EXTENSIONAL RHEOLOGY OF FIBER REINFORCED FLUIDS

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Abstract. *Understanding the benefits of fiber reinforcement in the properties of the polymers composites, shows that it is possible to improve the material characteristic performance and reduce costs. In many applications, fibers are added to improve the mechanical properties of the original material, and hence increase their competitiveness with metallic materials. The rheological properties of the polymer composites have important effects on the mechanical properties of the final products. On the other hand, characterization of composite materials is a difficult task, due to the several variables involved. In the present work, a rheological investigation of suspensions containing Wollastonite fibers and glass fibers is performed using the Paar Physica rotational rheometer and the CaBER extensional rheometer. The influence of fiber concentration and the effect of temperature on rheology in a Newtonian polybutene/kerosene matrix and in a viscoelastic fluid matrix have been analyzed. The results obtained show that both types of suspensions exhibit similar viscosities when subjected to shear flows. However, when exposed to extensional flows, an increase of the filament break up time is observed for the Wollastonite fibers, due to an increase of the extensional viscosity.*

Keywords: rheology, extensional viscosity, fiber reinforcement

1. INTRODUCTION

Plastics are increasingly replacing conventional materials, mainly due to their low production costs and their lower density. Fibers and other fillers are added to plastics to improve their mechanical properties and hence their competitiveness with metallic materials. Short fiber filled thermoplastics represent a major class of growing importance, since conventional equipment (extruder and injection machines) can be used to produce final parts using this kind of materials. The mechanical properties of the produced parts depend strongly on the process itself, on the rheological properties of the filled polymer and on the orientation of fibers during processing.

In the present work, shear and elongational properties of a short wollastonite fiber and a glass fiber reinforced fluids, using a Newtonian matrix and a viscoelastic one are studied. The extensional viscosity is determined using a capillary breakup extensional rheometer (CaBER) whereas the shear viscosity is obtained using a rotational rheometer Paar-Phisyca. The effects of fiber concentration and temperature are analyzed.

2. RHEOLOGICAL CHARACTERIZATION

2.1 Theoretical Approach

Filament stretching extensional rheometers (FiSER) had their origins with the work of Matta and Tytus (1990) who developed a falling fluid cylinder, which the upper part is held fixed, while the lower one is initially at rest and then is allowed to fall and stretch the adhering sample. In the same year, Bazilevsky et al. (1990) described a liquid filament microrheometer that suggested a simple way of determining the "stickness" of a suspicious unknown material, which is best compared to the quantitative version of the "thumb and forefinger" test (McKinley et al. 2001). A similar idea was used to develop the CaBER extensional rheometer. The main difference between the filament stretching rheometer and the filament breakup one (CaBER) is that in filament stretching devices, a cylindrical liquid bridge is formed between two rigid end plates, which are then actively stretched apart with an exponentially increasing separation profile. In the filament

breakup device, these end plates are rapidly separated and then held at a fixed axial gap, and the subsequent evolution of the mid filament diameter is monitored during the process of necking and breakup (Shelley L. Anna 2000). A small droplet of a fluid is set between two plates that slowly move apart. The free surface of the droplet takes a characteristic concave shape (a liquid bridge is formed). As the disks are separated still further, the bridge becomes unstable and begins to collapse under the action of capillary forces. As a result, a neck is formed, which, in the case of Newtonian fluids, rapidly thins and finally disintegrates. In the case of polymeric fluids, a filament uniform in diameter may be formed, which thins with time (Fig. 1). The breakup of bridges and filaments is governed by a competition between capillary, inertia, and internal rheological forces, which arise in liquids when they are deformed (Bazilevskii et al. 2001). The inertial effects that play a determining role for the experiment are governed by a dimensionalless number known as the Bond number, defined as Eq.1

$$Bo = \frac{\rho g R_0^2}{\sigma} \tag{1}$$

where σ is the surface tension and ρ is the density of the fluid. A Bond number $Bo \ll 1$ states that gravity can be neglected, whereas gravity becomes more important with increasing values of the Bond number.

Thus, studying the breakup of bridges and filaments may provide information about extensional rheological properties of liquids.

Figure 1 shows a scheme of a filament stretching rheometer. On the right side of fig. 1, it can be observed that the radius of the thin fluid column is almost uniform in the central region. This is true for a strongly strain-hardening fluid, such as a dilute polymer solution. As a result, it is shown that the midpoint radius of the filament evolves according to Eq.2 and Eq.3 for Newtonian fluids and viscoelastic fluids respectively (Entov and Hinch, 1997):
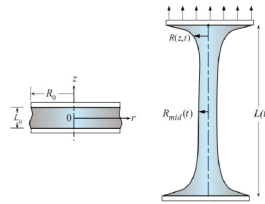

Figure 1: Schematic diagram of a filament stretching extensional rheometer.

$$\frac{D_{mid}}{D_0} = 1 - \frac{(2X-1)}{3}\frac{\sigma}{6\mu D_0}t \tag{2}$$

$$\frac{D_{mid}}{D_0} = \left(\frac{GD_0}{2\sigma}\right)^{1/3} exp\left(\frac{-t}{3\lambda}\right) \tag{3}$$

where X is the dimensionless tensile force, σ is the surface tension, G is the elastic modulus and λ is the characteristic relaxion time governing the capillary breakup.

