Design of Atomizers and Burners for Coal-Water Slurry Combustion

**Quarterly Report
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**DESIGN OF ATOMIZERS AND BURNERS FOR
COAL-WATER SLURRY COMBUSTION**

QUARTERLY ACTIVITY REPORT

**Period Starting: 5 January 1998
Period Ending: 31 March 1998**

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Abstract

The Falling Droplet apparatus for extensional viscosity measurements was redesigned for greater speed and efficiency of measurement.

Table of Contents

Disclaimer	2
Abstract	3
Executive Summary	5
Introduction	5
Results and Discussion	6
Conclusion	6
Projected Activity for Next Period	6

Attached Publication

Extensional Viscosity Measurements of Aqueous Polymer Solutions and Paint Resin Bases, ILASS-Americas 11 th Annual Meeting, 1720 May 1998, Sacramento, CA	7
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Progress Report for Period 1/5/98 - 3/31/98

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Executive Summary

Improvements to the Falling Droplet apparatus for measuring the extensional viscosity of liquids are complete. A one-component Phase Doppler Particle Analyzer has been refurbished and installed for measurements of droplet size and axial velocity in sprays of non-aqueous liquids.

Introduction

This report reviews the activities and results of the period 5 January 1998 to 31 March 1998 and the planned activities for the next period. The primary undertaken in this period is the improvement of the falling droplet technique for extensional viscosity measurements. The prior status of this activity is briefly reviewed in this introduction and the current progress is discussed in the results and discussion section. Preliminary tests on three different materials have been conducted and will be presented at the 11th annual meeting of the Institute for Liquid Atomization and Spray Systems, Americas section in Sacramento, California, on 17-20 May 1998. The extended abstract submitted to the conference organizers is appended to this report.

Previous work has shown that droplet size (both mean size and size distribution) does not always correlate with shear viscosity in non-newtonian fluids. It is suspected that extensional viscosity plays a dominant role in air-assisted atomization. Extensional viscosity is similar to the better-known shear viscosity, but relates the extension strain rate to the tensile stress rather than shear strain rate and shear stress. In the falling droplet technique, a droplet forms at the bottom of a vertical capillary tube. As the droplet falls, a thin filament is formed between the droplet and the capillary tube. Laser light sheets and photodiodes are used to measure the diameter and length of the filament, as well as the velocity and acceleration of the droplet by light attenuation. The resulting instantaneous ratio of tensile stress to extension rate gives a measure of the extensional viscosity of the fluid, in the form of a growth function versus time.

Results and Discussion

The construction of the new falling droplet apparatus was completed. The falling droplet technique relies on attenuation of laser light to perform measurements. One horizontal laser sheet passes through a 4 mm-diameter aperture and a color filter before striking a photodiode. When a filament intersects the light sheet, its shadow reduces the amount of light passing through the aperture. The reduction in total incident light flux onto the photodiode depends on the width of the shadow and, hence, the diameter of the filament. The second laser sheet strikes a photodiode array mounted vertically. As the droplet falls, it casts a shadow on each diode in sequence. The time at which the droplet passes each photodiode is recorded. Elapsed time measurements at each photodiode allow calculation of the droplet's position, velocity, and acceleration.

The photodiode used for the filament diameter measurement is calibrated using a high-magnification CCD camera. Water jets from very fine glass nozzles were imaged with the CCD camera and measured with the photodiode. All of the photodiodes were connected to a computer data acquisition system. Subsequent analysis produced simultaneous measurements of filament diameter and droplet position, velocity, and acceleration as functions of time during the fall of a single droplet.

A more complete description of the operation and theory of the Falling Droplet technique are given in the attached document, "Extensional Viscosity Measurements of Aqueous Polymer Solutions and Paint Resins".

Conclusion

The falling droplet apparatus has been redesigned and subjected to initial tests in accordance with the Statement of Work. In the coming quarter, it will be extensively investigated, also in accordance with the SoW.

Projected Activity for Next Period

In accordance with the Statement of Work from the renewal proposal for the third year, the following tasks are anticipated for the second quarter of 1998.

- Use the Malvern and PDPA to measure droplet size distributions, generated by the Triple Concentric Atomizer, of dilute polymer solutions under various operating conditions of liquid and air flows.
- Measure extensional viscosity for a range of solutions with the Falling Droplet.
- Use the Greenfield imaging system to examine the breakup region of the Triple Concentric Atomizer.

