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**EFFECT OF COAL BENEFICIATION PROCESS ON
RHEOLOGY/ATOMIZATION OF COAL WATER
SLURRIES.**

**Final Report
October 1, 1992 -July 31, 1996**

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**Technical Project Officer
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Pittsburgh Technology Energy Center
P. O. Box 10940
Pittsburgh, PA 15236**

**Work Performed for the Department of Energy Under
Contract #DE-FG22-92MT92019**

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EXECUTIVE SUMMARY

Advanced coal preparation processes have the potential to produce environmentally accepted compliance fuel. The end product of these processes contain considerable amounts of water which must be de-watered. The de-watering process is however, not cost effective. Thus, a practical way of handling these fuels is in the production of Coal-Water Slurries (CWS).

Efficient utilization of CWS requires the production of fine sprays during the atomization process, since carbon conversion efficiencies of CWS have been directly related to the droplet size distribution. Thus, to examine the factors that govern fine spray production during atomization of CWS, an experimental study of the effect of coal beneficiation and their rheological properties on atomization of clean CWS was proposed.

The objective of this study was to understand the effect of low shear, high shear rheology, and viscoelastic behavior on the atomization of beneficiated CWS. Three different CWS samples: An Uncleaned CWS derived directly from the parent coal, CWS derived from Heavy Media Cleaning Process (HMS), and CWS derived from Froth Flotation (FFS) were utilized in this study. In the atomization studies, the mean drop size of the CWS sprays were determined at various air-to-CWS ratios. A co-axial Delavan Solid Cone atomizing nozzle was used as the atomizer and a Malvern 2600 particle size analyzer was used to size spray droplets.

Solids-loadings, coal particle size distributions, and chemical additives were varied in order to determine the significant properties that influence CWS atomization. A correlation of the mass mean droplet size with high shear and viscoelastic behaviors were made in order to determine the influence of these parameters on CWS atomization.

The objectives of this project were:

- * Preparation of CWS from clean coal
- * Preparation of CWS from uncleaned coal
- * Determine the surface characteristics of the beneficiated CWS samples as well as, that derived directly from the parent coal
- * Perform rheological analysis of the CWS over a considerable shear rate and temperature range.
- * Measure the Rheological Properties of the CWS.
- * Measure the Rheological Properties of Simulated Fluids
- * Explore the atomization characteristics of the CWS (1-5 gph flow range) in order to determine the atomization quality.
- * Develop a Phenomenological model to relate Drop size to Air/Fuel and Rheological Properties.
- * Perform a statistical analysis of the spray droplets in order to develop a linkage between ratio of mass of CWS/air and SMD.
- * Investigate the Effect of the Rheological Properties on Atomization.

These objectives were accomplished by:

Preparing beneficiated CWS samples and identifying coal slurry fuel elements and properties such as :

particle size distribution of the coal particles

Additive type

Viscosity of CWS

CWS density and Gas-CWS interfacial tension

which influence the CWS rheology, and also, performing a literature search to further understand clean coal technology and the atomization characteristics of the coal-water slurries. This was followed by:

Selection of appropriate beneficiation process and coal samples.

Defining particle size distribution that correspond to the maximum amount of coal that could be slurried while maintaining fluidity.

Establishing baseline properties for the beneficiated coal-water slurries

Performing rheological properties on the coal-water slurries and simulated fluids

Performing atomization studies on coal-water slurry samples and simulated fluids as a function of air/CWS

Developing a phenomenological model to test the experimental results

Identifying the significant elements which influence atomization characteristics such as: the effect of beneficiation, particle size distribution of spray droplets, atomization air pressure, orifice diameter, nozzle velocity of air, and exit velocity of liquid

Testing the phenomenological model with experimental results

Examining the flow characteristics of the coal-water slurry samples and relating the flow characteristics to the quality of atomization.

Ascertain the statistical influence on coal slurry atomization

Application of air-assist atomization to coal-water slurries requires an analysis of the effects of slurry rheological properties which is greatly influenced by additives, particle size distribution, type of coal and dynamic surface tension. The effect of these properties on the spray

formation process for the beneficiated CWS samples and the uncleaned coal were investigated and the results were used to fit the phenomenological model developed in a previous work.

Newtonian and non-Newtonian liquids, derived from solutions of glycerol- water mixture, corn syrup-water mixture and glycerol-water-xanthan gum mixture were sprayed and the Sauter mean diameter (SMD) measurements were obtained at various nozzle pressures and Air to Fuel Ratio (AFR) values. This provided information on the effect of flow consistency index on the spraying characteristics. Also, spray data for three coal water slurry mixtures with varying formulations were collected, again at varying nozzle pressures and AFR values. This provided information on the relationship between drop size and AFR.

The experimental data obtained were then analyzed to explain the physical processes responsible for spray formation. The analysis began by considering an energy balance across a control volume that extended from the nozzle exit plane to the line of spray measurement. The inlet conditions were calculated using two-phase flow techniques and the outlet conditions were calculated by using conservation of momentum and assuming that the loss of kinetic energy of the fuel and the air was used in breaking up the fuel into droplets.

The results showed that air-assist nozzles effectively atomized CWS, as well as Newtonian and non-Newtonian fluids and that, the storage modulus of the slurries correlated very well with the sauter mean diameter. The viscoelastic properties of the CWS influenced the drop sizes produced in the air assist atomization. It was observed that the CWS derived from the parent coal exhibited higher storage modulus at all oscillation frequencies than the beneficiated coals. Also, the storage modulus increase with increase in coal content. The spray data of the CWS

correlated very well with the storage moduli, showing that there is a strong dependence of the spray droplet size on the storage modulus.

CHAPTER 1

INTRODUCTION

Considerable amount of electricity generated in the United States today is the direct result of coal combustion. The mineral matter, and sulfur and nitrogen containing compounds present in coal allow the emission of NO_x , CO , SO_x and particulate matter into the environment [1]. There is therefore, continued interest to reduce the sulfur and nitrogen containing compounds which cause acid rain.

A process for limiting SO_x and NO_x emissions and ash particulate matter usually consists of a combination of removing sulfur and mineral matter from the coal before combustion. Physical cleaning methods can be very effective in removing mineral matter, including pyritic sulfur from the coal [2].

There are two basic mechanism by which mineral matter is removed from coal by the process of physical coal cleaning [3]. Heavy Media and Cycloning involve one mechanism and Froth Flotation and Selective Agglomeration involve the other. Heavy Media process (HMS) and Cycloning (Cy) rely on the differences between the specific gravities of coal and mineral matter [4], and Froth Flotation (FF) and Selective agglomeration employ surface property differences to effect a separation [5]. The end products of all these physical processes contain considerable amounts of water. The large amounts of water present in these products create significant handling problems since these products can not be handled pneumatically.

One alternative for handling the end product is to convert these products to coal-water slurries (CWS). Previous studies have shown that CWS have the potential to be an immediate substitute for premium liquid and gaseous fossil fuels, in newly designed boilers and retrofit installations [6,7]. Optimization of the fundamental aspects of such fuels include (1) preparation

and handling CWS fuels, (2) combustion of these fuels, (3) the hardware which must be designed to accommodate fuel atomization requirements and different flame patterns necessary to insure complete combustion.

The combustion intensity and the burning velocity of fuels in general can be increased by increasing the surface to mass ratio of the fuel. This process helps to increase the vaporization, ignition and burnout of the CWS samples [8]. The quality of the atomization is characterized by factors which influence the evaporation and subsequent combustion. The size of the spray droplets governs the ignition and burnout rates of the CWS samples. The characteristic slurry properties:- solid/liquid interaction, fluid mechanics of atomizing influences the global flame geometry.

Coal-water slurry is a highly viscous, non-Newtonian, two-phase fluid that sometimes contains polymers in order to maintain suspension of the coal particles. The rheological properties and polymers make slurries hard to atomize, and coal particles make it abrasive and prone to clogging orifices [9]. The difficulty in atomizing CWS magnifies the problem of efficiently burning the fuel can be increased by exposing more surface area of the fuel to the hot combustion gases, but it is necessary to produce small drop sizes in order to accomplish that goal.

The majority of atomizers are incapable of efficiently atomizing CWS since they are sensitive to slurry rheological properties. In order to overcome rheological effects, some atomizers require that the injection velocity be increased. This is often accomplished by raising injection pressure and decreasing orifice diameter [10]. Increasing exit velocity is however, detrimental to nozzle operation since the abrasive effect of CWS increases. In addition, the

probability of clogging increases with decreasing nozzle diameter. Increasing AFR is undesirable due to the increase in cost associated with pumping large volumes of air at high pressure.

Several studies have been directed towards relating rheological properties of CWS to atomization quality [11,12,13]. The trend towards this work is due to the fact that low shear viscosity data had correlated well with droplets of Newtonian liquids. Coal water slurries are however, non-Newtonian. Thus, attempts to correlate low shear viscosity data with CWS atomization were unsuccessful. This is due to the fact that for such fluids, the effective viscosity is shear rate dependent, and this dependence can take two distinct forms; shear thinning (pseudoplastic) and shear thickening (dilatant). The behavior of CWS is complicated by their changing from one type of behavior to the other as the shear rate is varied. Much effort has therefore been directed towards correlating high shear viscosity data of coal-water slurries with atomization [14].

The significance of shear viscosity in CWS atomization is manifested in the formation of ripples on the fuel surface [15]. The rate of growth of the ripples is dependent on the Weber number, $(We = \frac{\rho_A U_R D_o}{\sigma_L})$, where ρ_A is the density of surrounding air, U_R is the relative velocity between liquid jet and surrounding air, D_o is the diameter of liquid jet, and σ_L is the surface tension of the liquid [16].

Previous investigations on CWS atomization covered the details of sprays and simplification of computational work necessary to simulate the physical history of the droplets in a multiphase [17]. Owing to the complexity of the various physical phenomena involved in pressure atomization, studies on CWS atomization has been pursued principally by empirical methods, relating the CWS properties (viscosities, surface tension and density) and atomizer

design and operating conditions (air velocity and air to liquid ratio), yielding correlations for the mean drop size of the general form [18]:

$$SMD = C \rho_a^{0.06} \mu_f^{0.385} \rho_f^{0.352} \sigma_f^{0.737} \Delta P_f^{-0.54} \quad 1-1$$

where SMD is the Sauter Mean Diameter, C is a constant, ρ_a is the density of air, ρ_f is the density of fuel, ΔP_f is the injection pressure differential, μ_f is the dynamic viscosity of the fuel and, σ_f is the surface tension of the fuel.

Previous studies have shown that the presence of ash minerals present in coal affect the rheological and physico-chemical properties of CWS. For this reason, it seemed particularly useful to examine the effect of different levels of coal beneficiation on CWS fluidity, stability and subsequent atomization. CWS show non-Newtonian fluid behavior. Thus, the shear rate needs to be known for determining the viscosity of CWS during atomization. The actual shear rate during atomization varies with the position of the CWS jet within the atomizer because of changes in the liquid thickness and relative velocity between atomizing air and CWS [19]. Studies of CWS rheology in 100,00/s shear rate regime has been shown to correlate very well with the sauter mean diameter of the atomized droplets. Thus, it was deemed necessary to investigate the effect of high shear rheology on the size of the atomized droplets.

Dooher and Wildman [20] have indicated that viscoelastic properties may be important predictors of atomization data. They however, did not characterize the effects of the elastic CWS properties on drop size as was done in the previous atomization studies on Newtonian fluids.

Thus, low and high shear rheological measurements as well as, oscillatory measurements were performed over the frequency range of 1 to 62 Hz in order to determine the storage modulus, G' as a function of frequency for each CWS, and also determine the elastic response.

Furthermore, it was deemed necessary to examine rheological properties and relate the data to the drop size of the CWS.

CHAPTER 2

Preparation and Characterization of Coal- Water Slurries.

2-1 Coal Selection

The three CWS samples were selected for this study were prepared by Amax R&D, Golden Colorado, as part of a subcontract with Grambling State University.

The three slurries received from Amax R&D were as follows:

Coal Cleaning- CWS derived directly from parent coal (Uncleaned)	45 gallons
Coal Cleaning-CWS derived from Heavy media Process (HMS)	40 gallons
Coal Cleaning-CWS derived from Froth Flotation (FFS)	40 gallons

The heavy media cleaning was done in a stirred vessel with a circulating magnetite slurry of specific gravity 1.35 as the parting medium. The parent feed coal was pre-crushed to minus 1/2 inch and screened to remove the minus 14-mesh fines before the separation. The fines were discarded. The magnetite media was rinsed from the float coal with spray water on a vibrating screen. The float coal was subsequently ground to minus 48 mesh in a 4x4-foot ball mill and filtered.

The parent coal was also ball-mill ground to minus 48 mesh for the froth flotation, and the flotation was accomplished in a series of seven 1-cubic foot Denver mechanical aeration flotation machines using 0.34 pound diesel fuel and 0.51 pound methyl isobutyl carbinol (MIBC) per ton of feed coal as reagents. The flotation clean coal and a portion of the ball-mill ground coal were also filtered ahead of the final slurry preparation.

The coal water slurries were prepared from filter cakes. In each case, a portion of the filter cake was ground to minus 45 μm in a stirred ball-mill and blended with the original filter cake in order to achieve the desired particle size distribution as listed in Table 2-2. The particle size

distribution shown in Table 2-1, were obtained by 5500 L Sedigraph sedimentation method in the subsieve range. Henkel A-23M, a naphthalene sulphonate, and a Pfizer flocon 4800C xantham gum were used to disperse the coal, reduce the viscosity, and prevent the formation of a hard packed sediment during storage.

All the samples exhibited good stability when received. The shipment also included a bucket of the parent Upper Elkhorn No.3 (Taggart) crushed coal under an Argon atmosphere. Table 2-1 lists the properties of the CWS received from Amax R&D. The samples were periodically stirred to prevent the formation of hard pack sediments. Samples were withdrawn from the bulk samples received and reformulated to meet the following specifications:

58-66 % by coal weight depending on the coal type

99% through 80 mesh and 100% less than 50 mesh sieve size.

Less than 5% increase in solids content measured at the bottom of settling column after 24 hours

Power Law index of less than 1.3

0.3% concentration of additive A-23 obtained from Henkel Corporation

pH of between 8-9.5

Zeta potential of less than -25 mV at a pH of 8.

