TEMPERATURE AND HIGH SHEAR VISCOSITY ON THE HANDLING OF COAL-WATER SLURRIES

Frank Ohene, Keith Bowman, Antonio Williams and Bryan Obonna
Chemistry Department, Grambling State University
Grambling, La 71270
and
John P. Dooher
Physics Department, Adelphi University
Garden City, NY 11530

ABSTRACT

An experimental study of the effect of high shear rheology and temperature on coal-water slurry, (CWS), was studied. Slurries for this study were formulated in our laboratory from four different coals, ranging from subbituminous western coal to eastern bituminous coals in order to gain a broader understanding of the CWS behavior. All the slurries exhibited a non-Newtonian flow and the packing efficiency of the particles was found to govern the slurry behavior.

(Key Words: rheological, viscosity, particle size distribution)

INTRODUCTION

Coal-Water Slurries have the potential of a near-term replacement for fuel oil [1]. The fundamental understanding of the preparation and handling of highly loaded CWS with low viscosity and desirable atomization and combustion properties is necessary in the commercialization of the CWS [2].

The design of flow systems of suspensions with high solids content such as Coal-Water Slurries, require a detailed rheological knowledge of the suspension [3]. Mathematical models such as Bingham plastic model, Power law model, or H.-Bulkley model have been used to define the flow properties of such suspensions [4,5]. For most suspensions however, the governing parameters have to be determined experimentally. This is due to the variability in characteristics such as the particle size distribution, shape of the particles, concentration of solids, surface chemistry of the particles, and dispersants used to stabilize the suspensions [6,7].

Solids concentration and particle size have been recognized as important hydraulic variables and particle size distribution (PSD) is of considerable importance in CWS formulation [8]. However, no universally acceptable method for its incorporation into models and correlations has been established. Thus, the specific influence of the various particle size fractions on the rheology of CWS continue to receive attention.

This paper reports the results of an experimental technique of examining the various particle size fractions on CWS rheology, using a combination of a Haake RV-20 concentric cylinder viscometer and an Extrusion Rheometer.

EXPERIMENTAL

The coals used in all the experiments were from the Pennsylvania State University Coal Data Bank. The Proximate and Ultimate analyses of the coals are as shown in Table 1.

The coal samples were ground to a distribution as shown in Figure 1 and carefully screened to obtain size fractions of: -400 mesh, +400/-325 mesh, +325/-270 mesh, +270/-200 mesh and +200/-100 mesh using standard U.S sieve screens. Slurries were prepared from blended distributions as shown in Table 2 and using either an ammonium naphthalene sulfonate (A-23) or Igepal 990 as an additive. Each slurry was made using a dosage of 0.3% dispersant based on dry coal and at a pH of 10. The packing concentrations were calculated from particle size distribution measurements obtained by using a Microtrac Particle Size Analyzer Model 2600, and a program based on truncated log-normal distribution which has been developed at the Adelphi Center for Energy Studies. The packing concentrations calculated increased with increase in the number of fines (-325 mesh) to a value of 40 % fines by weight. Above a value of 40% fines, the packing concentration decreased.

Rheological Testing

A Haake RV-20 concentric cylinder viscometer and an Extrusion Rheometer were used to determine the rheological properties of the CWS at low and high shear rates. In The RV-20, the slurry is sheared in the annular gap between a rotating bob and a 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 temperature tempering vessel (enclosed in a steel container to prevent moisture loss) connected with a constant temperature bath. The temperature can be controlled to ± 0.01°C.

The viscometer is integrated with an IBM ps/2 data acquisition and analysis system. The signals from the viscometer is monitored twice per second and converted to torque and rotational speed values. Viscosity as a function of shear rate was computed using one of the following flow models:

$\tau=\tau_o + \mu_p\gamma^{\cdot}$ (Bingham law) (1)

$\tau=K\gamma^{\cdot n}$ (Power law) (2)

$\tau= \tau_o + K\gamma^{\cdot n}$ (H.-Bulkley law) (3)

Where:

τ_o is the yield value

K is the flow consistency number

n is the flow behavior index.

n= 1 for a Newtonian flow

< for a pseudoplastic material

and > for a dilatant material.

