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Review

Yield stress fluid flows: A review of experimental data

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ABSTRACT

Yield stress fluids are encountered in a wide range of applications: toothpastes, cements, mortars, foams, muds, mayonnaise, etc. The fundamental character of these fluids is that they are able to flow (i.e., deform indefinitely) only if they are submitted to a stress above some critical value. Otherwise they deform in a finite way like solids. The flow characteristics of such materials are difficult to predict as they involve permanent or transient solid and liquid regions that are generally hard to locate a priori. Here we review the present state of the art as it appears from experimental data for flows of simple (non-thixotropic) yield stress fluids under various conditions, viz., uniform flows in straight channels or rheometrical geometries, complex stationary flows in channels of varying cross-section such as extrusion, expansion, flow through a porous medium, transient flows such as flows around obstacles, spreading, spin-coating, squeeze flow, and elongation. The effects of surface tension, confinement, and secondary flows are also reviewed. We focus especially on experimental work identifying internal flow characteristics that can be compared with numerical predictions. It is shown in particular that: (i) deformations in the solid regime can play a critical role in transient flows; (ii) the yield character is not apparent in the flow field when the boundary conditions impose large deformations; (iii) the yield character is lost in secondary flows.

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1. Introduction

A toothpaste flows like a liquid through the squeezed tube and spreads over the toothbrush where it will remain at rest while the brush is brought up to the mouth. It is then largely deformed once again by agitation and friction against the teeth. A mortar is strongly mixed in a container, then spread over a vertical wall to form a layer a couple of centimeters thick which will remain at rest from minutes to hours until it starts to set (chemical reactions leading to solidification of the structure). A mayonnaise prepared by strong mixing can be dispersed over a food surface and will remain at rest there.

These materials thus appear to maintain their shape in the same way as solids under the effects of gravity, and yet are able to flow like liquids, i.e., deforming significantly when subject to a high enough stress. A critical point is that, if chemical reactions do not have time to play a role, the transition between these two states is perfectly reversible: once at rest the material will soon recover the properties it had before flowing in the liquid regime. We are thus dealing with fluids in the sense that these materials can undergo any type of deformation without losing their intrinsic mechanical properties.

According to the above description it is natural to distinguish two main states: a solid regime and a liquid regime. There has been some controversy about the "true" existence of a solid regime. Some authors [1] suggest that it should in fact be considered as a very high viscosity regime. But there is actually a clear and significant transition of rheological behavior which justifies this distinction for most processes involving such materials [2], while the apparent low-stress Newtonian viscosity is an artifact that arises in non-steady-state experiments [3]. Consider for example a typical commercial hair gel. It can flow easily like a simple viscous liquid if mixed with a spoon, but the bubbles formed within it will subsequently remain in the same place for years, as they would in a solid. Since for almost all applications, we only consider the mechanical properties of such materials for periods of a few hours, they will look like solids whenever the applied stress is not too large.

Thus the fundamental feature of these fluids is that they are able to flow (i.e., deform indefinitely) only if they are submitted to a stress above a critical value. Otherwise they deform in a finite way like solids. The flow characteristics of such materials are difficult to predict as they involve permanent or transient solid and liquid regions that are generally impossible to locate a priori. The situation is even more complex for yield stress fluids whose apparent behavior depends on the flow history, i.e., thixotropic fluids. Here we review what is currently known about flows of simple (non-thixotropic) yield stress fluids (see Section 2) under various conditions: (i) uniform flows in straight channels or rheometrical geometries (Section 3); (ii) complex stationary flows in channels of varying cross-section, such as extrusion, expansion, and flow through a porous medium (Section 4); (iii) transient flows such as flows around obstacles, spreading, spin-coating, squeeze flow, and elongation (Section 5). We also review the effects of surface tension, confinement, and secondary flows.

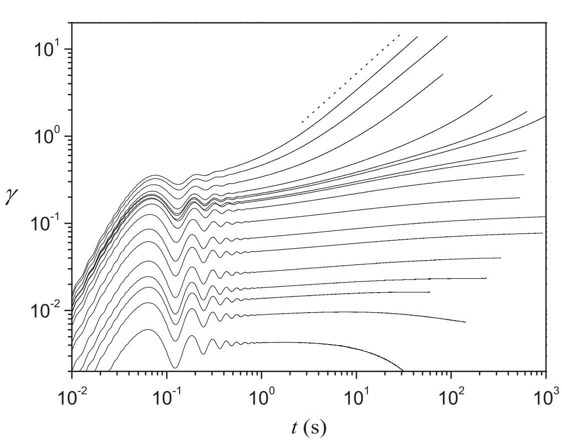

Fig. 1. Typical deformation vs time curves for different stress levels (from bottom to top) applied to a hair gel: 0.8, 4, 6, 8, 12, 20, 28, 40, 50, 56, 60, 63.2, 66.8, 70, 80, 90, 100 Pa. The dotted line is the curve of slope 1. Reprinted (Figure 1c) with permission from [4]. Copyright © 2006 by The Society of Rheology, Inc. All rights reserved.

2. Rheological characterization and scope of the review

A rheometrical procedure may be used to clearly distinguish and characterize the solid and liquid regimes. It consists in a series of creep tests, i.e., the deformation is monitored over time for a constant applied stress, and for different stress levels (using a new sample of the same material for each value). After a transient stage, the different deformation vs time curves evolve in two ways (see Fig. 1). For a stress above a critical value (say 62 Pa), they end up with unit slope on a logarithmic scale, indicating that the material flows at a constant shear rate. We thus consider the material to be in its **liquid regime**. For a lower stress, the deformation seems to tend to a plateau, and remains below a critical value, as it would for a solid. It can still be argued that, in the latter regime, the deformation goes on increasing in time, suggesting a very slow flow. However, the slope decreases in time, indicating that the apparent shear rate continues to decrease in time toward lower and lower values, without reaching a steady state flow. The apparently limited deformation and continuous decrease in the apparent shear rate toward very low values justifies treating this as a **solid regime**.

It must nevertheless be mentioned that, for stresses close to the critical value, the situation is not so clear, because the deformation seems to be able to reach a significant value, while the shear rate decreases significantly (slope less than one on a logarithmic scale). This illustrates how difficult it is to determine a precise value for the yield stress. Ideally, the yield stress is the stress associated with a steady flow at an infinitely small shear rate which, due to the finite deformation associated with the solid–liquid transition, would take an infinitely long time to reach. Note that in any case