Table 2-1

	Cleaning Procedure		
	None	Heavy Media	Froth Flotation
Slurry Composition (%)	62.43	62.39	62.41
Dispersant (A-23M)	2.51	2.54	2.53
Stabilizer (Flocon 4800C)	.025	.025	.025
Total Solids	65.96	65.95	65.96
Water	34.04	34.05	34.04
Slurry Density (lb/gal)	9.75	9.75	9.75
Slurry pH	7.8	7.9	7.7
Dry Solids Composition, %			
Volatile Matter	34.48	35.92	36.04
Ash	3.38	1.88	1.51
Fixed carbon	62.19	62.20	62.45
Total sulfur	1.20	1.19	1.21
Viscosity, Increasing Shear Rate			
100 s ⁻¹	1,000	950	1,000
500 s ⁻¹	995	900	1,015
1000 s ⁻¹	830	765	840
Viscosity, Decreasing Shear Rate			
100 s ⁻¹	500	400	580
500 s ⁻¹	445	440	525
1000 s ⁻¹	435	430	490

Table 2-2**Particle Size Distribution
Cleaning procedure**

	None	Heavy Media	Froth Flotation
Passing 300 μm	99.61	99.64	99.66
Passing 210 μm	97.93	97.83	98.18
Passing 150 μm	94.21	93.28	95.45
Passing 106 μm	89.05	88.28	91.01
Passing 75 μm	81.71	80.97	82.59
Passing 53 μm	74.67	75.72	75.54
Passing 45 μm	68.89	70.27	68.77
Passing 38 μm	66.51	66.71	68.41
Passing 30 μm	53.77	53.34	55.23
Passing 20 μm	43.49	42.30	42.09
Passing 15 μm	37.61	35.37	34.40
Passing 10 μm	29.78	27.60	27.24
Passing 8 μm	25.69	24.25	23.54
Passing 6 μm	21.26	20.06	19.69
Passing 4 μm	15.02	14.32	14.28
Passing 3 μm	11.65	11.21	11.14
Passing 2 μm	7.64	7.21	7.22
Passing 1 μm	2.35	2.15	2.10
mass mean Diameter	43.9	44.9	42.3

2-2 Characterization of Coal Surface Properties

There is a need to improve the stability and flow characteristics of the CWS in order to understand the rheological properties . The coal particle surface, grinding media and the presence of additives utilized in the CWS formulation, can influence subsequent utilization of the CWS [21,22]. The study of the beneficiation CWS and Uncleaned CWS samples, therefore, offered a fundamental and practical significance to further study and relate the surface chemistry of the coal samples to the rheology and subsequent utilization of the CWS. Three main effects which contribute to the coal surface properties are:

The number and type of polar groups (carboxylic and phenolic),

The ash content, and

The hydrocarbon skeleton.

The mineral matter of coal which constitutes the inorganic matter in coal is generally associated with the ash content in coal. Also, the C/O of the coal surface is decreased by the process of aging or oxidation during which polar functional groups such as -COOH, -CO, and phenolic, -OH groups are formed. The formation of these groups influence the quality, stability and flow characteristics of the slurries.

There are two basic mechanisms that contribute to the surface charge of the coal particles in aqueous media. The first is the dissociation of ionogenic groups on the coal surface, such as those having carboxylic, phenolic, and hydroxylic functionality. The surface charge is governed by the ionization of the acid groups

and for the surface containing hydroxyl groups which may be considered to be amphoteric, such as those that exist on the surface of inorganic oxides on the surface of coal, the charging process may be represented by:

Fourier Transform Infrared Diffuse Reflectance Spectroscopy, FTIR(DRT), Fourier Transform Infrared Reflectance Spectroscopy, FTIR (RAS), and Zeta Potential measurements used to characterize the surface characteristics of the CWS samples.

FTIR Analyses

All the samples were dried in a nitrogen atmosphere for a period of 24 hours after sampling, and the FTIR transmittance spectrum of each sample was taken, using KBr as a diluent.

A transmission spectra of as received coal (Elkhorn #3) is as shown in Figure 2-1. Based on previous infrared spectral studies of coals [23], the following assignments were made.

1. The peak at 3770 wavenumbers are due to the presence of hydroxyl groups (O-H) structural components of illitic and kaolinitic clay minerals inherent within the coal.
2. A broad composite band, arising from the O-H groups within the organic matrix of the coals (alcoholic, phenolic, acidic, etc.) spans the region from 3600 to 2500 wavenumbers.
3. A band at 3056 wavenumber is due to the presence of aromatic hydrocarbons (Ar-H). This is a band present in all aromatic hydrocarbons. The peaks at 2960 and 2852 wavenumbers are to the presence of terminal vibrational modes of methyl (CH₃) groups and the methylene -CH₂- and methene CH= groups appended to the polynuclear matrix

FIGURE 2-1. DIFFUSE REFLECTANCE SPECTRUM OF UNCLEAN CMS

FIGURE 2-2. DIFFUSE REFLECTANCE SPECTRUM OF FLOTATION CLEANED CWS

FIGURE 2-3. DIFFUSE REFLECTANCE SPECTRUM OF HEAVY MEDIA CLEANED CWS

4. The bands at 1606, 1446, and 1375 wavenumbers are due to $-C=C-$, CH_2 , CH_3 and organic oxygenates, $C-O-C$, $C-O-H$, $C-C-O$. Clay minerals also exhibit lattice mode of vibration in this region.
5. The band at 1031 is due lattice mode of vibration of clay and silicates.
6. The bands at 855, 816 and 749 wavenumbers are due to out of plane bending modes of $Ar-H$ and presence of silicates.

Figures 2-1 through 2-3 are the spectra of the CWS samples (Uncleaned CWS, Flotation CWS and Heavy Media CWS). Comparison of the Uncleaned CWS FTIR spectrum to that of the Heavy media and the Flotation cleaned samples show that there are no distinct differences in the spectra obtained.

Zeta potential

The theory of the electrical double layer associated with a charged particle in aqueous electrolyte solution has been well documented [24]. The charge is assumed to be smeared out uniformly over the particle surface, and this is balanced by ions, regarded as point charges, which are of opposite sign and distributed in the medium around the particle.

The dissociation constant expressions in equations 2-1 and 2-2, can be represented by:

$$K_{acid} = \frac{[COO^-][a_H^{+(s)}]}{[-COOH]} \quad 2-5$$

$$K_{Phenolic} = \frac{[O^-][a_H^{+(s)}]}{[-OH]} \quad 2-6$$

where $a_H^{+(s)}$ is the activity of the hydrogen ions at the surface of the coal, and it is related to the acidity in the bulk, i.e., pH by the relation:

$$a_H^{+(s)} = a_H^{+(s)} e^{-\frac{e\psi_o}{kT}} \quad 2-8$$

where ψ_o is the potential at the solid-liquid interface, e is the electronic charge, k is the Boltzmann constant and T is the absolute temperature.

The surface has an electrostatic potential, ψ_o , and on moving away from the surface, the potential decays exponentially to zero in the bulk liquid. The shear plane, which corresponds to the boundary of the layer of bound solvent, is the location of the zeta potential (Figure 2-4).

Zeta Potential Measurements:

The zeta potential was determined using a Micromeritics Zeta Potential Analyzer (model 1200). Operation allows the effective particle surface charge in a liquid/solid sample to be measured by the application of a constant electric current applied across a maximum of 50% by weight solids suspension. by determining the rate at which the particles migrate into a cell, electrophoretic mobility and zeta potential can be determined. All measurements were made in a constant ionic medium of 0.001 M KNO_3 in order to help eliminate any anomalies, due to changes in ionic strength of the aqueous phase as a result of leaching of ions from the coal into the aqueous phase. Values of -33 mV, -38 mV and -63 mV were obtained for the Heavy media cleaned, Flotation cleaned and the Unclean CWS respectively.

FIGURE 2-4. INTERPARTICLE INTERACTION

CHAPTER 3.

Rheology of Coal Slurries.

Conventional rheological evaluation of Coal-Water Slurries by steady shear flow measurements and specifications of plastic viscosity and yield stress, have provided a strong technical base for preparing and controlling the stability of CWS [25,26]. These specifications however, fail to provide complete insight into the CWS properties that control the flow properties and those necessary for their subsequent atomization [27,28]. This is because steady flow measurements reveal only the viscous, energy dissipative effects in the CWS flow for very long shearing time and with constantly increasing deformation.

3-1 Rheology

Many of the problems encountered in the utilization of coal-water slurries (CWS) are as a result of their flow properties. Rheology is the branch of mechanics dealing with the deformation and flow of materials in response to a mechanical force, or conversely, the prediction of the force system necessary to cause a given deformation or flow. From the study of the rheology of a system, one can gain insight into the factors that affect the structure of the system and to what extent. The behavior of a fluid under shear forces can be examined, such as the investigation of flow properties through pumps, pipes, and nozzles. The atomization of a fuel is also a function of its rheology. Rheological studies can be used in a predictive manner, for example, to determine the effects of varying one parameter of a system or how flow behavior will change from one configuration to another.

3-2 Newtonian vs. Non-Newtonian Rheology

For a Newtonian fluid, the shear stress, τ is directly proportional to the shear rate, $\dot{\gamma}$; the constant of proportionality is the viscosity, μ .

$$\tau = \mu \dot{\gamma} \quad (3-1)$$

Viscosity is measured in Pascal-seconds (Pa-s) in SI units; shear stress in Pascals (Pa) and shear in reciprocal seconds (1/s).

For pipe flow, the average shear rate is shown by equation 3-2:

$$\dot{\gamma} = \frac{8 \times \text{bulk Velocity}}{\text{pipediameter}} \quad (3-2)$$

The shear stress for pipe flow is the force/area at the wall resisting the flow. It is directly related to the pressure required to pump a fluid. However, many types of fluids, including CWS, are non-Newtonian, i.e. their viscosity is not constant but dependent on the shear rate to which the fluid is subjected. The non-Newtonian viscosity is denoted by $\eta(\dot{\gamma})$. If the shear stress is divided by the shear rate at a particular point, the apparent Newtonian viscosity is obtained.

In a viscometer or in a pipe, the shear stress can be measured as a function of shear rate. When this is done, a flow curve is generated. Figure 3-1 shows flow curves for some types of Newtonian and non-Newtonian fluids. Curve 4 represents a Bingham plastic. For these liquids, a certain shear stress, the yield point, must be applied before they start to flow. Shear thinning (pseudoplastic) behavior is seen in curve 2. In this type of liquid, the apparent viscosity decreases with increasing shear rate. Dilatant behavior, curve 3, is present in some concentrated suspensions. The apparent viscosity increases as the shear rate increase. Curve 5 shows a shear thinning fluid which also has a yield point. This flow is also seen in some concentrated suspensions.

In order to mathematically describe the relationship between shear stress and shear rate, equations have been developed to fit the flow curves obtained in a viscometer or pipeline.

Curves 2 and 3 are generally developed using a power law model:

$$\tau = k\dot{\gamma}^n \quad (3-3)$$

The constants k and n can be evaluated from the raw data from either a viscometer pipeline.

FIGURE 3-1. Shear Stress As A Function Of Shear Rate.

If $n = 1$, the fluid is Newtonian and $k = \mu$; if $n > 1$, the fluid is dilatant; if $n < 1$, the fluid is shear thinning. Curve 4, a Bingham plastic is described by:

$$\tau = \tau_o + \eta(\dot{\gamma})_{pl} \quad (3-4)$$

where τ_o is the yield point, and η_{pl} is the plastic viscosity.

A yield pseudoplastic fluid, curve 5, can be described by:

$$\tau = \tau_o + k\dot{\gamma}^n \quad (3-5)$$

where k , and n are as described above.

3-3 Time Dependency

The equations described above deal only with the effect of shear rate on viscosity; the effect of duration of shear is not included. When a constant or variable shear is applied to a fluid, the rheology can change with time as the structure of the fluid is altered. Figure 3-2 shows the effect of slowly increasing the shear rate to a maximum, and then slowly decreasing it. For a thixotropic fluid, the decreasing shear curve is lower than the increasing shear curve; the viscosity of the sample decreases with time. The opposite behavior is seen with rheopectic fluids. The samples of CWS that were studied previously at Grambling State University, exhibited both of these properties [29].

3-4 Effect of Particle Interactions

In suspensions, there are interactions between the particles, and between the particles and the continuous phase. These interactions may give rise to agglomerates, which can trap some of the continuous phase. At low shear rates, there is random orientation of these agglomerates and the shear force is not sufficient to affect either the size or the alignment of the agglomerates. As the shear is increased, the structure of the agglomerates is broken down, the trapped fluid is released, and the particles and smaller agglomerates are oriented in the direction of the flow. These effects give rise to a decrease in viscosity. When the maximum degree of de-agglomeration

FIGURE 3-2. Shear Stress As A Function of Shear Rate.

and orientation has occurred, the viscosity of the fluid again become constant, but at a much lower value than the original apparent viscosity.

3-5 Importance of Coal Properties

The CWS utilized in this program was derived from Elkhorn #3. A slurry derived from this coal had previously been studied at Grambling State University. This slurry derived from this coal was found to be dependent upon the following factors [30]:

Hydrodynamical interactions between coal particles and suspending medium (water);

Surface specific interactions between coal particles and suspending medium:

Interparticle interactions.

These factors were dependent upon the properties of the coal used for the slurry formulation. A relationship between coal properties and resulting rheology of a CWS developed in the previous program, was a vital step in establishing the baseline properties for the CWS needed for this study.

3-6 Rheology of Suspensions

The rheological properties of suspensions are predictable from basic principles in only a few cases for extremely dilute suspensions. One can, however, investigate the degree of structural formation in a suspension by studying the variables which affect the system through rheological measurements, thus obtaining a qualitative picture of the behavior of the system. Rheological analysis is also the best quantitative method to obtain information on the properties of a concentrated suspension as it settles. Besides examining the viscosity of the suspension at low shear rates for information on the structure of the system, the high shear rate behavior is important for practical use considerations.

The introduction of solid particles into a Newtonian fluid medium disturbs the flow pattern and increases the amount of energy dissipation. The viscosity of a suspension is independent of shear rate, i.e. Newtonian, when only the hydrodynamic interactions are taken into account. Agglomeration of the particles, needed to explain shear thinning and other non-Newtonian properties, must involve non-hydrodynamic forces of attraction, such as the London-van der Waals force. These forces will depend on the physics and chemistry of the coal particle surfaces. At high shear rates, when the structure is broken down, hydrodynamic effects become more important.