Figure 2 shows a typical flow curve for a CWS formulated at 65% solids content generated in this viscometer. The shear rate, to which the sample was subjected, was continuously increased from zero to a maximum determined by the viscosity of the CWS (curve 1). Curve 2 decreased to zero, curve 3 increased to a maximum, and curve 4 decreased to zero. The viscosity measurements were taken from curve 3, which represents the fluid after it has been sheared and its structure broken down.

RESULTS AND DISCUSSION:

Effect of Particle Size Distribution on Rheology of CWS.

Figure 3 shows the effect of particle size distribution on the flow behavior of the slurries. Table 3 lists the rheological data evaluated from these flow curves. The particle size distribution was formulated according to the information contained in Table 2, and all the slurries contained 65% solids content and 0.3% A-23 dispersant.

Rheological analyses of the flow curves show that the flow behavior changed from dilatant to pseudoplastic as the packing concentration increased. Also, the viscosity was found to decrease with increase in the packing concentrations of the slurries. This is an indication that a wider distribution is indeed necessary for more efficient packing.

Effect of Shear Rate on Flow Behavior

Figure 4 is the flow behavior of 63% solids loading of the four coals listed in Table 1. Their rheological properties are listed in Table 4. All the samples exhibit a pseudoplastic behavior with yield at this slurry concentration. PSOC-1493 and 1494 however, have higher yield values and viscosities relative to PSOC-1487 and 1475.

Previous studies on the effect of coal properties on slurry quality show that the acidic functional groups on the coal surface as well as the equilibrium moisture content of the coal samples have an adverse effect on the slurry quality [9,10,11]. ESCA analysis of these samples show a higher degree of carboxylic functional groups on PSOC-1494 and 1493 relative to PSOC-1475 and 1487. The differences in the flow patterns observed may be due to their characteristic properties.

High shear Rheology of 65% solids content of PSOC-1475 was determined using an Extrusion Rheometer. This device determines the apparent viscosity of the slurry under flowing conditions. The CWS volume flow rate, Q, and pressure drop, ΔP, were measured for laminar flow through a tube of Length, L, and radius, R. The shear stress, τ_p, and the shear rate, $\gamma^{\cdot}$, were obtained from the pipeline flow data as follows:

The shear stress at the pipe wall, τ_p, can be defined as:

$$\tau_p = \frac{R}{2} \left(\frac{\Delta P}{L}\right) \qquad (4)$$

against a pipe flow characteristic, Γ, given by:

$$\Gamma = \frac{4\,(Q)}{\pi R^3} \qquad (5)$$

where $\Delta P/L$ is the pressure gradient along the tube of length, L

Q is the volumetric flow

and R is the tube inside radius.

Γ relates to $\dot{\gamma}$ through the Rabinowitsch-Mooney relation [12]:

$$\dot{\gamma}_p = (1/4)\Gamma[(3+(d\ \ln\Gamma/d\ \ln\tau_p)] \qquad (6)$$

The apparent viscosity of the suspension then is given by

$$\eta=\tau_p/\dot{\gamma}_p \qquad (7)$$

The data obtained from the Extrusion Rheometer are shown in Table 5. Figure 5 is the rheogram generated from this data. Rheological analysis shows that the rheogram can be described by the relation:

$$\tau = 1.4 + 0.84\ (\dot{\gamma})^{0.96} \qquad (8)$$

The apparent viscosities of the slurry as a function of shear rate are listed in Table 6. There is a decrease in viscosity with increase in shear rate to a value of 4000 s^{-1} due to the existence of yield stresses, but the viscosity remains fairly constant after a shear rate of 4000 s^{-1}.

Effect of Temperature

The variation of viscosity of 67% solids of PSOC-1475 as a function of temperature is shown in Figure 6. The viscosity of CWS was found to decrease with increase in temperature between 19 °C and 50 °C. However, with Igepal 990 as an additive, there was an increase in viscosity between 45 °C and 60 °C. It is apparent that the flow behavior of the slurry in the low temperature range is governed by the behavior of water. Above 45°C, the flow behavior is dependent on the additive. The change in flow behavior can be caused by changes in the solubility behavior or changes in the interaction of the additive with the coal particles at higher temperatures [13]. This may explain the increase in viscosity with increase in temperature when Igepal 990 was used as a dispersant.

The high temperature behavior of CWS is of interest with regard to their atomization behavior. Thus, CWS prepared using Igepal 990 as an additive will require special handling techniques at higher temperatures.

