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Rheology of coal-water fuel from Enugu coal

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Abstract

An experimental study was undertaken to investigate the rheological properties of formulated coal-water fuel (CWF) slurries from Enugu coals. Ten slurries were prepared with varying particle size distribution. Viscosities covering a shear rate of approximately 10^4 s^{-1} were measured using three commercial viscometers. The principal conclusions of the investigations are: (1) CWFs in the 70% solid content range exhibit non-Newtonian rheological behaviour. (2) Slight dilution of highly loaded mixtures decreased the viscosity drastically which made it depart much less from Newtonian behaviour. The viscosity measurements at high shear rates have important implications related to CWF atomization relevant to burner design and subsequent combustion.

1. Introduction

Part of the investigations in the Coal Research Laboratories of the Department of Chemical Engineering, University of Science and Technology, Enugu involves the formulation of Coal-Liquid Mixtures (CLM) split into Coal-Water Mixture (CWM) and Coal Oil Mixtures (COM) (Onwu, 1999). After the beneficiation, investigations were made on the products either stabilized or unstabilised, with and without additives. This paper deals with investigation relating to their rheological properties essential for its fluid mechanics and combustion. The technology underlying modern coal-water fuel (CWF) can be sophisticated and has been delved in considerable depth by many organization as reported in several conferences namely; first, second and third European Conferences on Coal Liquid Mixtures. Fine particle science and surface chemistry (which is regulated by additives) comprise the two main aspect of the technology. These factors in turn control slurry fuel properties such as achievable solids content (concentration), viscosity, and stability. This paper represents a phenomenological study of the rheology of some ten different slurries prepared at Coal Research Laboratories from Enugu coals. Two particle size distributions were employed and five different formulations or additive samples were used for each. Also five dilutions of each of two selected slurries were made and evaluated. Blended coal from Okpara and Onyeama mines was used for the studies.

In theory, in most practical suspensions such as those of coal-water some flocculation occurs due to interparticle attraction. For that reason only empirical equations are used to describe the relative viscosity of the concentrated suspension. Of these the Mooney equation (1951) and its modification by Doughety and Krieger (1969, 1972) are perhaps the most applicable for qualitative description of the bulk viscosity (η) volume fraction of the suspension ϕ relationship, the relationship between the bulk density (η) and the volume fraction of the suspension. These are given by equations (1) and (2) respectively,

$$\eta_r = \exp\,[\eta]\,\phi \text{ ---} \quad (1)$$

$$\eta_r = [1 - (\phi/\phi_p]^{-[n]\,\phi_p} \text{ ---} \quad (2)$$

where ϕ is the volume fraction of the suspension, ϕ_p is the so called packing fraction (~0.6 for random spheres) and K is the so called crowding factor (= $1/\phi_p$) Both equations (1) and (2) predict a rapid increase in η_r with ϕ above a critical value as illustrated in Fig. 1.

2. Experimental

Raw coals used for these studies were obtained from different mines in Enugu namely Okpara and Onyeama mines and are similar to those used for previous investigation (Onwu, 1989, 2003; Akpa et al., 1987; Eneh, 1987; Mogbogu, 1988). Coal cleaning was carried out at the preparation plant after pre-treatment. After pre-treatment the coal is sent to a transfer station where it is blended (mixing), then screened and crushed with a jaw crusher below 200 mm before transferring to a coal bunker. The coal undergoes dense media preparation which effects the separation of fine coal and sand particles.

Certain properties of the washed coal were investigated including specific gravity and, sink and float analysis made so as to determine the yield of the clean coal and rejects at any given specific gravity of the dense medium. The washability curves for the blended coals were established as shown in Fig. 1. Proximate analysis was made on the coal as the first assessment of the coals; quality and type: All analyses were made on the oven dry basis (o.d.b) and for air dry basis (a.d.b). The ultimate analysis determined the carbon, hydrogen, nitrogen, sulphur, oxygen, chlorine content etc and is shown in Table 2 while proximate analysis and other properties of Enugu Coals are shown in Table 1 (Onwu, 1999).