The non-hydrodynamic forces acting on particles in a suspension include thermal forces, electrical forces, London-van der Waals, and the chemical and surface interactions between the particles. The London-van der Waals force between the particles in a suspension influences the formation of agglomerates. The depth of the secondary minimum in the potential energy-distance curve between particles determines the net attraction (Figure 2-4). The viscosity of the system is proportional to the depth of the secondary minimum..

If there is a surface charge on the particles in a suspension, an ion cloud is formed around each particle. This electric double layer stores energy like a capacitor and tends to resist deformation by flow, and also screens the charge on the particles, reducing the repulsive forces. Ionic dispersants bond to the particle surfaces effecting changes in the surface charges and therefore the ionic double layer. A change in the potential energy of interparticle interaction results. Dispersants can thereby be used to modify the viscosity of CWS by reducing the net attractive forces between coal particles. A reduction in agglomerate formation improves the rheological properties.

3-7 Effect of Particle Packing on CWS Viscosity.

Previous studies indicate that coal particle packing exert considerable influence on the CWS behavior. In previous work at Grambling State University, a computer program that had been developed at Adelphi University which allows for the calculation of the maximum packing based on coal particle distribution, was used to select the PSD in order to obtain a high efficiency packing. This program was also used to select the PSD for this study [31]. The optimum particle size distribution selected for the formulation of the coal-water slurries is shown in Table 2-2.

3-8 Viscoelastic Behavior

Dense suspensions will exhibit viscoelastic behavior depending on the type of strain or stress applied to the material. Viscoelastic properties of material relate directly to its internal structure. If a dense suspension is subjected to a varying external force of frequency, ω , then the dense suspension will behave as an ordinary viscous liquid if $\omega T < 1$ where T is the time during which the stresses are damped, and if $\omega T > 1$, the internal stresses will not be damped and the suspension will behave as an amorphous solid. When dense suspensions are elastically deformed during short intervals of time, shear stresses remain, which are damped after sufficiently long time, T .

The response of viscoelastic material which has been subjected to a small-amplitude oscillatory shear is given by [32]:

$$\gamma(t) = \gamma_o \exp(i\omega t) \quad 3-6$$

where ω , is the frequency and γ_o is the strain amplitude.

In oscillatory shear, a complex modulus, G^* , can be defined as:

$$\sigma(t) = G^*(\omega)\gamma(t) \quad 3-7$$

G^* can also be expressed as:

$$G^* = G' + iG'' \quad 3-8$$

where G' and G'' are the storage modulus and loss modulus respectively.

Dense suspensions such as coal-water slurries, can be treated as a continuum model where their response to applied stresses and strains can be examined.

For ideally elastic substances based on a model following Hooke's Law, the following relationship applies:

$$\tau(t) = G \cdot \gamma(t) \text{ with controlled strain.} \quad 3-9$$

$$\gamma(t) = \frac{1}{G} \cdot \tau(t) \text{ with controlled stress.} \quad 3-10$$

For ideally viscous substances, the relationship

$$\tau(t) = \eta \cdot \dot{\gamma}(t) \text{ with controlled strain or shear rate} \quad 3-11$$

$$\dot{\gamma}(t) = \frac{1}{\eta} \cdot \dot{\tau}(t) \text{ with controlled stress} \quad 3-12$$

The angular frequency ω , is related to both the strain and the stress sinusoidally thus:

$$\gamma(t) = \gamma_o \cdot \sin \omega t \text{ (controlled strain)} \quad 3-13$$

$$\tau(t) = \tau_o \cdot \sin \omega t \quad 3-14$$

The delay of $\tau(t)$ curve against $\gamma(t)$ curve has the phase displacement angle $0^\circ > \delta > 90^\circ$.

The storage modulus, G' , which is the strain energy reversibly stored in the sample and

recoverable is defined as:

$$G' = \frac{\tau_o}{\gamma_o} \cdot \cos \delta \quad 3-15$$

The simplest relationship between the storage modulus of a fluid, as a function of frequency, and

its relaxation time is given by:

$$\frac{G'}{\eta_o} = \frac{\lambda \omega^2}{1 + \lambda^2 \omega^2} \text{ (Maxwell's Model)} \quad 3-16$$

where ω is the frequency in rad/sec and λ is the relaxation time [33].

This characterizes the elastic behavior of the sample. The G' value represents the quantity of the strain energy reversibly stored in the substance and recoverable.

The loss modulus is given by:

$$G'' = \frac{\tau_o}{\gamma_o} \cdot \sin \delta \quad 3-17$$

alternatively

$$G''(\omega) = G_1 \frac{\omega t_R}{(1 + \omega^2 t_R^2)} \text{ (Maxwell's Model)} \quad 3-18$$

This quantity represents the energy which is irreversibly given off by the substance to its

environment and thus lost. It characterizes the viscous behavior of the substance. The loss factor,

$\tan \delta$, which is a ratio of the dissipated and the stored energy is given by:

$$\tan\delta = \frac{G''}{G'}$$

3-19

The study of the oscillatory behavior allows the systematic characterization of the CWS suspensions so that their flow properties could be described by mechanical parameters which represent the system in the region of interest. The oscillation test provide more detailed information about the elasticity of the sample. The relaxation test are made with a given constant load (shear stress, τ or shear rate, $\dot{\gamma}$) and permit the determination of the ratio between the viscous and the elastic portions, the retardation time, and the shear modulus. These values depend on the constant presetting and results are obtained only under these constant conditions. Oscillation test can be made under varying loads with controlled shear stress, τ or controlled shear strain, γ . especially, the characterization of the relative importance of elastic to viscous effects. Stress and strain relaxation as well as viscometric measurements are essential in relating elastic to viscous effects. Other parameters such as: yield points, shear moduli, storage moduli, and moduli of rigidity can be related to interparticle forces. These parameters form good basis for characterizing the flow properties.

3-9 Dynamic Flow

In a capillary, the material's law can be determined from the pressure, P and the flow rate, Q , if the tube flow fulfills the following criteria:

- (a) The flow is laminar, i.e. all volume elements of the sample within the tube with the same distance, r , from the tube axis, move at the same velocity in the direction of the tube axis.
- (b) The flow is steady- At any point within the tube, the flow velocity has the same value at consecutive time intervals, therefore, is independent of time.
- (c) The flow is isothermal- It is assumed that the temperature of the sample remains constant.

When flowing through the capillary, the sample can, however, be warmed up by shearing.

(d) The sample is incompressible and its viscosity is independent of pressure

(e) The sample adheres on the tube wall-No wall shearing.

The basic equation of capillary viscometry for any material's law is [34]

$$\tau(r) = \frac{P \cdot r}{2l} \quad 3-20$$

Where $\tau(r)$ is the shear stress dependent on the distance, r , from the tube axis,

P is the pressure drop along length, l , within the tube,

and l is the length of the tube

The shear rate can be expressed as a function of the distance, r , from the tube axis thus:

$$\gamma^*(r) = \frac{dv(r)}{dr} = f(\tau(r)) \quad 3-21$$

The flow rate, Q , can be obtained by integrating the velocity distribution, $v(r)$, across the tube cross section.

$$Q = \int_0^R v(r) \cdot 2\pi r dr \quad 3-22$$

3-10 Newtonian Flow in a capillary Tube

Newtonian fluid flow in a capillary tube can be evaluated from the relationship:

$$\tau(r) = \frac{P \cdot r}{2l} = \tau_w \text{ (shear stress at the wall)} \quad 3-23$$

Substituting these expressions in equation (3-22), results in the flow velocity, $v(r)$ expression:

$$v(r) = \frac{P(R^2 - r^2)}{4\eta l} \quad 3-24$$

and the flow rate, Q , is given by:

$$Q = \frac{\pi R^4 P}{8\eta l} \quad 3-25$$

where R is the inside radius of the tube.

For such Newtonian fluids, the shear rate at the wall, $\gamma_w^* = \gamma^*(R) = \frac{4Q}{R^3 \pi} = D$

3-11 Bingham's Fluid Flow:

Bingham's material's flow law is given by the relation:

$$\tau = \tau_f: \tau = \tau_f + \eta_B \cdot \gamma \quad 3-26$$

For distance of r smaller than $r_f = \frac{2\tau_f l}{P}$, γ becomes zero in the range $\tau(r) < \tau_f$, and no shearing is exercised on the sample.

The flow rate for a plug -shaped flow results is given by:

$$Q = \frac{\pi R^4 P}{8 \eta_B l} \left(1 - \frac{3}{4} \frac{r_f}{R} + \frac{1}{3} \left(\frac{r_f}{R} \right)^4 \right) \quad 3-27$$

and the shear rate is given by:

$$D = \frac{4Q}{R^3 \pi} = \frac{1}{\eta_B} \left(\tau_w - \frac{3}{4} \tau_f + \frac{1}{3} \left(\frac{\tau_f}{\tau_w} \right)^4 \cdot \tau_w \right) \quad 3-28$$

3-12 Rheometry

The flow behavior of the CWS received from Amax R&D were characterized by various rheological methods in order to gain insight into their flow properties and internal structure. Low shear, high shear and viscoelastic effects were examined using a Haake RV20-CV20 with oscillatory capabilities, RV20-M5 concentric cylinder viscometer, and Parr HVA-6 Capillary viscometer.

Results of Rheological Measurements.

Low shear viscosity as a function of shear rate were determined using the Haake RV20-M5 with MVIII, MVII, MV1, MVIIIP and MVIP sensors. In this system, the sample is sheared in an annular gap between a rotating bob and stationary cup. The torque necessary to rotate the bob at a given speed is measured by a torsion spring. The drive unit consists of a driving motor, a tachometer-generator and a reduction gear. The stator is surrounded by a tempering vessel connected with a constant temperature bath. The temperature bath can be controlled to 0.1C. This viscometer is integrated with an IBM ps/2 model 70 data acquisition and analysis system. The signal from the viscometer are monitored twice per second and converted to torque and rotational speeds. Viscosity as a function of shear rate were computed using one of the following flow models: Power law, yield power law, Bingham plastic, and modified Bingham plastic models. The shear rate to which the sample was subjected , was continuously increased from zero to a maximum as allowed by the sensor, decreased from maximum to zero shear rate, and this cycle repeated again (Figure 3-4A). Viscosity measurements were taken from the third curve which represents the fluid after it has been sheared and its structure broken down.

Four different viscosity standards (Cannon Viscosity Standards, Thomas Scientific, Swedesboro, NJ) having viscosities of 73, 1115, 3351 and 17050 mPas at 20 °C and glycerol,

were used to calibrate the rheological instrumentation. After calibration, the viscosity of each simulated fluid and CWS under study was determined by fitting the measured shear stress-strain rate curve to one of the several rheological models available on the data acquisition software. The analysis fitted the data to the Herschel-Bulkley viscosity model (Equation 3-5). This model accurately represented the rheological properties of the three classes of fluids used in this study.

Corn Syrup and glycerol solutions as well as, glycerol-xantham gum solutions were used as model Newtonian and non-Newtonian liquids. The low shear flow behavior of representative samples of these solutions generated in the RV20- M5-MVIII combination are as shown in Figures 3-3 through 3-6 and the viscosities are listed in Tables 3-1 , 5-1 and 5-2 .

The corn syrup was purchased from a local supermarket and the Glycerol was obtained from Aldrich Chemical Co. Milwaukee, WI). Newtonian liquids of high viscosity were formulated for use in this study by decanting a known volume of either the glycerol or the corn syrup and then diluting it with specific amount of distilled water in order to obtain the desired composition, and the non-Newtonian fluids were obtained by diluting glycerol with a specific amount of 0.1% xantham gum solution. Homogeneity of these solutions were insured by agitating the mixture with a stirrer (Eberbach Corporation, Ann Arbor, Mi., propeller driven by a Bodine Electric Motor, type NS1-12, Chicago, Ill). After complete mixing was obtained, the surface tension and rheological measurements were made.

Figures 3-7 through 3-21, show representative samples of the low shear flow curves obtained for the CWS using the Haake RV20-MVIII combination. The rheological data for the CWS obtained from the shear stress versus shear rate curves using Equation 3-5, are as listed in Tables 3-2 through 3-4. At high solids concentration (64 and 65%), the Uncleaned slurry

exhibited a thixotropic behavior. A fit of the experimental data obtained to equations 3-4 and 3-5 show that the uncleaned slurry exhibited a slightly higher viscosity than the cleaned slurries. It was also observed that the viscosities of the slurries decrease with increase in temperature between 25° C and 50° C (Figures 3-13 through 3-16).

The incorporation of the yield stress term in Equation 3-5, was necessary to minimize the error when curve-fitting the equation to some of the data. When the yield stress was not included (Equation 3-3), the curve-fit was forced to predict a zero shear stress (yield stress), at a zero strain rate. Unfortunately, the magnitude of the yield stress varied from one mixture to the next with no consistency between the different formulations of the CWS. As a result, yield stress values were used to facilitate curve fitting but were considered unreliable for analyzing the subsequent spray data.

3-13 Viscoelastic Behavior of CWS

Viscoelastic studies were performed using the RV20-CV20 in combination with PQ45 sensor (Plate/plate), ME15 coaxial cylinder sensor, and D45 sensor combination of Coutte (outer gap) and a Searle (inner gap) sensor system in order to investigate the relationship between interparticle structure and the relationship to rheological behavior. The viscoelastic behavior was determined in an oscillatory mode. The linear viscoelasticity was measured by subjecting the sample through a small amplitude oscillatory test. Measurement of the phase difference between the shear stress and strain and the amplitude ratio of the stress and strain wave forms, allowed the viscoelastic behavior of the CWS as a function of frequency to be determined. Figures 3-20 through 3-24 show plots of storage modulus (G') and loss modulus (G'') as a function of frequency for CWS with solids content 61% to 64 % of the different types of slurries:

Table 3-1

Physical data For the Corn Syrup Solution.

Corn Syrup Concentration(%)	Density (gm/mL)	Surface Tension (dynes/cm)	Viscosity (mPa.S)
100	1.37	80.64	750
90	1.31	76.1	234
80	1.26	73.8	196
70	1.23	70.9	103
60	1.19	59.8	72.4
50	1.08	51.2	34.2

FIGURE 3-3. FLOW BEHAVIOR OF 90% GLYCEROL SOLUTION

Figure 3-4 . Flow Behavior of 90% Glycerol-Xanthan Gum Solution.

