Journal of Non-Newtonian Fluid Mechanics 220 (2015) 33–43

Contents lists available at ScienceDirect

Journal of Non-Newtonian Fluid Mechanics

journal homepage: http://www.elsevier.com/locate/jnnfm

Flow characteristics around a plate withdrawn from a bath of yield stress fluid

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ARTICLE INFO

Article history:
Received 9 May 2014
Received in revised form 21 July 2014
Accepted 1 August 2014
Available online 10 August 2014

Keywords:
Yield stress fluid
PIV
Dip-coating

ABSTRACT

Dip-coating is a process widely used in industry to coat a fluid on a solid substrate. The general characteristics of dip-coating for simple liquids (Newtonian) are well known but a lot of applications involve complex fluids. Here we focus on the case of a solid plate coated with a yield stress fluid through the immersion followed by the withdrawal of a plate from a bath of such fluid. We carried out a precise analysis of the force applied to the plate during its withdrawal from the bath, and determined the velocity field developed around the plate in the fluid bath with the PIV technique. It appears that, inside the bath, after a transient regime during the plate withdrawal, a linear force regime is set up, which is associated with a stationary uniform flow (liquid region) settled along the plate while the rest of the material is in its solid regime. We show that the thickness of this liquid region increases slowly with the plate velocity and its value is almost the same for immersion and withdrawal, and independent of a possible period of rest preceding plate motion. Finally we show that the thickness of the liquid region is related to the force in the linear regime.

1. Introduction

Yield stress fluids, such as emulsions, colloids, or foams, form a class of complex materials that flow when submitted to a sufficiently large stress and stay in a solid state otherwise. A lot of operations in our everyday life need to extract an object from a bath of yield stress fluid such as mud, chocolate, paint, cement paste, cream, which leads to coat these objects with a layer of fluid, before spreading or pouring them somewhere else. Various industrial processes (food industry, automobile) rely on this technique for coating or treating the surfaces. The stakes of research in that field are to understand the fluid flow under the effect of the solid displacement to optimize the process parameters: geometrical dimensions of the solid coated and container, distance between the solids, velocity of the object to coat, rheological characteristics of the fluid.

Dip coating with Newtonian liquids (of viscosity μ) has been the object of much research and there now exists a solid background of knowledge. To sum up very briefly, most studies in that field focused on the film formation and thickness [1–3]. The value of the film thickness results from a balance between gravity, capillary and viscous effects. In particular, at constant velocity a uniform film forms along the plate, the thickness (h) of which mainly varies as a power-law of the capillary number ($Ca = \mu V/\sigma$, in which σ is the fluid surface tension) as long as gravity effects are negligible. The thickness was observed to increase as a power law of V with an exponent 2/3 in the viscous-capillary regime and an exponent 1/2 in the viscous-gravity regime [1,2]. However a fundamental aspect of this process with simple liquids is that as soon as the plate motion stops, the fluid drains and the thickness decreases. Much less is known concerning the flow inside the bath. At least it was shown that different flow regimes can be observed, but the liquid flows at any point inside the bath [4], so that the transition from the bath to the surface is smooth.

A very limited number of (phenomenological) studies concerned non-linear fluids. It was shown that elastic effects tend to increase h [5,6]. For a shear-thinning behavior a thickness increase [7] or decrease [8] was observed when the power-law index decreases. For yield stress fluids some numerical simulations [9,10] suggested that h increases with τ_c. A theoretical analysis [11] in the case of dominant yielding effect (i.e. plastic flow) and negligible gravity effects finally predicted $h \propto \tau_c^2$. Recently the first experimental study with yield stress fluids showed that the coated layer remains stuck on the plate after its withdrawal, and that the coated thickness is approximately proportional to the yield stress of the material [12]. The thickness at vanishing velocity was found to be equal to $0.3\tau_c/\rho g$. Moreover it was suggested that the coated

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http://dx.doi.org/10.1016/j.jnnfm.2014.08.001
0377-0257/

thickness is related to the flow characteristics inside the bath [12]. The present work looks in more details at the characteristics of dip-coating with yield stress fluids. In particular we study in depth the different flow regimes during withdrawal, we analyse in detail the force on the plate as a function of velocity in these different regimes, and we study how this information may be used to deduce the coated thickness, and we describe the flow characteristics inside the bath during the plate withdrawal as this can provide key information for understanding the origin of the formation of the coated layer. Finally we compare these results with those obtained in the case of plate immersion.

The withdrawal of a solid object from a bath of yield stress fluid is a problem related to the displacement of an object through a yield stress fluid. This problem has so far been mainly studied in the case of a compact object (see for example [13]). The displacement of a sphere or a cylinder moving through a yield stress fluid has been studied in depth via theory and simulations assuming an undeformed rigid region beyond some distance from the object [14–19]. Force versus velocity expressions have been deduced and partly confirmed experimentally (although some unexplained discrepancies remain) [20–23]. Basically the force follows a Herschel–Bulkley type expression with an apparent shear rate equal to the ratio of the velocity to an "apparent" sheared thickness proportional to the sphere radius. The drag force on a cylinder [24] and on a disk [25] were recently determined from systematic experiments with well-controlled yield stress fluids.