CONCLUSION

An experimental technique of examining the influence of particle size distribution and high shear rheology of CWS has been made. The results of the study indicate a range of rheological behavior depending on solids content, particle size distribution, and coal type. Solids with low packing efficiency have relatively high time-independent yield points and also have high viscosities at a shear rate of 100 s^{-1}.

Slurries prepared from coals with low moisture content however, have low time-independent yield values compared to slurries prepared with high moisture content.

The behavior of a slurry at high temperatures is dependent on the additive type. With Igepal 990 as an additive, the slurry viscosity increases with increase in temperature indicating that preheating of such a slurry may present handling problems.

REFERENCES:

1. Manfred, R. F., and Ehrlich, S., "Combustion of Clean Coal-Water Slurry", Proc. Am. Power Conf. 1982, **44**, 1042.

2. Kikkawa, H., Okiura, K., Arikawa, Y., Hitachi, K., and Kure, K., "Development of Highly Loaded CWM Preparation System". Proc. Sixth Int'l. Symp. on Coal Slurry Fuels Preparation and Utilization, 1984, 949.

3. Faddick, R.R., Proc. 3rd Int'l Conf. on Hydr. Transp. of solids in Pipes. Banff, Canada, 1976, May 18-21.

4. Hoffman, R. L., Trans. Soc. Rheol., 1972, 16, 155.

5. Dinger, D. R., Funk, J. E., Jr., and Funk, J. E., Sr., " Rheology of High Solids Coal-Water Mixture." Proc. 4th Intl. Symp. on Coal Slurry Combustion, Orlando, Fl., (1982)

6. Cluine, J. S., and Ingram, B.T., in "Adsorption from solutions at the Solid/Liquid Interface." (G.D. Praffit and C. H Rochester, Eds.), Academic Press, New York, 1983, p. 105.

7. Fuerstenau, D. W., Resenbaum, J. M. and J. Laskowski, Colloids and Interface Science, 1983, **8**, 153.

8. Mooney, M., "Viscosity of a Concentrated Suspension of Spherical Particles", J. Coll. Sci., 1951, 6, 162.

9. Botsaris, G. D. and K. N. Astill, "Effect of Interaction Between Particles On The Viscosity Of Coal Water Slurries". Proc. 6th Intl. Symp. on Coal Slurry Combustion and Technology, Orlando, Fl., 1984, 304.

10. Casassa, E. Z., G. D. Parfitt, A. S. Rao and E. W. Toor, "The Effects of Surface Active Agents On Coal-Water Slurry Stability". Proc. 6th Intl. Symp. on Coal Slurry Combustion and Technology, Orlando, Fl., 1984, 251.

11. Ohene, F., Third Quarterly Report. DOE/DE-FG22-88PC925 (1988).

12. Antonini, G., Francois, O., Gislais, P., and A. Touret, "A Direct Rheological Characterization Of Highly Loaded Coal-Water Slurries Flowing Through Pipes". Proc. 6th Intl. Symp. on Coal Slurry Combustion and Technology, 1984, 899.

13. Rosen,M. J. "Surfactants and Interfacial Phenomena". Wiley Interscience, New York, 1978.

ACKNOWLEDGEMENT

The authors will like to thank the U. S. Department of Energy for Financial Support.

Table 1

Proximate and Ultimate Analyses Of Coal Samples.

	PSOC-1494 Kentucky #9	PSOC-1487 Adaville#1	PSOC-1493 Illinois#6	PSOC-1475 Elkhorn#3
Proximate Analysis				
% Moisture	7.12	18.99	9.43	3.37
% Ash	10.97	4.55	13.74	3.22
% Volatile	35.77	34.67	34.34	36.03
% Fixed Carbon	46.14	41.78	42.50	57.38
ULTIMATE ANALYSIS				
% Ash	10.97	4.55	13.74	3.22
% Carbon	65.32	57.96	59.98	78.38
% Hydrogen	3.98	4.09	3.74	5.20
% Nitrogen	1.14	0.84	1.15	1.44
% Total Sulfur	4.50	1.06	4.51	0.95
% Oxygen	6.97	12.50	7.41	7.45
C/O	9.37	4.64	8.09	10.45
FC/VM	1.29	1.21	1.24	1.59
HG Index	72.00	61.10	62.20	58.70

