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Rheological Characterization of Yield-stress Materials: Flow Pattern and Apparent Wall Slip

Flávio H. Marchesini[1,2], Mônica F. Naccache[1]*, Aline Abdu[1], Alexandra A. Alicke[1], Paulo R. de Souza Mendes[1]

[1]Department of Mechanical Engineering, Pontifícia Universidade Católica-RJ, Rua Marquês de São Vicente 225, Rio de Janeiro, RJ 22453-900, Brazil
[2]Current address: Halliburton Brazil Technology Center, Rua Paulo Emídio Barbosa 485, Rio de Janeiro, RJ 21941-907, Brazil

* Corresponding author: naccache@puc-rio.br

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Abstract:
An experimental and numerical investigation of the rotational rheometry of yield-stress materials is performed, using water-based Carbopol dispersions. The flow and fluid characterization in different rheometer geometries, namely the smooth Couette, the grooved Couette, and the vane-in-cup are analysed. The bi-dimensional flow governing equations are solved numerically, using the finite volume method and Fluent software (Ansys Inc.). The viscoplastic behavior of Carbopol dispersions is modeled using the Generalized Newtonian constitutive equation with the regularized viscoplastic viscosity function proposed by de Souza Mendes and Dutra [1], herein called SMD function. The flow pattern and the presence of apparent wall slip in rheometric measurements of yield-stress materials are investigated and discussed.

Key words:
Rheometry, apparent wall slip, yield stress, viscoplastic materials

1 INTRODUCTION

Structured materials are generally formed by discrete components dispersed in a homogeneous and continuous phase [2]. Usually, these materials present a threshold stress, known as yield stress, below which they feature a solid-like behavior, with no noticeable deformation. Above the yield stress there is a steep viscosity decay followed by a pseudoplastic or Newtonian behavior, and the material is able to flow like a liquid. For some of these materials there is measurable, albeit very slow, irreversible flow below the threshold stress [3, 4], in this case called the apparent yield stress. Recently, Boisly et al. [5] introduced a new terminology, defining solids, liquids and yield stress fluids as distinct materials. Such materials can be found in our daily life, as well as in several industrial applications. Therefore, it is important to obtain their rheological properties and to predict their mechanical behavior. Recently, the rheometry of such materials has received a lot of attention in the literature [6–8], especially with regard to the development of techniques, designed to mitigate possible sources of error in rheological measurements. Some of the main challenges reported in the rheological characterization of structured materials are: evaporation, sedimentation, thixotropy, shear banding, and apparent wall slip.

As reviewed by Barnes [9] in detail, apparent wall slip or wall depletion effects can occur in flows of structured materials and is mainly observed when low shear rates, large components in the disperse phase, smooth walls, and small dimensions are present. Apparent wall slip is caused by the creation of a thin layer of the continuous phase alone at the solid boundaries, where the strain rates are maximum. This lower-viscosity depleted layer plays a lubricating role, facilitating the flow. Due to this fact, one can obtain distinct viscosity values with different rheometric geometries, as shown in Barnes [9], where lower viscosities are obtained for smaller-gap geometries. In addition, unreal Newtonian plateaus at stresses below the yield stress and kinks in the flow curve may be obtained [9–11].

To circumvent apparent slip problems in the rheological characterization of structured materials, two strategies are usually employed: (i) the use of different gaps to obtain enough data to perform mathematical manipulations to end up with the bulk flow properties [12, 13], or (ii) modifications of the wall surface to elimi-

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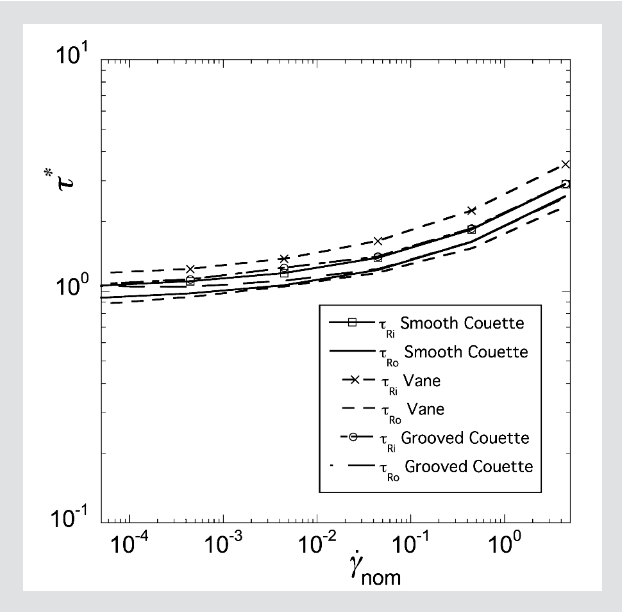

