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Analysis of Rheological behaviour of Coal Oil Slurry Fuel with Additives

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Abstract—*The scope of the present study aimed at the analysis of the rheological behavior of coal oil slurry fuel with additives (COSFWA). The rheological behavior of coal samples were investigated by using Anton Paar (Rheolab QC) rheometer to generate extensive rheological data with a perspective to study the effects of particle size distribution (PSD), use of an additive as dispersant, and temperature variation on the slurry fuel rheology. The additive used was Sodium Silicate (Na_2O_3Si) and the oil used was high-speed diesel oil. The COSF showed a decrease in shear stress and hence in the apparent viscosity on addition of the additive up to 1.00%. The rheological investigation also showed that there was an increase in apparent viscosity of the COSF at higher temperatures (45-60 ℃) in the presence of the additive. Among all the rheological models studied, best fit was obtained by the Herschel-Bulkley model.*

Keywords: *Coal oil slurry; rheology; viscosity.*

1. INTRODUCTION

Many countries including India which are scarce in fossil fuels are spending an enormous amount of valuable foreign exchange in importing crude oil from abroad. Due to the increasing demand of energy sources (since 1970), the quest for an alternative for fuel oil has become a dire need for modern society. Very often COSFs are being used as a plenteous source for energy generation in many industrial sectors [1].

COSF is prepared by mixing pulverized coal with liquid fuels like bio-oil, alcohol, kerosene, Residual 6 oil, etc. The slurry normally consists of 40-70% pulverized or micro-ionized coal, 30-50% liquid fuel and less than 1% chemicals to disperse the coal particles in the liquid fuels and prevent sedimentation of coal [2]. The utilization areas of COSF are (i) thermal power plants, (ii) diesel engine fuel, owing to its efficient combustion, (iii) coal gasification, and (iv) Industrial heating etc [3].

For efficient utilization as a fuel, the coal concentration in COSF should be as high as possible, maintaining its apparent viscosity at a minimum level in order to cause its suitability for storage and transportation via pipelines [4]. The primary factors that are responsible for the preparation of COSF depends on the physiochemical properties of coal, such as its (i) surface hydrophobicity, (ii) particle size distribution (PSD), (iii) oxygen content, (iv) zeta potential, (v) pH sensitiveness, (vi) shear rate-shear stress relation, (vii) temperature sensitiveness, and (viii) surface chemistry of coal etc. [5-6].

The objective of the present study was to analyze and study the rheological behavior of COSF prepared by keeping the concentration of solid loading constant at 40% by wt. and to determine the effects of PSD, use of an additive as dispersant, and temperature variations on the rheology of COSF. The rheological data generated were fitted to the rheological models by regression analyses and best fit were obtained.

2. MATERIALS AND METHODS

2.1. Materials

The material used in the project was a low-rank coal. It was obtained in pulverized form from Guru Gobind Singh Super Thermal Power Plant, Ropar, Punjab. The oil used for the preparation of slurry fuel was high-speed diesel oil. The proximate analysis of coal was carried out in order to determine the percentages of ash, inherent moisture, volatile matter and fixed carbon present in the particular sample by the prescribed testing method in IS 1350 and the results of the same are shown in table 1.

Table 1: Proximate Analysis of Coal Samples on Dry Basis

Parameter (% by wt.)	Values (%)
Total Moisture	2.60
Volatile Matter	22.54
Ash	41.00
Fixed carbon	33.86

2.2. Coal oil slurry preparation

The particles of the coal sample were segregated based on their sizes using a mechanical sieve shaker. The particles having size less than 106 μm (< 106 μm) were collected in order to form the slurry samples. The solid concentration was kept constant at 40% solids by weight through all the tests. The procedure of preparation of the COSF was standardized for all the tested samples. Weighed amount of high-speed diesel oil was transferred into a glass beaker, and then the weighed coal sample was slowly transferred into the beaker. The contents were stirred by hand shaking for 15-20 minutes to ensure homogeneity of the slurry. The same procedure was repeated with different test conditions.

An additive namely Sodium Silicate (Na_2O_3Si) was added at dosages ranging from 0.5% to 1.5% by weight of solids. The selected additive was prepared in the pre-determined ratio and dissolved in a little amount of diesel oil before adding it to the COSF. The coal samples that were prepared are stated in table 2. The rheology of the samples was tested at 3 different temperatures viz 30°C, 40°C, and 50°C.

