DOE/PC/95105--T2
M96050253

DESIGN OF ATOMIZERS AND BURNERS FOR COAL-WATER SLURRY COMBUSTION

Grant Number: DE-FG22-95PC95105
Progress Report for Period 1/1/96 - 3/31/96

Adel Mansour and Norman Chigier
Department of Mechanical Engineering
Carnegie Mellon University
Pittsburgh, PA 15213

RECEIVED
USDOE/PETC
96 MAY -7 AM 9:59
ACQUISITION & ASSISTANCE DIV.

ABSTRACT

A novel extensional rheotester was developed to measure the extensional properties of aqueous solutions of Polyacrilamide E10 and coal water slurries (CWS). When a drop of viscoelastic liquid or CWS containing additives is allowed to form at the end of a capillary tube, it starts to fall once its weight exceeds the retaining force exerted by surface tension. In experiments with aqueous solutions of Polyacrilamide it was observed that a long filament of fluid connected the droplet to the end of the capillary tube. The filament partially supported the droplet slowing its rate of fall. In order to evaluate the transient elongational stresses and elongational viscosity that are developed in the long threads of liquid before breakup, the mass (m), the diameter (D), the velocity (V) and the acceleration (a) of the suspended droplet along with the diameter of the filament (d) are measured. The length of the trailing filament is also measured as a function of time in order to determine the filament stretch rate ($\dot{\epsilon}$). The time dependent behavior of the filament diameter was also measured using a laser attenuation technique. The strain rate of the filament was determined from the experimental values of $\dot{L}/L$ and $-2\dot{d}/d$, where the dot refers to differentiation with respect to time. Seven different aqueous solutions of Polyacrilamide E10 were prepared spanning a wide range of polymer concentration (0.5%, 0.25%, 0.125%, 0.0625%, 0.03125%, 0.015625%, 0.0078125%). The data gave a single relaxation time for each solution. This relaxation time for uniaxial extension is found to increase with E10 concentration.

INTRODUCTION

Currently available methods to measure the extensional viscosity are limited to highly viscous liquids. Low viscosity liquids present a special difficulty. Many of the difficulties in the measurement of the extensional viscosity of low viscosity liquids have been described by Walters (1992). In order to measure the steady state extensional viscosity, the fluid must be subjected to a constant rate of extension for a time that is sufficient for the stress to reach a constant value, or alternatively subjected to a constant stress for the rate of extension to become constant. Most

DISCLAIMER

**Portions of this document may be illegible
in electronic image products. Images are
produced from the best available original
document.**

reported cases in which it is certain that a steady state was reached involve fluids of very high viscosity and rates of extension not greater than 0.1 sec^{-1} . In this limited range the Trouton viscosity has invariably been found to be either nearly constant or, at the highest rates of extension, an increasing function of the stretch rate $\dot{\epsilon}$. With decreasing viscosity it becomes more difficult to control these transient experiments because the limits of the apparatus are exceeded before a steady state shear viscosity is achieved. Then an instantaneous elongational viscosity which depends upon both the deformation rate and the complete deformation history can be evaluated. Only in the case of quasi-steady elongation or elongations which have essentially the same history, can this instantaneous elongational viscosity be used for a unique characterization of the material behavior (Weinberger et al., 1974). Otherwise the instantaneous rate of stress to strain rate still represents a convenient parameter for practical comparison (Schummer et al. 1983). In this study, we have developed a technique for measurement of the extensional viscosity of polymer solutions and coal-water slurries. The technique is based on the uniaxial extension of a viscoelastic filament by a falling droplet. The technique was capable of yielding satisfactory results for very dilute polymer solutions having very low shear viscosities.

THEORETICAL BACKGROUND

In order to measure the extensional viscosity of polymeric solutions and coal water slurries (CWS) a novel free-fall extensional device was developed. The drip mode of breakup is used to extract information on the extensional properties of polymer solutions and CWS. When a drop of viscoelastic liquid or CWS containing additives is allowed to form at the end of a capillary tube, it starts to fall once its weight exceeds the retaining force exerted by surface tension. In experiments with aqueous solutions of Polyacrilamide it was observed that a long filament of fluid connected the droplet to the end of the capillary tube (see Fig. 1). The filament partially supported the droplet slowing its rate of fall. To achieve a purely elongational flow the filaments have to be cylindrical, i.e. the free surface must be a coordinate surface in an orthogonal coordinate system.