Table 2

Weight Fractions And Packing Concentrations

WT %>200 MESH	WT% -200/325 MESH	WT %<325 MESH	PACKING CONCENTRATION
53.7%	8.5%	37.8%	83.4%
47.7%	9.4%	42.9%	83.1%
41.7%	9.0%	49.3%	83.6%
43.6%	9.4%	47.0%	76.4%
53%	8.3%	39.7%	85.3%
36.2%	15.4%	48.4%	72.1%
26.5%	18.1%	55.4%	73.4%
9.6%	15.6%	74.8%	69.6%
58.1%	2.2%	39.7%	85.2%

Table 3

Rheological Properties Of 65% (PSOC-1475) CWS
With Varying Packing Concentrations.

PACKING	n	τ_o	K	R^2	η_{100}(mPas)
69.6	1.036	3.25	0.276	0.99	335
72.1	0.970	2.01	0.340	0.97	320
73.4	0.907	1.76	0.322	0.98	301
76.4	0.884	4.10	0.827	0.97	248

Table 4

Rheological Properties of 63% CWS.

Sample	n	τ_o	K	R^2	η_{100}(mPas)
1494	0.680	24.0	0.676	0.86	445
1493	0.729	11.3	1.42	0.98	527
1487	0.913	0.250	0.879	0.93	293
1475	0.916	0.082	0.238	0.99	180

Table 5

Extrusion Rheometer Flow Data.

Weight of Slurry/s	Pressure (psig)	Shear Rate(s^{-1})	Shear Stress(mPa)	Viscosity mPa.s
1.6195	10	1181	7860	665
2.55	20	1866	15721	642
5.4995	30	4008	23581	588
7.3921	40	5391	31441	583
9.999	50	7292	39302	539
11.615	60	8471	47162	557
14.237	70	10383	55022	530
15.4417	80	11262	62882	558
17.4041	90	12692	70743	557
20.2955	100	14801	78603	531

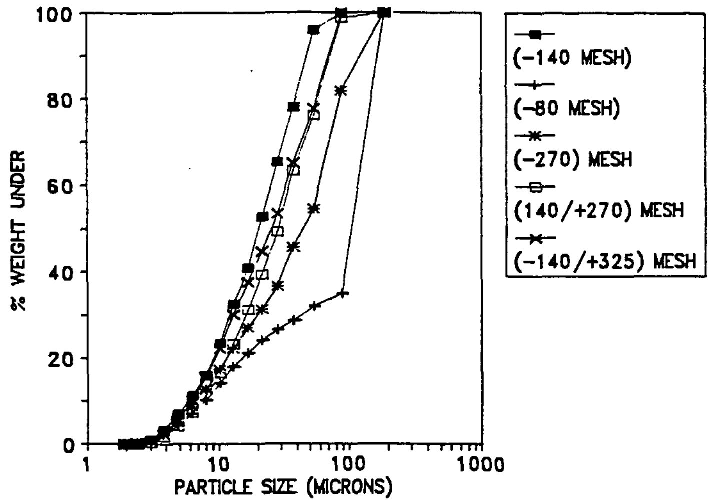

FIGURE 1. PARTICLE SIZE DISTRIBUTION

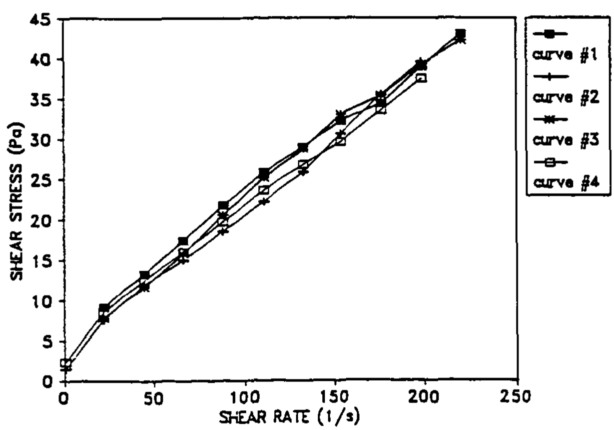

FIGURE 2. FLOW CURVE OF 65% CWS.

