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Short communication

The free-fall of viscoplastic drops

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ABSTRACT

The free-fall of liquid drops under the action of gravity is studied experimentally by high-speed imaging, with focus on drops of viscoplastic fluids (i.e., those materials which exhibit a fluid behaviour only when the applied stress exceeds a certain threshold value, called the yield stress), and compared to the behaviour observed in Newtonian drops. The yield stress of the fluid is shown to alter significantly the drop shape during free-fall. The results can be interpreted in terms of a dimensionless number comparing the yield stress magnitude and the capillary pressure.

1. Introduction

The free dynamics of a liquid drop falling under the action of gravity through a fluid medium after detaching from a nozzle has attracted the interest of scientists for more than one century [1–3]. Besides the scientific appeal, these studies have a number of practical applications, for example in spray cooling [4], measurement of fluid properties [5], and nuclear physics [6].

When the drop detaches from the nozzle, the pinch-off induces oscillations, which are dampened down by viscosity until the equilibrium spherical shape is retrieved [7,8]. The motion of drops in free-fall is analogous to a spring-dashpot system, with the elastic constant being related to the surface tension, and the dashpot damping coefficient being related to the viscosity of the fluid. The solution of the initial value problem was studied in detail by Prosperetti [9].

While these works focus on drops of Newtonian fluids, comparatively little attention has been received by non-Newtonian drops. To the authors' knowledge, so far only the effects of viscoelasticity have been investigated using the Jeffreys constitutive equation [10]. This work shows that elastic effects give rise to a type of shape oscillation that does not depend on the surface tension.

To broaden our understanding of the effects of the fluid bulk rheology, the present work investigates experimentally the free dynamics of viscoplastic drops, and compares it with that observed in Newtonian drops of different viscosity. In particular, viscoplastic properties were reproduced by water solutions of a Carbopol-based commercial polymer gel. In this context, it is interesting to observe how a gelation process can be used to freeze the shape of droplets deformed under the action of a flow field [11–13].

The results show a number of significant morphological differences determined by the fluid rheology, interpreted in terms of a dimensionless number that compares the yield stress and the capillary pressure, which was previously introduced to characterise the flow of a gel in capillary tubes [14] as well as the capillary breakup of viscoplastic fluids [15,16].

2. Materials and methods

2.1. Fluids characterisation

Model yield stress fluids were prepared using a commercial hairdressing gel (density: 1194 kg/m^3). The typical composition of these gels includes a blend of water, polymers (Carbopol), alcohol, silicones, glycerine, and surfactants (in this case, Polysorbate 20). In order to change the value of the yield stress in a continuous fashion, the gel was diluted into de-ionized water at different concentrations. The solutions were mixed slowly in a container to avoid the formation of bubbles, left to settle for 24 h to allow diffusive transport to reach equilibrium, and then mixed again using a magnetic stirrer.

The yield point of each solution was determined using a Haake-Mars II rheometer (equipped with a plate–plate sensor having a diameter of 35 mm and a gap of 1 mm) in a controlled stress mode, and imposing a stress ramp (100 points in 300 s) on the fluid sample. Sandpaper was glued on both the rotating and the fixed surface in order to avoid wall slip effects.

For small values of the stress, the sample behaves like a solid and has a little deformation; when the stress grows beyond a critical

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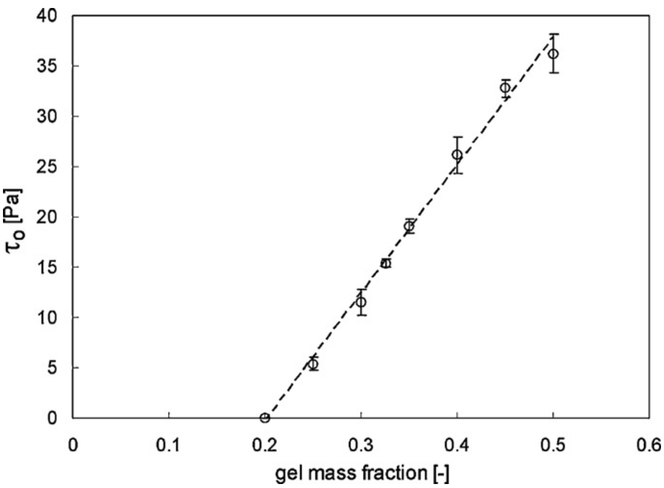

Fig. 1. Measured yield stress of the model fluid as a function of the gel concentration.

value, the sample starts flowing and therefore the angular displacement of the disk grows indefinitely at a faster rate. The crossover of the two straight lines interpolating the deformation-stress curve in a log–log scale before and after its bending point defined the yield point. Such definition-based procedure allows one to obtain measurements which have a practical significance, without entering the debate on the physical meaning of yield stress [17]. The results are reported in Fig. 1, which shows that the yield stress is a linear function of the hair-gel mass fraction.

