DESIGN OF ATOMIZERS AND BURNERS FOR COAL-WATER SLURRY
COMBUSTION

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In the period extending from March 30th to June 30th 1996 the following tasks were completed.

- We have successfully developed the falling droplet technique to measure the extensional viscosity of very dilute polymeric solutions. We have also determined that the polymeric materials used behaved as elastic solids even at very low concentrations of the order of 30 ppm. Please see the published paper for a complete description of the technique. In the coming months we hope to apply the technique to determine the extensional viscosity of coal-water slurries containing additives. As was already demonstrated, the addition of very small quantities of high molecular weight polymer to water resulted in a very large increases in the extensional viscosity. The development of viscoelastic properties in liquids has a negative effect on their atomization characteristics. We also expect that the addition of stabilizers to coal-water slurries will negatively influence their breakup behavior.
- We have designed and built the air-assist effervescent atomizer. The co-axial effervescent air-assist atomizer is shown in Fig. 1. The cylindrical chamber, preceding the injection orifice, has an internal diameter of 69.9 mm and a total length of 254 mm. Two circular plates, with large diameter holes (i.e. 88.9 mm), are glued at each end of the cylindrical chamber, thus providing a leak proof, rigid assembly. Extruding from the chamber is a 3 mm inside diameter tube used for liquid delivery. The tube is epoxied in place to a large disc, and is centered by a profiled cone. The effervescent air flows co-axially into the liquid delivery tube. The atomizing air flows radially into a converging channel through four diametrically opposite inlet ports. Extreme care was taken in order to make a smooth contour and minimize flow disturbances. The air channel ends with a circular orifice having an ID of 9.53 mm. The air channel is topped with a profiled cap. Both the cone and the air channel cap have the same profile. Extra support to the total assembly is provided by four rigid poles, not shown in figure. The poles are fixed to a mounting plate, which in turn is mounted to a bracketed assembly. The mounting support is made of rigid I-beams. The total unit (i.e. chamber, nozzle, mounting support) is fixed to a rugged three dimensional traversing mechanism. The nozzle is mounted vertically on an xyz

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positioner with an accuracy of 0.1 mm in all directions.

- We have mounted the atomizer to the spray chamber. We have made all the air and liquid connections.
- We have set up the phase Doppler to make droplet size and velocity measurements in the flow field of the air assist effervescent atomizer.
- We are also currently working on submitting an extended paper to the journal of non-Newtonian fluid mechanics. The paper title is "Measurement of the extensional properties of Polyacrilamide solutions using the falling droplet technique."

Fig. 1 The Effervescent Air-Assist Atomizer

Publications

MEASUREMENT OF THE EXTENSIONAL PROPERTIES OF POLYMERIC SOLUTIONS USING THE FALLING DROPLET TECHNIQUE

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ABSTRACT

A novel extensional viscometer was developed to measure the extensional properties of aqueous solutions of polymeric material and coal water slurries (CWS) containing additives. 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. The falling droplet technique is used to determine the extensional properties of polymeric solutions and coal-water slurries. Nine different aqueous solutions of Polyacrilamide E10 were tested spanning a wide range of polymer concentration (1.0%, 0.5%, 0.25%, 0.125%, 0.0625%, 0.03125%, 0.015625%, 0.0078125%, and 0.003906% by weight). The extensional viscosity for all solutions was found to be orders of magnitude larger than the shear viscosity. The extensional viscosity increases rapidly with time after the start of stretching. It was also shown that there is a linear relationship between the stress and the strain in the fluid filament, indicating that the fluid behaves like an elastic solid. The modulus of elasticity of the fluid was found to increase with polymer 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 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. In future work, the technique will be applied to coal-water slurries.

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. Figure 1 shows a droplet during its initial stages of fall. 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 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

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

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 the extensional 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 (d) and length (L) of the filament are required. The strain rate of the filament is determined from the experimental values of $\dot{L}/L$ and $-2\dot{d}/d$. 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 diameter and mass of the droplet are measured using a digital image analyzer.

