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Flow of a yield-stress fluid over a cavity: Experimental study of the solid–fluid interface

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ABSTRACT

This paper presents an experimental characterization of the flow of an elasto-viscoplastic fluid (Carbopol) over a dead zone constituted of the same material. The studied configuration consists of a closed rectangular channel with a cavity in its base. A curved solid–fluid interface forms into the cavity, separating a yielded flowing layer above from an unyielded dead zone below. The hydrodynamics of the flow is investigated by means of high-resolution optical velocimetry (PIV). We focus in particular on the velocity profiles and shear-rate evolution in a quasi-longitudinal flow domain located around cavity mid-length. Our measurements show a non-monotonous evolution of the shear rate, which increases from zero at the solid–liquid interface, passes through a peak (sometimes leveling off at its maximum value), and returns to zero in a plug zone sufficiently far above the cavity. Two main flow zones can be distinguished: a Poiseuille zone, in which velocity profiles are the same as in the flow over a rigid wall, and a boundary layer ensuring the transition with the dead zone. Hence, consistently with our previous work (Luu et al., 2015 [9]), the flow self-organizes to partially smooth out the bottom perturbation. The characteristic thicknesses of the flow zones are shown to evolve with cavity length and hydrodynamic properties of the incoming flow. The study also points out the influence of elastic effects, notably on the shape (asymmetry) of the solid–fluid interface.

1. Introduction

A large number of materials involved in geophysical or industrial flows present the property to behave either as fluids or solids depending on the applied solicitation: mud, snow, grains, pastes, paints, etc. In many of these complex materials, the solid–fluid transition is governed, at least as a first approximation, by a single stress threshold called yield stress [1–3]. Existence of this yield threshold gives rise to strong feedbacks between flow dynamics and the state of the material, in the form of co-existing yielded and unyielded regions (where the latter can be either static or mobile) in the flows [4]. Static dead zones close to the solid boundaries form, for instance, in flows down wavy channels [5] or through expansions and contractions [6–10], in flows around objects [11–13], and in dip-coating processes [14,15]. Mobile plugs are encountered in free-surface flows [16–20] or in flows through conduits [5,21]. In geophysical context, the solid–fluid transition also plays a crucial role in the initiation of mass flows [22,23] and in the erosive processes arising during the propagation of these phenomena [24,25].

In detail, the location of the solid–fluid interfaces, and the characteristics of flow and deformation patterns around them, are strongly connected to the rheological properties of the materials in the vicinity of the yield threshold. Numerical simulations have shown that the shape of the dead zones in expansion–contraction configurations [26,27] or in lid-driven cavities [28] is affected by the (visco-)elastic strains developing in the yielded regions. Similarly, elasticity and normal stresses are deemed responsible of the occurrence of fore–aft asymmetry in flows of yield-stress materials around objects [12,13]. When existing, thixotropic properties can also play a strong role on the formation of dead zones. Occurrence of viscosity bifurcation [29], in particular, promotes localization of flows in thin layers called shear bands, while most of the material remains unyielded [30–32]. Investigating flow characteristics in the vicinity of unyielded zones therefore represents a promising pathway to probe and better understand the solid–fluid transition in yield-stress materials.

Yet, detailed experimental investigations of the velocity field close to solid–fluid interfaces remain rare in the literature. A previous study [6] documented the location of the interface in an expansion–contraction experiment with Carbopol, but did not provide direct measurements of flow dynamics. In a similar configura-

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tion, and using an inverse emulsion, other authors [7] reported on the local velocity field in the flow measured by MRI. They argued that flow in the cavity is structured into a shear band of uniform thickness separating two unyielded zones, one static and one mobile. The shear band was characterized by a quasi-constant shear rate. A similar feature, namely a shear band of quasi-uniform thickness, was observed by PIV during the withdrawal of a plate from a Carbopol bath [14,15]. On the base of these results, it was suggested that such shear bands constitute a generic feature of the *frustrated* flows developing close to dead zones with yield-stress materials [7]. Since these shear bands are observed even in materials that are *a priori* non-thixotropic, they are presumably of a different nature from the shear bands forming in thixotropic materials, and the mechanisms explaining their formation remain unclear. It shall be noted, however, that velocity measurement resolution in these latter studies is hardly sufficient to ascertain the existence of a constant shear rate in the so-called shear bands. In a recent work [9], we used PIV to monitor (with Carbopol) the velocity field above a dead zone formed in a channel presenting an abrupt contraction, and did not observe any zone of constant shear rate in the flow. Sufficiently far from the solid–fluid interface, the flow structure was identical to that observed in absence of contraction, with a central plug and a sheared layer underneath. The shear rate progressively increased when moving away from the plug, reached a maximum at a certain distance from the dead zone, and then decreased to smoothly reach zero at the solid–fluid interface.

In this context, the objective of the present study is to provide high-resolution experimental data on the flow developing in the immediate vicinity of a solid–fluid interface in a yield-stress material. A specific focus was set on obtaining accurate shear-rate data, from which the existence of shear bands could be clarified. To facilitate comparison with existing results, we chose to work in an expansion-contraction configuration. Compared to our previous study [9], this configuration also presents the advantage to give rise, around the center of the cavity, to a zone where the solid–fluid interface is parallel to channel bottom and the flow is almost longitudinal. Shear rates can be derived relatively accurately in this zone, without the need of differentiating all velocity components or of considering tilted reference frames as in [9].