Flow curves obtained by controlled shear rate tests in the shear rate range $0 < \dot{\gamma} < 100\,\mathrm{s}^{-1}$ reveal a shear-thinning behaviour, which was fitted using the Herschel–Bulkley model:

$$\tau = \tau_0 + \dot{\gamma}^n \tag{1}$$

where $\dot{\gamma}$ is the shear rate, τ_0 is the yield stress, and K and n are constants. The viscoplastic fluid properties and the Herschel–Bulkley model parameters obtained by best-fit of rheometric data are reported in Table 1. Despite its simplicity, Eq. (1) captures the essential features of the model viscoplastic fluids (i.e., the yielding point and shear-thinning). We note, in particular, that these fluids do not exhibit any noticeable viscoelastic effect, which is also confirmed by their commercial use. However, a more accurate description of the yield stress fluid phenomenology can be achieved only through advanced rheophysical models [18].

For the sake of comparison, Newtonian fluids with viscosities in the range $0.056\,\mathrm{Pa\,s} \le \mu \le 0.925\,\mathrm{Pa\,s}$ were prepared by dissolving glycerol into de-ionised water with mass fractions equal to 0.98, 0.96, 0.94, 0.9, and 0.8, respectively.

The equilibrium surface tension of all fluids was measured with a Krüss EasyDyne tensiometer equipped with a De Nouy ring. Unlike the classic instrument, where the fluid sample surface tension is balanced by a counterweight [19], this instrument operates in a controlled sensor displacement mode. As the liquid film is lifted from the sample surface, the vertical component of the force acting on the ring sensor grows until the film is perfectly aligned with the direction of displacement, then decreases due to the film thinning. Just after the maximum force has been passed through, the instruments moves the sensor back and records the force value as it goes through the maximum again. In these conditions, the fluid film is not sheared nor subject to an extensional flow, and the only forces acting on the ring are due to surface tension and to the weight of the volume of fluid lifted, F_w. Surface tension is then calculated as:

$$\sigma = \frac{F_\mathrm{max} - F_\mathrm{w}}{L \cos\theta} \tag{2}$$

where L is the wetted length and θ the fluid/sensor contact angle.

In the case of viscoplastic model fluids, this method turned out to give measurements that are not affected by the yield stress of the fluid (at least, within the range of yield stresses considered in the present work). In fact, the measured surface tension was $34 \pm 2\,\mathrm{mJ/m^2}$ for all solutions (i.e., independent of the yield stress magnitude), and in good agreement with the value measured for aqueous solutions of Polysorbate 20 surfactant (a component of the gel used in these experiments) above the critical micellar concentration, which is $36\,\mathrm{mJ/m^2}$ [20].

2.2. Experimental setup and procedure

Drops were created at the tip of a blunt hypodermic needle by a screw-driven syringe dispenser, and detached under their own weight. Two needles with inner diameters respectively of 0.838 mm (gauge 18) and 0.495 mm (gauge 21) were used. The growth of pendant drops before detachment was kept as slow as possible to avoid shear-thinning of the fluids and ensure to be close to equilibrium conditions.

Shape oscillations were recorded as free-falling droplets passed through the field of view of a high-frame rate CMOS camera (Mikrotron MC1311) equipped with a 18-108/2.5 macro zoom lens and aligned horizontally. Back-to-front illumination was provided by a fluorescent lamp equipped with light diffuser, which ensured a uniform illumination intensity, and images with a resolution of 720×512 pixels were captured at 1000 frames per second. Magnification was kept constant throughout all experiments and lengths on the image could be calculated by comparison with a reference length (maximum spatial resolution: 33 μm). To ensure a fine optical alignment, the camera, the surface and the backlight were fixed to an optical breadboard.

Because drops remain within the field of view of the camera for a very short time (variable depending on their velocity), in order to investigate oscillations during longer periods of time the release height was increased up to 500 mm using a Vernier height gauge. Consistency of measurements was ensured by an optical switch triggering the camera simultaneously to drop release.

Drop weight measurements made with a precision balance (Mettler Toledo MT100) allowed calculation of the equivalent drop diameter at equilibrium, $D_\mathrm{E} = \sqrt[3]{6m/\pi\rho}$, averaged over 50 samples. Newtonian drops were generated from the gauge 18 needle, and had diameters of 3.12 ± 0.018 mm. To increase the number

Table 1
Properties of yield stress fluids and coefficients of the Herschel–Bulkley equation obtained by linear best-fit of rheometric data.

Hair-gel mass fraction	Density [kg/m^3]	Surface tension [N/m]	Measured yield–stress (τ_c) [Pa]	Consistency coefficient (K) [Pa s^n]	Power law index (n)
0.2	1037	0.034 ± 0.0008	0	1.443 ± 0.009	0.475 ± 0.005
0.25	1047	0.034 ± 0.0008	5.4 ± 0.6	3.096 ± 0.019	0.431 ± 0.007
0.3	1057	0.034 ± 0.0015	11.5 ± 1.3	5.533 ± 0.015	0.377 ± 0.004
0.325	1062	0.034 ± 0.0021	15.4 ± 0.4	6.292 ± 0.025	0.375 ± 0.004
0.35	1067	0.034 ± 0.0024	19.1 ± 0.7	6.982 ± 0.030	0.373 ± 0.005
0.4	1076	0.034 ± 0.0031	26.1 ± 1.8	7.936 ± 0.033	0.372 ± 0.004
0.45	1086	0.034 ± 0.0040	32.7 ± 0.9	12.048 ± 0.039	0.358 ± 0.007
0.5	1096	0.034 ± 0.0041	36.2 ± 1.9	19.925 ± 0.051	0.312 ± 0.006