Table 2: Prepared Samples of Coal Oil Slurry Fuel

Samples	Coal concentration (% by wt.)	Additive (Na_2O_3Si) (% by wt.)
I	40	0.00
II	40	0.50
III	40	1.00
IV	40	1.50

2.3. Methods

The heating value of the obtained coal sample was determined by bomb calorimeter using the prescribed method in IS 1350-II. The heating value of the coal was found to be 4791.72 kcal/kg.

The Anton Paar (Model: RheolabQC) rheometer was used for the rheological study of COSF. It is a rotational rheometer working on Searle principle, consists of a high precision encoder and a highly dynamic EC motor. The measurements can be obtained by selecting either controlled shear rates or controlled shear stress test settings. It has wide speed and torque ranges and very short motor response time. The measuring systems can be detected automatically by the inbuilt Toolmaster™ system that ensures the exact measuring data to be used with more precision. The measuring system used was DG42/SS/QC-LTD (for lower concentrations (≤ 40% by wt.). The rheometer component consists of concentric bob and cup with a small annular gap in between them. The COSF was prepared for each measurement and was filled up to the mark in the measuring cup. The measuring cup was then inserted into the measuring cylinder and the system was coupled to the rotating spindle by pushing down the flanged coupling. The slurry was subjected to shearing action in between the annular gap between the measuring cup and bob and hence shear stress is measured as a function of shear rate. The output results were obtained on the Rheoplus software installed on a computer which was connected to the rheometer by LAN connection.

50ml of the suspension was prepared by mixing the required quantity of coal with the high-speed diesel oil to obtain the desired concentration. An electronic balance with a resolution of 10^{-4}gm was used for weighing the materials accurately. The complete slurry was poured into the cup. The desired speed of rotation was selected by adjusting the gear ratios. The shear rate was applied from 17.2 to 500s^{-1} for a period of 2 minutes to measure the corresponding apparent viscosity and shear stress under controlled shear rate. The rheological results were obtained on a computer screen.

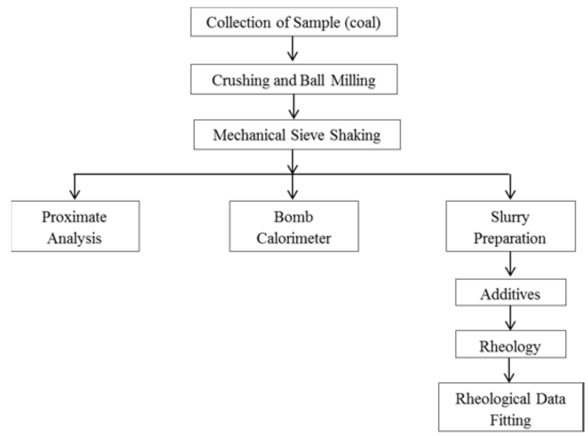

Fig. 1: Flow Diagram

3. RESULTS AND DISCUSSIONS

3.1. Particle size distribution

The PSD curve of the coal sample is shown in Fig. 2. It can be seen that the mean median diameter i.e. d_{50} of the coal sample is around 240µm.

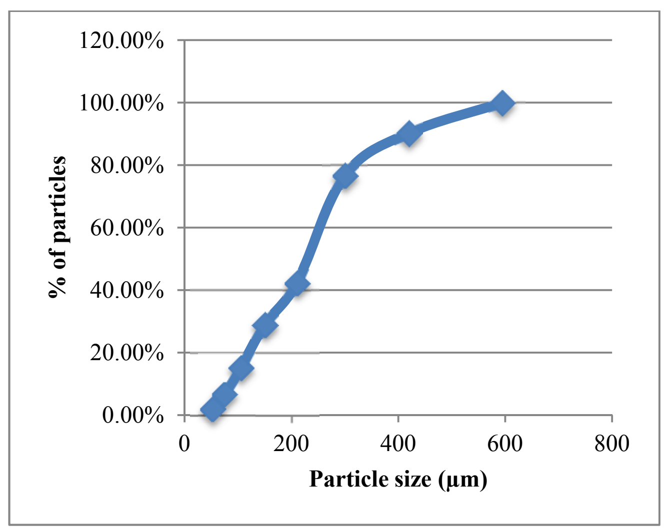

Fig. 2: PSD curve of the coal sample

3.2. Effect of additive on rheology

Fig. 3 illustrates the relationship between shear stress and shear rate for the 106µm particle size sample at 40% by wt. solid concentration using varied dosages of sodium silicate as a dispersant agent, the rheology been studied at temperature 30^{0}C. The dispersant dosage was expressed as percentage of total solids. It can be seen that the shear stress decreases with an increase in the percentage dosage of the dispersant from 0.00% to 1.00% and then increases with an increase in the percentage dosage of the dispersant from 1.00% to 1.50%. The best percentage dosage of the dispersant, sodium silicate (Na_2O_3Si) is 1.00%, as it gives the minimum shear stress for all the shear rates.

