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Drag Reduction Studied by Splashing Visualization

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***Abstract*:** The splash is a phenomenon which happens on droplet impact against a shallow liquid surface (target), forming a structure called crown. After the collapse of the crown, a liquid column (Rayleigh jet) arises on the surface. Splashing has been studied from a great variety of viewpoints, in different fields such as: agronomy, biology, engineering, astronomy, photography and marketing. The visualization of the splash was used, in our case, to study the drag reduction effect that happens when very low concentrations of a high molecular weight polymer is present in the fluid under investigation.

We have developed a controlled drop-releasing device, fitted with a high-speed CCD camera [with shutter speed of 1/10000 s], and an image acquisition and processing system. Using this assembly, it was possible to observe large changes in the splash structures of water, especially in the extension of the Rayleigh jet. This result was associated with the drag reduction effect produced by the polymer.

Result obtained with the dyed drop technique has shown that the presence of the polymer affects the mixture of the liquids from the droplet and target.

***Keywords*:** splash, drag reduction, visualization, poly(ethylene oxide).

1. Introduction

When a fluid moves relative to a solid surface, a force is exerted on the surface in the direction of the motion, which is called the drag force. Frictional drag results in a corresponding dissipation or degradation of energy and for many years, scientists and technologists have considered methods to minimize this effect. In 1946, B.A. Toms found that a very diluted polymeric solution required a lower pressure gradient, in pipe flow, than the solvent alone to produce the same flow rate in turbulent flow (Hemmings and White, 1976). The reduction of friction is therefore often termed the "Toms effect." The possible levels of drag reduction (*DR*) under laboratory conditions range up to 80% (Andreis et al., 1989).

There are different theories proposed for the *DR* phenomenon, based on either a molecular approach or fluid dynamical continuum considerations, but neither can explain the whole effect. Usually, the pressure loss in pipes and the torque in rotating disks can be used to measure the *DR* effect. In this work, we are showing, for the first time, the results of the *DR* studies based on the splashing visualization.

The splash occurs when a drop or a solid sphere impacts against a liquid surface, forming a crown and a cavity (Coghe et al., 1997). Figure 1 shows a typical crown with the secondary droplets and jets. A liquid column is formed in the region of the impact due to the collapse of the crown and the cavity as schematically shown in Fig. 2. This column is called as Rayleigh jet (Hobbs and Osheroff, 1967).

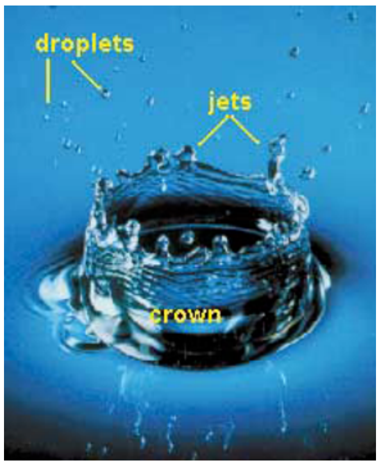

Fig. 1. The splash of a drop.

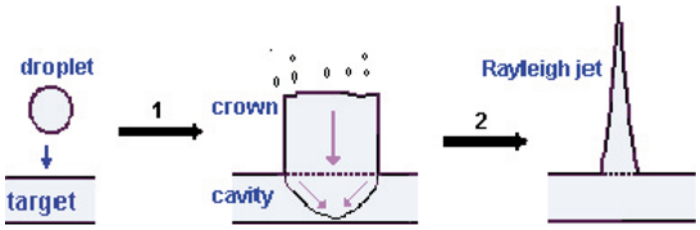

Fig. 2. A schematic formation of Rayleigh jet after the collapse of the crown and the cavity.

Hoyt (1989) used small quantities of polymer dissolved in water to visualize the jets trajectories of the droplets formed in the top of the crown. The splash of polymeric solutions was studied also to verify the rheological influences of the macromolecule (Cheny and Walters, 1999). However, there is not information in the literature associating the *DR* and the splashing.

We used poly(ethylene oxide), PEO, dissolved in water in very small concentration, to study the morphological modifications on the splash structures. We observed that the height (maximum amplitude) of the Rayleigh jet (produced after the collapse of the crown and the cavity) could be used as a quantitative parameter of *DR*.

