International Journal of Engineering Science 109 (2016) 165–201

Contents lists available at ScienceDirect

International Journal of Engineering Science

journal homepage: www.elsevier.com/locate/ijengsci

Transient motions of elasto-viscoplastic thixotropic materials subjected to an imposed stress field and to stress-based free-surface boundary conditions

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A R T I C L E   I N F O

Article history:
Received 16 April 2016
Revised 29 July 2016
Accepted 28 August 2016

Keywords:
Elasto-viscoplastic thixotropic materials
Numerical solution
Finite difference marker and cell method
Transient computations
Free-surface boundary conditions

A B S T R A C T

In the present work, we present an approach to handle transient flows of elasto-viscoplastic thixotropic (EVPT) materials under the action of the gravity force field and subjected to free-surface boundary conditions that are stress-based. This kind of conditions are common in problems where the motion is unknown *a priori*, i.e. the motion is treated as a consequence while the forces are the cause. The model for the EVPT material employed is within the scope of a recently developed thermodynamic backbone for elasto-viscoplastic thixotropic materials. The finite difference Marker and Cell method is used to investigate effects of elasticity, thixotropy, and plasticity varying the Weissenberg number, the dimensionless thixotropic equilibrium time, and the yield number, respectively. The Cartesian Poiseuille flow is used to test the main features of the numerical scheme. The evolution in time of an initially square and fully-structured block is captured. The structure level and shape evolutions of the block reveal the capability of the present numerical approach to handle the complexity of the material and the free-surface motion.

1. Introduction

1.1. General aspects

Many materials exhibit thixotropic and other time-dependent characters. Examples are encountered in many industries such as oil, food, cosmetics, mining, etc. In fact, time-dependent materials reflect the fact that it takes a finite time for the microstructure to achieve a new state once the stress has changed to a new value. In this sense, every microstructured material can exhibit time-dependency. However, a system is classified as time-dependent if the time scale associated to microstructure change is comparable to the process time scale.

Important recent advances on the understanding of thixotropic and other time-dependent phenomena were reported after careful conduction of experiments. In this connection, many findings and discussions concerning the detection of

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http://dx.doi.org/10.1016/j.ijengsci.2016.08.004

aging (Nigmatullin, Nakanishi, Tran-Cong-Miyata, Tahara, & Fukao, 2010), the yielding process (Balmforth, Frigaard, & Ovarlez, 2014; Coussot, 2014; Denn & Bonn, 2011), the avalanche effect (Coussot, Nguyen, Huynh, & Bonn, 2002a; 2002b), the bifurcation phenomenon (Coussot et al., 2002a), shear-banding (Bautista et al., 2012; Fall, Paredes, & Bonn, 2010; Olmsted, 2008), and others, became crucial on analyzing the time-dependent nature of these kinds of complex materials. Some important works in the literature (Coussot et al., 2002a; Fall et al., 2010; Moller, Fall, Chikkadi, Derks, & Bonn, 2009; Møller, Mewis, & Bonn, 2006) have shown that there are classes of materials where the yielding phenomenon takes place which are susceptible to time-dependency. In this sense, it is important to understand the connections between these phenomena.

In an attempt to follow these findings and aiming to predict the behavior of microstructured materials, a number of models has been proposed. Since time-dependent in general constitute a broad class of materials, the great majority of these models focus on the important sub-class of the thixotropic materials. Thixotropic materials are common time-dependent systems that have their structure level decreased by the action of stress but they re-built reversibly when stresses are removed. Although thixotropic models are available for quite a time, being employed in simulations to solve benchmark and, less commonly, applied problems, only recently the elastic character of thixotropic materials, associated to a more structured state, has been incorporated to viscoplastic thixotropic models. In this context, de Souza Mendes, Rajagopal, and Thompson (2013) developed a thermodynamic framework for EVPT materials where a maximization of the entropy production is performed after assumptions of how the elasto-viscoplastic-thixotropic material stores and dissipates energy in consonance to a general thermodynamic theory developed by Rajagopal and co-workers (e.g. Rajagopal & Srinivasa, 1998a; 1998b; Rao & Rajagopal, 2002; Rajagopal & Srinivasa, 2004a; 2004b).