GSU RHEOLOGY LAB

Operator:
jb

Substance:
10% Xanthan
Gum

Test No.:
1

Test of:
04-10-1993

System:
M5/MV3

Temperature:
23.0 °C

--- JGLYC2.ROT

FIGURE 3-5. FLOW BEHAVIOR 80% GLYCEROL-XANTHAM GUM SOLUTION

FIGURE 3-6. FLOW BEHAVIOR OF GLYCEROL-XANTHAM GUM SOLUTION

FIGURE 3-7. FLOW BEHAVIOR OF 65% UNCLEAN CWS

FIGURE 3-8. FLOW BEHAVIOR OF 64% UNCLEAR CWS

FIGURE 3-9. FLOW BEHAVIOR OF 62.5% UNCLEAN CMS

FIGURE 3-10. FLOW BEHAVIOR OF 61.5% UNCLEAR CWS

GSU RHEOLOGY LAB.

Operator:
francis & kath

Substance:
unclean61.45

Test No.:
2

Test of:
06-15-1996

System:
M5/MV3

Temperature:
23.0°C

--- UNCL61.ROT

FIGURE 3-11. FLOW BEHAVIOR OF 64% FLOTATION CLEANED CMS

FIGURE 3-12. FLOW BEHAVIOR OF 63% FLOTATION CLEANED CMS

FIGURE 3-13. FLOW BEHAVIOR OF 62% FLOTATION CLEANED CMS AT 25 C

Figure 3-14. Flow Behavior of 62% Flotation Clean CWS at 30 C.

Figure 3-15. Flow Behavior of 62% Flotation Clean CWS at 35 C.

Figure 3-16. Flow Behavior of 62% Flotation Clean CWS at 45 C.

FIGURE 3-17. FLOW BEHAVIOR OF HEAVY MEDIA CLEANED CWS

FIGURE 3-18. FLOW BEHAVIOR OF 64% HEAVY MEDIA CLEANED CMS

FIGURE 3-19. FLOW BEHAVIOR OF 63% HEAVY MEDIA CLEANED CMS

TABLE 3-2

RHEOLOGICAL PROPERTIES OF SIMULATED FLUIDS

GLYCEROL-WATER AND GLYCEROL/XANTHAM GUM MIXTURE

Temp	R ²	n	τ_0	k	%Composition	η_{100} (mPas)
25 C	.96	1.01	0.03	0.89	70/30*	75.9
25 C	.99	.99	0.014	0.20	90/10*	196
25 C	1.0				70/20	750
25 C	1.00				70/30	200
25 C	.87	1.36	16.8	.007	70/40	198

* Glycerol-Xantham Gum

TABLE 3-3

RHEOLOGICAL PROPERTIES OF CWS

COAL SAMPLE (Uncleaned Slurry)

Temp	R ²	n	τ_0	k	Coal(%)	η_{100} (mPas)
25 C	.97	1.08	1.2	.75	62	1009
25 C	.97	.84	0	.49	61	217
25 C	.87	1.06	2.5	.71	64	1370
25 C	.89	1.09	4.3	1.03	65	2309
25 C						

TABLE 3-4
RHEOLOGICAL PROPERTIES OF CWS
COAL SAMPLE (Flotation Cleaned Slurry)

Temp	R ²	n	τ_o	k	Coal(%)	η_{100} (mPas)
25 C	0.83	1.11		.60	64	1124
25 C	.99	1.1	.04	.59	63	948
25	.99	1.1		.32	62	536
30 C	.93					479

TABLE 3-5
RHEOLOGICAL PROPERTIES OF CWS
COAL SAMPLE (Heavy Media Cleaned Slurry)

Temp	R ²	n	τ_o	k	Coal(%)	η_{100} (mPas)
25 C	.99	1.33			65	1113
25 C	.93	1.14		.04	62	99
25 C	.95	1.16		.08	61.5	183
25 C	.96	1.03			64	961
25	.95	1.22		.12	63	391

Figure 3-20. Comparison of Oscillatory Flow Mode of 61% (Unclean, Heavy Media and Flotation) CMS.

Date: 16.06.96, 17:58 Operator: Francis & Kath Sample: f1ot61%
 Sensor system : 045 System : CU20

FIGURE 3-21. COMPARISON OF OSCILLATORY FLOW MODE OF 62% (UNCLEAN, HEAVY MEDIA AND FLOTATION) CWS

Date: 16.06.96, 17:58 Operator: francis & kath Sample: flot62%
Sensor system : Q45 System : CU20

FIGURE 3-22. COMPARISON OF OSCILLATORY FLOW MODE OF 63% (UNCLEAN, HEAVY MEDIA AND FLOTATION) CMS

Date: 16.06.96, 18:58 Operator: Francis & Kath Sample: flot63.2%
 Sensor system : 045 System : CV20

FIGURE 3-23. COMPARISON OF OSCILLATORY FLOW MODE OF 64% (UNCLEAN, HEAVY, MEDIA AND FLOTATION) CWS

Date: 06.07.96, 16:23 Operator: Francis & Kath Sample: heavy64%
 Sensor system : ME15 System : CU20

FIGURE 3-24. COMPARISON OF OSCILLATORY FLOW MODE OF 61%-63% (FLOTATION) CMS

Date: 16.06.96, 17:58 Operator: francis & kath Sample: flot61%
 Sensor system : 045 System : CU20

Uncleaned slurry (Uncl), Flotation cleaned (Flot) slurry, and Heavy Media Cleaned (Hvy) Slurry. The data obtained for these measurements (Figures 3-20 through 3-23), indicate that the Uncleaned CWS exhibited a higher storage modulus than the cleaned CWS samples at all solids content. Furthermore, the Flotation CWS exhibited a slightly higher storage than the Heavy media cleaned CWS. Ultimate analysis shows that all these samples varied in their ash content (Table 2-1). The Uncleaned CWS samples had the highest ash content and these sample also exhibited the highest storage modulus. This observation indicate a direct correlation between the ash content and the storage modulus. Figure 3-24 shows that the storage modulus increase with increase in the coal content. This is an indication that the degree of interaction increases with increase in the coal content.

Relaxation Times.

The simplest relationship between the storage modulus of a fluid, as a function of frequency, and its relaxation time is given by the Maxwell Model [35]:

$$\frac{G'}{\eta_0} = \frac{\lambda \omega^2}{1 + \lambda^2 \omega^2}$$

where ω is the frequency and λ is the fluids complex relaxation time and η_0 is the viscous component of the fluid at zero shear rate.

This model assumes that the entire fluid is elastic. This may not be true for the CWS samples and thus, a better approximation is the Rouse model. The Rouse model [36] approximates an elastic fluid as a series of freely jointed chains connected by Hookian springs. The data obtained in Figures 3-25 through 3-27 indicate that the CWS samples exhibit a range of relaxation times at low frequencies and remains constant at higher frequencies. These varying relaxation times at low frequencies observed for these slurries, can be attributed to the polydisperse nature of the CWS samples examined.

FIGURE 3-25. COMPARISON OF RELAXATION AND VISCOSITY OF 61% (UNCLEAN, HEAVY MEDIA AND FLOTATION) CWS

Date: 16.06.96, 17:58 Operator: francis & kath Sample: flot62%
 Sensor system : Q45 System : CV20

Date: 16.06.96, 17:58 Operator: francis & kath Sample: flote1%
 Sensor system : 045 System : CV20

FIGURE 3-37. COMPARISON OF RELAXATION AND VISCOSITY OF 63% (UNCLEAN, HEAVY-MEDIA AND FLOTATION) CMS

Date: 06.07.96, 16:23 Operator: Francis & Kath Sample: heavy64%
 Sensor system : ME15 System : CU20

FIGURE 3-28
MECHANICS OF THE HVA-6
CAPILLARY VISCOMETER

MECHANICS AND ELECTRONICS OF THE HVA 6

Abb.: 1
Fig.: 1

3-15 Results of High Shear Rheological Measurements

The HVA-6 Capillary Viscometer was used to determine the dynamic flow rates of the slurries. The HVA-6 automated high shear viscometer (Figure 3-28) permits measurements from low to high flow rates. Capillary tubes of diameters 0.8mm, 1.5mm and 3.0mm and 100 mm in length were used in these measurements. In this device, the sample to be measured is forced through a capillary tube at definite pre-adjusted pressure and pressed into a burette where the flow rate is measured.

Figure 3-29 compares the high shear flow behavior of simulated Newtonian (glycerol solution) and non-Newtonian samples (0.1% xantham gum-glycerol solution), and Figure 3-30 compares their viscosities as function of shear rate. The xantham gum-glycerol solution exhibited turbulence over the shear rate regime investigated. This was accompanied by abrupt changes in viscosity within the shear rate regime of 100,000 /s.

Figure 3-31 compares the high shear flow behavior of 63% solids loading of the three slurries: Unclean, Heavy media and Flotation clean CWS through a capillary tube of 0.8mm diameter and 100 mm in length. The flow behavior of all the CWS samples were Newtonian in the high shear rate regime, and they all exhibited identical flow behavior. Lower shear rates however, were obtained when capillary tubes of larger diameters were used. Figure 3-32 compares the flow behavior of the Unclean slurry through capillary tubes of diameters 0.8 mm, 1.5 mm and 3.0 mm and 100 mm in length. This difference is attributed to slippage along the capillary walls.

The slippage during the capillary flow was analyzed using an approach based on the method of Lupton and Regester [37]. The apparent wall stress at the wall can be expressed as:

$$\frac{4Q}{\pi R^3} = 4V_R \cdot \frac{1}{R} + \frac{4}{3} \int_{\tau_w}^{\tau_w} \tau^2 \gamma d\tau \quad 3-37$$

 A P P A A R
 H V A - 6

FIGURE 3-29. COMPARISON OF HIGH SHEAR FLOW BEHAVIOR OF GLYCEROL AND XANTHAN GUM

FIGURE 3-30. COMPARISON OF HIGH SHEAR VISCOSITIES OF GLYCEROL SOLUTION AND XANTHAN GUM SOLUTION

*** A P P A A R H V A - 6 ***

FIGURE 3-31. COMPARISON OF HIGH SHEAR FLOW BEHAVIOR OF (UNCLEAN, FLOTATION AND HEAVY MEDIA) CMS

*** AP PAR HVA - 6 ***

FIGURE 3-32. COMPARISON OF HIGH SHEAR FLOW BEHAVIOR OF: UNCLEAN SLURRY IN CAPILLARY TUBES OF (0.8, 1.5, 5.0) MM DIAMETERS

*** APPAAR HV A - 6 ***

FIGURE 3-31. ANALYSIS OF SLIPPAGE IN A CAPILLARY FLOW

Figure 3-3 . Analysis of Slippage in a Capillary Flow.
Constant Shear Stress of 3,000 Pa.

Figure 3-36 is a plot of the apparent shear rate as a function of the reciprocal radius ($1/R$) at a fixed shear stress of 3,000 Pa. The lack of a horizontal line indicate the presence of slip at the capillary wall.

3-15 Surface Tension Measurements.

Surface tensions was measured by using a du-Nuoy type ring tensiometer (Fisher Model 21). The tensiometer was calibrated by placing known weights (as determined by a Mettler P400 balance) on the instrument's Pt-Ir ring and measuring the resulting gravitational force. The instrument's performance was verified by determining the surface tension of de-ionized water. Excellent agreement was obtained between the measured value and the literature value of 72 dynes/cm. After each measurement, the Pt-Ir ring was washed in a water bath, dipped in alcohol, and heated thoroughly over a bunsen burner flame before the next measurement.

Table 3-1 and Tables 5-1 through Table 5-9 list the surface tension data obtained for the simulated fluids as well as the CWS studied. The data indicate that the surface tension decreases as the percent amount of either the glycerol or the corn syrup decreases. The surface tension data for the formulated Newtonian fluids are however, lower than the corresponding values for the glycerol-xantham gum solutions.

CHAPTER 4

Atomization Studies

4-1 Summary of Atomization Experimental Set-up

This section explains in detail the operation of the atomizer and experimental apparatus as well as the operation and calibration of the instrumentation used to acquire the atomization data. The description of the nozzle begins at the liquid and air inlets and proceeds to the final orifice. It includes descriptions of the various components and the flow path of the fluids. The description of the experimental apparatus begins with the air and fuel supply systems and ends at the nozzle inlets. The systems used to analyze the spray are then described and the theory behind their operation summarized. Equipment calibration procedures are also included.

4-2 Flow Pattern Exiting The Nozzle

During operation, it was often important to determine the two-phase flow pattern exiting the nozzle. Experiments were therefore, conducted for coal-water slurry flows in a series of horizontal capillary tubes of diameters 0.8, 1.5 and 3.0 mm and 100 mm in length, in order to simulate the effect of concentration, pressure drop, and the transitional Reynolds number from laminar to turbulent flow for the two-phase flow pattern exiting the nozzle.

The analysis of flow characteristics of coal-water slurries can go through different grades of complexity depending on the concentration profile of the dispersed phase, the rheological properties of the system and on the intensity of the flow [38,39].

The flow of a slurry can be influenced by several factors including drag, turbulence, the particles free fall velocity, particle-particle interaction, and the rheological properties of the carrier fluid [40]. Although a large number of experimental investigations have been conducted for the

determination of one more of these effects, the complexity of the two-phase flow, limit the ability to describe the exact flow behavior for such systems [41].

Although many numerical models have been developed for multiphase flow, their application is still very limited, The dependence of empirically-determined stress expressions are not very clear due to lack of complete elucidation of the mechanism of the complex flow through numerical modeling [42].

Heavy media cleaned coal was used to study the flow pattern of the CWS exiting through the nozzle. The coal concentration was varied from 15% to 63% in 0.1% xantham gum solution. Pressure drop and the volume flow measurement were made using HVA-6 Capillary viscometer. The experimental parameters were chosen in order to emphasize the effect of turbulence, so as to allow the determination of possible transitional Reynolds number from laminar to turbulent flow.