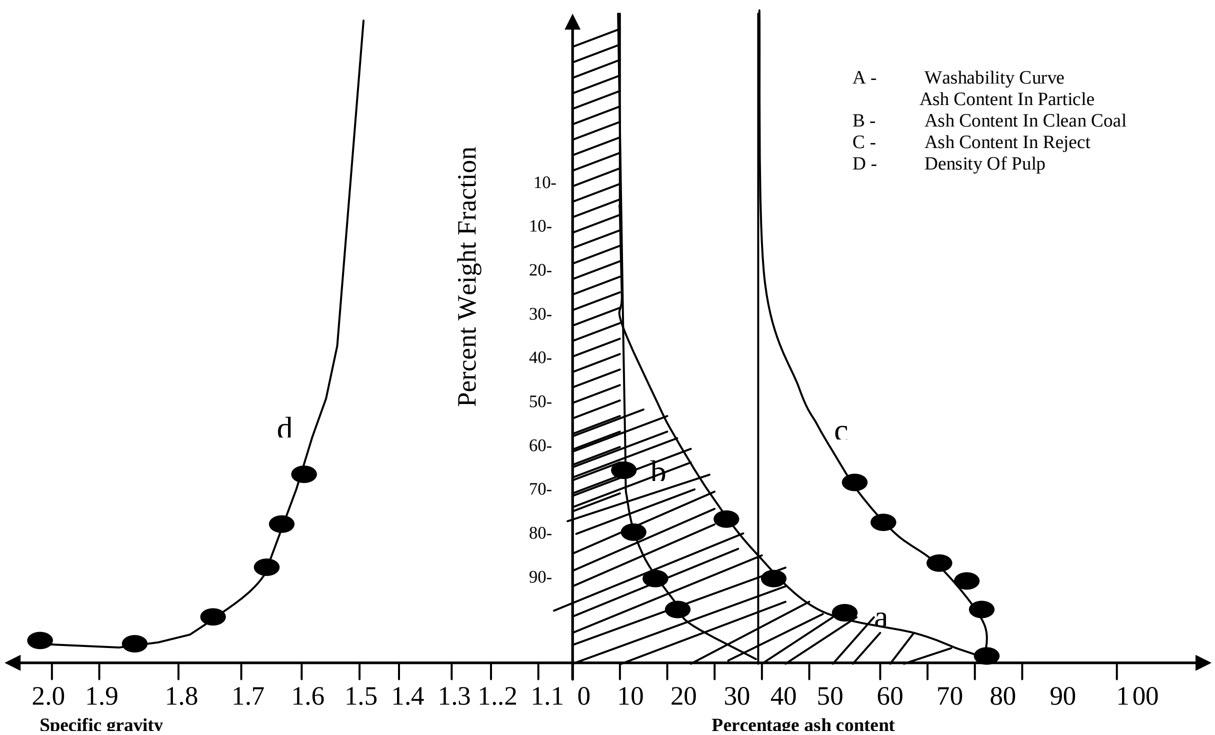

Fig. 1. Washability curves for blended okpara and onyeama.

Source: Onwu (2006)

Table 1:
Properties of Enugu coal

Property	Enugu Coal
Moisture %	3.50
Ash (d.b) %	31.60
Volatile matter (d.b) %	36.40
Volatile matter (a.d.b) %	46.40
Carbon	61.40
Fixed carbon (a.d.b) %	54.80
Fixed carbon (d.b) %	43.00
Total sulphur (d.b) %	0.79
Swelling index	-
Structural strength Mkp/kg	770
Net calorific value raw (over heating value)	5688
Power local/kg d.b	6014
a.d.b	7765
Gross calorfic value raw	5935
(Higher heating value) d.b	6243
d.a.f	8070

Source: Onwu (2006)

The analysis of the washed coal for different particle sizes are given in Table 3.

The ash was further analyzed and the result of tabulate in Table 4. The cleaned-dried coal was pulverized using a ball-mill, sieved and sized. The comprehensive size analysis for the coal used for making the slurry is given in Table 5.

