lamella diameter
d_i	impact drop diameter
d_m	maximal lamella diameter
d_t	target diameter
$De_\mathrm{i}=\theta v_\mathrm{i}/d_\mathrm{i}$	impact Deborah number
$\boldsymbol{E}$	strain rate tensor
E_e	specific elastic energy
E_k	specific kinetic energy
$\boldsymbol{G}$	elasticity modulus
$\boldsymbol{I}$	unit tensor
J	$We_\mathrm{i}^{3/4}(d_\mathrm{i}G/\gamma)$
K_1	$(\rho d_\mathrm{i}^3/(\gamma\theta^2))\times We_\mathrm{i}^{3/8}$
K_2	$We_\mathrm{i}^{5/4}De_\mathrm{i}^{-2}(d_\mathrm{i}G/\gamma)^{-1/3}$
m	droplet mass
M	molecular mass
N	number of fingers in the lamella rim
p	pressure
P	$\pi a_0\gamma(3\theta)^2/(m\beta_\mathrm{m}d_\mathrm{i}/2)$
r	radial coordinate
r_f	distance of the droplet (or the mass centre of the droplets) from the centre of the target
R	$r_\mathrm{f}/(\beta_\mathrm{m}d_\mathrm{i}/2)$
$Re_i=\rho v_\mathrm{i}d_\mathrm{i}/\mu$	impact Reynolds number
s	index denotes the values at $r=0$
t	time
T	$(t-t_0)/(3\theta)$
v	liquid velocity
v_i	impact velocity
V_d	volume of drop before impact
$V(\tau, Y)$	dimensionless velocity of the liquid in the lamella
$We_\mathrm{i}=\rho v_\mathrm{i}^2d_\mathrm{i}/\gamma$	impact Weber number
Y	r/d_i
z	distance between initial position of the liquid particle in the drop before impact and vertical axis of drop symmetry

Greek symbols

$\beta=d/d_\mathrm{i}$	lamella spread factor
$\beta_\mathrm{m}=d_\mathrm{m}/d_\mathrm{i}$	maximal lamella spread factor
γ	surface tension
λ_∞	finite extensibility of macromolecules
μ	liquid viscosity
λ_r	radial extension
λ_χ	polar extension
θ	relaxation time
$\theta=Bc^n$	extrapolation formula
ρ	liquid density
$\boldsymbol{\sigma}$	stress tensor
τ	$tv_\mathrm{i}/d_\mathrm{i}$
$\nabla\boldsymbol{v}$ (respectively, $\nabla^\mathrm{T}\boldsymbol{v}$)	(respectively, transposed) velocity gradient

driven by the capillary forces, moves against the stream sweeping the liquid into a thickening rim [10,11]. In addition, due to capillary instability, the rim thickness becomes non-uniform along the perimeter. As they move outwards, all the rim elements are subjected to a very high radial deceleration, but because of their higher inertia, the thicker parts are less decelerated than the thinner ones. As a result, the thicker parts transform into droplets which detach from the liquid rim and generate splashes [7,8].

We have recently discovered that addition of a small amount of a high molecular weight additive in water suppresses the splashes and makes the drop to look like a spider or like a steering wheel when impact occurs on a small target [9]. Addition of polyethylene oxide (PEO) with molecular weight $M=4{,}000{,}000$ g/mol and at concentrations ranging between 10 and 1000 ppm, gives elastic properties to the liquid, which drastically modifies the detachment of the droplets. Actually, thinning liquid filaments are formed between the droplets and the main drop, which attaches the droplets and pulls them back to the main drop (Fig. 1b). If the filaments rupture before the droplets can coalesce with the main drop, then the latter detach and splashing sets in. In the opposite case, splashing is suppressed. The filament lifetime increases with the polymer concentration. With the polymer-free solution and with the very dilute ones, all the filaments rupture and splashing is intense. With the 10 ppm solution, a few filaments rupture and the splashing is moderate. With the 100 and 1000 ppm solution, all the attached droplets coalesce back to the main drop giving rise to this spider or steering wheel like aspect.

The present work was undertaken to further study the polymer influence on drop impact for a wider range of rheological properties than in [9]. We have studied another high molecular weight agent namely polyacrylamide (PAM). PAM solutions exhibit stronger elastic properties than the polyethylene oxide solutions at the same concentration. Therefore, new hydrodynamic effects are likely to be observed. Moreover the PEO and PAM concentrations were varied in the range of four decimal orders (1–10,000 ppm) instead of two (10, 100 and 1000 ppm) and only for PEO in [9].

2. Materials and methods

2.1. Tested liquids

Aqueous solutions of polyethylene oxide (PEO) with molecular mass $M=4{,}000{,}000$ g/mol and polyacrylamide (PAM) with molecular mass $M=11{,}000{,}000$ g/mol at concentrations ranging from 1 to 10k ppm are used in this work. PEO was supplied by Aldrich and PAM by Giprovostokneft. The surface tensions of