2. Experimental Apparatus and Procedure

A schematic diagram of the experimental apparatus is shown in Fig. 3. Using a Mariotte flask (9) as the liquid reservoir, which is connected to a solenoid valve (8), it was possible to produce controlled droplets. The droplets are released from a chosen height by the valve position (7) over a 2 meters ruler (5). The metallic ruler is fixed in the stabilized heavy base (1) and the solenoid valve is controlled by an electronic circuit (6).

The released drop falls on the surface of a liquid contained in a tank (3); an aluminum plate was used as a rigid impact surface under the liquid film (4). The liquid film thickness was adjustable by changing the position of the plate using an elevator with a micrometry screw (2). In the experiments, the depth of the liquid film was maintained in 0.30 ± 0.05 cm.

The structures of impact formed were filmed by a CCD camera (11) with a 100 mm 1:3:5 Macro focusing lens (10). The camera operated with a shutter-speed of 1/10000 s (two lamps of 300W were used to achieve the appropriate illumination). The camera was connected to an adaptor (12) to allow the visualization of the images on a monitor (13). The images were recorded on a tape recorder (14).

Each frame was digitalized using a frame grabber board (15). The morphologic parameters were obtained by using the software for image treatment. It was used an average of 20 frames to obtain the morphological parameter. The temporal evolution of the splash was filmed in a digital CCD with 1000 frames per second.

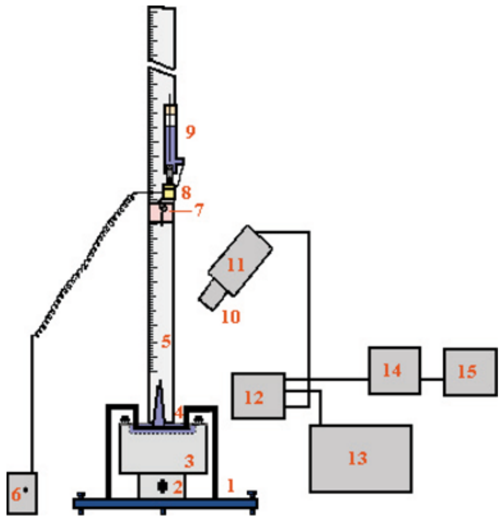

Fig. 3. The experimental set-up.

3. Results and Discussion

The crown is formed by the contribution of the droplet and the liquid film. The lifetime for the formation of the crown (on the order of milliseconds) is not enough to permit a very large mixture of the liquids. The presence of PEO dissolved in water (present in the liquid film and in the droplet) changes the extension of the mixture. The extension of the mixture can be visualized using a dye dissolved in the liquid of the droplet (Fig. 4).

The mark of the dye produced in the liquid film, after the collision of a colored drop (blue dye), when all the liquid movement stopped (last picture in each sequence) is smaller for the polymeric solution than for water. The mark's measurement (area) is an indicative parameter of the extension of the mixture. It is possible to observe, after many experiments using this technique, that the extension of mixture is twice bigger for water than for the polymeric solution as shown in Table 1.

This result is in agreement with the fact that the phenomenon for the polymeric solution happens is lower turbulence, resulting in a small mark.

Table 1. The area of the mark produced by a dye droplet (released at 2 m) in the liquid film for water and PEO solution (40 ppm, molar weight 4×10^6 g.mol^{-1}).

Solution	Area / cm^2
Water	11$\pm$1
PEO	5$\pm$1

A comparative example of a typical evolution for the splash in water and in the polymeric solution is shown in the Figs. 5(a) and 5(b), respectively. The frames were obtained at the time (after the impact instant) indicated between the pictures.

Table 2. The Rayleigh jet's height for water and PEO solution (40 ppm, molar weight of 4×10^6 g.mol^{-1}). The