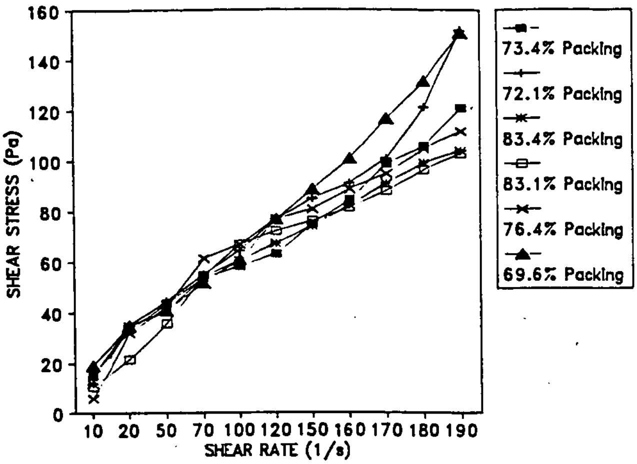

FIGURE 3. THE EFFECT OF PARTICLE SIZE DISTRIBUTION ON THE FLOW BEHAVIOR OF 65% CWS

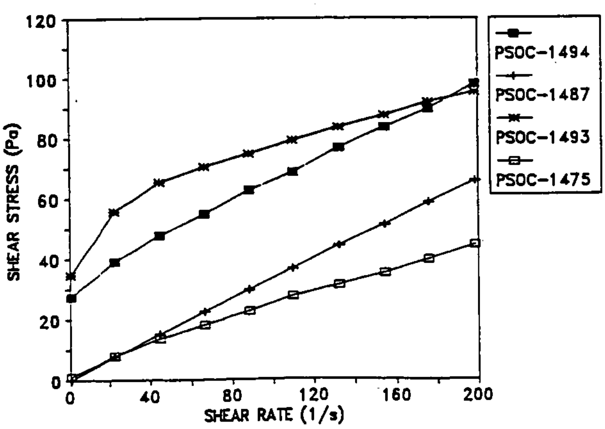

FIGURE 4. VARIATION OF VISCOSITY AS A FUNCTION OF TEMPERATURE

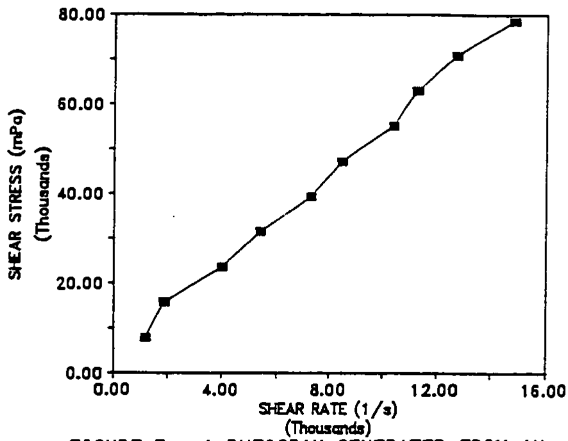

FIGURE 5. A RHEOGRAM GENERATED FROM AN EXTRUSION RHEOMETER DATA

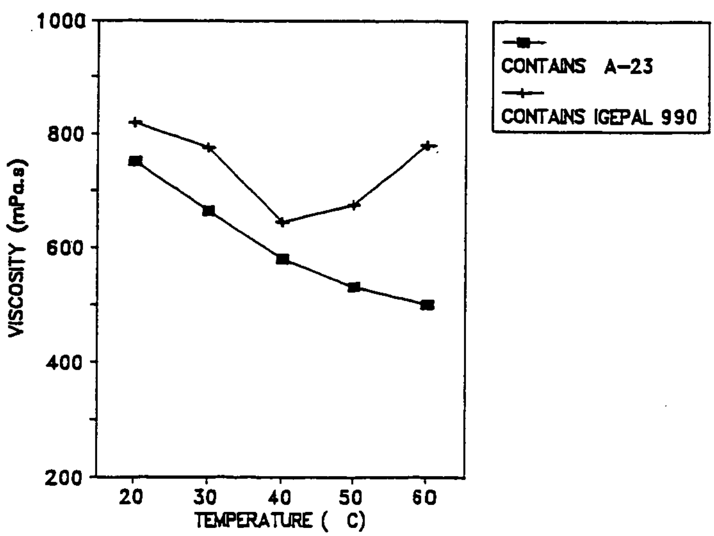

FIGURE 6. VARIATION OF VISCOSITY AS A FUNCTION OF TEMPERATURE