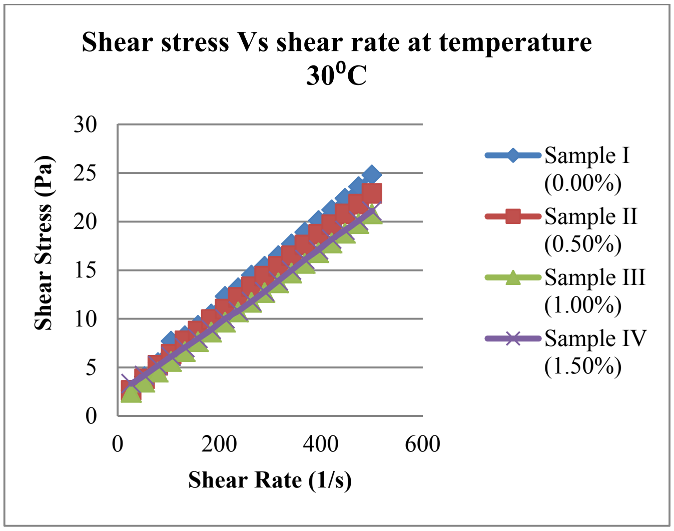

Fig. 3: Rheogram at additive concentrations of 0, 0.5, 1.0, and 1.5% by wt. at 30⁰C

The same results were obtained (figures 4 and 5) when the rheological analysis was carried out at temperatures 40⁰C and 50⁰C respectively. The best dosage for the additive, Na_2O_3Si, is 1.00% as shown by the above-mentioned figures. A further increase in the additive concentration did not lead to an improvement in the rheological behavior of the COSF.

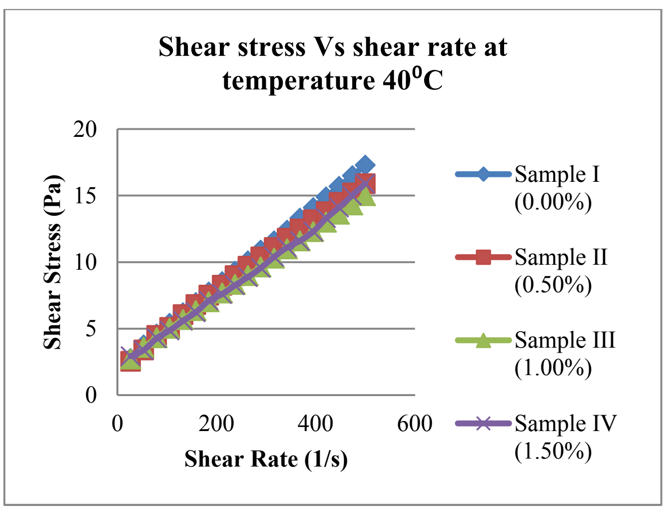

Fig. 4: Rheogram at additive concentrations of 0, 0.5, 1.0, and 1.5% by wt. at 40⁰C

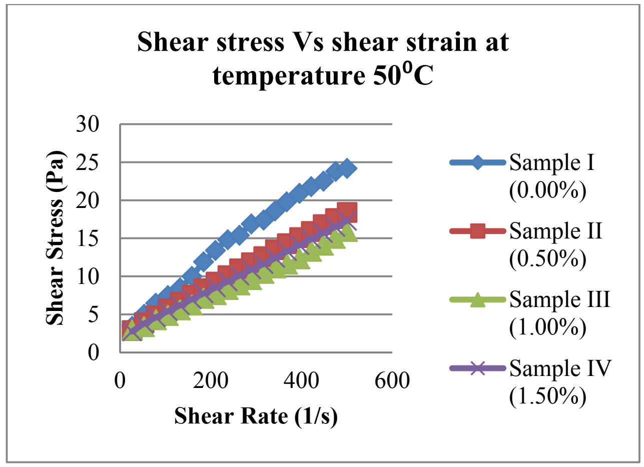

Fig. 5: Rheogram at additive concentrations of 0, 0.5, 1.0, and 1.5% by wt. at 50⁰C