The most important feature shown in Fig. 1 is that the fluid necks rapidly and is essentially cylindrical over most of the trailing filament. The geometry thus appears to provide a means of implementing uniform uniaxial extension. The filament is assumed to be in cylindrical form undergoing uniaxial extension, with one end fixed and the other end moving with a velocity V , the axis of the filament coinciding with the z -axis. The initial length and radius are L_0 and r_0 , and after a time t they are L and r . The length of the specimen at time t is given by

$$L(t) = L_0 + \int_0^t V(t') dt' \quad (1)$$

The strain for uniaxial extension is

$$\epsilon = \ln(L/L_0) \quad (2)$$

so the strain rate is

$$\dot{\epsilon} = \frac{d}{dt} [\ln(L/L_0)] = \frac{1}{L} \frac{dL}{dt} = \frac{V}{L} \quad (3)$$

Assuming that the volume of the filament remains constant during the stretching, then the strain rate can also be defined as

$$\dot{\epsilon} = -2 \dot{d}/d \quad (4)$$

where d is the diameter of the filament ($d = 2r$). Provided that there are no extreme conditions imposed by the geometry, the balance of the drop weight and surface tension determines the size of the drops. The subsequent fall of the drop is determined by inertia, surface tension, viscosity, elasticity, gravity and drag. The total stress T_{zz} in the axial direction is given by:

$$T_{zz} = \frac{m(g-a)}{\pi r^2} - \frac{2\pi\sigma r}{\pi r^2} - \frac{D_r}{\pi r^2} \quad (5)$$

where σ is the surface tension, m is the mass of the suspended droplet, g is the gravitational acceleration, a is the droplet acceleration and D_r is a correction for the aerodynamic drag on the droplet. Due to the presence of surface tension, the total stress in the radial direction T_{rr} within the filament is

$$T_{rr} = -\frac{\sigma}{r} \quad (6)$$

The extensional viscosity (effective) growth function η_E of the fluid in the extending filament is defined by

$$T_{zz} - T_{rr} = \eta_E \dot{\epsilon} \quad (7)$$

Thus,

$$\eta_E = \frac{\left(\frac{m(g-a)}{\pi r^2} - \frac{\sigma}{r} - \frac{D_r}{\pi r^2} \right)}{\dot{\epsilon}} \quad (8)$$

Using the empirical drag law model of a sphere as a function of Reynolds number, Eq. 8 becomes

$$\eta_E = \frac{\left(\frac{m(g-a)}{\pi r^2} - \frac{\sigma}{r} - \frac{24}{Re} \left(1 + \frac{1}{6} Re^{2/3}\right) \frac{\pi D^2}{4} \frac{1}{2} \rho_a V^2 \right)}{\dot{\epsilon}} \quad (9)$$

where Re is defined as

$$Re = \frac{\rho_a D V}{\mu_a} \quad (10)$$

where D is the droplet diameter, V is the droplet velocity, ρ_a and μ_a are the ambient density and viscosity, respectively.

In order to evaluate the transient elongational stresses and elongational viscosity that are developed in the long threads of liquid before breakup, the mass (m), the diameter (D), the velocity (V) and the acceleration (a) of the suspended droplet along with the diameter of the filament (d) are required. In order to determine the strain rate ($\dot{\epsilon}$) both the instantaneous velocity of the droplet and the length of the filament (L) are required. The position, velocity, and acceleration of droplets are

measured using a laser attenuation technique. The velocity and acceleration of the droplets are determined from the slopes of the position vs. time curve and velocity vs. time curve, respectively. The strain rate of the filament is determined from the experimental values of $\dot{L}/L$ and $-2\dot{d}/d$. Any discrepancy between the experimental values of $\dot{L}/L$ and $-2\dot{d}/d$, will indicate that the volume of the filament during the stretching process is not exactly constant. The diameter and mass of the droplet are measured using a digital image analyzer.

EXPERIMENTAL TECHNIQUE

Development of a laser attenuation technique for measurement of filament diameter and filament length as a function of time

A schematic of the laser attenuation technique is shown in Fig. 2. Measuring the filament diameter relies on the principle of light attenuation. A 15 mW Helium Neon laser beam is spread into a laser sheet by using a cylindrical lens. The laser sheet is passed through the filament before being captured by the photodiode. The amount of light being attenuated by the filament is directly proportional to the diameter of the filament. After passing through the filament, the laser sheet is directed through additional optics and onto a photodiode. This allows correlation of the diode output to the filament diameter. In order to measure the filament length as a function of time a second laser sheet was positioned at a known distance from the first. The time required for the drop to traverse the distance between both laser sheets was measured as a function of laser sheet separation distance.