Table 2
Ultimate analysis of Enugu coal

Property	Enugu Coal
Carbon	61.5 –69.4
Hydrogen	3.2 –4.3
Nitrogen	1.2 – 2.0
Sulphur	0.4 – 1.5
Oxygen	8.1 – 13.5
Hand grove Grindability index	52

Source: Onwu (2006)

Table 3
Analysis data on Enugu washed coal

Size	0-20 µm	20 - 50µ
Moisture %	4.54	4.54
Ash %	4.70	10.40
Volatile matter %	38.10	48.30
Fixed carbon %	56.30	60.20
Sulphur %	0.95	0.98
Hydrogen %	4.45	4.50
Nitrogen %	1.50	1.60
Oxygen	8.65	6.75
Carbon (total)	75. 65	76. 56

Source: Onwu (2006)

Table 4
Ash analysis of the coal sample

Sio_2%	65.40
$Al_2 O_3$ %	26.60
$Fe_2 O_3$ %	3.40
$Ti O_2$	2.00
Ca O %	0.90
K_2 O %	0.50
Ash fussion Temperature	
First sintering	1126^{o}C
Softening point	1210 ^{o}C
Melting point	1600 ^{o}C
First expansion	1465 ^{o}C

The cleaned-dried coal was pulverized using a ball-mill, sieved and sized. The comprehensive size analysis for the coal used for making the slurry is given in Table 5.

Table 5
Comprehensive size data of pulverized coal used for liquid fuel preparation

Sieve Aperture (um)	Wt Fraction Retained	Cumulative Wt Fraction Retained	Cumulative Wt Fraction Passed	Average Particle Size (um)
250	0.008	0.008	0.992	-
160	0.032	0.040	0.960	45.0
125	0.32	0.72	0.928	17.50
100	0.115	0.181	0.813	12.50
80	0.389	0.576	0.424	10.0
63	0.167	0.743	0.257	8.50
50	0.134	0.877	0.123	6.50
45	0.056	0.933	0.67	2.50
-45	0.064	0.997	0.003	-

The plot of the mass fraction of dimension noted against the average particle size is shown on Fig. 2. while the histogram is shown in Fig. 3.

From the histogram it is observed that the greatest fraction lies between 80 to 100 µm. while more than 81% of the particle sizes lies below 100µm. The size distribution of the particles is adequate for the preparation of coal liquid mixtures that is 80% of the particles below 100µm (Onwu, 1999).

The different slurries with identification and the additive packages are listed in Table 6. While particle distributions for the CWFs used in this rheological study is shown in Fig. 4.

C.G and F.G represent standard (coarse) and fine grinds respectively. Values listed in addition n columns represent relative amounts. As with all producers of CWF the exact identify of additives is regarded as proprietary; however it can be mentioned that additive A is a dispersant, B a dispersant aid and C a stabilizer all of which are commercially available. Additives B is often beneficial in reducing viscosity and increasing stability of slurries with certain coals. It can exhibit no effect or negative effect with certain coal.

Viscosities as a function of temperature has been reported by Scheffe et al. (1983) for CWFs made with Montcoal. As expected it was found that viscosity decreased with increasing temperature up to 50^0C and the decrease has also been found to continue to 150^0C for slurry under pressure. The temperature sensitivity for these CWFs is approximately the same as for water, and they are much less sensitive than fuel oil.

