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General Aspects of Yield Stress Fluids – Terminology and Definition of Viscosity

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Abstract:
This work contributes to general theoretical aspects of yield stress fluids with significance for practical phenomenological material modeling. It introduces a terminology so that the material class 'yield stress fluid' is defined and can be distinguished from the terms 'solid' and 'liquid'. This new material classification is based on two criteria, the equilibrium relation and the flow function. In line with this terminology, an experimental procedure for classifying the material behavior is presented. The second key aspect of this paper is a discussion on the proper definition of the term 'viscosity'. The benefit of the differential viscosity over the dynamic viscosity in case of non-Newtonian fluids in general is worked out. This is shown by the most elementary yield stress fluid, the friction element, because it is the basis of the yield stress concept. Its constitutive equations are given for positive as well as negative strain rates and are also able to represent the preyield behavior. The theory presented in this article is also applied to the Maxwell, Kelvin-Voigt, and Bingham element to demonstrate the working principle.

Key words:
yield stress fluid, differential viscosity, apparent viscosity, equilibrium stress, friction element, Bingham element

Supplementary Information attached and also available at http://www.complexfluids.ethz.ch/SI_AR_24_14578.pdf

1 INTRODUCTION

The material behavior of soft matter can often be described by material models belonging to the class of yield stress fluids. So, how can yield stress fluids be distinguished from classical materials – solids and liquids – in case of phenomenological modeling? This directly leads to the question of convenient classification criteria to separate solids, liquids and yield stress fluids from each other. The search for a definition of the terms solid and liquid has a long history [1]. For example Bingham [2] said "If a body is continuously deformed by a very small shearing stress, it is a liquid, whereas if the deformation stops increasing after a time, the substance is a solid". Noll defined solids and liquids relating to its symmetry properties [3–8]). But Greve [7] pointed out that there are materials which are neither solids nor fluids in the sense of Noll's definitions. There also exists a classification into solid and liquid-like behavior depending on the storage and loss modulus. Solid-like behavior occurs if $G' > G''$, otherwise liquid-like behavior [9–14]. A disadvantage of this definition becomes obvious for example in case of the Maxwell element with the elastic moduls G and the viscosity η, which has to be classified either as solid or liquid depending on the angular frequency ω. For $\omega < G/\eta$ the loss modulus is greater than the storage modulus so that the Maxell element has to be treated as fluid. On the other hand it has to be classified as liquid for $\omega > G/\eta$ since the storage modulus dominates over the loss modulus. Thus, the search of phenomenological definitions of 'solid' and 'liquid', which can be applied theoretically as well as practically, is still necessary in general and especially to define the class of yield stress fluids. Furthermore, this contribution investigates the way of defining the term 'viscosity' since the behavior of yield stress fluids is dramatically different to the one of Newtonian fluids due to yielding.

Classifying materials as well as defining 'viscosity' is essential also in practice e.g. for material modeling. To determine the class of a material behavior should be the first step before applying constitutive equations. Determining the differential viscosity enables to extract the pure viscous properties of a yield stress fluidic material specimen which is necessary to model it. That is why, this article places a great emphasise on basics of yield stress fluids in the sense of phenomenological modeling, material classification as well as the differential viscosity and is useful in terms of practical questions. It

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Information A and included the description in terms of the classical theory of plasticity. As consequence, the terms 'preyield' and 'postyield' were defined for the friction element by the loading and unloading conditions which in turn are connected with the Karush-Kuhn-Tucker and consistency conditions. In this work the latter two were illustrated in a convenient way by the evaluation of logical expressions in Supplemental Informationg A.1 and A.2 without considering the optimisation problem with constraints in form of inequalities.

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