The HVA-6 Capillary Viscometer was used to determine the flow rates of the slurries. The HVA-6 automated high shear viscometer permits measurements from low to high flow rates. Capillary tubes of diameters 0.8mm, 1.5mm and 3.0mm and 100 mm in length were used in these measurements. The exit samples were collected and the coal content determined at each applied pressure.

The pressure drop in slurry flows is a key design parameter since it governs the pumping power required to move the slurry through the system. The change from laminar to turbulent flow results in a change in the flow resistance or friction loss. The prediction of the transition from laminar to turbulent flow can be inferred from the variation in the friction factor, which is dependent on the pipe diameter, the rate of flow, the length of the pipe, and the acceleration due to gravity.

In a horizontal flow, the actual deposition of the suspended particles is determined by the competing effects of gravity, particle-particle interaction and the rheological properties of the carrier fluid. As a result, either concentric or eccentric plug flow may result.

The CWS utilized in this work followed the Herschel- Bulkley model (Figure 3- 1). The Herschel- Bulkley models can be represented by:

$$\tau = \tau_o + k\gamma^n \text{ (H. Bulkley Model)} \quad 4-1$$

where k and n are rheological constants, and τ and γ are the shear stress and shear rate respectively.

For slurries whose properties are time independent, the dependence of the shear stress (τ) on the shear rate (γ) can be expressed as $\gamma = f(\tau)$. The distribution of velocity in the radial direction and the relation between volumetric flow rate, Q and loss of pressure ΔP , can be easily obtained through Rabinowitsch's Equation [43].

$$\frac{Q}{\pi R^3} = \frac{1}{3} \int_0^{\tau_o} \tau^2 f(\tau) d\tau \quad 4-2$$

Where τ_o is the wall stress.

For a fluid described by the Herschel-Bulkley model,

The Constitutive Equation is [44]

$$\gamma = \begin{cases} 0 & \text{when } \tau < \tau_o \\ \left[\frac{\tau - \tau_o}{k} \right]^c & \text{when } \tau > \tau_o \text{ and } c = \frac{1}{n} \end{cases} \quad 4-3$$

From the equation of force equilibrium on a cylindrical element given the radius, r and length, L , the shear stress, is:

$$\tau = r \frac{\Delta P}{2L} \quad 4-4$$

By substituting equation (4-3) in equation (4-4), we obtain

$$\tau = \begin{cases} 0 & \text{when } r < r_p \\ \Gamma \left(\frac{\Delta P}{2L} - \tau_o \right)^c & \text{when } r > r_p \text{ where } \Gamma = (1/k)^c \text{ and } r_p = \frac{2L}{\Delta P} \tau_o \end{cases} \quad 4-5$$

By integration of equation (4-5), with the boundary conditions

$$\int_0^U du = -\Gamma \int_R^r (r \frac{\Delta P}{2L} - \tau_o)^c dr \quad 4-6$$

$U(R)=0$, gives the velocity profile.

$$U(r) = \frac{\Gamma}{c+1} \frac{2L}{\Delta P} \{ (R \frac{\Delta P}{2L} - \tau_o)^{c+1} - (r \frac{\Delta P}{2L} - \tau_o)^{c+1} \} \quad 4-7$$

Near the pipe axis, where $\tau < \tau_o$ the slurry displacement can be treated as a solid plug with radius r_p . By substituting the value of r_p in the above equation, we obtain the plug velocity as:

$$U_p = \frac{\Gamma}{c+1} \frac{2L}{\Delta P} (R \frac{\Delta P}{2L} - \tau_o)^{c+1}; \quad \tau_o = R \frac{\Delta P}{2L} \quad 4-8$$

Figure 4-1 compares the flow curves of the slurries studied, and Tables 4-1 through 4-5 list the experimental data obtained. The data show a transitional Reynolds number of 1500. The results indicate that the turbulence intensity is damped as the solids concentration increase.

The coal content in the exit slurry at each applied pressure did not differ significantly from the initial slurry concentration. This suggests a concentric flow through the capillary tubes.

Increasing the applied pressure increases the flow rate and thus, the kinetic energy. For slurry concentration greater than 25% solids, the effect of increasing the initial applied pressure had no significant effect on the Reynolds number. This effect is however, pronounced in slurries having solids concentration less than 20% solids. The effect of increasing the capillary size, for the high solids concentration slurries, had no significant effect on the Reynolds Number.

This is an indication that within the solids concentration regime employed in this study, the flow pattern exiting the nozzle could be described as concentric plug flow.

Table 4-1.

Flow Rate of 61% CWS Through 0.8mm Capillary Tube

P(bar)	Flow Rate(ml/s)	Reynolds Number	Coal Content in Exit Sample(%)
10.2	.56	6	62
12.2	.66	7	60
14.9	.81	8	60
18.1	1.0	10	59
20.6	1.1	12	59

Table 4-2.

Flow Rate of 61% CWS Through 1.5mm Capillary Tube

P(bar)	Flow Rate(ml/s)	Reynolds Number	Coal Content in Exit Sample(%)
4.0	.41	0	59
6.1	1.9	5	61
8.0	2.5	6	59
10.4	3.3	8	59
12.7	4.2	11	60
14.4	4.8	13	60

Table 4-3

Flow Rate of 61% CWS Through 3.0mm Capillary Tube

P(bar)	Flow Rate(ml/s)	Reynolds Number	Coal Content in Exit Sample(%)
1.2	0.47	0	55
1.7	1.7	0	60
3.2	3.5	1	59
5.1	5.6	2	60
6.4	8.7	3	59

Table 4-4.

Flow Rate of 35% CWS Through 0.8mm Capillary Tube

P(bar)	Flow Rate(ml/s)	Reynolds Number	Coal Content in Exit Sample(%)
2.6	2.4	344	37
4.6	3.9	557	36
6.8	6.1	995	34
8.3	6.5	906	35
10.2	5.3	439	36

Table 4-5.

Flow Rate of 15% CWS Through 0.8mm Capillary Tube

P(bar)	Flow Rate(ml/s)	Reynolds Number	Coal Content in Exit Sample(%)
1.2	2.6	1047	14
3.1	5.2	1858	13
4.6	7.2	3851	14
6.3	9.6	4947	14

FIGURE 4-1. A Plot of Log Pressure vs. Log Flow Rate.

4-3 Atomization Unit

The feed system for the fluid atomization consisted of a 5-gallon feed tank whose bottom feeds into a Monyo progressive cavity pump. The configuration of the fuel flow was chosen to allow accurate flow measurements in a low flow regime of 1.44 gm/sec and a high flow regime of 34 gm/sec. Calibration of the fluid flow was performed by collecting and timing tap water as it flows at a given setting of the pump. The accumulated water at each pump configuration setting, was then weighed on a Mettler balance (model PJ6000) and the flow rate was determined. This calibration allowed the measured and predicted flow rates to be matched at high, moderate and low values. The calibration curve for the fluid mass flow is shown in Figure 4-2.

Atomizing air was provided by a general purpose air compressor which cycles between 85 psig and 150 psig. Air flow was controlled manually by turning a valve to give a line pressure. Calibration of the air flow was performed by measuring the volume of water displaced by the air as it flowed through a rotameter at 23 C. The mass of the volume of water displaced by a given quantity of air flowing through the rotameter, was determined by multiplying the volume of water displaced by the density of water at 23 C, and a calibration curve for the air flow rate was determined (Figure 4-3). This calibration also, allowed the measured and predicted flow rates to be matched at high, moderate and low values.

The atomizer used in this study was the Delavan Airo Solid Cone Atomizing Nozzle (Figure 4-4). This is an internal mix atomizer. Air and fuel mix and breakup begins at the first contact between the air and the fuel. The nozzle assembly during the fuel atomization study was suspended over a 102 cm wide, 65 cm high, 153 cm long aluminum spray box . The box served as a collection vessel. Spray recirculation was minimized by exhausting the atomized fluid by a

FIGURE 4-2. CALIBRATION CURVE FOR FLUID FLOW

Figure 4-2. Calibration of Fluid Flow.

FIGURE 4-3. CALIBRATION CURVE FOR AIR FLOW RATE

Figure 4-3. Calibration of Air Flow Rate

AIRO™

FIGURE 4-4. AIRO SOLID CONE
ATOMIZING NOZZLE

Solid Cone Air Atomizing Nozzle

Ako

Max. Design Pressure: 100 psig (700 kPa)

Max. Design Temperature: 180°F (82°C)

AIRO Nozzle Assembly

AIRO CAPACITY CHART

NOZZLE* NUMBER	H ₂ O Flow GPH	AIR AND WATER FLOW									
		20 PSIG		30 PSIG		40 PSIG		50 PSIG		60 PSIG	
		SCFM	Spray Angle	SCFM	Spray Angle	SCFM	Spray Angle	SCFM	Spray Angle	SCFM	Spray Angle
30615-1 or 30615-3	5	1.7	45°	2.4	35°	3.1	30°	—	—	—	—
	10	.7	75°	.9	65°	2.1	60°	—	—	—	—
	15	.2	80°	.7	75°	.8	70°	—	—	—	—
30615-15 or 30615-17	10	2.3	50°	3.6	40°	4.7	30°	—	—	—	—
	15	1.7	60°	2.9	50°	3.9	40°	—	—	—	—
	20	1.2	70°	2.1	60°	3.1	50°	—	—	—	—
	25	.7	80°	1.7	70°	2.4	60°	—	—	—	—
	30	.4	80°	1.0	80°	1.7	70°	—	—	—	—
30615-44 or 30615-46	30	—	—	2.7	65°	3.9	55°	4.9	45°	—	—
	35	—	—	2.2	65°	3.3	55°	4.2	45°	—	—
	40	—	—	1.8	70°	2.8	60°	3.7	50°	—	—
	45	—	—	1.4	70°	2.3	60°	3.1	50°	—	—
	50	—	—	1.0	75°	1.9	65°	2.7	55°	—	—
	55	—	—	.8	75°	1.5	65°	2.3	55°	—	—
30616-11	60	—	—	.5	80°	1.2	70°	2.0	60°	—	—
	60	—	—	5.3	60°	7.7	50°	10.0	40°	—	—
	65	—	—	4.9	60°	7.2	50°	9.5	40°	—	—
	70	—	—	4.4	65°	6.8	55°	8.9	45°	—	—
	75	—	—	4.0	65°	6.3	55°	8.4	45°	—	—
	80	—	—	3.7	65°	5.8	55°	7.8	45°	—	—
30616-17	85	—	—	3.3	65°	5.2	55°	7.1	45°	—	—
	90	—	—	3.0	70°	4.8	60°	6.1	50°	—	—
	90	—	—	6.3	55°	7.8	45°	10.3	35°	—	—
	95	—	—	4.9	60°	7.2	50°	9.5	40°	—	—
	100	—	—	4.6	60°	6.6	50°	8.9	40°	—	—
	105	—	—	4.2	65°	6.1	55°	8.3	45°	—	—
30616-27	110	—	—	3.8	65°	5.7	55°	7.8	45°	—	—
	115	—	—	3.5	70°	5.4	60°	7.5	50°	—	—
	115	—	—	—	—	8.1	45°	10.5	40°	13.1	35°
	120	—	—	—	—	7.7	50°	10.3	45°	12.9	40°
	125	—	—	—	—	7.3	50°	10.0	45°	12.6	40°
30616-32	130	—	—	—	—	7.0	55°	9.6	50°	12.2	45°
	135	—	—	—	—	6.6	55°	9.2	50°	11.8	45°
	140	—	—	—	—	6.2	60°	8.5	55°	10.8	50°
	140	—	—	—	—	6.4	55°	8.8	50°	11.2	45°
	145	—	—	—	—	6.1	60°	8.5	55°	10.9	50°
30616-32	150	—	—	—	—	5.7	60°	8.1	55°	10.5	50°
	155	—	—	—	—	5.2	65°	7.6	60°	9.9	55°
	155	—	—	—	—	5.2	65°	7.6	60°	9.9	55°
	160	—	—	—	—	4.7	85°	6.9	60°	9.0	55°

*No. 30615-1, -15, -44 Brass (for use with optional No. 23034-1 brass adapter).

No. 30615-3, -17, -46 Hardened stainless steel (for use with optional No. 23034-2 stainless steel adapter).

No. 30616-11, -17, -27, -32 Hardened stainless steel (for use with optional No. 30678-2 stainless steel adapter).

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AIRO

OPTIONAL ADAPTER

SPRAY CHARACTERISTICS:

- Fine atomization of many liquids that can't be atomized by hydraulic pressure alone.
- Uniform solid cone. Spray angle varies with air pressure and flow. Separate metering device, such as orifice, metering pump or valve required.
- Large flow passages -- greatly reduce clogging.

CONSTRUCTION AND MATERIALS:

- Three part construction:
 - (1) Nozzle body - brass or 303 stainless steel. Thread sizes: 3/4"-20 UNEF on No. 30615 and 1-1/8"-18 NEF on No. 30616
 - (2) Distributor - Brass, 303 stainless, or tungsten carbide (requires special body with replaceable tungsten carbide orifice disc, integral with body)
 - (3) Screw pin - brass or 303 stainless steel

TYPICAL INSTALLATION

(Based on Water)

centrifugal blower whose volume flow rate was sufficient to draw all the atomizing air out of the atomizing chamber. The co-axial nozzle was mounted on a fixed table. The air enters the nozzle in an axial direction.

The spray droplet sizing was determined using a Malvern Particle Size Analyzer (model 2600, which analyzes the Fraunhofer diffraction pattern formed when a laser beam traverses the sprayed droplets field. A He-Ne laser beam passes through the openings in the duct and the centerline of the spray cone, at a distance of 13.5 cm from the atomizer tip. The laser diffraction principle and the sizer's application have been discussed previously [45]. The laser beam generator and receiver are positioned on each side of the spray chamber, with the longest focal length lens, (300 mm), fitted to the receiver by changing the relative position of the atomizer and the light guide tube, the particle size distribution of the spray within 300 mm radius can be measured from the sprays centerline to its edge. The bench scale atomization set-up is as shown in Figure 4-5.

4-4 Procedure For Malvern Instruments:

Experimental measurements focused on the region immediately downstream (13.5 cm) from the atomizer. A number of different arrangements were tested in order to optimize the drop size measurements. A guide was used to shield the laser beam from part of the spray. With this arrangement, there was minimal accumulation of the droplets on the collection lens surface. However, slurry gradually accumulates outside the guide, and periodic cleanings were performed to keep a build up of the slurry from affecting the measurements. A wide range of air/fuel mass ratios were examined. Depending on the fuel flow rate, air to fuel ratios varied from 0.1 to 0.5.