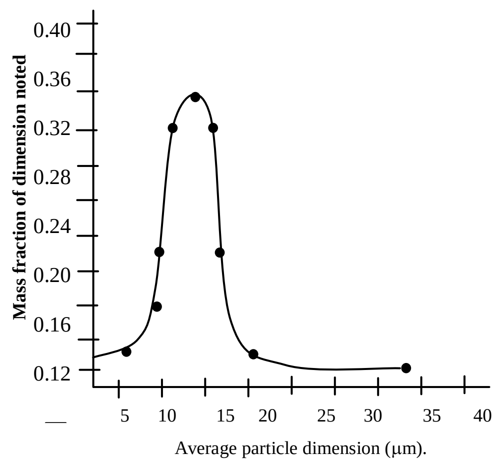

Fig. 2. Mass fraction of dimension versus average particle size

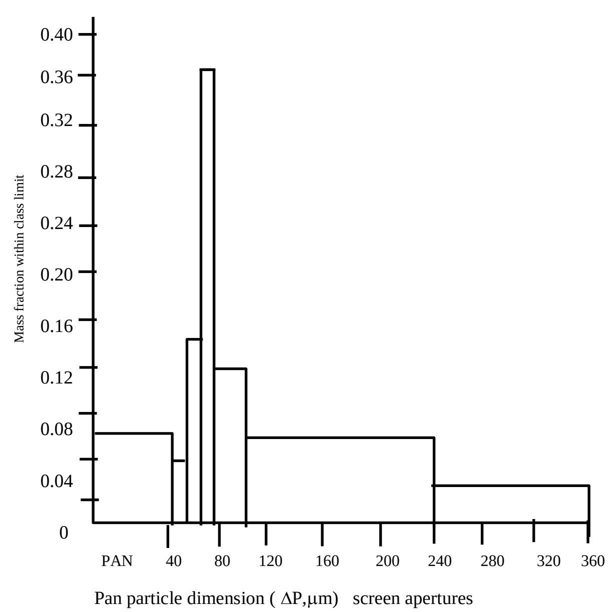

Fig. 3. Mass fraction against screen size.

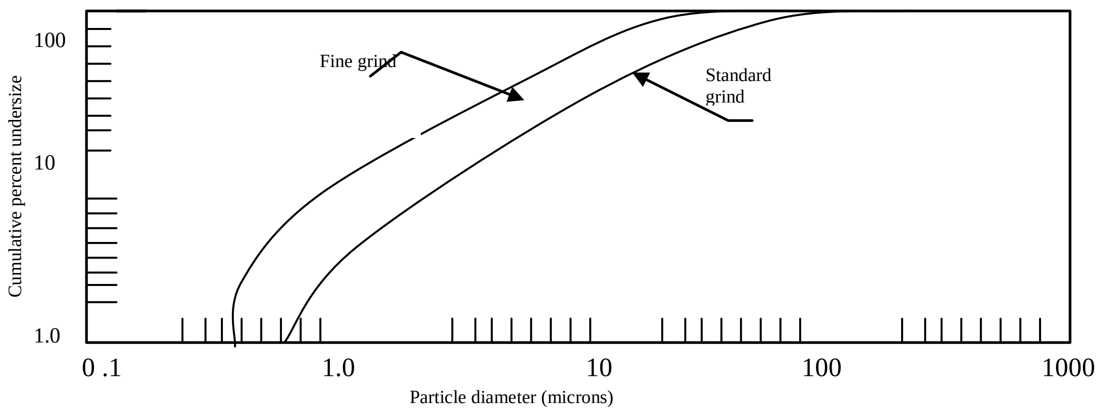

Fig. 4. Particles size distributions for cwfs used in study.

Table 6

Formulation of cwf used in rheology study

CWF.I.D	A	B	C
CG – 1	1.0	0.5	0
CG – 2	1.5	0.5	0
CD – 3	1.0	1.5	0
CG – 4	1.5	1.5	0
CG – 5	1.0	0.5	0.1
FG -1	2.5	0.5	0
FG - 2	3.5	0.5	0
FG - 3	2.5	1.5	0
FG - 4	3.5	1.5	0
FG - 5	2.5	0.5	0.1

3. Results and discussion

The size distributions for CWFs used in study is shown in Fig. 4. This is prepared specially for this rheological studies. The flow characteristics (rheology) of coal suspensions, whether in water or oil depends on a number of parameters of which the following are the most important (a) the volume fraction of the suspensions; (b) the particle size range and its distribution; (c) the interparticle interactions in the suspension which affected by the nature of surface group, the pH, pressure of electrolytes and chemical additives such as surfactants, polymers and polyelectrolyte; (d) the temperature of the suspension.

Several procedures have been applied to the preparation of the coal-liquid mixtures but they depend on the coal available and the type of mixture to be prepared. Coal is a complex substance consisting of various constituents of organic and inorganic materials. This results in the presence of various iogenic groups on the surface e.g., -C = O, -COOH (attributable to carbon surfaces) and – OH (attributable to oxide components, e.g., Silica, alumina, iron oxide, calcium oxide, magnesium oxide, etc).

In aqueous solution such surface groups dissociate and, depending on the pH, negative or positive; sites may be produced. A unique pH may be defined at which the surface group is undissociated; this is usually referred to as iso-electric point (i.e.p) or point of zero charge (p.z.c) of that of that group. The pH at the i.e.p varies from one surface group to another (Parks, 1965). For example, the silanol groups have an i.e.p. at pH 2-3 (depending on the nature of the silica surface) whereas the hydroxyl groups on an alumina surface have an i.e.p at pH 7-9 (depending on the nature of the alumina surface). In addition most coal powders contain a proportion of clay minerals whose surface charge arises from the isomorphic substitution of a Si^{4+} by AL^{3+} or Mg, $^{2+}$, resulting in a negatively charged surface with Na^{+} or Ca^{2+} counterions (van Olphen, 1977).