EXPERIMENTAL TECHNIQUE

Laser technique for measuring filament diameter and length as a function of time

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 a pinhole. 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.

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 sufficiently small to block the non-linear portion of the laser sheet, yet large enough to allow the measurement of the largest diameter filaments.

RESULTS

Measurement of filament diameter

The diameter measurement using the laser attenuation technique was triggered when the filament

diameter is equal to the capillary tube inside diameter which is equal to 1.19 mm. The laser sheet was positioned at an axial location $z = 2$ mm downstream from the tube exit. This was necessary to stay clear of the initial converging region of the fluid filament. The success of the technique relies principally on the measurements being made in the homogenous part of the stretched filament. The converging region is generally less than 1.2 mm in length and varies little with polymer concentration (see Fig. 1). Diameter profiles as a function of time were measured using the laser attenuation technique for nine aqueous solutions of Polyacrilamide E10. The diameter decay of each sample, plotted on a log-log plot as a function of time, is shown in Fig. 2. It is apparent from these plots that the fluid undergoes two distinct stretching regimes during the course of the droplet fall. The initial regime, spanning a time interval 0 to t_i , corresponds to significant necking of the filament when subjected to sudden stretching from the rest state. The second regime, spanning a time interval t_i to t_f , corresponds to the homogeneous deformation of the fluid filament. As observed in Fig. 2, the radial time dependence, over the initial and final stretching intervals, is well approximated by a power law relationship. With this relationship, one can easily show that the elongation rate for all nine trials varies inversely with time. Thus, the data in Fig. 2 was fitted to the following equation

$$d(t) = d_0 t^{-\alpha} \quad (11)$$

over the two distinct deformation regimes and for all concentrations of E10. Table 1 shows the results of the least square fit to the data (i.e., d_0 and α) along with the applicable time interval separating the two distinct stretching regimes. The instantaneous stretch rate is determined by substituting Eq. 11 into Eq. 4. The instantaneous stretch rate is thus given by $(2\alpha/t)$. From the data shown in Table 1, a time averaged stretch rate is computed for all solutions of E10. The time averaged stretch rate is computed by integrating the instantaneous stretch rates $2\alpha_i/t$ and $2\alpha_f/t$, corresponding to the two stretching regimes, over their respective time intervals 0 to t_i and t_i to t_f .

$$\epsilon_{av} = \frac{\int_0^{t_i} 2 \alpha_i / t \, dt + \int_{t_i}^{t_f} 2 \alpha_f / t \, dt}{t_f} \quad (12)$$

α_i and α_f are the initial and final diameter decay constants, respectively, and they are shown in Table 1. Table 1 also shows the time intervals delimiting the two stretching regimes. The computed time averaged stretch rates are shown in Table 2 for all E10 solutions.

Table 1 Filament Diameter Decay Parameters

Initial Deformation Regime
(Filament Necking)

Final Deformation Regime
(Homogeneous Stretching)

Conc.	Time domain	d_0 [μm]	α_i	Time domain	d_0 [μm]	α_f
1.0	$t < 1.90$ s	473	0.188	$1.90 < t < 4.52$ s	1959	3.04
0.5	$t < 1.30$ s	476	0.166	$1.30 < t < 3.06$ s	697	3.61
0.25	$t < 0.63$ s	530	0.135	$0.63 < t < 1.63$ s	163	3.77
0.125	$t < 0.60$ s	411	0.191	$0.60 < t < 1.15$ s	33.1	4.84
0.0625	$t < 0.50$ s	406	0.166	$0.50 < t < 0.80$ s	4.22	4.17
0.03125	$t < 0.30$ s	346	0.156	$0.30 < t < 0.40$ s	0.138	4.55
0.015625	$t < 0.14$ s	189	0.243	$0.14 < t < 0.20$ s	0.195	2.91
0.0078125	$t < 0.10$ s	46.0	0.491	$0.10 < t < 0.14$ s	0.165	2.36
0.003906	$t < 0.04$ s	14.7	0.615	$0.04 < t < 0.06$ s	0.240	1.69