FIGURE 4-5. BENCH SCALE ATOMIZING NOZZLE

Corn syrup solutions were used to test the atomization conditions. The data obtained for the corn syrup solutions at a fixed Air/Fuel Ratio (AFR) of 0.302 is shown in Figure 4-6.

4-5 Phenomenological Model

The expression derived in this report relates the Sauter mean diameter, SMD, to the fluid surface tension and density, the initial air and fluid velocities and the air-fluid mass ratio, AFR

The development of the model is assumed that Mass of air, M_A with velocity, V_A and mass of fuel, M_F with velocity, V_F produces mass of air entraining N fuel droplets with diameter $(d_i)_{i=1, \dots, N}$

The Conservation of momentum requires that the fuel-air collision produces a mass of fuel droplets and air moving with a center of mass having a velocity V . Since the mass is conserved, it follows that:

$$M_A V_A + M_F V_F = (M_A + M_F) V \quad 4-9$$

where

$$V = \frac{1}{(M_A + M_F)} (M_A V_A + M_F V_F) \quad 4-10$$

The sum of the initial total kinetic energy of the air the fuel can be expressed as:

$$E_{air+Fuel} = \frac{1}{2} (M_A V_A^2 + M_F V_F^2) \quad 4-11$$

The kinetic energy of the entrained droplets is given by:

$$E_{droplets} = \frac{1}{2} (M_A + M_F) V^2 \quad 4-12$$

This loss of energy can be expressed as:

$$\Delta E = \frac{1}{2} (M_A V_A^2 + M_F V_F^2) - \frac{1}{2} (M_A + M_F) V^2 \quad 4-13$$

Substituting equation 4-10 into equation 4-13, yields:

$$\Delta E = \frac{1}{2} \frac{M_A M_F}{(M_A + M_F)} (V_A - V_F)^2 \quad 4-14$$

The surface energy of the N droplets is given by:

$$\Delta E_\sigma = \sigma \sum_{i=1}^n n_i d_i^2 \frac{\pi}{2} \quad 4-15$$

where $\sum_{i=1}^n n_i = N$

The total mass of the fuel droplets is given by:

$$M_F = \rho_F \sum n_i d_i^3 \frac{\pi}{6} \quad 4-16$$

where ρ_F is the fuel density.

The Suater Mean Diameter, SMD, is defined as:

FIGURE 4-6. PARTICLE SIZE DISTRIBUTIONS OF CORN SYRUP SOLUTIONS

$$SMD = \frac{\sum n_i d_i^3}{\sum n_i d_i^2} \quad 4-17$$

Combining Equations 4-14, 4-16, and 4-17, yields:

$$\Delta E_\sigma = \frac{3\sigma}{\rho_F} \frac{M_F}{SMD} \quad 4-18$$

Combining Equations 4-14 and 4-18, yields:

$$SMD = \frac{3\sigma}{\rho_F (V_A - V_F)^2} \left(1 + \frac{M_F}{M_A} \right) \quad 4-19$$

For $\frac{V_A}{V_F} \sim \frac{\rho_F}{\rho_A} \sim 10^3$

$$SMD = \frac{3}{\rho_F} \frac{\sigma}{V_A^2} \left(1 + \frac{M_F}{M_A} \right) \quad 4-20$$

CHAPTER 5

Atomization Results

The goal of this research program was to demonstrate the effect of coal beneficiation influence the production of fine spray droplets during the atomization of CWS. Accomplishment of these goals required an analysis of the effect of coal-water slurry rheological properties as well as, nozzle operating parameters on fine spray production. The CWS property analyses included the flow consistency index, coal particle size distribution, flow behavior in the high shear regime, viscoelastic characterization, surface tension and density.

Rheological characterization of simulated fluids were made and the flow behavior index and the consistency index were derived from either the Herschel Bulkley expression (Equation 3-5) or the Power law model expression (Equation 3-3). The composition of the simulated fluids were varied and the effect of the changes in the flow behavior index on the Sauter mean diameter, (SMD) observed. This was followed by similar studies on the CWS.

Rheological analysis of mixtures of glycerol-water, corn syrup-water, and polymer-glycerol were made to simplify analyses, minimize the number of independent variables in order to facilitate a fit of the data to the model equation expressed in Equation 4-20. The glycerol-water mixture was Newtonian (Figures 3-3). Based on a typical composition, the densities and surface tensions of the simulated fluids were identical to those obtained for the CWS. Thus, these mixtures allowed the influence of the flow behavior index on SMD to be studied while removing the influence associated with the coal particles. Data describing the physical properties of the simulated Newtonian fluids are reported in Table 5-1, and those of the simulated non-Newtonian fluids in Table 5-2. Figures 3- 3 through 3-6 represent the low shear

TABLE 5-1
ATOMIZATION DATA
GLYCEROL-WATER SOLUTION

VISCOSITY	A/F	SURFACE TENSION	DENSITY	SMD
(mPas)		dynes/cm	g/ml	μM
384	.387	63	1.23	19.1
384	.367	63	1.23	22.8
384	.364	63	1.23	21.8
384	.361	63	1.23	29.9
384	.356	63	1.23	34.2
384	.305	63	1.23	40.8
384	.274	63	1.23	64.2
384	.246	63	1.23	80.0
384	.186	63	1.23	105
384	.127	63	1.23	149
410	.392	65	1.26	22.8
410	.381	65	1.26	25.3
410	.361	65	1.26	32.8
410	.312	65	1.26	45.8
410	.288	65	1.26	67.3
410	.212	65	1.26	91.2
410	.174	65	1.26	131.2

TABLE 5-1 (CONTINUED)**ATOMIZATION DATA****GLYCEROL-WATER SOLUTION**

VISCOSITY	A/F	SURFACE TENSION	DENSITY	SMD
(mPas.s)		dynes/cm	g/ml	μM
598	.412	66	1.26	20.6
598	.392	66	1.26	24.3
598	.366	66	1.26	38.2
598	.343	66	1.26	44.2
598	.310	66	1.26	51.1
598	.300	66	1.26	52.4
598	.283	66	1.26	67.2
598	.233	66	1.26	91.2
598	.198	66	1.26	129
760	.425	66	1.28	18.9
760	.381	66	1.28	35.4
760	.362	66	1.28	47.2
760	.355	66	1.28	54.1
760	.341	66	1.28	59.6
760	.302	63	1.28	71.2
760	.288	66	1.28	83.7
760	.243	66	1.28	94.2

TABLE 5-1 (CONTINUED)**ATOMIZATION DATA****GLYCEROL-WATER SOLUTION**

VISCOSITY	A/F	SURFACE TENSION	DENSITY	SMD
(mPas.s)		dynes/cm	g/ml	μM
812	.393	67	1.28	22.8
812	.387	67	1.28	34.6
812	.371	67	1.28	44.2
812	.321	67	1.28	63.2
812	.302	67	1.28	70.4
812	.279	67	1.28	101.2
812	.273	67	1.28	181.2
836	.411	67	1.29	20.6
836	.392	67	1.29	26.3
836	.386	67	1.29	48.2
836	.303	67	1.29	63.2
836	.286	67	1.29	126.1
836	.234	67	1.29	209.4
836	.189	67	1.29	231.3

TABLE 5-2
ATOMIZATION DATA

GLYCEROL-XANTHAM GUM MIXTURE

VISCOSITY	A/F	SURFACE TENSION	DENSITY	SMD
(mPas)		dynes/cm	g/ml	μM
450	.431	64	1.25	28.0
450	.386	64	1.25	34.2
450	.362	64	1.25	41.2
450	.303	64	1.25	61
450	.245	64	1.25	85
450	.186	64	1.25	132
450	.127	64	1.25	276
200	.402	61	1.13	24.5
200	.386	61	1.13	26.7
200	.362	61	1.13	33
200	.303	61	1.13	41
200	.245	61	1.13	72
200	.186	61	1.13	113
200	.127	61	1.13	211

TABLE 5-2 (Continued)**ATOMIZATION DATA****GLYCEROL-XANTHAM GUM MIXTURE**

VISCOSITY	A/F	SURFACE TENSION	DENSITY	SMD
(mPas)		dynes/cm	g/ml	μM
55.7	.412	61	1.13	14.3
55.7	.386	61	1.13	22.0
55.7	.362	61	1.13	39.0
55.7	.303	61	1.13	47.0
55.7	.245	61	1.13	95.0
55.7	.186	61	1.13	105
55.7	.127	61	1.13	152

low shear behavior of these simulated fluids. The properties relevant to this study were identified to be the flow behavior index (n), surface tension, density, and the flow consistency index (k).

5-2 Newtonian Fluid Spray Data

Several studies were undertaken using the glycerol-water solution. Five different compositions of the corn-syrup-water solutions were sprayed and drop sizes were measured using the instrumentation described in section 4-3. The spray droplet size distribution plotted as a percent weight under as a function of particle size, for different concentrations of corn syrup, at a fixed air to fuel ratio (AFR) of 0.302 are as shown in Figure 4-6. The atomization data collected for the glycerol-water solution, glycerol-xantham gum solution and the coal-water slurries are listed in Tables 5-1 through 5-8, and representative data sheets are found in Appendix A-1.

The spray data for the Glycerol solutions as a function of air-fuel ratio is shown in Figure 5-1 and that of the glycerol- xantham gum solution is shown in Figure 5-2. Figure 5-1, also compares the SMD as a function of AFR for varying compositions of glycerol-water solutions with different viscosities. In the high AFR, viscosity has no significant effect on SMD (Figure 5-1). This is due to the fact that at high AFR, energy losses associated with entrainment is large and all contributing factors are leveled off. Thus, any increase in AFR has no significant effect on SMD. At low AFR however, all the energy input goes to break up the fuel droplets since very little energy is lost to the ambient. This is an indication that the fluid properties which include viscosity plays a significant role at low AFR, but at high AFR, the energy associated with the large mass of air, is able to dominate the atomization process and overcome the influence of the effect of viscosity and the surface energy contribution to the atomization process.

Figure 5-1. A Plot of SMD As A Function of Air/Fuel.
Glycerol-Water Solutions

Figure 5-2. A Plot of SMD As A Function of Air/Fuel.
Glycerol-Xanthan Gum Solutions

The plots in Figures 5-1 and 5-2 indicate that the SMD for both the glycerol solution and the glycerol-xantham gum solution increase with decrease in the AFR. Further comparison of Figures 5-1 and 5-2 indicate that the addition of xantham gum to the glycerol solution increases the SMD values especially in the low AFR regime. The shear viscosity of the glycerol-water solutions at $\eta_{100} \text{ s}^{-1}$ were higher than that of the glycerol- xantham gum solutions for a given composition (Table 3-1). However, the glycerol-xantham gum solutions exhibited a higher storage modulus than the glycerol-water solutions. The observed shifts in the SMD values for the glycerol-xantham gum solution is a function of the viscoelastic properties of this solution. This is an indication that the storage modulus exerts a direct influence on fine spray production.

The glycerol solution atomization data were further used to fit Equation 4-20. Figure 5-3 shows a plot of SMD as a function of $(1+\frac{F}{A})$. Linear regression analysis was used to determine whether the empirical model, (Equation 4-20) could describe the atomization data effectively. A good correlation was obtained for the glycerol-water solution, but not for the glycerol- xantham gum solution.

According to Lefebvre [46], the average drop size is governed by air velocity, the AFR, viscosity and the surface tension of the fluid. The properties of the air are less significant and thus, the average drop size becomes more dependent on the fluid properties. Thus, equation 4-20 was further modified in order to take into account the effect of viscous forces.

5-3 Simulated non-Newtonian Spray Data.

The model equation (equation 4-20), was further modified in order to explain the atomization process for the non-Newtonian fluids. The model equation was modified by assuming that the kinetic energy transfer goes into breaking the fluid into ligaments which requires an increase in surface energy.

$$\Delta E = \Delta E_{\sigma} + \Delta E_{\mu}$$

5-1

Figure 5-3. A Plot of SMD As A Function of $(1 + \text{Fuel}/\text{Air})$
Glycerol-Water Solutions

$$\Delta E = \Delta E_{\sigma} + \Delta E_{\mu} \quad 5-1$$

where ΔE_{σ} is the increased surface energy of the spray and ΔE_{μ} is the dissipative viscous energy.

$$\Delta E = \Delta E_{\sigma} \left(1 + \frac{\Delta E_{\mu}}{\Delta E_{\sigma}} \right) \quad 5-2$$

Expressing $\frac{\Delta E_{\mu}}{\Delta E_{\sigma}}$ as $k \frac{Re^{-1}}{We^{-1}}$ and substituting in Equation 5-2, yields:

$$\Delta E = \Delta E_{\sigma} \left(1 + k \frac{Re^{-1}}{We^{-1}} \right) = \frac{\Delta E_{\sigma}}{We^{-1}} (We^{-1} + kRe^{-1}) \quad 5-3$$

where the Reynolds number, $Re = \rho_F \frac{VD_F}{\mu}$ is the ratio of the inertial to viscous forces in the fuel flowing through a passage with diameter, D_F , with viscosity, μ , and velocity, V , and the Weber number, $We = \frac{\rho_A V_A^2 L}{\sigma}$, represents the ration of inertial forces due to air velocity, V_A , and the surface forces, L is the characteristic length, and k is a constant.

It follows that:

$$\frac{We^{-1}}{(We^{-1} + kRe^{-1})} \Delta E = \frac{3\sigma M_F}{\rho_F S M} \quad 5-4$$

This can be expressed as:

$$\frac{\sigma}{\rho_A V_A L} \frac{M_A M_F}{(M_A + M_F)} \frac{V_A^2}{(We^{-1} + kRe^{-1})} = \frac{3\sigma M_F}{\rho_F S M} \quad 5-5$$

which results in

$$\frac{SMD}{L} = \frac{1}{3} \frac{\rho_A}{\rho_F} (We^{-1} + kRe^{-1}) \left(1 + \frac{M_F}{M_A} \right) \quad 5-6$$

The above equation was finally expressed in the form:

$$\frac{SMD}{L} = \frac{1}{3} \frac{\rho_A}{\rho_F} We^{-1} \left(1 + \frac{M_F}{M_A} \right)^m + \frac{1}{3} \frac{\rho_A}{\rho_F} Ck\gamma^n \left(1 + \frac{M_F}{M_A} \right)^b \quad 5-7$$

The above equation shows that there are two possible mechanisms responsible for the fluid breakup. The first term is due to competition between surface tension forces and aerodynamic shearing force, and the second term is due to the competition between viscosity forces and surface tension forces. The modified model equation, (equation 5-7), was applied to the glycerol-xantham gum data in order to determine the exponents in equation 5-7. A fit of the glycerol-xantham gum solution atomization data to equation 5-7, suggests that the model equation can best be represented when $m=1.2$ and $b=0.2$. For comparison purposes, a fit of the experimental data to equation 4-20 and equation 5-7 for the glycerol-xantham gum solutions are as shown in

Figure 5-4. A better correlation was obtained when the glycerol-xanthan gum solution atomization data was used to fit Equation 5-7 compared to 4-20.