From the above discussion it is clear that the surface of coal is heterogeneous containing various types of surface.

Table 7

Yield point data for cwfs

CWF.I.D	Yield point (Pascals)	CWF I.D.	Yield point (Pascals)
SG – 1	3.3	SG – 1 70%	3.3
SG – 4	1.6	69%	Too low to measure
SG – 3	4.1	68%	``
SG – 4	2.4	67%	``
SG – 5	16	65%	``
FG -1	8.2	FG – 1 70%	8.2
FG - 2	6.5	69%	4.1
FG - 3	6.5	68%	2.4
FG - 4	4.9	67%	2.4
FG - 5	14	66%	2.4
		65%	1.6

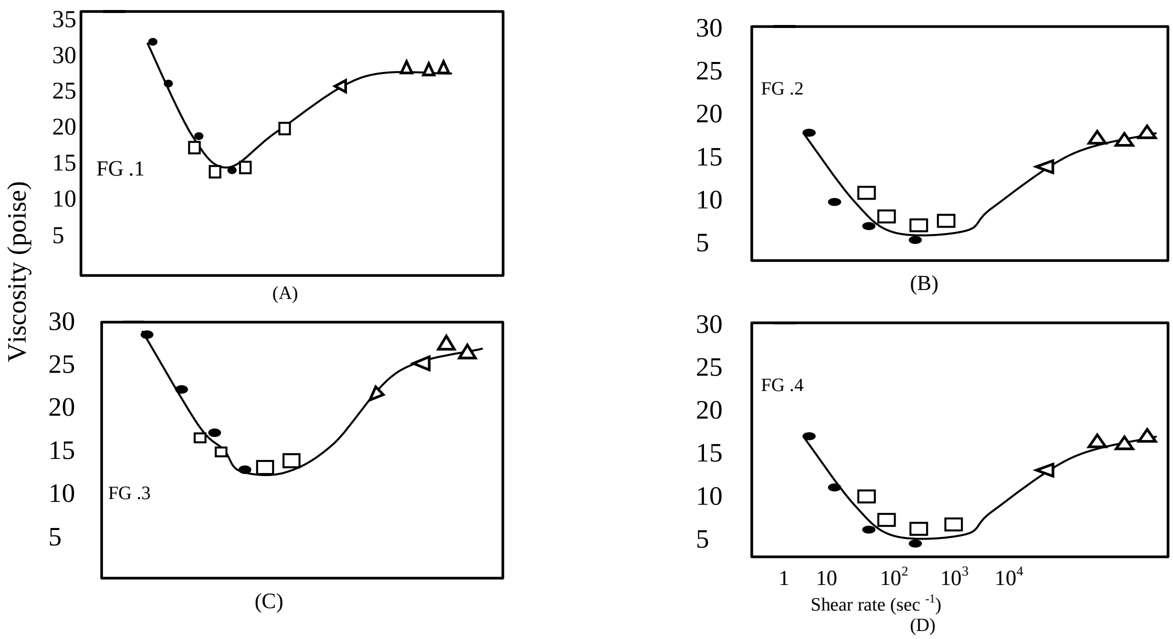

Fig. 5. Rheograms obtained for 70% fine grind CWFs made with four different additive packages.