At time $t = 0$, the upper plate is set in motion and the resulting midpoint radius of the filament $R_{mid}(t)$ and tensile force $F_z(t)$ exerted by the elongating column are measured. The endplate velocity profile $\dot{L}_p(t)$ is chosen such that the midpoint of the fluid filament decreases exponentially with a constant stretching rate $\dot{\epsilon}_0$ given by

$$\dot{\epsilon}_0 = -\frac{2}{R_{mid}}\frac{dR_{mid}}{dt} \tag{4}$$

Selection of this velocity profile is difficult, due to the no-slip pinning condition imposed by the rigid endplates. The

total Hencky strain experienced by the fluid elements at the midplane of a filament stretching is calculated by Eq.5

$$\epsilon = \int_0^t \dot{\epsilon}_0 dt' = ln\left[(R_0/R_{mid}(t))^2\right] \tag{5}$$

The apparent extensional viscosity is defined in Eq. 6.

$$\eta_{app}(\epsilon) = \frac{[\tau_{zz} - \tau_{rr}]_{total}}{\dot{\epsilon}(t)} = \frac{\sigma}{\frac{dD_{mid}}{dt}} \tag{6}$$

2.2 Rheological Measurements

To perform the rheological testings, the polybutene and kerosene solutions with 0.0, 5 and 10 wt% of wollastonite and fiber glass and the remaining Boger fluids with 0.0, 5 and 10 wt% of wollastonite fiber are prepared. The Newtonian matrix consists of 6.98% of kerosene and 92.78% of polybutene (PB). The viscoelastic matrix or Boger fluid consists of 0.24% of polyisobutylene (PIB), 6.98% of kerosene and 92.78% of polybutene (PB). The Boger fluid is a non-Newtonian one, with constant shear viscosity, and elasticity. The density of the wollastonita fiber is 2900 kg/m^3 and the fiber glass is 1200 kg/m^3.

The shear viscosity of the fluids and fibers suspensions is measured using a Physica MCR 301, of Anton Paar. The parallel-plate geometry is used instead of the cone-and-plate geometry to avoid wall effects. For all measurements a 1.0 mm gap is used. The temperature variation is measured using a Peltier device. The capillary thinning experiments reported here are carried out using a CaBER version 1 (Thermo Electron) using circular end plates with diameter of $D_p = 6$ mm.

3. RESULTS

Figures 2 and 3 show the effect of fiber concentration on shear and extensional viscosity for the Boger samples. The temperature of the samples is equal to 25^oC. Observe that, the fiber concentration enhance the shear and extensional viscosity rather than the fiber type. A slightly shear-thinning is observed in the Boger fluid (viscoelastic fluid).

For the PB + kerosene solution, this behavior is not observed, as it can be observed with the aid of Figs.4 and 5. In the Newtonian solution the reinforcement of wollastonita fibers enhance the shear and extensional viscosity more than fiber glass.

Boger fluids solution exhibit much higher and increasing extensional viscosity for all fiber concentrations. Moreover, the fibers increase the extensional relaxation times, as it is shown in Figs.6 and 7.
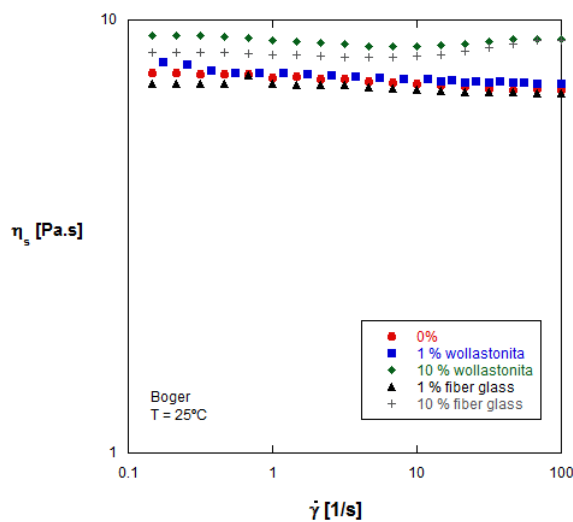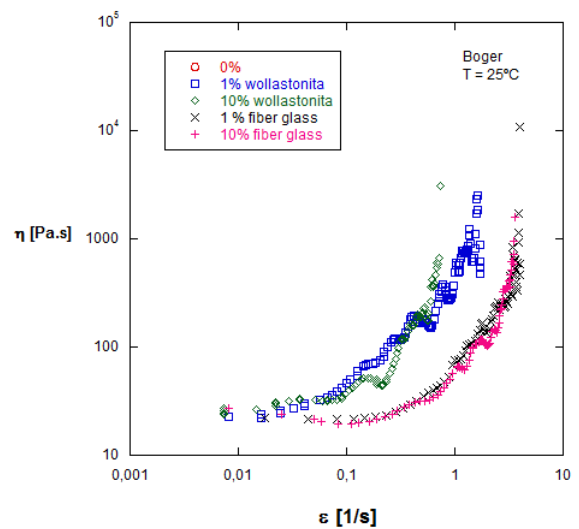

Figure 2: Shear viscosity of boger fluid at 25^oC.

