THE YIELD ZONE CONCEPT AND ITS APPLICATION ON A 4:1 ABRupt CONTRACTION FOR AN APPARENT-YIELD-STRESS FLUID

G.G. RAMOS†, E.J. SOARES‡ and R.L. THOMPSON‡
† Mechanical Engng. Department, UFES, Vitória, ES 29075-910, Brazil. ramos@ct.ufes.br, edson@ct.ufes.br
‡ Mechanical Engng. Department, UFF, Niterói, RJ 24210-240, Brazil. rthompson@mec.uff.br

Abstract— The yield surface, a concept widely used in the literature that was born together with the Bingham model is discussed from the perspective of other models that are more related to apparent-yield-stress materials. As a consequence, it is necessary to define a yield zone, an intermediate transition region in the flow domain where plasticity manifests itself. A Galerkin Finite Element Method is used to investigate the performance of a SMD viscoplastic material through a 4:1 abrupt contraction. The influence of dimensionless parameters, like the Jump number and an equivalent to the Bingham number, on the size of the yield zone and on the pressure loss of the contraction are investigated.

Keywords— Viscoplastic material, abrupt contraction flow, finite element method, yield surface, yield zone.

I INTRODUCTION

A. Motivation

The importance of non-Newtonian materials is becoming recognized in many important industries such as: the petroleum industry, the food industry, the cosmetic and pharmaceutical industry, etc. One first reasons is the increasing necessity of determining more accurately certain global quantities that are related to the efficiency of processes that have a traditional Newtonian calculation counterpart. It was not uncommon, in the past, to use Newtonian results as an approximation for non-Newtonian flows. A second important reason is that non-Newtonian materials are much more complex, and can exhibit features that are not present in Newtonian fluids world such like pseudoplasticity, viscoplasticity, elasticity, thixotropy. These features can be used to understand and produce new synthetized fluids and to conceive new methodologies in order to optimize standard processes (Sifontes et al., 2010). In the recovery of oil and drilling mud removal, among other procedures, non-Newtonian fluids are widely used (Morales et al., 2011). An approach to compute friction loss coefficients for some non-Newtonian fluids is given by Kfuri et al. (2011). The present work deals with one important class of non-Newtonian materials, namely the apparent-yield-stress fluid. These fluids are microstructure and can change significantly their viscosity from a higher level one, when the material is fully structured, to a lower one, when the material is almost unstructured. The concept of yield zone as an apparent-yield-stress fluid counterpart of the yield surface associated to yield-stress materials is presented and analyzed for the particular case of the flow in a 4:1 abrupt contraction.

B. Yield-stress materials

There is a large variety of materials that have a viscoplastic-like behavior (Pereira et al., 2010). Conceptually, a viscoplastic material is a material that possesses a yield-stress, \( \tau_0 \), a stress limit below which the material does not flow. The first model that could predict this kind of behavior was proposed by Bingham (1922) as

\[
\eta = \frac{\tau_0}{\dot{\gamma}} + \mu_p \tau \geq \tau_0, \dot{\gamma} = 0, \tau < \tau_0
\]

where \( \tau \) is the norm of the extra-stress tensor and \( \dot{\gamma} \) is the norm of the deformation rate. The quantity \( \eta \) is the viscosity function associated to the Generalized Newtonian Liquid equation, \( \tau = \eta \dot{\gamma} \). The relation presented in Eq. (1) cannot be written as a function for the stress. When \( \dot{\gamma} = 0 \), there are an infinity of values, in the interval \( [0, \tau_0] \) that \( \tau \) can assume and the viscosity is infinite. In order to represent the Bingham model numerically, it is common to use a bi-viscosity function using a very high viscosity value for low values of the shear rate.

\[
\eta = \begin{cases} 
\frac{\tau_0}{\dot{\gamma}} + \mu_p \tau, \tau \geq \tau_0, \\
\eta_{\text{HIGH}}, \tau < \tau_0
\end{cases}
\]

C. Apparent-yield-stress fluids

There is a controversy in the literature, with respect to the yield stress. This controversy was triggered by Barnes and Walters (1985) where the existence of this entity was questioned. By conducting a series of experiments benefiting from the improvement of the accuracy of a new generation of rheometers, they claimed that some materials, considered as yield-stress materials, do flow below its apparent yield stress. In this sense, this critical stress, would mark a transition between two states of the structure level of the material. Below the (apparent) yield stress, the material is fully structured with a very high viscosity. Above this limit, the material starts a breakdown process that ends with a very low viscosity. An important review on the subject was made by Barnes (1999). A recent discussion on the existence or non-existence of the yield-stress is found in de Souza Mendes and Thompson (2013). As suggested by Hartnett and Hu (1989), Astarita (1990) the relevant issue is related to how we model the material for engineering purposes. Therefore, the yield stress can be considered “an engineering reality.” Independently of the existence...