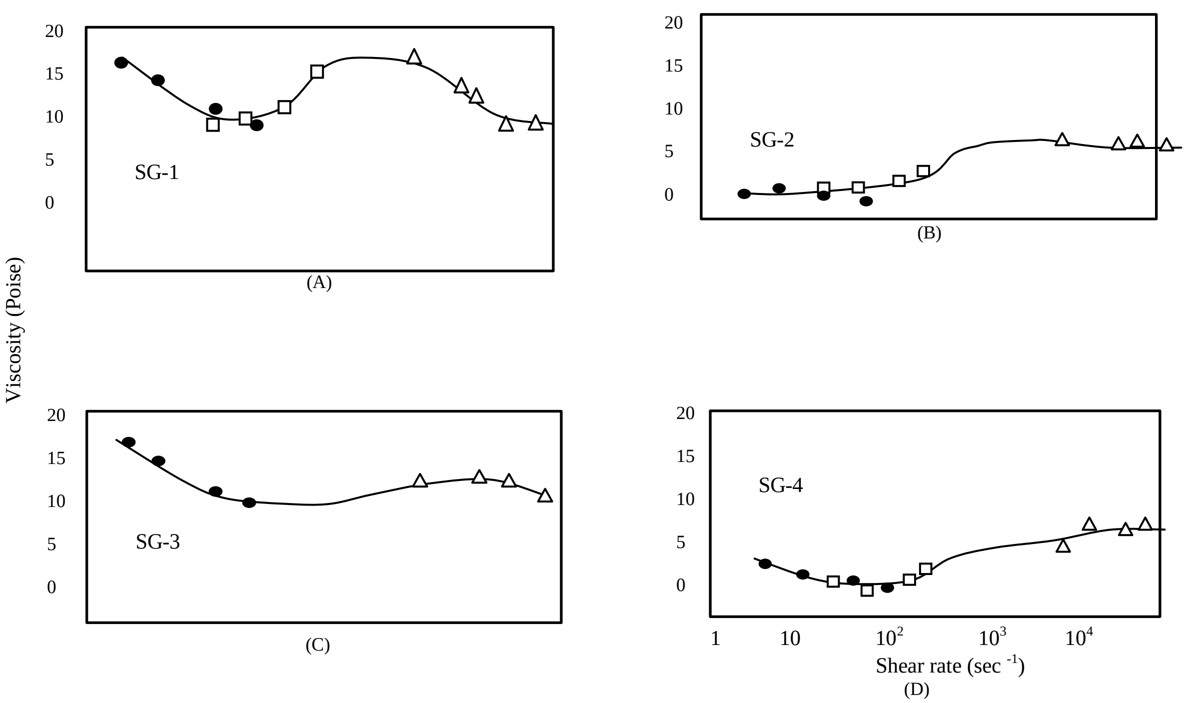

Fig. 6. Rheograms obtained for 70% standard grind cwfs made with four different additive packages.

groups whose nature and population vary from one coal to another. A suspension in water will, therefore, produce particles with various ionized surface groups and various constituents may also leach from the surface to bulk dilution, thus introducing species managing from simple electrolytes to complex hydrolysable components. It is highly unlikely that a universal chemical additive will be found for which is able to disperse coal from various sources and produce suspension with the desirable properties. For the purpose of dispersing the coal particles it is necessary to wet both the external and internal surfaces (Tadros, 1980). This is achieved by the use of surface active agents which are ionic or non-ionic and are cable of diffusing quickly to the solid/ solution interface and displacing any air the by rapidly penetrating through the channels between and the inside the agglomerates. Once such a dispersion process is completed (which is usually aided by high speed stirrers) it is necessary for the dispersing agent (which should be absorbed on the particle surface) to maintain the particles formed in a dispersed state. This is achieved by creating an energy barrier that opposes aggregation on particle approach.

The second and most important function of the dispersing agent is to lower the bulk viscosity of the suspension at the desirable volume fraction. As seen from experimental work, the bulk viscosity of the suspension can be manipulated to a large extent by controlling the particle size distribution (usually a binodial or trinodial distribution is used). However, this is not sufficient to produce low viscosity suspensions of > 60% w/w, since floculation increases the viscosity of the resulting suspension. Without additives, the viscosity usually rises and/or polymers usually shift these rapid increases in viscosity to higher concentrations. Unfortunately, this area of research is very much underdeveloped and most industries arrive at the chemical additives by simple trial and error methods. Moreover, most workers tend not to disclose the nature of the agent, because of commercial considerations or because they want to protect findings that may or may not be original.

Rheograms for CWFs, comprising two particle size distributions and five additive packages each, are shown in Figs. 5 and 6.

There are two features in these rheograms that are immediately evident. The first is that the fluids exhibit non-Newtonian behaviour over the range of shear rates. Not only is the behaviour non-Newtonian, it changes in character from pseudo plastic to dilatant, or vice versa, over the range. The second feature, with one exception, the viscosity data obtained in data agree well. The only serious disagreement occurs in Fig. 4 and is believed t be related to the high yield point found for that slurry, although the slurry of Fig. 5 also has a high yield point, and the viscometer still should treasonable agreement. The following detailed agreement can be made.

