Effect of concentration, size, granularity, shear time and temperature on rhological properties of coal water slurries

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Abstract. Coal water slurries (CWS) were proposed as a substitute for the fuel oils century ago. As there is a huge demand for energy, it is necessary for us to use such concepts with good understanding of the alternative fuels. As the use of CWS depends on physio-chemical properties of coal and rheological properties of the slurry, coal obtained from Dugda coal washery, Jharkand, India were subjected to examination. These coals are ground and segregated according to the sizes and the samples of CWS were prepared. The prepared samples were tested for their physio-chemical properties first. various samples of coal water slurries were prepared and examined for rheology of the samples by varying their concentration, size and granularity of the particles, shearing time and temperature. A detailed analysis on stress strain relation was analyzed during this study. It is found that the stresses would increase with concentration of CWS when the strain rates are varied. It is found that the size of the particles would play active role in deciding the shear forces when the samples were subjected to varying shear rates with their self assembly. The granularity of the particles in the sample has significant effect in rheological properties of the CWS samples. The temperature has no effect.

1. Introduction

Fine coal particles suspended in water is termed as coal water slurry (CWS). Presence of water in CWS has advantages like reduction of harmful emissions into atmosphere, making explosion resistant and can be used as a substitute for liquid fuel. In any size of heating and power stations the CWS can be used as fuel. CWS is proven to be compatible fuel which is suitable for existing gas, oil and coal boilers with little modifications. Use of CWS as a substitute for oil in boilers was an ancient idea which was implemented a century ago. These came into light when people started using coal tailings in the boiler without de-watering them and usually as a coal oil mixture [1].

It was proposed that the fuel oil can be replaced with CWS based on the calorific values. As the cost of CWS is cheaper than the oil, it will have its own impact on techno economical aspects [2]. Usually the CWS fuel that is used in the boilers and gasifiers has an apparent viscosity of 800 to 1200 m Pas with a loading of 70% of dry solids [3]. It is suggested that the typical concentration of CWS consists of 60-75 % coal, 25-40 % water, and about 1 % chemical additives [4].
The important factors effecting the CWS being the coal properties, size of the coal particles and their distribution, solid loading of coal. Apart from this, the other factors being the method of preparation and the additives present in CWS and importantly the rheological behavior of the slurry [5]. The three important factors in combustion of coal burning are the size of the particles, concentration and viscosity of the slurry. However, the characterization of coal water mixture becomes necessary before it is sent for burning in industrial boiler. Characteristics of CWS is more complex than that of coal characteristics itself since CWS requires the physio-chemical properties along with the rheological understanding [4,6].

The transportation of CWS plays crucial role in many industrial applications ranging from their combustion to gasification. Hence a correct prediction of the rheological properties of coal water slurries minimizes the power consumption [7]. It is known that for several years, the Atlantic Research Corporation has been developing coal-water slurries as a low-cost liquid boiler fuel.

The CWS are highly-loaded and stable that need to be transported, stored, pumped, and burned like residual fuel oil. To achieve the required rheological properties in highly-loaded suspensions requires a very carefully selected distribution of particle sizes. The effect of particle sizes and their distribution, the method of preparation of the slurry and the effect of its rheological properties are very important factors to be considered in the analysis of behavior of CWS [8].

The CWS usually behave as non-Newtonian nature and its rheological properties are functions of water content, coal particle size distribution, etc. As the viscosity and stress strain relation being important factors in the transportation of CWS, a particular coal water slurry should have high loading with low viscosity value. Particle size distribution exceeding a limit determines the apparent viscosity of CWS that increases with the increase of solid concentration [9,10].

Coal type is not important parameter when preparing CWS but its water absorption capacity plays an important role in the rheological properties of CWS hence the effect of coal properties on the viscosity of CWS should be determined [11]. In the wide particle size distribution of coal, the particle interactions does have its effect on the rheological properties as they modify the volume fractions of coal when small particles fills the gaps between the course particles. The rank of coals also has the probability of altering the volume fractions.

2. Materials and methods
Coal from Dugda coal washery, Jharkhand, India were taken for analysis. Coal collected as samples were graded to requisite size for preliminary test, such as, proximate analysis, calorific value, ultimate analysis and in the preparation of coal water slurry (CWS). These samples are ground in a crusher and classified according to Taylors standard meshes after grinding. The stack of meshes that were used have mesh sizes 48, 65, 100, 200 that has openings of 295, 147, 104, 74 µm, respectively.

2.1. Proximate analysis of coal
2.1.1. Moisture content The inherent moisture content of the coal varies depending on the surrounding conditions of temperature and humidity. To determine the moisture content, one gram of coal that pass through 72 mesh sieve was weighed and taken in a pair of watch glasses. The coal is spread evenly in the watch glass and then kept in an air oven with temperature maintained at 110± 2 °C for one hour with the lid partially open. Before the removal of the sample from the oven, lid is covered and samples are taken out and placed in a desiccator. These samples are cooled for 15 minutes and weighed. The difference in weight is reported as the moisture content.
2.1.2. Ash content
To determine the ash content, one gram of the coal that pass through 72 mesh sieve was weighed and placed in a crucible. This crucible is placed in a muffle furnace for one hour at 750 °C. The residue left over is weighed and is reported as ash content of coal.