The use of a laser sheet instead of a cylindrical beam has the purpose of generating a uniform light intensity (at least within the central portion of the sheet) before interaction of the laser with the filament. If the laser intensity is not spatially uniform, any swaying of the liquid filament will result in erroneous diameter measurements. The edges of the laser sheet, where the intensity is not spatially uniform, is blocked by using pinholes. A number of pinhole sizes (i.e., diameter) are used and calibration curves are generated for each pinhole by using liquid jets of various diameter. Initially, the experiment relied on the attenuation of a laser beam, unaltered by the cylindrical lens. This method produces ambiguity, however, due to the Gaussian nature of the intensity profile intrinsic to any laser. Such a distribution would indicate a non-linear relation between the intensity of light which strikes the diode and the diameter of the filament. This complexity is effectively reduced by the use of the cylindrical lens. Specifically, the lens stretches the profile of the laser to expose its central, most intense portion. This stretched central region is effectively constant in intensity, and thus will produce a linear relation between the diode signal and the filament diameter. In addition to a more linear relationship, the laser sheet helps to prevent the error caused by 'swaying' filaments. When the droplet falls, the trailing filament becomes very small. As a result,

the filament is influenced by air drafts and can easily sway away from the path of a single laser beam. With the laser sheet, the filament remains in the field of view.

The system was calibrated by using a magnifying CCD camera and an array of fine bore glass nozzles. The nozzles produced water jets varying in size from approximately 120 to 2000 microns. Once the exact diameter for each stream was determined with the magnifying camera, the corresponding output voltage from the photodiode was determined by placing the jet in the path of the laser sheet. With each jet, a different voltage was determined and thus the curve relating the diode voltage to the filament diameter was obtained. The collecting optics were contained within a protective housing fitted with a 3 mm aperture. Such an aperture was sufficient small to block the non-linear portion of the laser sheet, yet large enough to allow the measurement of the largest diameter filaments. In addition, it was necessary to eliminate the influence of fluctuating laser intensity. This was done by normalizing the output voltages associated with each jet with voltage values recorded with no filament present. Figure 3 shows the normalized output voltage for jet diameters ranging from 120 to 2000 μm using the 3 mm diameter pinhole. The measured signal is proportional to the jet diameter; the signal decreases with increasing diameter.

RESULTS

Measurement of filament diameter

During the diameter measurements, the laser sheet was positioned downstream from the capillary tube at an axial location of 4 mm. The initial fall of the droplet was recorded using a digital image analyzer in order to measure the initial filament diameter and length (see Fig. 4). Figure 4 shows a photograph of the droplet during its initial stages of fall. From Fig. 4 it can be determined that the initial converging region connecting the filament to the capillary tube is 1.2 mm in length; the filament diameter is 228 μm , and the filament length at this particular diameter is equal to 2 mm. Assuming that the total mass inside the filament is conserved (i.e., no flow of liquid from the filament into the droplet or back flow from filament into the converging section), it is possible to extrapolate the dimension of the filament and determine the initial conditions of the experiment (i.e., when the filament extends to the position of the laser sheet $x = 4$ mm). Taking into account the converging section which has a total length of 1.2 mm, the laser sheet position at $x = 4$ mm corresponds to an initial filament length of 2.8 mm, which from conservation of mass yields an initial filament length of 192 μm . The diameter collection of the laser attenuation technique was thus triggered when the filament diameter is equal to 192 μm .

Diameter profiles as a function of time were measured using the laser attenuation technique for seven aqueous solution of Polyacrilamide E10. The diameter decay of each sample, plotted on

semi-logarithmic coordinates as a function of time, is shown in Fig. 5. To a first approximation, it is seen that the curves fit a single exponential relaxation time defined as the rheotester relaxation time λ_R (Liang et al., 1994), where

$$d(t) = d_0 \exp(-\dot{\epsilon}t/2) = d_0 \exp(-t/3\lambda_R) \quad (11)$$

Equation 11 is obtained by direct integration of Eq.(4) assuming a constant stretch rate. This rheotester relaxation time is plotted in Fig. 6. as a function of polymer concentration. Figure 6 shows that the rheotester relaxation time λ_R increases monotonically with increasing concentration. All the data of Fig. 5 was fitted to Eq. (11). Table 1 shows the values of the initial diameter d_0 , the relaxation time λ_R , the stretch rate and the coefficient of correlation for all seven aqueous solution of Polyacrilamide E10. It is seen the exponential decay closely approximates the decay of the filament diameter with a coefficient of correlation generally higher than 0.96.

