**Measurement of Extensional Viscosity Using the
Falling Drop Technique
CRADA PC92-007, Final Report**

October 27, 1992 - September 27, 1996

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Measurement of Extensional Viscosity Using the Falling Drop Technique

Daniel K. Jones and David J. Wildman

Abstract

In the falling drop technique, a drop is formed by slowly extruding a liquid downward through a small tube. The drop eventually falls, and fluid adheres to both the tube and the drop, creating a distinct extending fiber. Extensional viscosity may be determined by measuring the dimensions of the fiber as it extends. The flow of fluid in a falling drop has been modeled in order to determine extensional viscosity by measuring the extending fiber.

A falling drop rheometer was built, and fiber dimensions were measured using two digital cameras and an image processing system. Extensional viscosity was measured for various solutions of glycerol, xanthan gum, and water. The falling drop technique proved to be an effective extensional rheometer for a range of solution concentrations.

Introduction/Background

Extension has traditionally been used to determine the tensile properties of solid materials, but experiments have shown that fluids are also capable of supporting tensile stresses. Extensional viscosity is a dynamic material property, a measure of the ability of a material to resist extension. Extensional viscosity is determined by stretching a material and measuring the stress and extension rate.

Trouton started using extensional viscosity in 1906.¹ He defined extensional viscosity and showed that the extensional viscosity was three times the shear viscosity for Newtonian fluids. Research on extensional viscosity was relatively dormant for most of the early 1900s. Shear rheometry received most of the attention because shear viscosity was known to influence flow, and shear flow was easily produced in the laboratory. Over the past 20 years, there has been increased interest in extensional flows. This is due, in part, to the increased use of polymer solutions and melts which undergo large extensional strains. The response of materials in extension must be better understood for the development and testing of new constitutive equations. The Pittsburgh Energy Technology Center became interested in extensional viscosity of coal-water mixtures and its role in the atomization and combustion.²

The Falling Drop Technique

The falling drop rheometer, originally developed by Jones et al.,^{3,4} subjects a test fluid to uniaxial extension. The fluid is slowly extruded through a vertical capillary tube. A pendant drop forms at the bottom of the tube and is pulled downward by gravity. As the drop falls, a fiber forms between the drop and the tube, as shown in Figure 1.

Because fluid adheres to both the tube and the drop, the fiber stretches as the drop falls, producing a long cylindrical fiber. The weight of the drop extends the fiber, while surface tension and extensional viscosity resist extension of the fiber. Dilute polymer solutions produce fibers that are quite long and uniform in diameter.

Model

For derivation of the falling drop model and equations for determining extensional viscosity from the measured parameters, refer to the doctoral dissertation by Jones.⁵

In cylindrical coordinates, extensional viscosity is defined as

$$\eta_e = \frac{\tau_{zz} - \tau_{rr}}{\dot{\epsilon}}$$

Extensional viscosity is a measure of the normal stress difference divided by the extension rate. The model describes the uniaxial extension of a fiber, including the effects of inertia, extensional viscosity, and surface tension.

Equipment

In the falling drop apparatus, fluid was driven downward by gravity through a funnel, a flexible tube, and a glass tube with a ground tip and inside diameter of 0.8 mm. Refer to Figure 2 for a sketch of the equipment used for falling drop experiments. A valve provided adjustment to produce consistent drops at a rate of 5 drops per second, with repeatable extending fibers for a variety of test fluids. Two digital cameras and an image processing system measured the dimensions of the falling drops and extending fibers at 500 Hz. This typically produced 50 measurements of the extending fibers over a time interval of 0.1 to 0.2 seconds.

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Extensional viscosity was determined when extending fibers were uniform in diameter.

Uncertainty was determined for extensional viscosity measurements according to ASME standards.⁶

Results

Experiments were conducted for various solutions of corn syrup, glycerol, xanthan gum, and water. Extensional viscosity was measured for pure glycerol, 0.4% xanthan gum in deionized water, and various concentrations of xanthan gum in 90:10 glycerol:water solutions. Special care was taken to ensure that measurements were made only on fibers with uniform diameters.

The test fluids produced repeatable fibers that were up to 20 cm long and remarkably uniform in diameter. Figure 3 shows plots of extensional viscosity verses extension rate for representative materials.

Table 1 lists the range of extensional viscosity measurements for various solutions along with the associated uncertainties. By inspecting the curves in Figure 3, the peak values may be used to characterize the material.

Discussion

Extensional viscosity of pure water could not be measured using the falling drop technique. When pure water drops fell, they quickly snapped away from the tube tip without forming fibers. However, adding a small amount of xanthan gum to the water

had a dramatic effect on fiber formation. Dilute xanthan gum solutions produced uniform fibers that exceeded 6 cm in length. Similar effects were observed with glycerol-water solutions. Adding small amounts of xanthan gum to the water and glycerol-water solutions did not have a substantial effect on the measured surface tension. Consequently, the changes in fiber extensions are attributed to changes in the extensional viscosity.

The falling drop technique provides a limited ability to control the extension rate, and this method cannot measure extensional viscosity at a constant extension rate. Further analysis is ongoing to provide a more complete characterization of the extensional viscosity for the various solutions.

References

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Figure 1. Falling Drop and Stretching Fiber.

Figure 2. Equipment Used for Falling Drop Experiments.

Figure 3. Extensional Viscosity verses Extension Rate for Representative Materials.

Table 1. Summary of Extensional Viscosity Measurements.

Material	Temp. (°C)	$\dot{\epsilon}$ (sec ⁻¹)	$\eta_e \pm U_{\eta_e}$ (poise)
glycerol	26	30-40	0-26 $\pm$ 20
0.4 % xanthan	21	23-40	0-18 $\pm$ 20
0.4 % xanthan	27	20-40	15-48 $\pm$ 30
0.4 % xanthan	31	25-32	0
GWX 90:10, 50ppm	24	18-23	0-21 $\pm$ 15
GWX 90:10,100ppm	22	8-10	20-140 $\pm$ 30
GWX 90:10,200ppm	27	7	12-133 $\pm$ 30
GWX 90:10,100ppm	38	22-27	9-20 $\pm$ 15