The paper is structured as follows. Experimental methods are described in Section 2. Section 3 provides a global overview of the flow pattern above the cavity, as a preliminary to the quantitative characterization of the flow presented in Section 4. Finally, Section 5 discusses the main implications of our results in relation to previous studies.

2. Experimental setup

2.1. Materials and methods

Our experimental setup is depicted in Fig. 1. It consists in a closed parallelepipedic cell with a length of 30 cm (streamwise direction x), a height of $H = 6.5$ cm (crosswise direction y), and a width of 8 cm (spanwise direction z). In the middle of the cell, two steps create a central cavity of length D and height h. To allow for visualization, all the walls of the cell are made of transparent plexiglas. The surface of the steps is roughened to prevent wall slip. Flow rate Q in the cell is imposed by a gear pump, in the range 6.4–40.2 cm^3/s. Six different cavity configurations were studied, by combining three cavity lengths ($D = 1.5$ cm, 3 cm and 6 cm) and two cavity depths ($h = 1.5$ cm and 3 cm). Note that the thickness $H - h$ of the incoming channel, upwards of the cavity, varied (in the range 3.5–5 cm) as cavity depth h was changed. Similarly, the length of the upward channel varied (in the range 12–14.25 cm) with cavity length D, but was always sufficient for the incoming flow to be fully established at the entrance of the cavity (see below). Setup geometry is thus completely described by the reduced cavity height $h/(H - h)$ (in the range 0.3–0.86) and the reduced cavity length $D/(H - h)$ (in the range 0.3–1.7).

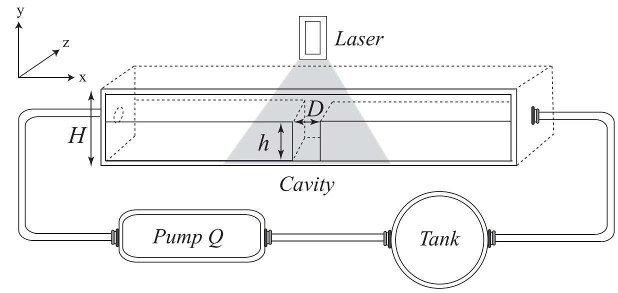

Fig. 1. Schematic representation of the experimental setup. Dimensions of the cell are: length 30 cm, height $H = 6.5$ cm, width 8 cm. The cavity of depth h and length D is located in the middle of the cell. Flow rate Q is controlled by a pump in a closed-loop circuit. A vertical laser sheet illuminates the cavity area at half-width of the cell.

Table 1
Mass concentration, Herschel–Bulkley rheological parameters τ_c, K, n, and elastic shear modulus G, of the five Carbopol samples. Note that samples F1 and F3 result from the same preparation, but F1 was let to age during 3 months, which induced a strong lowering of its HB parameters. Rheometric tests were performed within the week following experiments.

Fluid	wt (%)	τ_c (Pa)	K (Pa s^n)	n	G (Pa)
F1	0.1	0.2	1.1	0.45	1.9
F2	0.08	0.8	1.4	0.44	6.9
F3	0.1	3.8	3.0	0.41	26.0
F4	0.2	15.3	7.1	0.40	70.4
F5	0.3	21.3	9.6	0.40	87.2

As a yield-stress material, we used EDT 2623 Carbopol microgel solutions. As illustrated in Fig. 2a, the steady-state flow curve of this material is well represented by a viscoplastic Herschel–Bulkley (HB) constitutive law (for shear rates in the range 10^{-2}–10^{2} s^{-1}). In simple shear, HB law relates shear stress τ to shear rate $\dot{\gamma}$ according to:

$$\begin{cases} \tau > \tau_c, & \tau = \tau_c + K\dot{\gamma}^n \\ \tau \le \tau_c, & \dot{\gamma} = 0 \end{cases} \quad (1)$$

where τ_c is the yield stress of the material, K is its consistency, and n is the flow index. Although frequently used as a model viscoplastic material, Carbopol is also known to present more complex rheological trends that are not captured by HB law. In particular, its soft gel-sponge microstructure gives rise to significant visco-elastic properties in solid regime and in unsteady flows [33,34]. Time effects, such as hysteresis and long transients, have also been described close to flow threshold [35,36].

Five different Carbopol samples, with different concentrations, were prepared for this study; their rheological characteristics are summarized in Table 1. The density ρ of all samples is equal to 1000 kg/m^3. The HB parameters τ_c, K, and n were inferred by fitting the flow curves (Fig. 2a) measured with a parallel-plate laboratory rheometer (using roughened tools to avoid slip). Shear tests consisted in applying progressively decreasing shear-rate values ranging between 10^2 and 10^{-2} s^{-1}, and monitoring the resulting shear stress. Measurement errors on the rheological parameters (determined through systematic repeatability tests) have been evaluated at 10% for τ_c and K, and less than 2% for n [19]. As a minimal characterization of the elastic properties, we also performed oscillatory tests consisting in imposing stress oscillations with a constant amplitude, approximately equal to 10% of τ_c, and a progressively increasing frequency from 1 to 10 Hz. The in-phase