Table 1 Filament Diameter Decay Parameters

Concentration	Initial d_0 [μm]	λ_R [s]	ϵ [s^{-1}]	c.o.c.
0.5	134	0.433	1.54	0.981
0.25	163	0.201	3.32	0.967
0.125	183	0.107	6.23	0.990
0.0625	223	0.058	11.40	0.995
0.03125	259	0.035	18.92	0.992
0.015625	291	0.026	25.19	0.987
0.0078125	253	0.0112	59.73	0.964

Measurement of filament length

The time required for the drop to traverse the distance between the two laser sheets was measured as a function of laser sheet separation distance. Preliminary trials with water were conducted to determine the accuracy of the experiment and the significance of the air drag on a free falling droplet. Figure 7 shows a plot of the measured fall distance vs. time for a 3.53 mm diameter water droplet. From the linear least square fit for the filament length a constant acceleration of 9.67 m/s^2 is measured. Thus, even if the drag is neglected, the fall acceleration is measured with an accuracy of 2%. Figure 8 shows an example of a few selected frames taken during the fall of 0.5% aqueous solution of Polyacrilamide E10. The time history of the measured droplet fall distance for all concentrations of E10 is shown in Fig. 9. Fitting the data to the following equation

$$L(t) = L_0 \exp(\dot{\epsilon}t) \quad (12)$$

for all concentrations of Polyacrilamide E10 yields the parameters shown in Table 2.

Equation (12) is obtained by direct integration of Eq.(3) assuming a constant stretch rate. The

stretch rates as determined by the filament diameter and filament length are shown in Fig. 10 as a function of polymer concentration. Note that there is some discrepancy between the stretch rate measured by both methods particularly at low concentrations. This discrepancy disappears almost entirely at high concentrations. The agreement between the radius and length determined extension ratio improves at higher concentrations of Polyacrilamide E10. For the low concentrations, however, the extension rate is much less for the length than the radius deduced value. This indicates that at low concentrations the extension is not necessarily a purely uniaxial extension and that the volume of the filament is not necessarily constant.

Table 2 Filament length parameters

Concentration	Initial L_0 [mm]	ϵ [s^{-1}]	c.o.c.
0.5	3.53	1.44	0.986
0.25	5.97	2.62	0.943
0.125	6.47	4.07	0.919
0.0625	5.43	6.28	0.927
0.03125	3.83	9.94	0.951
0.015625	3.50	12.89	0.947
0.0078125	1.77	23.37	0.965

FUTURE WORK

In the period extending from March 30th to June 30th 1995 the following tasks will be undertaken.

- Apply the results of the correlations of Eqs. 11 and 12 to Eq. 9 to determine the extensional viscosity.
- Build the air-assist effervescent atomizer.
- Mount the atomizer to the spray chamber.
- Make all air and liquid connections.
- Test flow meters, pressure sensors.
- Setup the phase Doppler to make droplet size and velocity measurements in the flow field of the air assist effervescent atomizer.
- Make shear viscosity measurements for all solutions of Polyacrilamide E10.

REFERENCES

- Schummer, P., and Tebel, K.H., J. N. New. Fluid Mech., 12, 331, (1983).
Walters, K., Proceedings of the Sixth International Congress on Rheology, Brussels, (1992).
Weinberger C.B., and Goddard, J.D., Int. J. Multiphase Flow, 1, 465, (1974).
Liang, R. F. and Mackley, M. R., J. Non-Newtonian Fluid Mechanics, 52, 387, (1994).

Fig. 1 Stretching of a Filament of a viscoelastic fluid

Fig. 2 Laser Attenuation Technique

Fig. 3 Normalized Signal vs. Jet Diameter

Fig. 4 Initial fall of a droplet of a viscoelastic fluid

Fig. 5 Filament diameter vs. time

Fig. 6 Rheotester relaxation time as a function of Polyacrilamide E10 concentration

Fig. 7 Fall distance for a water droplet

Fig. 8 Sequence of photographs of the stretching of a filament of an aqueous solution of 0.5% Polyacrilamide E10, at various times, at a stretch rate of 1.54 s^{-1} . The initial diameter and length of the filament at the laser sheet position are $192 \mu\text{m}$ and 2.8 mm , respectively.

Fig. 9 Time history of the measured fall distance for all concentrations of E10

Fig. 10 Stretch rates determined by diameter decay and filament length measurements

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.