DOE/PC/95105--T1

Grant Number: DE-FG22-95PC95105
Carnegie Mellon University
February 15, 1996
Grant Date: 10/1/95 - 9/30/98
Government Award: $90,565.00
Program Manager:
Principal Investigator(s) Dr. Norman Chigier
COR: Phillip Goldberg

DESIGN OF ATOMIZERS AND BURNERS FOR COAL-WATER SLURRY COMBUSTION

Objectives:

- Design and test atomizers for the generation of coal-water slurry droplets of small size. Maximize the energy transfer between the slurry and the atomizing air in order to enhance atomization at low air/liquid mass ratios.
- Design and test a coal-water slurry burner. The burner will be equipped with air-assist effervescent atomizers. The primary air register will be equipped with swirlers of various designs.
- Study the dynamics of interaction between coal-water slurry sprays and primary air flows.
- Study the effects of additives typically used in coal-water slurry fuels for their influence on rheological properties and atomization. Determine the influence of shear viscosity, extensional viscosity, normal stress difference and maximum Darcy viscosity of coal-water slurries on atomization.
- Measure the coal-water slurry spray characteristics: particle size, velocity, number density and flux using the phase Doppler particle analyzer (PDPA) and the laser diffraction particle analyzer.
- Study the fundamental mechanisms of atomization of coal-water slurries. Develop models for the breakup of coal-water slurries using air-assist effervescent atomizers.

Background

In order to measure the extensional viscosity of polymeric solutions and coal water slurries (CWS) a novel free-fall extensional device will be developed and its usefulness in measuring the extensional viscosity will be demonstrated. Photographic visualization of the breakup of viscoelastic materials in the drip mode has shown that these materials exhibit completely different breakup patterns when contrasted to viscoinelastic materials. The ligaments were seen to undergo a very large stretching motion before they breakup, resulting in long threads of liquid attached to droplets (see Fig. 1). The drip mode of breakup can be used to extract useful information on the extensional properties of polymer solutions and CWS. When a drop of CWS containing additives is allowed to form at the end of a capillary tube, it will start to fall once its weight exceeds the retaining force exerted by the surface tension. To get 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. We assume the ligament to be in cylindrical form undergoing uniaxial extension, with one end fixed and the other end moving with a velocity V, the

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

axis of the ligament coinciding with the z-axis. The initial length and radius are L_o and r_o, and after a time t they are L and r. The length of the specimen at time t is given by

$$L(t) = L_o + \int_0^t V(t')\,dt' \tag{1}$$

The strain for uniaxial extension is

$$\varepsilon = ln(L/L_o) \tag{2}$$

so the strain rate is

$$\dot{\varepsilon} = \frac{d}{dt}\left[ln(L/L_o)\right] = \frac{1}{L}\,\frac{dL}{dt} = \frac{V}{L} \tag{3}$$

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

$$\dot{\varepsilon} = -2\,\dot{d}/d.$$

where d is the diameter of the filament (d = 2 r). Provided that there are no extreme conditions imposed by the geometry, the balance of the 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:

$$T_{zz} = \frac{m(g-a)}{\pi r^2} - \frac{2\pi\sigma r}{\pi r^2} - \frac{D_r}{\pi r^2} \tag{4}$$

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

$$T_{rr} = -\frac{\sigma}{r} \tag{5}$$

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

$$T_{zz} - T_{rr} = \eta_E\,\dot{\varepsilon} \tag{6}$$

Thus,

$$\eta_E = \frac{\left(\dfrac{m(g-a)}{\pi r^2} - \dfrac{\sigma}{r} - \dfrac{D_r}{\pi r^2}\right)}{\dot{\varepsilon}} \tag{7}$$

Using the empirical drag law model of a sphere as a function of Reynolds number, Eq. 7 becomes

$$\eta_E = \frac{\left(\dfrac{m(g-a)}{\pi r^2} - \dfrac{\sigma}{r} - \dfrac{\dfrac{24}{Re}\left(1 + \dfrac{1}{6}\,Re^{2/3}\right)\dfrac{\pi d^2}{4}\,\dfrac{1}{2}\,\rho_a V^2}{\pi r^2}\right)}{\dot{\varepsilon}} \tag{8}$$

where Re is defined as

$$Re = \frac{\rho_a D\, V}{\mu_a} \tag{9}$$

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 ligament (d) are required. In order to determine the strain rate ($\dot{\varepsilon}$) both the instantaneous velocity of the droplet and the length of the ligament (L) are required. The position, velocity, and acceleration of droplets will be measured using a laser attenuation technique. The velocity and acceleration of the droplets will be determined from the slopes of the position vs. time curve and velocity vs. time curve, respectively. The strain rate of the filament will be 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 will be measured using a digital image analyzer.