Solution	Rayleigh jet's height / cm
Water	1.5$\pm$0.2
PEO	5.0$\pm$0.8

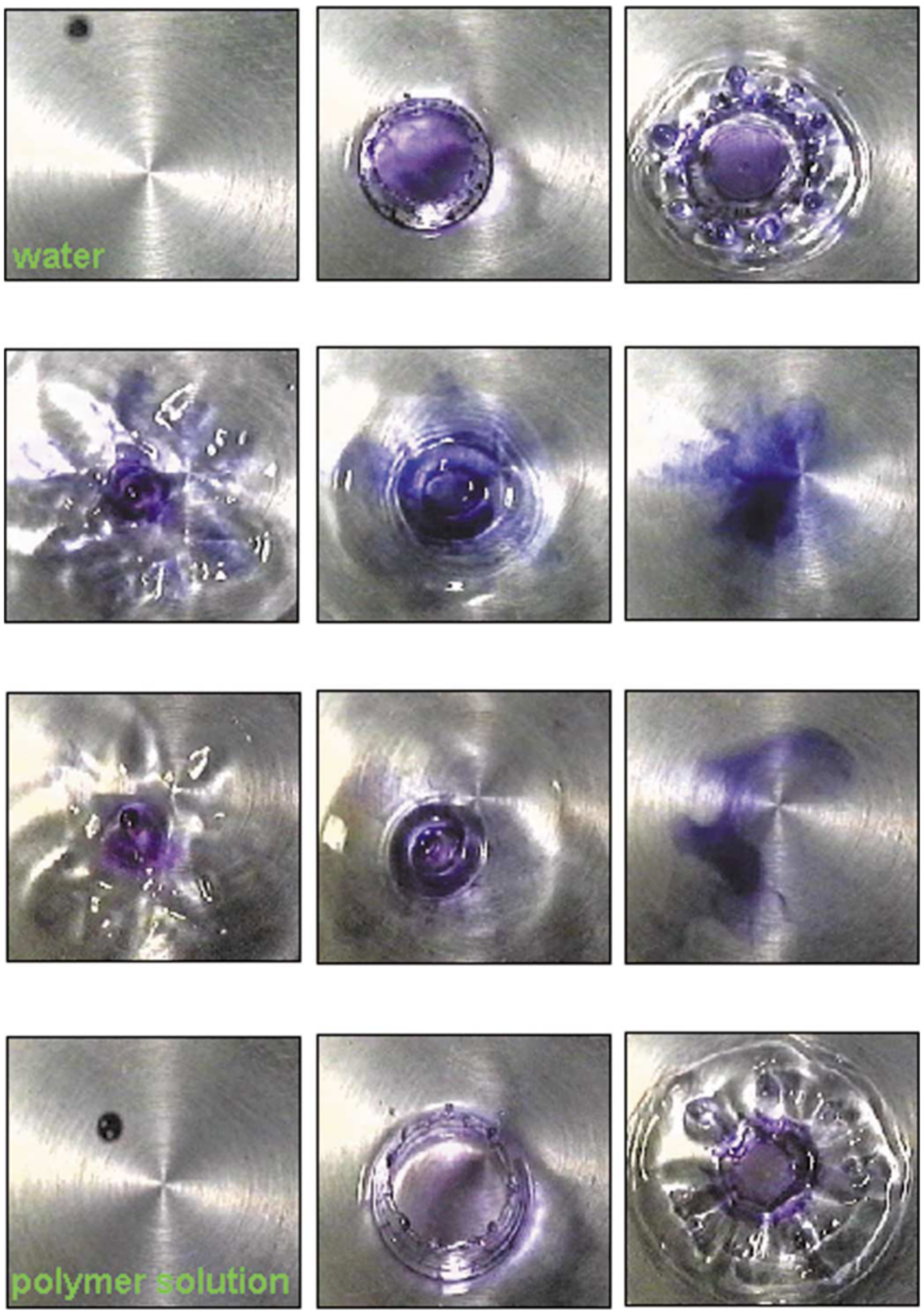

Fig. 4. Impact of an aqueous dye droplet against aqueous surface. The six pictures on the top correspond to the impact for pure water and the other six for a very small PEO concentration. The droplets were release at 2 m and the depth of the target liquid is 0.3 cm.