In many problems of practical interest EVPT materials are subjected to a stress field originated from body and contact forces. In this case, there are no boundary nor initial conditions which are based on flow rate or velocity profile. The motion is completely treated as a consequence, while the forces are the cause. From the philosophical point of view, a deep discussion on this matter of causality was conducted by Rajagopal and co-workers and used as insight to build new classes of constitutive equations (e.g. Rajagopal, 2011; Bustamante & Rajagopal, 2011; Muliana, Rajagopal, & Wineman, 2013; Gou, Mallikarjuna, Rajagopal, & Walton, 2015).

There are important problems associated to geophysical flows of viscoplastic materials where the action of gravity coupled with free surface boundary conditions constitute a crucial aspect (see Ancey, 2007). Examples where this kind of coupling was investigated are: the dam-break problem (e.g. Ancey & Cochard, 2009; Balmforth, Craster, Perona, Rust, & Sassi, 2007); the slump test (e.g. Dubash, Balmforth, Slima, & Cochard, 2009; Staron, Lagrée, Ray, & Popinet, 2013), also referred to as the “fifty-cent” rheometer (e.g. Pashias, Boger, Summers, & Glenister, 1996; Roussel & Coussot, 2005); the uniform flow of a layer of fluid on an inclined plane (e.g. Chambon, Ghemmour, & Naaim, 2014; Huynh, Roussel, & Coussot, 2005); the flow of a fixed amount of material on an inclined plane (e.g. Coussot, Nguyen, Huynh, & Bonn, 2002b; Hewitt & Balmforth, 2013); among others.

1.2. Viscoplastic time-dependent phenomena

Careful reviews on thixotropic systems were performed in Barnes (1997); Mewis and Wagner (2009); Mujumdar, Beris, and Metzner (2002) and the reader is referred to these articles in order to get an overview of this phenomenon.

Thixotropy yield-stress materials exhibit remarkable differences when compared to ideal yield-stress ones (Coussot et al., 2002a; Fall et al., 2010). Yield-stress materials exhibit solid-like to liquid-like transition when a viscoplastic material that was in a free-stress state for a long time (fully structured state) is exposed to a stress level above the yield stress. In this case, the material starts an internal process that is associated to an evolution towards less structured states until it reaches an equilibrium structure configuration associated to the imposed stress. Thixotropic systems have a spontaneous “internal” build-up agent, like Brownian motion for example, responsible for the aging of the material even at rest in a stress free state, and a breakdown agent that acts as a rejuvenation source. The competition between these two sources leads to aging, rejuvenation, or equilibrium. When the stress level is above, but close to the yield stress, the break-up rate is low and the time dependency nature of the material is more pronounced.

A striking phenomenon where the thixotropic character of the material is unequivocally present is the so-called “avalanche effect”, as discussed in Coussot et al. (2002a, 2002b). When a structured material is subjected to gravity forces on an inclined plane, above a certain angle, the stress overcomes the yield stress, starting a breakage process. When the material breaks, its viscosity decreases, what enhances the flow rate of the material, what, in turn, favors more breakage. Therefore, a continuous cyclic self-feeding process takes place, rendering the achievement of high distances at the end.

Shear banding or shear localization is also a phenomenon typical of viscoplastic materials where thixotropy plays an important role (Bautista et al., 2012; Fall et al., 2010; Olmsted, 2008; Ovarlez, Rodts, Chateau, & Coussot, 2009). Shear banding occurs when similar stress levels lead to the coexistence of remarkably different shear rate levels. When the flow curve is non-monotonic, depending on the imposed variable, stress or shear-rate, different parts of the stress-shear-rate space are attainable or unattainable. In fact, there are parts of the flow curve that can be always unattainable, leading the necessity of the performance of a stability analysis approach. This phenomenon is related to the presence of a dynamic yield stress value which is lower than the static yield stress value. While the dynamic yield stress is usually defined as the stress value at the transition from liquid to solid behavior, the static yield stress is the stress value at the transition from solid to liquid behavior.