5-4 Coal-Water Spray Data

Several CWS samples were sprayed using the Malvern Instruments particle size analyzer. The drop size data are presented in Figures 5-3. This Figure also shows the effect of AFR on SMD. An increase in the AFR decreases the SMD values. The values also suggest that low SMD values can be obtained using the Delavan solid cone nozzle, depending on the formulation of the CWS. The data indicate that in the high AFR regime, the SMD values obtained for the CWS are higher than those obtained for the Newtonian and non-Newtonian fluids. This is an indication that the presence of the solids tend to influence the size of the spray droplets.

A fit of the experimental data to equation 4-20 and equation 5-7 for the CWS samples are as shown in Figures 5-8 through 5-10. There was a better fit of the data to Equation 5-7 than that obtained for equation 4-20 for both the Unclean slurry and the Flotation cleaned slurry. There was however, no significant difference between the results obtained for the Heavy media cleaned slurry using Equation 5-7 and equation 4-20 (Figure 5-9). The viscoelastic behavior and the high shear flow behavior of these samples are shown in Figures 3-20 through 3-24 and Figure 3-31. The high shear flow behavior of these samples are almost identical (Figure 3-31) and in the shear rate regime of 100,000/s, they have almost identical shear viscosity. Figures 3-21 through 3-25 however, indicate the Uncleaned CWS had the highest storage modulus at all solids loadings. The Uncleaned CWS also produced larger droplet sizes at all AFR than the clean CWS samples.

Oliver and Young-Hoon [47] have previously observed that fluids of increasing pseudoplasticity have lessened interaction between the phases and that viscoelasticity damps

Figure 5-4. A Plot of SMD As A Function of $(1 + \text{Fuel}/\text{Air})$
Glycerol-Xanthan Gum Solution

TABLE 5-3**ATOMIZATION DATA (COAL-WATER SLURRY 63%-Unclean)**

VISCOSITY	A/F	SURFACE TENSION	DENSITY	SMD
(Pa.s)**		dynes/cm	g/ml	μM
94	.441	67	1.16	38.5
94	.414	67	1.16	69.6
94	.347	67	1.16	95
94	.281	67	1.16	129
94	.186	67	1.16	251
94	.145	67	1.16	354

TABLE 5-4**ATOMIZATION DATA (COAL-WATER SLURRY (60%-Unclean)**

VISCOSITY	A/F	SURFACE TENSION	DENSITY	SMD
(mPas)**		dynes/cm	g/ml	μM
81	.421	67	1.16	33.5
81	.387	67	1.16	66.6
81	.334	67	1.16	97.2
81	.281	67	1.16	135.5
81	.196	67	1.16	188
81	.156	67	1.16	321

**** VISCOSITY AT A SHEAR RATE OF 100,000/S.**

TABLE 5-5**ATOMIZATION DATA (COAL-WATER SLURRY MIXTURE 63%- Flotation Cleaned)**

VISCOSITY	A/F	SURFACE TENSION	DENSITY	SMD
(mPas)**		dynes/cm	g/ml	μM
91.4	.427	67	1.14	24.5
91.4	.401	67	1.14	52.6
91.4	.336	67	1.14	84.0
91.4	.271	67	1.14	163
91.4	.207	67	1.14	176
91.4	.127	67	1.14	256

TABLE 5-6**ATOMIZATION DATA (COAL-WATER SLURRY MIXTURE 60- Flotation Cleaned)**

VISCOSITY	A/F	SURFACE TENSION	DENSITY	SMD
(mPas.s)**		dynes/cm	g/ml	μM
89.2	.412	67	1.14	23.1
89.2	.396	67	1.14	48.6
89.2	.318	67	1.14	67.2
89.2	.284	67	1.14	79.2
89.2	.216	67	1.14	135.3
89.2	.191	67	1.14	207

**** VISCOSITY AT A SHEAR RATE OF 100,000/S.**

TABLE 5-7**ATOMIZATION DATA (COAL-WATER SLURRY MIXTURE (63% -Heavy media)**

VISCOSITY	A/F	SURFACE TENSION	DENSITY	SMD
(mPas @100,000/s)		dynes/cm	g/ml	μM
88.6	.437	67	1.16	23.6
88.6	.411	67	1.16	49.6
88.6	.340	67	1.16	75.2
88.6	.281	67	1.16	81.3
88.6	.221	67	1.16	136
88.6	.176	67	1.16	260

TABLE 5-8**ATOMIZATION DATA (COAL-WATER SLURRY MIXTURE 60% -Heavy media)**

VISCOSITY	A/F	SURFACE TENSION	DENSITY	SMD
(mPas @100,000/s)		dynes/cm	g/ml	μM
84.3	.437	67	1.16	22.4
84.3	.411	67	1.16	444.6
84.3	.340	67	1.16	71.3
84.3	.281	67	1.16	79.6
84.3	.221	67	1.16	167
84.3	.176	67	1.16	201

Figure 5-5. A Plot of SMD As A Function of Air/Fuel.
Coal-Water Slurries

Figure 5-6. A Plot of SMD As A Function of Air/Fuel
Coal-Water Slurries.

Figure 5-7. A Plot of SMD as A Function of $(1 + \text{Fuel}/\text{Air})$
Flotation Clean Coal

Figure 5-8. A Plot of SMD as A Function of $(1 + \text{Fuel}/\text{Air})$
Unclean CWS

Figure 5-9. A Plot of SMD as A Function of $(1 + \text{Fuel}/\text{Air})$
Heavy Media Clean CWS

waves that occur in air-Newtonian fluid flow. Thus, the variation in the SMD as a function of the viscoelastic property of the CWS is due to the fact that the restoring force must be overcome before a drop can break up since more energy would be required to overcome the forces associated with viscoelasticity. This property is still dominant even at high AFR for fluids that have high storage modulus. The energy associated with the large mass of air is not completely able to dominate and overcome the fluid viscoelastic properties. As a result, the SMD values at high AFR showed significant differences for the CWS atomized. This observation also, accounts for the increase drop sizes of the glycerol-xanthan gum solutions when compared to the glycerol-water solutions.

Comparison of the results obtained from the fit of the experimental data to Equation 5-7 show that the atomization of the CWS is governed by a term involving inertial forces and a term representing viscous forces. In the high AFR regime, the inertia force term is a strong function of the air velocity and the atomizer type. The viscoelastic characteristics of the CWS characterizes the viscous term in Equation 5-7 and the elastic viscosity replaces the shear viscosity for Newtonian fluids. The elastic viscosity is negligible for Newtonian fluids, but significant elastic forces are present in the CWS studied. The observed increase in drop size of the CWS from the clean slurries to the Unclean slurries depend directly on the elastic viscosities of the slurries.

Chapter 6

Conclusion and Recommendations For Future Work.

This work was proposed in order to better understand the effects of coal beneficiation on the atomization of CWS. Detailed rheological analysis of the CWS indicate that differences in the atomization behavior of the CWS can be inferred from viscoelastic measurements.

It was found to be of practical significance to simulate the CWS flow pattern flowing through the nozzle and therefore, a pipe. Thus, a capillary viscometer was used to determine a two-phase flow pattern through a series of capillary tubes of diameters 0.8, 1.5 and 3.0 mm and 100 mm in length, in order to determine the effect of solids concentration and pressure drop across the capillary tubes. Analysis of the flow data indicate that within the concentration range examined, the flow could be described as a concentric plug-flow for the different types of slurries examined.

An expression for SMD as a function of AFR was also developed using two-phase flow, momentum and energy conservations. The model developed in sections 4-5 and 5-4 were applied to the atomization data generated in the course of this work. The model in section 4-5 was found to provide a good fit to the atomization data obtained for the Newtonian fluids and a poor fit to the non-Newtonian fluids. However, a better fit was obtained when the model in section 5-4 was applied to the non-Newtonian and CWS atomization data.

The data presented in Chapter 5 indicate that the Delavan solid cone nozzle successfully atomized the CWS. The data also shows that the SMD increases as AFR decreases. This effect is more pronounced for the Unclean CWS than for the clean CWS. In the high AFR, there is no significant difference in the SMD obtained for the different CWS. This observation is due to the

fact that, in order to transfer the energy of the air to the fluid, both the air and the fluid must establish good contact. At low AFR, the atomizing air is surrounded with the fluid that shields it from losses to the ambient so that a large portion of the atomizing energy goes into increasing the fluid surface energy, causing a break of the fluid into ligaments. As AFR increases however, the air shield in the fluid becomes thinner resulting in the production of fine droplets. Energy losses are therefore minimized and the effect of AFR is levelled off.

The data further reveals that the SMD increase with increase in the elastic viscosity of the CWS. This trend indicate that there is energy loss associated with overcoming the stored energy present in the slurries and this is more pronounced in the Uncleaned slurry than the clean slurries. This stored energy makes it more difficult to atomize the Uncleaned slurries compared to the clean slurries. The Heavy Media cleaned slurry had a lower storage modulus (G') among the three slurries examined, and this slurry produced the smallest sized droplets at all AFR. The beneficiation of the coal samples thus, results in a significant reduction of the SMD relative to the Unclean samples.

Recommendations For Future Work

This study indicate that the Unclean CWS exhibited a higher storage modulus compared to the clean CWS. This observation is due to the fact that the presence of multi-charged cations present in the ash contribute to the crosslinking of the polymer (flocon) added to stabilize the CWS and therefore, make the CWS more difficult to atomize.

Thus, a systematic study of the correlation of the viscoelastic behavior of CWS, with the variation of the amount of multi-charged cations present in the CWS containing polymer additives, and their effect on the production of fine spray droplets should be made.

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MALVERN

Instruments SB.8D

14 Jul 1994

3:44 pm

SAMPLE: Air: 2.0 scmh Flot clean Slurry 32 ml/min
 Lens: 300 mm 22.4 mm
 Distance: 14" from lens 5" from nozzle

000000000000770

Air guage: 14 psig Mixing Energy: hp-hr/1000# liq.
 Liquid guage: psig Solids 64.0%
 Additive: Density g/ml
 Viscosity: cp Yieldstress: dynes/cm2

Upper	in	Lower	Under	Upper	in	Lower	Under	Upper	in	Lower	Under	Span
				173	2.2	150	86.2	29.5	6.0	25.4	22.7	4.12
				150	2.8	129	83.4	25.4	5.2	21.9	17.6	D[4,3]
				129	3.0	111	80.4	21.9	4.3	18.9	13.3	85.33µm
				111	2.9	96.0	77.5	18.9	3.4	16.3	9.9	
564	1.8	487	98.2	96.0	3.7	82.5	73.8	16.3	2.7	14.1	7.2	D[3,2]
487	1.7	420	96.5	82.5	4.6	71.5	69.2	14.1	2.2	12.1	5.0	33.11µm
420	1.6	362	94.8	71.5	5.8	61.5	63.3	12.1	1.7	10.4	3.4	
362	1.5	313	93.4	61.5	6.4	53.0	56.9	10.4	1.1	9.05	2.3	D[v,0.9]
313	1.3	270	92.0	53.0	6.7	45.8	50.2	9.05	0.7	7.80	1.6	204.65µm
270	1.1	233	91.0	45.8	7.2	39.5	43.1	7.80	0.6	6.70	1.0	
233	1.1	201	89.8	39.5	7.4	34.1	35.7	6.70	0.5	5.80	0.6	D[v,0.1]
201	1.5	173	88.3	34.1	6.9	29.5	28.8	5.80	0.6	1.50	0.0	16.38µm
Source = :Sample				Beam length = 22.4 mm				Model indp				D[v,0.5]
				Log. Diff. = 2.258								45.64µm
Focal length = 300 mm				Obscuration = 0.1825				Volume Conc. = 0.0099%				
Presentation = lds				Volume distribution				Sp.S.A 0.1812 m²/cc.				Shape OFF

Malvern Instruments

MALVERN

Instruments SB.0D

14 Jul 1994

3:02 pm

SAMPLE: Air: 2.5 scmh Unclean Slurry 32 ml/min
 Lens: 300 mm 22.4 mm
 Distance: 14" from lens 5" from nozzle

000000000000768

Air guage: 34 psig Mixing Energy: hp-hr/1000# liq.
 Liquid guage: psig Solids 61.8%
 Additive: Density g/ml
 Viscosity: cp Yieldstress: dynes/cm²

Upper	in	Lower	Under	Upper	in	Lower	Under	Upper	in	Lower	Under	Span
				173	1.5	150	92.7	29.5	8.2	25.4	33.2	3.20
				150	2.2	129	90.5	25.4	8.2	21.9	25.0	D[4,3]
				129	2.9	111	87.6	21.9	7.5	18.9	17.5	61.87µm
				111	3.3	96.0	84.3	18.9	5.9	16.3	11.5	D[3,2]
564	0.9	487	99.1	96.0	3.6	82.5	80.7	16.3	4.2	14.1	7.3	29.33µm
487	0.8	420	98.3	82.5	3.5	71.5	77.3	14.1	2.8	12.1	4.5	D[v,0.9]
420	0.8	362	97.5	71.5	3.8	61.5	73.5	12.1	1.9	10.4	2.6	125.30µm
362	0.7	313	96.8	61.5	4.2	53.0	69.2	10.4	1.2	9.05	1.5	D[v,0.1]
313	0.6	270	96.2	53.0	5.2	45.8	64.1	9.05	0.7	7.80	0.8	15.55µm
270	0.5	233	95.7	45.8	6.6	39.5	57.5	7.80	0.4	6.70	0.3	
233	0.6	201	95.2	39.5	7.8	34.1	49.7	6.70	0.2	5.80	0.1	
201	0.9	173	94.2	34.1	8.2	29.5	41.4	5.80	0.1	1.50	0.0	
Source = :Sample				Beam length = 22.4 mm				Model indp				D[v,0.5]
				Log. Diff. = 2.388								34.30µm
Focal length = 300 mm				Obscuration = 0.0777				Volume Conc. = 0.0035%				
Presentation = lds				Volume distribution				Sp.S.A 0.2045 m ² /cc.				Shape OFF