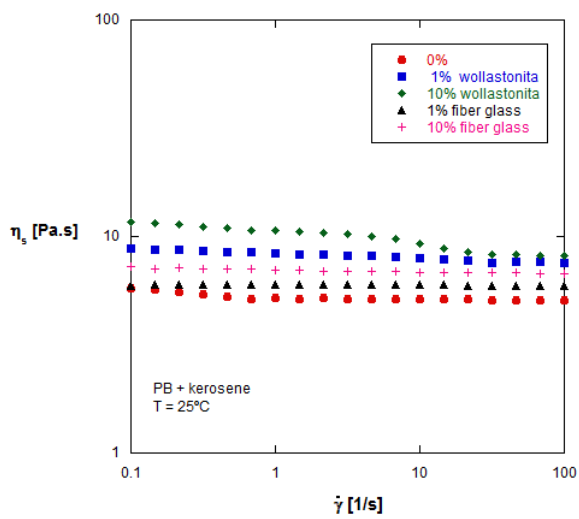Figure 3: Extensional viscosity of boger fluid at 25^oC.

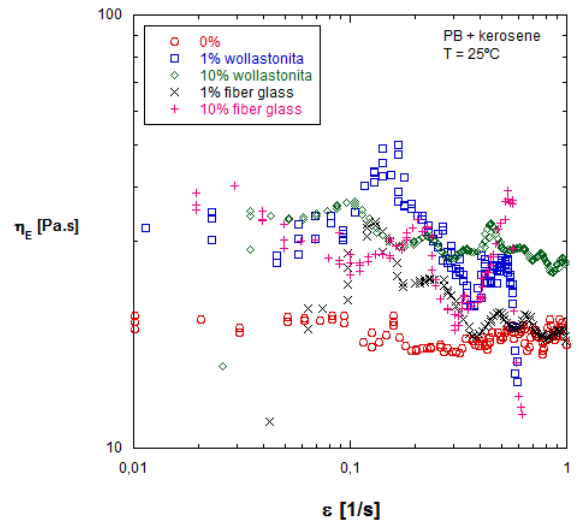Figure 4: Shear viscosity of PB + kerosene at 25^oC.

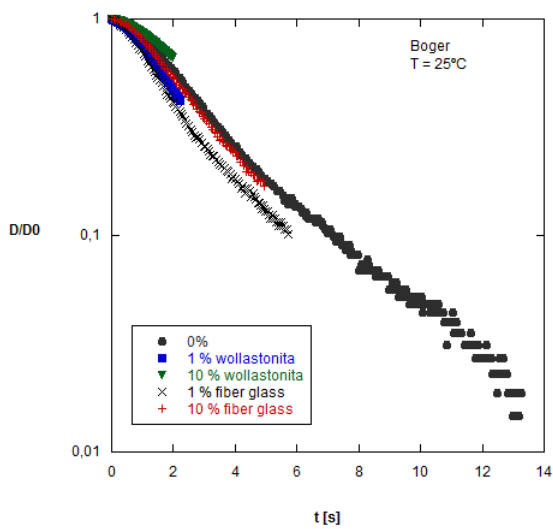Figure 5: Extensional viscosity of PB + kerosene at 25^oC.

Figure 6: Effect of fiber concentration in relaxation time for Boger fluid.

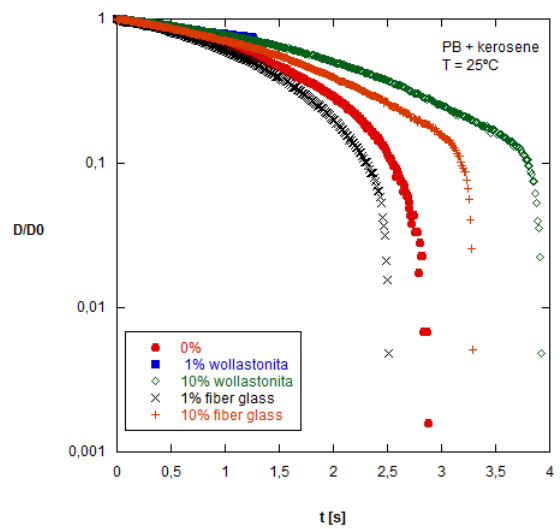Figure 7: Effect of fiber concentration in relaxation time for PB+ kerosene solution.

4. REFERENCES

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