Figures 6, 7, and 8 illustrates the relationship between apparent viscosity and shear rate at different dosages of the dispersant, rheology been studied at 30⁰C, 40⁰C, and 50⁰C respectively. The apparent viscosity decreases with an increase in concentration of the additive from 0.00 to 1.00% and then increases with the further increase in the additive dosage from 1.00 to 1.50%. This is in agreement with the previously reported study on coal-oil-water slurry system [7-8]. The tendency of increase in viscosity beyond a certain concentration is attributed to the fact that the surface active agents used as additives get absorbed first and produces a layer surrounding the coal particles. This layer helps to reduce the inter-particle attraction. In other words, it helps to prevent coagulation and produces stable slurry, which results in a decrease in the apparent viscosity [9]. When the formation of a monolayer is completed, further addition of the additive does not help in reducing the viscosity of the slurry. On the contrary, the additive itself being highly viscous and has high molecular mass than the slurry and therefore tends to increase the viscosity of the slurry at higher concentration.

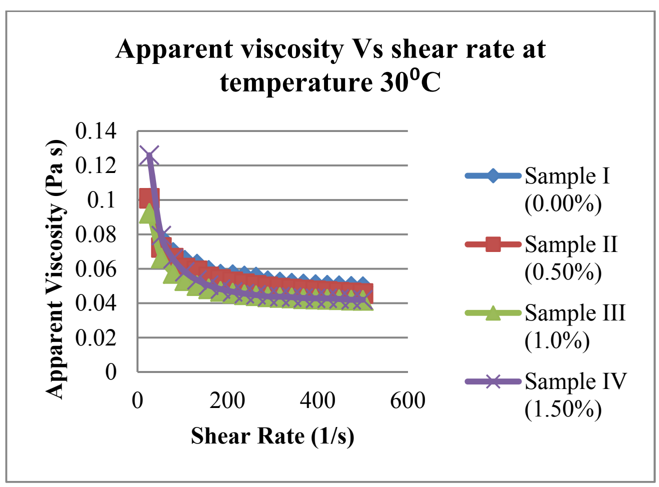

Fig. 6: Rheogram at additive concentrations of 0, 0.5, 1.0, and 1.5% by wt. at 30⁰C

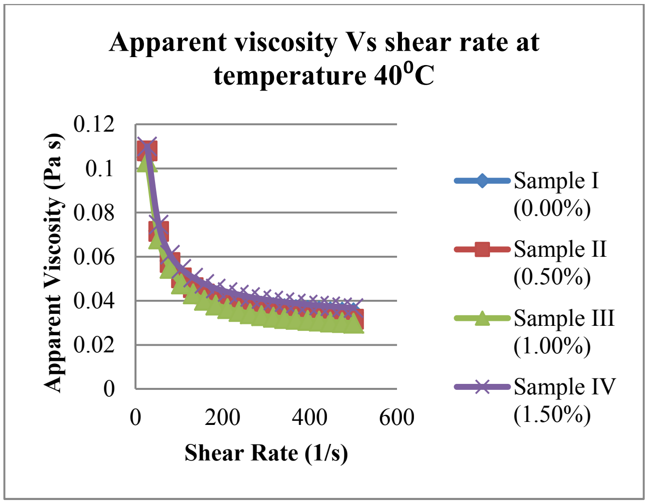

Fig. 7: Rheogram at additive concentrations of 0, 0.5, 1.0, and 1.5% by wt. at 40^{0}C

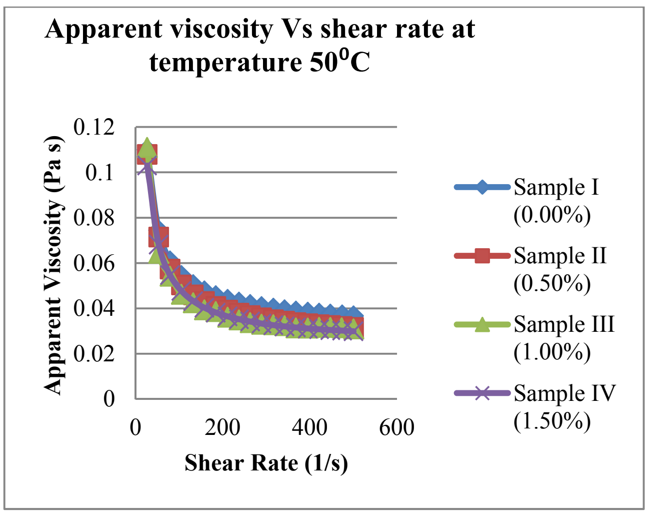

Fig. 8: Rheogram at additive concentrations of 0, 0.5, 1.0, and 1.5% by wt. at 50^{0}C