Malvern Instruments

MALVERN

Instruments SB.0D

14 Jul 1994

1:41 pm

SAMPLE: Air: 3.0 scmh Glycerol/xanthan gum 32 ml/min
 Lens: 300 mm 22.4 mm
 Distance: 14" from lens 5" from nozzle

000000000000736

Air guage: psig Mixing Energy: hp-hr/1000# liq.
 Liquid guage: psig
 Additive: Density 1.14 g/ml
 Viscosity: cp Yieldstress: dynes/cm2

Upper	in	Lower	Under	Upper	in	Lower	Under	Upper	in	Lower	Under	Span
				173	1.9	150	96.2	29.5	8.2	25.4	32.5	2.79
				150	2.7	129	93.5	25.4	7.0	21.9	25.5	D[4,3]
				129	2.9	111	90.7	21.9	5.5	18.9	20.0	47.85µm
				111	2.5	96.0	88.2	18.9	3.8	16.3	16.2	
564	0.0	487	100	96.0	2.8	82.5	85.4	16.3	2.7	14.1	13.6	D[3,2]
487	0.0	420	99.9	82.5	3.4	71.5	81.9	14.1	2.3	12.1	11.2	23.31µm
420	0.1	362	99.9	71.5	4.7	61.5	77.2	12.1	2.5	10.4	8.7	
362	0.1	313	99.8	61.5	5.7	53.0	71.5	10.4	2.3	9.05	6.4	D[v,0.9]
313	0.1	270	99.7	53.0	6.0	45.8	65.5	9.05	1.8	7.80	4.5	106.78µm
270	0.1	233	99.6	45.8	7.0	39.5	58.5	7.80	1.5	6.70	3.1	
233	0.4	201	99.2	39.5	8.7	34.1	49.8	6.70	1.2	5.80	1.9	D[v,0.1]
201	1.0	173	98.2	34.1	9.1	29.5	40.7	5.80	1.9	1.50	0.0	11.29µm
Source = :Sample				Beam length = 22.4 mm				Model indp				D[v,0.5]
				Log. Diff. = 2.537								34.20µm
Focal length = 300 mm				Obscuration = 0.0534				Volume Conc. = 0.0019%				
Presentation = lds				Volume distribution				Sp.S.A 0.2574 m ² /cc.				Shape OFF

Malvern Instruments

MALVERN

Instruments SB.8D

14 Jul 1994

4:20 pm

SAMPLE: Air: 2.0 scmH HEAVY MEDIA SLURRY 32 ml/min
 Lens: 300 mm 22.4 mm
 Distance: 14" from lens 5" from nozzle

000000000000787

Air guage: 50 psig Mixing Energy: hp-hr/1000# liq.
 Liquid guage: psig Solids .0%
 Additive: Density g/ml
 Viscosity: cp Yieldstress: dynes/cm²

Upper	in	Lower	Under	Upper	in	Lower	Under	Upper	in	Lower	Under	Span
												2.80
				173	1.0	150	97.9	29.5	5.4	25.4	46.8	
				150	1.5	129	96.5	25.4	5.1	21.9	41.7	D[4,3]
				129	1.9	111	94.6	21.9	5.2	18.9	36.5	40.21µm
				111	2.3	96.0	92.3	18.9	5.6	16.3	30.8	
564	0.0	487	100	96.0	3.9	82.5	88.4	16.3	5.7	14.1	25.1	D[3,2]
487	0.0	420	100	82.5	5.2	71.5	83.2	14.1	5.3	12.1	19.8	18.75µm
420	0.0	362	100	71.5	5.5	61.5	77.7	12.1	5.5	10.4	14.4	
362	0.0	313	100	61.5	4.4	53.0	73.3	10.4	4.7	9.05	9.6	D[v,0.9]
313	0.0	270	100	53.0	4.0	45.8	69.3	9.05	3.6	7.80	6.0	87.07µm
270	0.1	233	99.9	45.8	4.8	39.5	64.6	7.80	2.5	6.70	3.6	
233	0.3	201	99.6	39.5	6.2	34.1	58.4	6.70	1.6	5.80	2.0	D[v,0.1]
201	0.6	173	99.0	34.1	6.2	29.5	52.2	5.80	2.0	1.50	0.0	9.16µm
Source =	:Sample			Beam length = 22.4 mm				Model indp				D[v,0.5]
				Log. Diff. = 2.739								27.83µm
Focal length =	300 mm			Obscuration = 0.1129				Volume Conc. = 0.0033%				
Presentation =	lds			Volume distribution				Sp.S.A 0.3201 m ² /cc.				Shape OFF

Malvern Instruments

* * *

A P P A A R

H V A - 6

* * *

R E S U L T S from 04/04/1994

Operator : Terrance File : OHUNL8A
Sample : uncleaned Number : 1
Solvent : 1000
Density (kg/m3) : 1096 Temperature($\frac{1}{2}$ C) : 25
Capillary-length (mm) : 100.00 Capillary-diameter (mm) : 0.800

HVA 6 - Table lin (measured)

No.	TAU(Pa)	TAU corr(Pa)	D(1/s)	ETA(Pa.s)	Reynolds	tv(s)
1	1.840E+03	1.834E+03	1.557E+04	0.1178	12	0.0642
2	2.360E+03	2.350E+03	1.990E+04	0.1181	15	0.0502
3	2.800E+03	2.787E+03	2.273E+04	0.1226	16	0.0440
4	3.360E+03	3.340E+03	2.878E+04	0.1160	22	0.0347
5	3.920E+03	3.891E+03	3.419E+04	0.1138	26	0.0292
6	4.680E+03	4.639E+03	4.082E+04	0.1136	31	0.0245
7	5.580E+03	5.522E+03	4.879E+04	0.1132	38	0.0205
8	6.640E+03	6.557E+03	5.798E+04	0.1131	45	0.0172
9	7.860E+03	7.735E+03	7.144E+04	0.1083	58	0.0140
10	9.140E+03	8.937E+03	9.093E+04	0.0983	81	0.0110
11	1.016E+04	9.957E+03	9.093E+04	0.1095	73	0.0110

* * *

A P P A A R

H V A - 6

* * *

R E S U L T S from 11/07/1993

Operator : ohene File : FC63A
Sample : floatation 63%, xanthum gum Number : 1
Solvent : 1000
Density (kg/m3) : 1028 Temperature($\frac{1}{2}$ C) : 20
Capillary-length (mm) : 100.00 Capillary-diameter (mm) : 0.800

HVA 6 - Table lin (measured)

No.	TAU(Pa)	TAU corr(Pa)	D(1/s)	ETA(Pa.s)	Reynolds	tv(s)
1	9.800E+02	9.785E+02	7.954E+03	0.1230	5	0.1257
2	1.600E+03	1.594E+03	1.607E+04	0.0992	13	0.0622
3	2.320E+03	2.308E+03	2.313E+04	0.0998	19	0.0432
4	2.820E+03	2.802E+03	2.817E+04	0.0994	23	0.0355
5	2.920E+03	2.897E+03	3.175E+04	0.0912	29	0.0315
6	3.600E+03	3.572E+03	3.479E+04	0.1027	28	0.0287
7	4.220E+03	4.181E+03	4.124E+04	0.1014	33	0.0242
8	4.920E+03	4.869E+03	4.707E+04	0.1034	37	0.0212
9	8.800E+03	8.440E+03	1.250E+05	0.0675	152	0.0080

* * *

A P P A A R

H V A - 6

* * *

R E S U L T S from 24/07/1993

Operator : Terr/Greg/Lon File : HVY63B
Sample : Hvy.media Number : 4
Solvent : 1000
Density (kg/m3) : 1084 Temperature($\frac{1}{2}$ C) : 20
Capillary-length (mm) : 100.00 Capillary-diameter (mm) : 0.800

HVA 6 - Table lin (measured)

No.	TAU(Pa)	TAU corr(Pa)	D(1/s)	ETA(Pa.s)	Reynolds	tv(s)
1	1.000E+03	9.987E+02	7.196E+03	0.1388	4	0.1390
2	2.020E+03	2.009E+03	2.174E+04	0.0924	20	0.0460
3	3.440E+03	3.408E+03	3.637E+04	0.0937	34	0.0275
4	4.480E+03	4.426E+03	4.707E+04	0.0940	43	0.0212
5	5.700E+03	5.613E+03	5.971E+04	0.0940	55	0.0167
6	7.020E+03	6.887E+03	7.409E+04	0.0930	69	0.0135
7	8.320E+03	8.119E+03	9.093E+04	0.0893	88	0.0110
8	1.000E+04	9.700E+03	1.111E+05	0.0873	110	0.0090
9	1.164E+04	1.124E+04	1.291E+05	0.0871	129	0.0077
10	1.262E+04	1.212E+04	1.429E+05	0.0849	146	0.0070

Sensor system : Q45

System : CV20

M-Factor : 4.3

Gap [mm] : 1

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f	δ	Eta*	G'	G''	W
[Hz]	[rad]	[Pa s]	[Pa]	[Pa]	[1/s]
1.00E-01	1.33E+00	2.09E+00	2.39E-01	1.29E+00	6.28E-01
1.47E-01	1.18E+00	2.10E+00	8.37E-01	1.75E+00	9.24E-01
2.17E-01	1.12E+00	4.89E+00	2.62E+00	6.13E+00	1.36E+00
3.19E-01	1.04E+00	4.10E+00	3.92E+00	7.22E+00	2.00E+00
4.63E-01	1.05E+00	4.36E+00	5.20E+00	1.16E+01	2.91E+00
6.79E-01	1.07E+00	3.59E+00	5.46E+00	1.43E+01	4.27E+00
1.00E+00	1.01E+00	3.78E+00	8.79E+00	2.20E+01	6.28E+00
1.45E+00	8.95E-01	3.19E+00	1.17E+01	2.66E+01	9.11E+00
2.16E+00	8.05E-01	1.15E+02	1.09E+03	1.13E+03	1.36E+01
3.13E+00	6.73E-01	1.07E+02	1.65E+03	1.32E+03	1.97E+01
4.63E+00	4.74E-01	7.36E+01	1.90E+03	9.77E+02	2.91E+01
6.94E+00	2.76E-01	5.74E+01	2.41E+03	6.82E+02	4.36E+01
9.62E+00	1.09E-01	3.78E+01	2.27E+03	2.49E+02	6.04E+01

Data sheet HAAKE OSC 2.0.5

Date: 16.06.96, 18:58

Operator: francis & kath

Sample: flot63.2%

System : CV20

M-Factor : 4.3

Gap [mm] : 1

File : A:\FLOT63.OSD

f	$\dot{\theta}$	Eta*	G'	G''	w
[Hz]	[rad]	[Pa s]	[Pa]	[Pa]	[1/s]
1.00E-01	1.33E+00	5.61E-01	6.48E-02	3.47E-01	6.28E-01
1.47E-01	1.22E+00	3.50E-01	1.27E-01	2.97E-01	9.24E-01
2.17E-01	1.12E+00	3.79E-01	2.01E-01	4.76E-01	1.36E+00
3.19E-01	9.77E-01	3.02E-01	3.23E-01	5.13E-01	2.00E+00
4.63E-01	1.03E+00	2.83E-01	3.56E-01	7.43E-01	2.91E+00
6.79E-01	1.02E+00	2.60E-01	4.52E-01	1.01E+00	4.27E+00
1.00E+00	9.66E-01	2.54E-01	6.51E-01	1.46E+00	6.28E+00
1.45E+00	8.92E-01	2.69E-01	9.92E-01	2.25E+00	9.11E+00
2.16E+00	7.83E-01	1.12E+01	1.07E+02	1.07E+02	1.36E+01
3.13E+00	5.98E-01	1.19E+01	1.94E+02	1.32E+02	1.97E+01
4.63E+00	4.07E-01	1.10E+01	2.94E+02	1.27E+02	2.91E+01
6.94E+00	2.18E-01	9.93E+00	4.23E+02	9.38E+01	4.36E+01
9.62E+00	7.73E-02	9.25E+00	5.58E+02	4.32E+01	6.04E+01

Data sheet HAAKE OSC 2.0.5

Date: 06.07.96, 16:23

Operator: francis & kath

Sample: heavy63%

Sensor system : ME15

System : CV20

A-Factor : 22

M-Factor : 3

File : A:\HY63.OSD

f	Ö	Etas*	G'	G''	w
[Hz]	[rad]	[Pa s]	[Pa]	[Pa]	[1/s]
1.00E-01	1.23E+00	1.70E-01	3.75E-02	9.98E-02	6.28E-01
1.47E-01	1.15E+00	1.60E-01	5.87E-02	1.36E-01	9.24E-01
2.17E-01	1.18E+00	1.15E-01	5.16E-02	1.48E-01	1.36E+00
3.19E-01	1.08E+00	1.03E-01	8.93E-02	1.87E-01	2.00E+00
4.63E-01	8.87E-01	1.06E+00	1.67E+00	2.60E+00	2.91E+00
6.79E-01	8.63E-01	5.44E-02	1.27E-01	1.95E-01	4.27E+00
1.00E+00	1.04E+00	7.48E-02	1.63E-01	4.41E-01	6.28E+00
1.45E+00	9.13E-01	6.83E-02	2.39E-01	5.75E-01	9.11E+00
2.16E+00	7.49E-01	8.01E-02	4.82E-01	9.74E-01	1.36E+01
3.13E+00	6.84E-01	7.58E-02	5.62E-01	1.38E+00	1.97E+01
4.63E+00	5.21E-01	7.50E-02	7.98E-01	2.03E+00	2.91E+01
6.94E+00	2.18E-01	6.55E-02	1.30E+00	2.55E+00	4.36E+01
9.62E+00	5.81E-03	7.28E-02	2.21E+00	3.81E+00	6.04E+01