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Star-like breakup of polymeric drops in electrical field

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ABSTRACT

The disintegration of liquid drops upon the impact with solid obstacles in presence of an electric field is investigated experimentally. Water and solutions of polyethylene oxide (PEO) and polyacrylamide (PAM) are used as tested liquids. We used a hydrodynamic configuration that reduces the viscous drag on the solid: a spherical drop impacted a small disk-like solid target. Impacting water drop formed a lamella, circular free film with a toroidal rim, which firstly increased in diameter, and then retracted with ejection of secondary droplets from the rim. The use of a disk-like target allowed performing a liquid/solid collision in the absence of liquid/solid viscous resistance. Polymeric additives did not influence the growth and the retraction rate. However they modified the disintegration process: thinning filaments were formed between secondary droplets and lamella rim, preventing the secondary drops detachment and the corresponding splashing. To impose an electric field on the lamella, a high positive voltage was applied directly to the steel disk-like target. The other ground pole was a cylindrical copper sheet located axisymmetrically with the disk-like target surrounding the target. As a result a radial electric field formed around the target and in the same time the target charged positively the liquid of the impacting drop. The potential difference between target and copper sheet was changed from zero up to 10 kV. Experiments showed that the applied voltage has no effect on the rate of lamella growth and retraction. Also no change was observed in the disintegration of very dilute (1 ppm) and very concentrated (10k ppm) polymer solutions. On the other hand new features of lamella disintegration could be initiated by high voltage in the intermediate range of concentrations. During breakup of drops of PEO of concentrations 10, 100 and 1k ppm as well as of drops of PAM of concentration of 10 ppm, additional secondary filaments were ejected from the secondary droplets under the action of the electrical field. These secondary filaments are outward directed from the lamella centre and look thinner and longer than the primary polymeric filaments. As a result star-like liquid structures are formed. Wheel-like lamellas of 100 and 1k ppm PAM solutions become only slightly disturbed under the action of high electrical field.

1. Introduction

Polymer liquid elasticity and electrically driven liquid extension are two crucial factors which form the basis of new technologies, the most important of which is electrospinning – perspective method for nanofibers and nanotubes production [1]. The desirable technological outcome can be achieved only by appropriate interaction of these factors. Thus an effective control of the correspondent technological processes requires the knowledge of the features of the liquid elasticity, the electrically driven liquid extension and the interplay of these two factors in a given flow.

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One of the simplest experimental configurations which displays clearly the roles of the liquid elasticity and the electrically-driven extension is the polymeric drop breakup in electrical field when both elasticity and electricity control the splashing [2]. Between all possible variants of drop breakup, the most convenient for research study is the one resulting from the impact of a liquid drop on a small disk-like target [3–7]. Upon impact with the small disk-like target, the drop liquid is radially ejected from the target into a thin liquid sheet – lamella, which expands and then retracts with discharge of secondary droplets from the toroidal rim (Fig. 1).

Under high impact Reynolds number $Re_i = \rho v_i d_i/\mu$ and impact Weber number $We_i = \rho {v_i}^2 d_i/\gamma$ (where ρ is the liquid density, γ is the surface tension, μ is the liquid viscosity, v_i is the impact velocity, d_i is the impact drop diameter) the pure water drop impact is controlled only by liquid inertia and capillarity. Similar impact on a plane plate is controlled additionally by the viscous drag between the liquid and the solid surface. Therefore if we want to consider two new factors,