3.3. Effect of temperature variation on rheology

The variation of viscosity at 40% solid concentration by wt. as a function of temperature and the additive concentration is shown in Fig. 9. It can be seen that the viscosity of COSF decreases with an increase in temperature between 19^{0}C and 50^{0}C without any additive, owing to the reason that the resistance of the carrier fluid i.e. oil decreases with increase in temperature. However, with the addition of the dispersant, sodium silicate (Na_2O_3Si) into COSF, the viscosity tends to increase in the temperature range 45-60^{0}C. It can be seen that the flow behavior of the slurry in the low-temperature range is governed by the behavior of oil. However, above 45^{0}C, the flow behavior gets 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 [10].

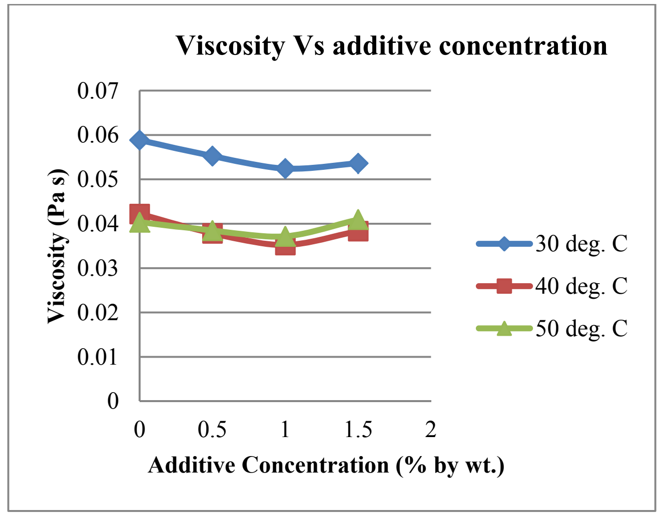

Fig. 9: Viscosity at additive dosage 0, 0.5, 1.0, and 1.5% at temperatures 30^{0}C, 40^{0}C and 50^{0}C respectively

3.4. Rheological data fitting

All the experimental results obtained from COSF with a concentration of 40% by wt. have been fitted using different rheological models viz Power Law model, Bingham model and Casson model each having two parameters and Herschel-Bulkley model having three parameters. The best fit was obtained by Herschel-Bulkley model. The mathematical expression for the model is:

$$\tau = \tau_y + K \quad (1)$$

where τ is the shear stress, τ_y is the yield stress, γ is the shear rate, and n are the model parameters.

Table 3 presents the detailed report of the Herschel-Bulkley model parameters. The value of the parameter n is found to be always less than 1 (< 1), giving an indication of the pseudoplastic (shear thinning) behavior of the COSF. Similar results were obtained using the Herschel-Bulkley model, for pseudoplastic behavior of coal water slurry [11].

Table 3: Herschel-Bulkey model parameters

Samples (solid conc. 40% by wt.)	Yield stress (τ_y) (Pa)	Flow consistency (K) (Pa s^n)	Model parameter (n)
At (30^o C)			
I	0.747	0.1131	0.86
II	1.115	0.0768	0.908
III	1.354	0.044	0.9796
IV	1.965	0.051	0.938
At 40^o C			
I	2.361	0.036	0.991
II	1.95	0.095	0.932
III	1.879	0.051	0.901

IV	1.79	0.055	0.92
At 50° C			
I	1.5	0.0378	0.954
II	1.685	0.054	0.942
III	1.850	0.0451	0.903
IV	1.962	0.056	0.934

4. CONCLUSIONS

From the present work, it is seen that the rheological behavior of coal oil slurry fuel is affected by the factors like the concentration of additives, temperature, etc. The following conclusions can be stated:

- The shear stress of the COSF decreases with increase in concentration of the additive sodium silicate up to 1.00%. Beyond this concentration, the shear stress increases with increase in the additive dosages.
- The apparent viscosity of COSF also decreases with increase in additive dosages up to 1.00% and increases beyond this concentration of the additive.
- The viscosity of the COSF decreases with increase in temperature with no additive. But with the addition of the dispersant, sodium silicate, the viscosity tends to increase between the temperature ranges of 45 - 60^{0}C, owing to the dependence on the behaviour of the additive.

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