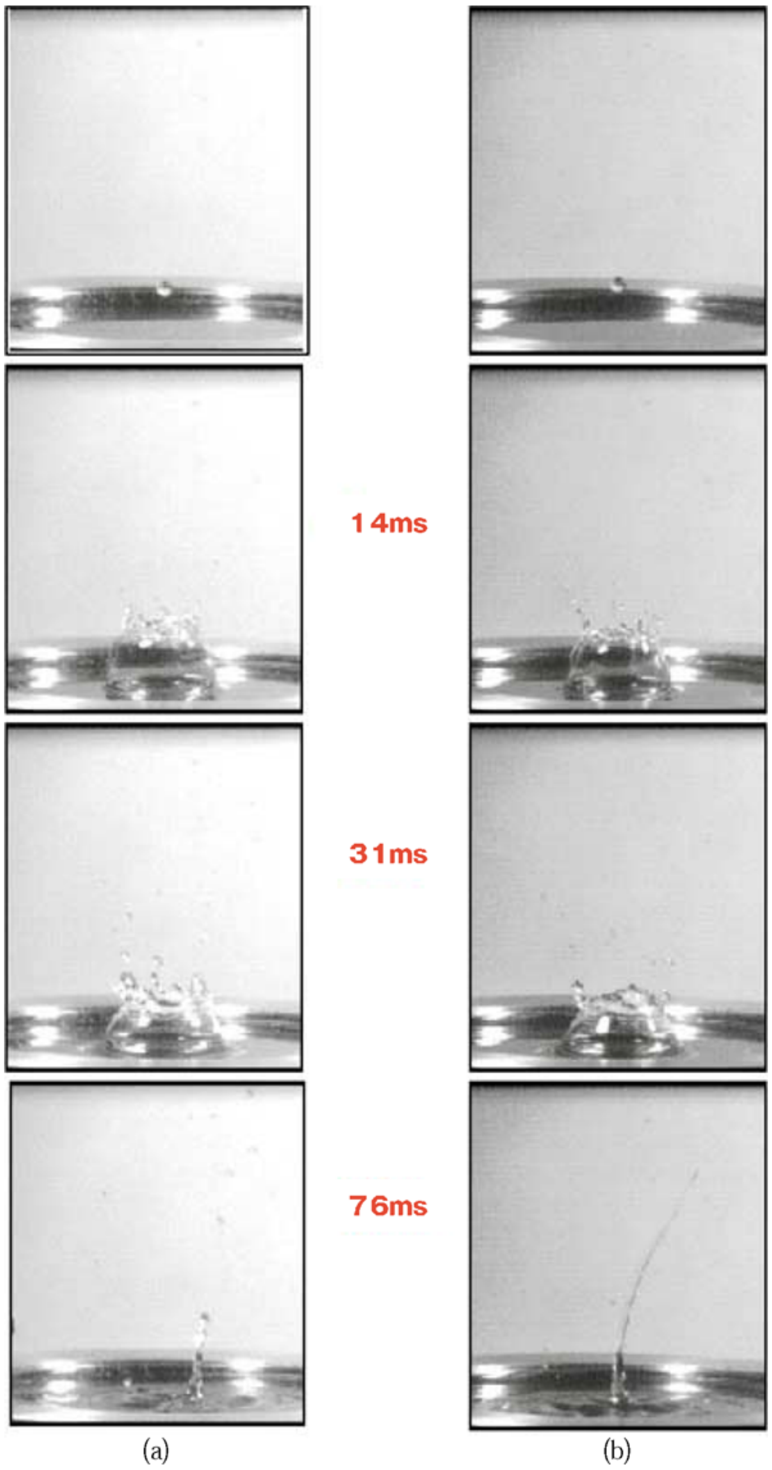

Fig. 5. The temporal evolution of the splash after the impact of the droplet for (a) water and (b) PEO solution.

After the collapse of the crown and the cavity, the Rayleigh jet arises in the center of the crown. The presence of PEO modifies dramatically the jet height, as shown in Table 2. In this experiment, the maximum height of the Rayleigh jet is reached in almost 70 ms after the impact. This result indicates that the impact energy (potential and surface energy of the drop) is stored in a larger amount in polymeric solution than in water. It means that the dissipative processes (as the mixture of liquids from droplet and target) occur in small intensity in the polymeric solution.

We have used Eq. (1), which is similar to Savins equation (Savins, 1964) for *DR* for pipes, to quantify the *DR* in the splash:

$$\%DR = (1 - H_s/H_p) \times 100 \tag{1}$$

where H_s and H_p are the height of Rayleigh jets for the solvent and for the polymeric solution respectively.

Using the Eq. (1), it is possible to determine 60% of *DR* in the studied conditions. This result is in agreement with that observed in *DR* in pipes, for the same aqueous solution of PEO (Hoyt et al., 1982). Additional studies have been done, making possible to observe that the Rayleigh jet is also sensitive to polymer molecular weight and concentration (Alkschbirs and Sabadini, 2001).

4. Conclusions

The splash visualization was used to study quantitatively the drag reduction, produced by a very small concentration of polymer dissolved in water. The Rayleigh jet obtained after the collapse of the crown and the cavity is highly sensitive to the polymeric solution, and can be used as a parameter to determine the intensity of the drag reduction.

The impact energy is less dissipated for the polymeric solution than for water. Part of this energy is used in the mixture of liquids from the droplet and the target.

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