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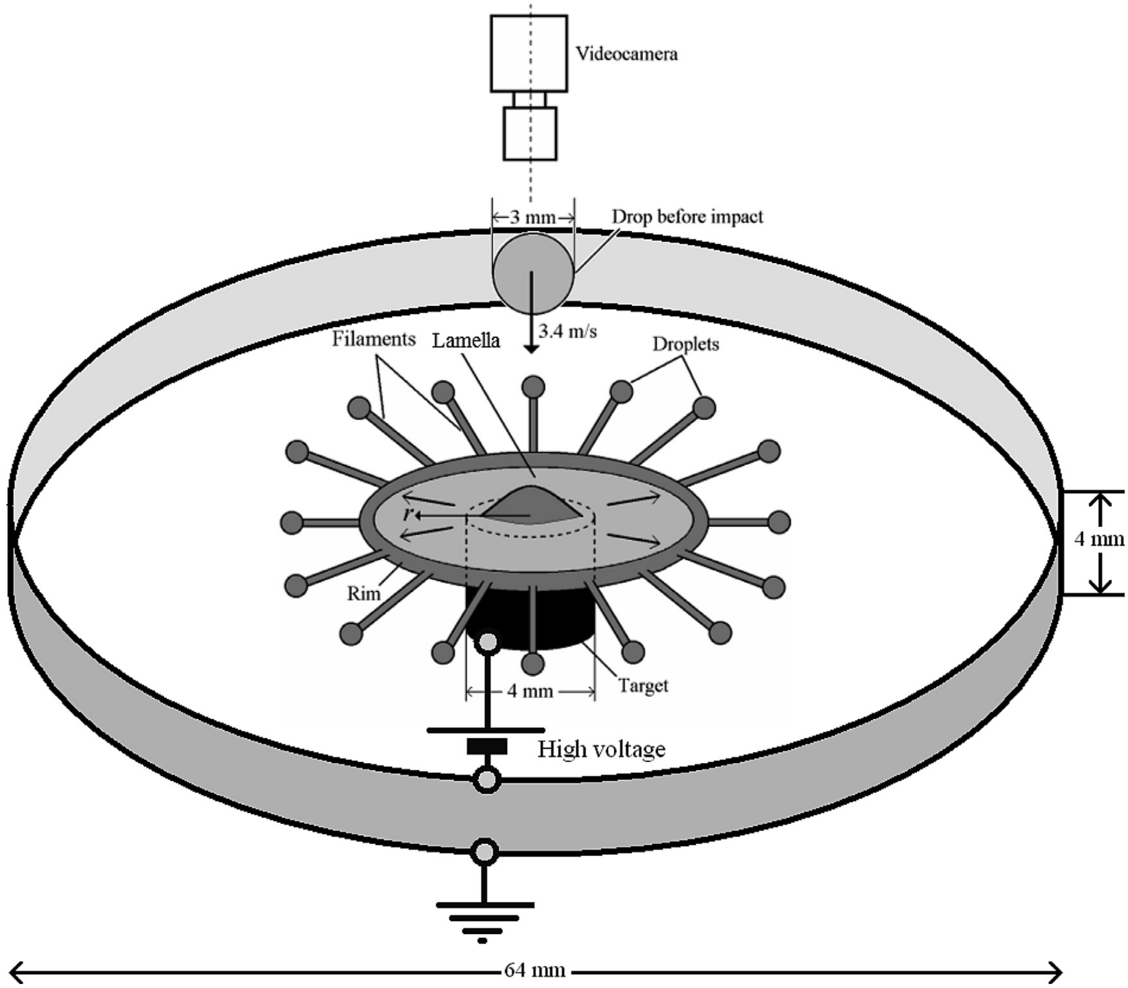

Fig. 1. Scheme of the experiment. During the impact on disk-like target, a liquid drop forms a liquid sheet with toroidal rim. Secondary droplets are detaching from the rim. Polymeric additives reduce the droplet detachment by means of thinning capillary filaments formed between the secondary droplets and the main drop. High voltage is applied to the target.

such as elasticity and electricity, it is more convenient to use a small target because, in this case, the number of influential factors, i.e. inertia, capillarity, elasticity and electrical forces is minimal.

Such experimental configuration is also motivated by drop breakup driven by an electrical field in such technological processes as spray coating, agricultural spray, inkjet printing [8]. Sometimes it is desirable to use electrically charged elastic liquids for some reasons and the breakup happens in the jet flight and as the result of drop impact on substrates of complex shapes. For example, in continuous inkjet printing the ink droplets "are electrostatically charged by induction as they break off and then directed (deflected) by electrostatic deflection plates to print on the receptor material (substrate)" [9]. Often ink contains polymer additives as in the case of "the printing of functional and biological materials" [9]. Another motivation of the work consists in understanding of reasons which provide electrospinning of high and bad quality in the case of very similar polymers [10]. Modelling experiment can display different respond of these polymers on strong deformation in electrical field. Finally, drop breakup of electrically charged drops is a simple method of creation of controlled strong deformations in the liquids during the investigation of their elastic properties.

We have demonstrated that a small amount of high molecular polyethylene oxide (PEO) or polyacrylamide (PAM) in water suppresses the splashes during drop impact on small target and makes the drop looks like a spider, or a steering wheel, or a smooth wheel [4]. Steering wheel and spider like liquid structures are due to the formation of capillary liquid filaments between detaching secondary droplets and lamella rim. They are the same filaments, which are formed during polymer solution drop extension or jet disintegration [11] and provided by high distortion of macromolecules coils. At the initial stage of the secondary droplets detachment, the filaments are thick and short enough, so the lamella looks like steering wheel. For high enough polymer concentrations, the elastic stress in the filament decelerates droplet detachment causing its return to the lamella and preventing splashing. Thus, in the intermediate stage, the lamella behaves as a spider that initially stretches out his legs and then retracts them. A smooth wheel is formed by enough concentrated PAM solutions. The PAM solution is 'rigid' enough to form in the rim an axial elastic stress that is sufficient to suppress the Rayleigh capillary instability according to the mechanism described by Bazilevskii et al. [12]. Criteria of transition from one to another regime of drop impact were proposed. The splashing and the rim instability thresholds are defined by dimensionless parameters that describe the competition between the inertial, elastic and capillary forces during drop breakup.

The present work is carried out with the same liquids and with the same experimental procedure as in our previous work [4], but in the presence of an electrical field. The purpose of this work is to investigate the effects of this electrical field on the polymer drop breakup and the interaction of the elastic and electrical forces in the process of liquid fragmentation. Previous works demonstrated a possibility of