The CWF of Fig. 4 would represent a practical slurry that would show good handling properties and good atomization behaviour. The high shear viscosity is approximately 12.50 poise (1 Pa s = 10.0 poise). The addition of approximately 50% more dispersant (see Table 6) had a dramatic effect on reducing viscosity over the entire shear rate range as can be seen in Fig. 4. Addition of the dispersant aid (additive B) to either C.G.-1 or CG.2 produced little or no effect. It did however cause a small increase in the yield point for these two slurries as can be seen in Table 7. This increase in yield point would produce a slight increase in slurry stability against settling.

In the same context, the rheogram of Fig. 5 should be examined also, since this represents slurry SG-1, whose rheogram is shown but without stabilizer added. The stabilizer produced a dramatic effect in the lower shear regime, causing viscosity and yield point to increase substantially. The yield point increase was measured to be a factor of five for SG-5 the range of thousand of 5-1 was affected very little by the addition of stabilizer. There are practical implications here related to an atomization and slurry stability. The addition of stabilizer will improve slurry storage stability by creating a high yield point, but may not adversely affect the quality of atomization. This is not a proven fact but an observation that calls for further investigation.

Turning to the viscosity displayed by the finer particles Fig. 5 it is obvious that that the fine particles slurries depart much more widely from Newtonian behaviour than slurries made with standard grind coals. The rheogram shows viscosity to be increasing rapidly with decreasing shear viscosity to be increasing rapidly with decreasing shear rate in the very low shear regime. This is attributable to the high yield points associated with the finer grind slurries Table 6. The addition of the dispersant aid to the fine grind slurries caused the yield points to considerably drop, which is the opposite effect that was found for the coarse grand slurries. The effect of dilution two (S.G-1 and FG-1) of previously discussed slurries affected the viscosity showing how shear measurements for these fine grinds slurries are substantially lower than high shear values, by a factor of well over 50% in most cases as shown in Fig. 5.

4. Conclusions

In this experimental study undertaken to investigate the rheological properties of practical coal-water fuel (CWF) it has been seen that dilution and additives affected the viscosities of the sample. The principal conclusion of the study are: CWFs in the 70% solids content range exhibit non-Newtonian rheological behaviour, which, for any given slurry, can change from pseudo plastic to dilatant, or vice versa, over a wide shear rate range. A 1% dilution can reduce viscosity by 50%, equivalent to a 50% increase in dispersant concentration, and the slight dilution of some slurries also cause them to depart much less from Newtonian behaviour and show much greater non-Newtonian behaviour than slurries made with coarser 'standard' grind of coal. The viscosity measurements at high shear rates have important implications on CWF atomization and combustion.

Acknowledgments

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References

Akpa, S. I., Nnadi, P. U., Okonkwo, P., 1987. Design of Burner for Augumented Combustion of Pulverized Coal. B.Eng. Project, Department of Chemical Engineering, University of Science and Technology, Enugu.

Eneh, M. O., 1987. Characteristics of Long Pulverized Coal Flame for the Production of Cement Clinkers. B.Eng. Project, Department of Chemical Engineering, University of Science and Technology, Enugu.

Krieger, I., Dougherty, M., 1969. Trems. Soc. Rheol. 3, 137.

Krieger, I., 1972. Advanced Colloid Interface Sci. 3, 111.

Mogbogu, R., Eziolisa, B., 1988. Fludisation Characteristics of Pulverized Enugu Coals. B.Eng. Project, Department of Chemical Engineering, University of Science and Technology, Enugu.

Mooney, M. J., 1951. Colloid Interface Sci. 6, 162.

Onwu, D. O., 2006. Preparation and evaluation of coal – liquid mixtures from Enugu coals. Proceedings of the 36th Annual Conference of the Nigerian Society of Chemical Engineers, pp. 264 – 265.

Onwu, D.O., 1999. Coal Fundamentals and Conversion Technology. Immaculate Publications, Enugu.

Parks, G. A., 1965. Chem. Rev. 66, 77.

Scheffee, R.S., Macttale, E.T., 1983. Technology of Coal-Water Slurry Fuel. Proceedings of Institute of Energy Conference, Leatherhead, England.

Van Olphen, H., 1977. An Introduction to Clay Colloid Chemistry. Inter-science, London.