Extensional Viscosity Measurements of Aqueous Polymer Solutions and Paint Resins

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Abstract

The “Falling Droplet” concept for measuring extensional viscosity [Mansour, et al, '97] was improved to afford greater reliability, repeatability, and ease of use. Measurements of the extensional properties of a variety of dilute aqueous polymer solutions and solvent-borne paint resin base materials have been made.

Introduction

Background

In “classical” predictive models of sprays, the drop size is consistently related to the shear viscosity of the liquid being sprayed. When the spray breakup processes are studied in detail, however, it is evident that, in the breakup region, the velocity gradients within the liquid necessary to generate shear stresses which could lead to liquid breakup are not present. Large droplets and “blobs” of fluid, such as that in Figure 1, are stretched by aerodynamic forces in the breakup region. Atomizers which initially generate ligaments, such as rotary and some effervescent atomizers, also produce droplets by stretching, necking, and breaking of the ligaments. Extensional viscosity plays a significant role in governing the breakup process.

All liquids exhibit an extensional viscosity. Newtonian liquids have an extensional viscosity which is approximately three times the shear viscosity, as shown by Trouton [Trouton, '06]. Non-newtonian liquids, such as polymer solutions in water or organic solvents, display a more complex behavior. In these fluids, shear viscosity is a function of shear rate, total shear, and the time history of shear. Extensional

Figure 1: Typical Ligaments in Break-up
Region of Air-Assisted Spray

viscosity is also a function of extensional strain rate, total strain, and time history of strain. The ratio of the extensional to shear viscosity (the Trouton ratio) can reach values in the tens of thousands for dilute solutions of high molecular weight polymers.

Theory

To measure the shear viscosity, one must establish a shear flow field; to measure extensional viscosity, one must establish a purely extensional flow field. The method chosen for this study is the extension of a filament of liquid stretched by the fall of a droplet from the end of a capillary tube. Figure 2 shows a time-sequence photograph of such a filament. The filament is very nearly a perfect cylinder and thus the fluid within the filament experiences uniaxial extension.

Figure 2: Time-Sequence Photograph of Droplet and Filament

The strain rate experienced within the filament is given by:

$$\dot{\epsilon} = \frac{\dot{L}}{L} = \frac{V}{L} \quad (1)$$

Here, $\dot{\epsilon}$ is the strain rate, L is the filament length, and V is the droplet velocity.

The total axial stress within the filament as it falls is governed by gravity, drop acceleration, surface tension, aerodynamic drag, and extensional viscosity:

$$T_{zz} = \frac{m(g - a)}{\pi r^2} - \frac{2\sigma}{r} - \frac{F_D}{\pi r^2} \quad (2)$$

Here, T_{zz} is the axial tensile stress, m is the mass of the droplet, a is the acceleration of the droplet, σ is the surface tension of the liquid, r is the radius of the filament, and F_D is the aerodynamic drag force on the droplet.

The presence of surface tension creates an internal pressure within the filament. The radial stress caused by surface tension is given by:

$$T_{rr} = -\frac{\sigma}{r}. \quad (\text{Eq. 3})$$

The difference between the axial and radial stresses, the first normal stress difference, is used in the definition of extensional viscosity. The extensional viscosity, η_E , is defined as the ratio of the first normal stress difference to the strain rate:

$$\eta_E = \frac{T_{zz} - T_{rr}}{\dot{\epsilon}}. \quad (\text{Eq. 4})$$

In order to measure the extensional viscosity with the falling droplet technique, one must determine the mass of the droplet, the velocity, and

acceleration of the droplet as it falls, the drag on the droplet, and the length and diameter of the filament as functions of time during the extension of the filament. The mass is known from a simple balance between surface tension and droplet weight given the diameter of the capillary tube:

$$m = \frac{\sigma \pi c}{g} \quad (5)$$

(where c is the diameter of the capillary tube). The filament length is determined from the position of the droplet. The position, velocity, and acceleration of the droplet and the diameter of the filament must be recorded during the process.