Summary of Technical Progress

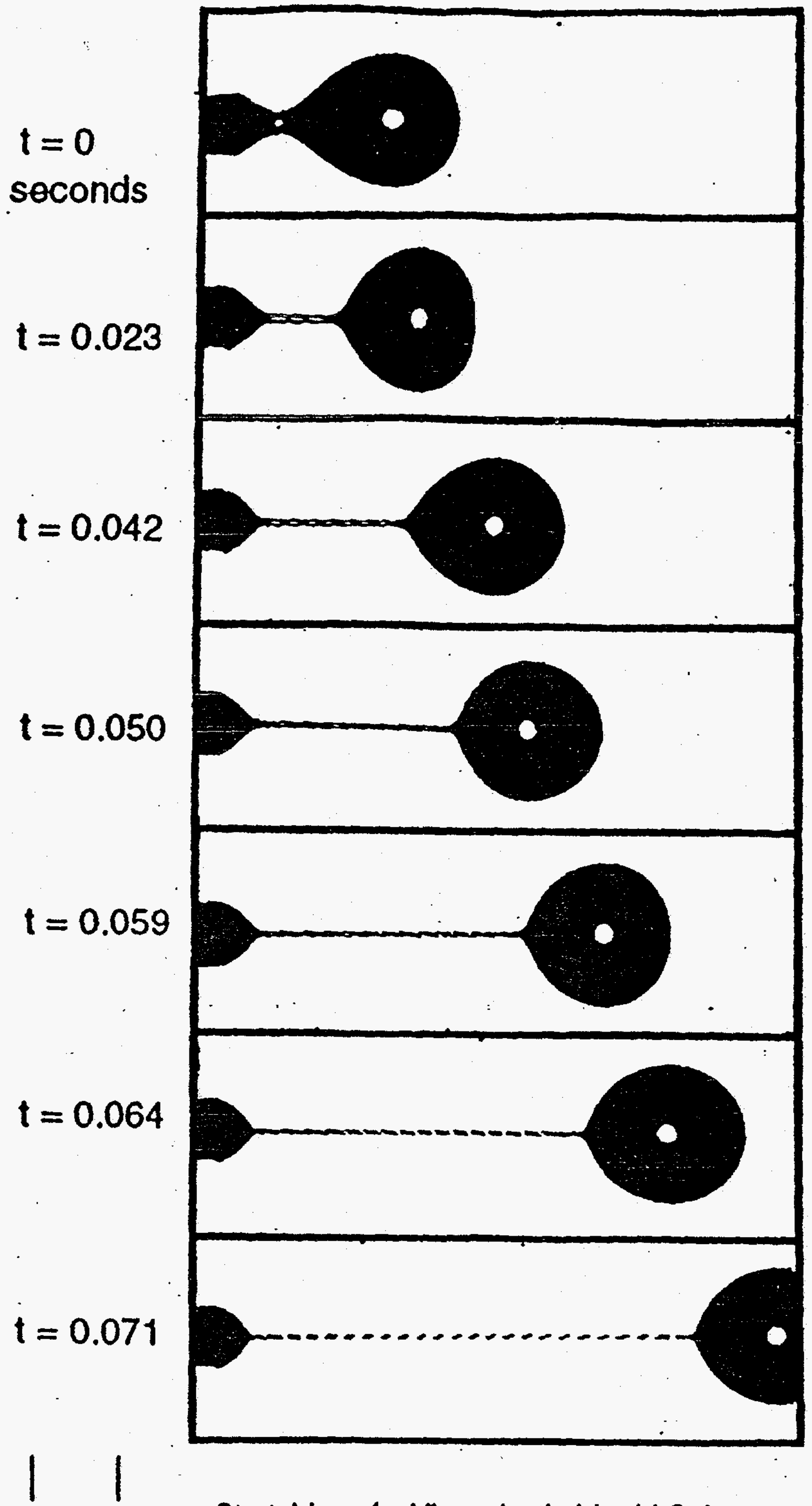
Development of a Laser Attenuation Technique for Measurement of Ligament Diameter:

This reporting period was dedicated to the development of the laser attenuation technique (see Fig. 2). Measuring the ligament 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. As such, we can correlate the diode output to the ligament diameter.