Figure 14: Dimensionless inner and outer shear stress for the three geometries.

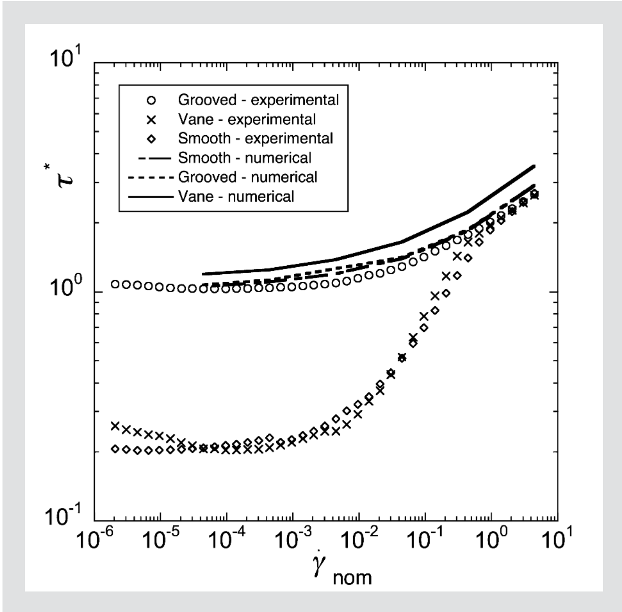

Figure 15: Experimental and numerical results of dimensionless inner wall shear stress.

formed using sandpaper at the walls [34], a slender gauze basket inserted inside the outer cylinder [35], or a serrated or profiled cylindrical cup [20] to prevent apparent wall slip at the outer wall.

For all the reasons mentioned above, it becomes clear that, in rheological measurements of yield-stress materials, more attention should be given to the apparent wall slip at the outer cylinder wall, where the shear stresses are lower. In addition, it can be noted that the grooved Couette geometry was successful in eliminating apparent wall slip during the rheological measurements carried out in this work, while the vane-in-cup did not present a good performance. Thus, care needs to be taken before selecting the vane geometry as a good option to prevent apparent wall slip in rheological measurements.

6 FINAL REMARKS

In this paper, a numerical and experimental investigation was performed to analyze the flow pattern and apparent wall slip in rheological measurements of yield-stress materials in rotational rheometers. Three different geometries were used in the study: the smooth Couette, the vane-in-cup and the grooved Couette. Rheometrical data of Carbopol dispersions were presented, and an analysis was performed regarding the conditions needed to obtain valuable data for the flow curve of yield stress materials. If on one hand rather long times are needed in the low shear rate range to reach the steady state from rest, on the other hand these times can be considerably shortened if the sample is pre-sheared. This behavior is in accordance to that presented in Ovarlez et al. [6].

Numerical simulations were performed using the finite volume technique. The results were compared to the experiments, showing that for Carbopol dispersions, apparent wall slip occurs at lower shear stresses. At this range, the outer wall slip velocity in the smooth Couette is much higher than the inner one for the Carbopol dispersions studied, in contrast to Buscall et al. [21], who found no slip at the outer cylinder wall for weakly attracted particle dispersions. For higher shear stresses, no slip was detected, and all geometries performed reasonably well in rheological measurements. It is also shown that flow kinematics is affected specially in the vane-in-cup geometry, which could lead to experimental errors in viscosity measurements. Finally, it is important to point out that the performance of the grooved geometry was much better than the other ones in the rheological measurements carried out and that precautions must be taken when using the vane geometry.

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