The aerodynamic drag is calculated based on an empirical model for low-Reynolds number flow over a sphere.

$$F_D = \frac{24}{\text{Re}} \left(1 + \frac{1}{6} \text{Re}^{2/3} \right) \frac{\pi D^2 \rho_a V^2}{4} \quad (6)$$

Re is the Reynolds number based on the droplet diameter, ρ_a is the density of air. The droplet diameter, D , is computed from the droplet mass.

$$D = \sqrt[3]{\frac{6m}{\pi \rho}} \quad (7)$$

Apparatus

The falling droplet technique relies on attenuation of laser light to perform measurements. Figure 3 shows the layout of the instrument. Two 15 mW Helium-Neon lasers are used. The first laser beam passes through a set of optical-quality cylindrical lenses to produce a wide, horizontal laser sheet. The sheet then passes through a 4 mm-diameter aperture and a color filter before striking a photodiode. When a filament intersects the light sheet, its shadow reduces the amount of light passing through the aperture. The reduction in total incident light flux onto the photodiode depends on the width of the shadow and, hence, the filament. The second laser beam is passed through a 3 mm-diameter glass rod to produce a very wide, vertical laser sheet. This sheet strikes a photodiode array mounted vertically as shown

in Figure 3. The photodiodes in the vertical array are spaced with 1 mm between centerlines. As the droplet falls, it casts a shadow on each diode in sequence. The time at which the droplet passes each photodiode is recorded. The elapsed time between the droplet's passing of any two adjacent diodes allows the calculation of the droplet's velocity. By using three diodes, the acceleration can be computed.

The photodiode used for the filament diameter measurement is calibrated using a high-magnification CCD camera. Water jets from very fine glass nozzles were imaged with the CCD camera and measured with the photodiode. The resulting calibration yields a linear relationship, shown in Figure 4, between diode output signal and jet.

All of the photodiodes were connected to a computer data acquisition system. The output of the photodiodes is recorded and stored for analysis at rates of up to 1000 Hz. Subsequent analysis produced simultaneous measurements of filament diameter and droplet position, velocity, and acceleration as functions of time during the fall of a single droplet.

Results

The extensional viscosity of three different fluids was measured using the falling droplet technique: an aqueous solution of polyacrilimide in water, an aqueous solution of xanthan gum in water, and a solution of acrylic polymer resin in an organic solvent. The polyacrilimide (designated "E10") has an average molecular weight of approximately 20 million; the xanthan gum has an average molecular weight of approximately 2 million. The polyacrilimide solution used was 0.05% by weight in distilled water. The xanthan gum solution was 0.2% by weight in distilled water. The xanthan gum polymer is a branched

polymer molecule, in contrast to the long-chain E10. The acrylic polymer resin and organic solvent are a primary base component used in the manufacture of automotive paint. The resin comprises nearly 50% by weight of the solution, but is of low molecular weight compared to the E10 and xanthan gum.

Figure 5 shows a typical trace of position versus time of the droplet during the experiment. Figure 6 shows the corresponding measurement of filament diameter measured simultaneously. The resulting extensional viscosity growth functions for the three materials are given in Figure 7.

Discussion

All three polymer solutions tested here display significant extensional viscosity and marked growth in extensional viscosity during the filament stretching process. It is interesting to note that the paint base material exhibits the highest ultimate extensional viscosity. The polyacrilimide filaments survive the longest and grow, ultimately, the longest before breaking. The polyacrilimide filaments grow longer than the vertical photodiode array, so an extension to the photodiode array is underway to complete the measurement of the ultimate extensional viscosity.

Although the requirements for a true measure of extensional viscosity (constant strain rate or constant tensile stress) are not achieved with this technique, it will be a valuable asset in the investigation of sprays of polymeric materials such as paint. The time history of the stretching motion is very similar to the stretching of ligaments in an air-assisted spray. Comparative measurements of such liquids will be used in deducing the relationship between extensional viscosity and spray performance.

The results of the extensional viscosity calculations are contrary to initial expectations. The polyacrilimide forms very long, visible filaments with long lifetimes. The xanthan gum is extremely viscous and is visibly viscoelastic. The paint base, while viscous, is less so than the xanthan gum. The filaments of paint base

formed by a falling droplet are the shortest, both in length and lifetime. However, the extensional viscosity of the paint base is of the same magnitude as the aqueous polymer solutions. This evidence supports two conclusions. First, the shear behavior of a liquid has no direct, visible bearing on the extensional behavior. Second, the extensional viscosity of a liquid, as measured by the falling droplet technique, is an important parameter in the spray breakup process, but not the only such parameter.

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