During the experiments it will be insured that the diameters measured are within the homogeneous part of the filament. 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 ligament. This unneeded complexity is effectively reduced by the use of the cylindrical lens. Specifically, the lens will stretch 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 ligament diameter. In addition to a more linear relationship, the laser sheet will help to prevent the error caused by ‘swaying’ ligaments. When the droplet falls, the trailing ligament becomes very small. As a result, the ligament is influenced by air drafts and can easily sway away from the path of a single laser beam. With the optics, however, the ligament cannot sway out of the range.

Calibration of the system involved a magnifying CCD camera and an array of fine bore glass nozzles. Using the nozzles, we were able to produce water jets varying in size from approximately 120 to 2000 microns. Once the exact diameter for each stream was determined with the magnifying camera, we could find the corresponding output voltage from the photodiode by placing the jet in the path of the laser sheet. With each jet, we obtained a different voltage and thus we could construct the curve relating the diode voltage to the ligament diameter. 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 proper measurement of the largest diameter ligaments. 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 ligament present. Figures 3 and 4 show the raw and normalized output voltages, respectively. Figures 3 and 4 show the calibration curves using a 3 mm diameter pinhole. Observe that the measured signal is proportional to the jet diameter; the signal decreases with increasing diameter.

References/Publications: None



Stretching of a Viscoelastic Liquid Column
by a Falling Drop - 0.10% Polyacrylamide e10
Time Sequence

FIGURE 1:

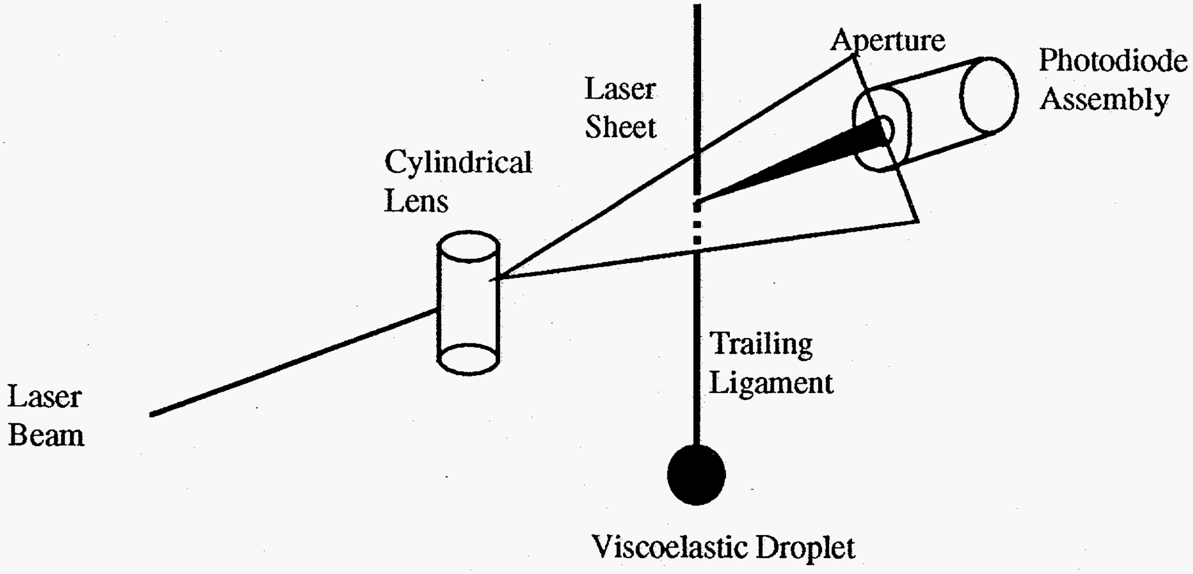


Fig. 2 Laser Attenuation Technique

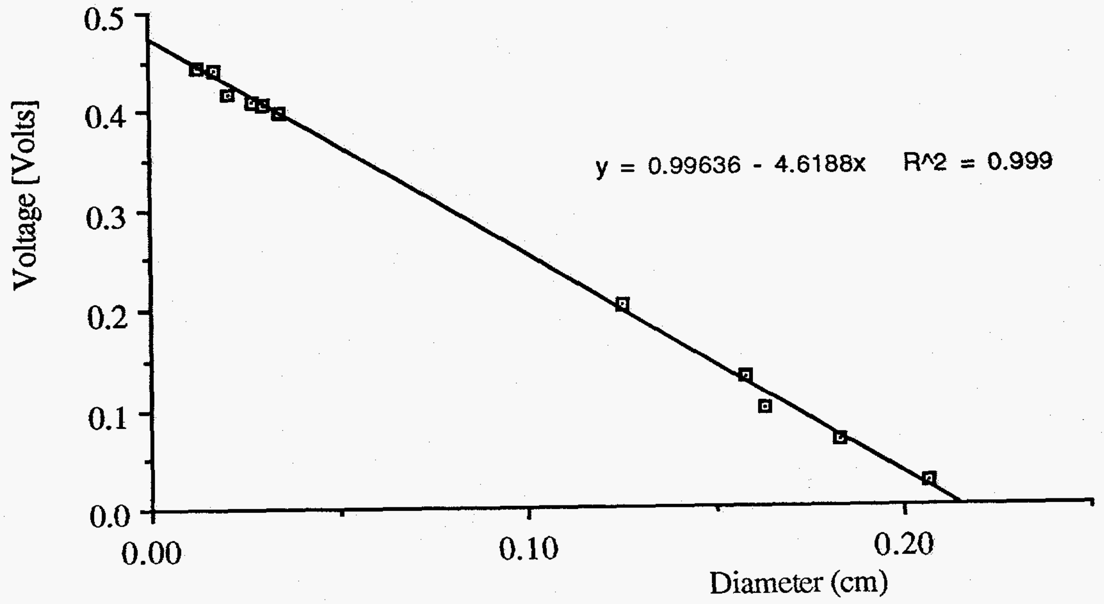


Fig. 3 Photodiode Voltage vs. Jet Diameter

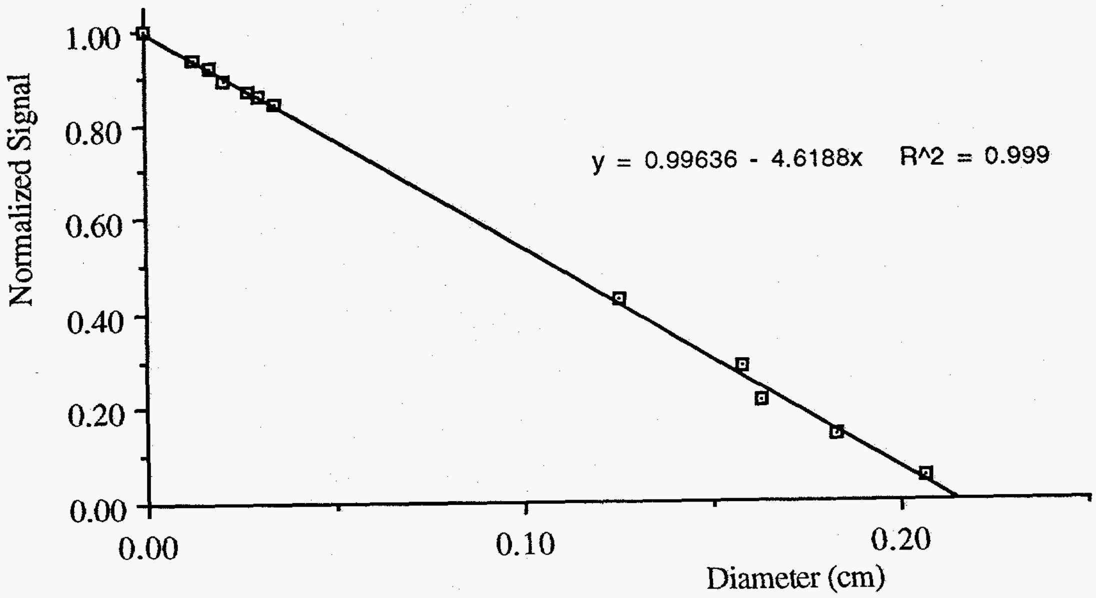


Fig. 4 Normalized Signal vs. Jet Diameter