Only a few works aimed at measuring directly the flow field around the object. Atapattu et al. [20] were the first to measure the tangential velocity profiles around a sphere. Gueslin et al [26] provided an in-depth study of the velocity field but this concerned a thixotropic material for which there can be a further, and maybe dramatic, impact of the intense shear rate close to the object surface. Finally some works [27,28] (for spheres) and [24] (for cylinders) provided new detailed data concerning the velocity field around an object moving through a yield stress fluid. They found a significant discrepancy of the velocity field with that computed from simulations. In particular they remarked an asymmetry on the flow field, the extent of the sheared zone ahead of the object being larger than expected from theory. A significant flow asymmetry was also observed in 2D foam flow around an obstacle by Dollet and Graner [29] which was attributed to elastic effects.

It is likely that an issue in these works, which nevertheless might not explain the observed asymmetry, is the following: although they are generally considered as the flow characteristics of the fluid in the liquid regime, the measurements concern the apparent velocity field which could include both flow in the liquid regime and deformations in the solid regime. This means that new deformations of the material in the solid regime continuously occur around the object and might play a significant role in the process. This conclusion was confirmed by the analysis of the flow field around an object of simpler form, i.e. a plate, penetrating through a bath of yield stress fluid [30]: although the fluid seems to exhibit a complex velocity distribution from the instantaneous velocity field, it was shown that only a layer of small thickness along the plate effectively flows in the liquid regime while the rest of material undergoes small total deformations in the solid regime.

Here we study the withdrawal of a thin plate from a bath of yield stress fluid by analyzing the evolution of the force applied on the plate during its displacement and measuring the velocity field by PIV. First, we present the materials, equipments and procedures used (Section 2). Then, we analyze the different regimes that occur during the withdrawal of the plate looking first at the time evolution of the force applied on the plate (Section 3), then at the velocity field inside the bath (Section 5). We also discuss the impact of different parameters (geometry, fluid properties, velocity) (Section 4). Finally, we compare these observations with those corresponding to plate immersion [30,31] (Section 6) before studying the impact of a time of rest between the plate immersion and withdrawal (Section 7).

2. Materials and methods

2.1. Materials

As yield stress fluids, we used solutions of Carbopol 980 in water at different concentrations (see details on these materials in [32]). Rheometrical tests were carried out with a Bohlin C-VOR rheometer equipped with two circular rough parallel plates to prevent slippage (diameter 4 cm; waterproof sandpaper of average particle diameter 120 μm). Sweep tests were carried out: the stress was increased logarithmically in time (for 3 min) and then decreased for the same time. The data in the decreasing ramp are considered as describing the material behavior in steady state. Various data of that type have been published recently (see for example [33]). They showed that these materials behave as simple yield stress fluids without thixotropy. The flow curve representing the steady state shear stress as a function of the shear rate can be very well fitted over four decades in shear rate [10^{-2}; $10^2\ \mathrm{s}^{-1}$] by a Herschel–Bulkley model. The resulting behavior in simple shear is $\tau < \tau_c \Rightarrow \dot{\gamma} = 0$ (solid regime) and $\tau > \tau_c \Rightarrow \tau = \tau_c + k\dot{\gamma}^n$ (liquid regime), where $\dot{\gamma}$ is the shear rate and τ_c, k and n are parameters depending on the material characteristics. For such materials it was shown from MRI measurements that, in contrast with more complex (thixotropic) yield stress fluids, this macroscopic constitutive equation effectively corresponds to their local rheological behavior inside the bulk [32]. For our experiments, we used 9 different Carbopol gels (see [31] for details on material preparation) with τ_c in the range [9–82], the flow curves of the 4 gels mainly used in this study are shown in Fig. 1.

2.2. Dip-coating

We studied the dip-coating of a solid plate with the same experimental set-up used for the immersion of a plate in a yield stress fluid [30]. Here a vertical plate initially partially immersed is withdrawn at constant velocity V from a container filled with Carbopol gel. The solid is directly linked to a dual-column testing system (*Instron* 3365) which controls its position with a resolution of 0.1 μm. The apparatus is equipped with a 10 N force sensor able

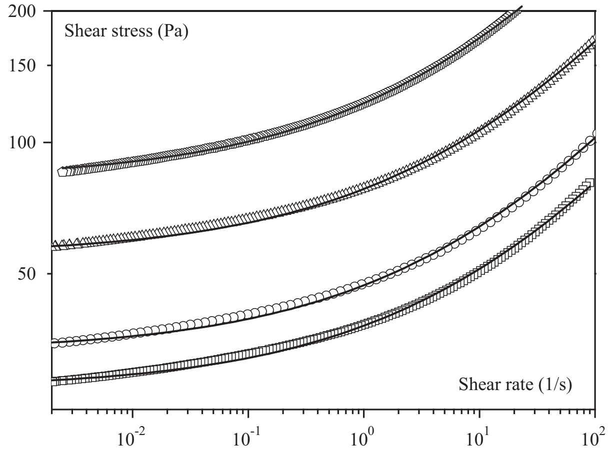

Fig. 1. Flow curves of our different Carbopol gels. The continuous lines correspond to a Herschel–Bulkley model fitted to data with the following parameters (n = 0.35): τ_c = 27 Pa, k = 10.7 Pa s^n (open squares); τ_c = 33 Pa, k = 13.8 Pa s^n (circles); τ_c = 55 Pa, k = 23 Pa s^n (open triangles) and τ_c = 82 Pa, k = 40.7 Pa s^n (open pentagones).