Table 2 Time Averaged Stretch Rate Based on Filament Diameter Decay

Conc.	Time domain	Stretch Rate $\dot{\epsilon}$ [s^{-1}]
1.0	$0.0 < t < 4.52$ s	1.73
0.5	$0.0 < t < 3.06$ s	2.72
0.25	$0.0 < t < 1.63$ s	5.35
0.125	$0.0 < t < 1.15$ s	7.36
0.0625	$0.0 < t < 0.80$ s	7.62
0.03125	$0.0 < t < 0.40$ s	10.99
0.015625	$0.0 < t < 0.20$ s	23.1
0.0078125	$0.0 < t < 0.14$ s	42.8
0.003906	$0.0 < t < 0.06$ s	98.3

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. From the linear least square fit for the droplet distance as a function of time, a constant acceleration of 9.67 m/s^2 was measured. Thus, even if the drag is neglected, the fall acceleration is measured with an accuracy of 2%. The time history of the measured droplet fall distance for all concentrations of E10 is shown in Fig. 3. Figure 3 shows that the filament length increases in an exponential manner with time. Fitting the data to an exponential growth function

$$L(t) = L_0 \exp(\dot{\epsilon}t) \quad (13)$$

for all concentrations of Polyacrilamide E10 yields the parameters shown in Table 3. Equation (13) 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. 4 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 is reduced 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 3 Filament length parameters

Conc.	Initial L_0 [mm]	Stretch Rate $\dot{\epsilon}$ [s^{-1}]	c.o.c.
1.0	4.3	0.89	0.978
0.5	6.8	1.37	0.961
0.25	7.2	2.76	0.940
0.125	6.6	4.05	0.943
0.0625	5.9	5.24	0.951
0.03125	6.3	6.80	0.947
0.0015625	6.2	8.79	0.933
0.0078125	6.4	13.31	0.930
0.003906	6.3	19.92	0.929

Measurement of the Total Filament Stress

The filament stress T_{zz} , defined by Eq. 5 was determined. The filament radius is taken from the data shown in Fig. 2. The droplet velocity and acceleration were calculated from the data shown in Fig. 3. Figure 5 shows T_{zz} versus the principal extension ratio defined as $(r_0/r)^2$, where r_0 is the radius of the ligament at time $t = 0$. The data clearly indicates that the stress is proportional to the strain and that the fluid behaves as an elastic solid. It is also seen in Fig. 5 that the slope of the curves, defining the modulus of elasticity of the fluid increases with polymer concentration. Figure 6 shows a plot of the modulus of elasticity vs polymer concentration. It is seen that very small additions of polymeric material to water results in a very dramatic increase of the modulus of elasticity. There is a limit however to the increase of modulus of elasticity with increasing polymer concentration. Increasing the concentration beyond 0.0625 results in only a marginal increase in the modulus of elasticity.

Measurement of Extensional viscosity

Since the stress continues to increase, even though the deformation rate decreases with strain, a true measure of the extensional viscosity is not possible. The extensional viscosity growth function was computed using Eq. 9. The droplet velocity and acceleration were determined from the droplet

position data shown in Fig 3. The droplet position data was fitted to a third order polynomial from which the velocity and acceleration were computed. The stretch rate used in the computation of the extensional viscosity was the time averaged stretch rate which was determined from the filament diameter decay, (see Table 2). The resulting extensional viscosity is shown in Fig. 7. It is seen that the extensional viscosity is a rapidly increasing function of time for all solutions of Polyacrilamide E10. The extensional viscosity reaches values as high as 10^5 Pa.s. It is also seen that the highest concentrations of E10 yield higher extensional viscosities both at the start and at the end of the stretching process.

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Fig. 1 Stretching of a Filament of a viscoelastic fluid (0.1% of Polyacrilamide E10)

Fig. 2 Filament diameter vs. time

Fig. 3 Time history of the measured fall distance for all concentrations of E10

Fig. 4 Stretch rates determined by diameter decay and filament length measurements

Fig. 5 Stress vs. strain

Fig. 6 Modulus of Elasticity vs. polymer concentration

Fig. 7 Extensional Viscosity vs. Time