2.1.3. Volatile matter
To determine the ash content, approximately one gram of coal that pass through 72 mesh sieve was weighed and taken in a watch glass. The coal is spread evenly in the watch glass and then kept in an air oven with temperature maintained at 110± 2 °C for one hour. This sample is weighed for loss in moisture content and then immediately placed in a crucible. This crucible is fitted with a cover and placed in the furnace at 750 °C for 7 minutes. The loss in weight after moisture removal and furnace heating is reported as the volatile matter.

2.1.4. Fixed carbon
The percentage of fixed carbon is obtained by subtracting the sum of moisture percent, ash percent and volatile matter percent from 100.

2.2. Ultimate analysis of coal
Vario EL III CHNS Analyzer from Elemental Germany was used for determination of nitrogen, carbon, hydrogen, sulfur and Oxygen.

2.3. Swelling index of coal
To determine the swelling index 1 gm of air dried coal that passed through 72 mesh size is heated in a crucible with a lid until volatile matter ceases to evolve. Rate of heating is maintained such that the temperature of the inner surface of the base of the crucible reaches 800 within 1.5 minutes and 820 within 2.5 minutes of lighting the burner. After 2.5 minutes the crucible is cooled and the coke button is removed. The shape and size of the coke button is compared with the standard coke profile number from 1 to 9 at the interval of 0.5. This is called swelling number or free swelling index (FSI).

2.4. Hard grove grind ability index (HGI) of coal
50 grams of coal that pass through 30 mesh is collected. This sample is ground in standard mill for 60 revolutions. After grinding, the coal is screened through a 200 mesh sieve. Hard grove grind ability index (HGI) is then calculated as

\[ G = 16 + 6.93W \]

where G is hard grove grind ability index and W is weight of the sample passing through the 200 mesh sieve.

2.5. Specific gravity of coal
Weight of water (W2) and kerosene(W3) that were filled in a 25 ml specific gravity bottle were noted down. In another 25 ml specific gravity bottle, the coal power that pass through 200 mesh screen is filled partially (approximately 50% of bottle) and its weight is noted down(W4). This bottle containing coal is slowly filled with kerosene until the coal inside the bottle is saturated with kerosene oil. After makeup of kerosene, the bottle is weighed and the weight is noted down(W5). If W1 is the weight of the empty specific gravity bottle, the specific gravity of the sample is calculated as

\[ \text{Specific gravity} = \frac{(W4 - W1) (W3 - W1)}{[(W3 - W1) - (W5 - W4)] (W2 - W1)} \]
2.6. Preparation of coal water slurry (CWS)

Coal water slurry samples were prepared by blending coal of different particle sizes with water on weight basis. The Rosin-Rammler relationship was used for representing the size distribution of powdered coal, as given in equation 3

$$R = 100e^{(-\frac{X}{K})^n}$$  \hspace{1cm} (3)

where $R$ is cumulative weight percent of particular fraction of total mass, $X$ is mean particle size in a fraction in micron, $n$ is dispersion constant and $K$ is absolute size constant [12].

In the present study, the values of dispersion constant were chosen as 1.5, 1.6, 1.7, 1.8 and 1.9 and the values of absolute constant were chosen as 50, 60, 70, 80, 90 $\mu$m and the cumulative weight fraction is calculated for different mean particle size using equation 3.

2.7. Rheological experiments

Anton Paar (Rheolab QC) Quality Control Rheometer was used to determine the rheological properties of the CWS at low and high shear rates. The present investigation is mainly aimed to study the effect of coal concentration, coal particle size, size distribution, shear rate, shear time at room temperature and also at varying temperature on the Coal water slurry. The investigations were carried out with coal sample mainly weakly caking type having 33.63% ash and 18.96% volatile matter. The coal is chosen from weakly caking type because the CWS have to undergo through combustion in the boiler or in the furnaces.

In the present work, initially the physio-chemical properties of the coal were estimated. Then the coal water slurries were prepared with different concentrations of the powdered coal according to the absolute size constant values. The rheological analysis is performed by varying the absolute size constant values and the concentrations of the samples. Selective sizes of the coal fractions were chosen based on their sizes and the CWS were prepared. The rheological analysis on these samples were performed to test the granularity effect. The effect of shearing times at two different concentrations of the CWS were estimated. The effect of temperature on CWS were determined at varying concentrations and at various temperatures.

3. Results and discussion

3.1. Proximate analysis of coal

Proximate analysis is one of the significant test that determines the quality of the coal. This test is important for both supplier and user to determine the ratio of combustible and incombustible matter in the given coal. Table 1 gives the various constituents present in the given coal analyzed for proximate analysis with the procedure as described in section 2.1.

| S.No | Content            | % Composition |
|------|--------------------|---------------|
| 1    | Moisture           | 0.97          |
| 2    | Volatile matter 5 | 18.96         |
| 3    | Ash 8              | 33.63         |
| 4    | Fixed carbon 15    | 46.43         |
3.2. **Ultimate analysis of coal**

It is an elemental analysis that determines the quantities of carbon, nitrogen, hydrogen, sulfur and oxygen content that were present in a solid fuel. It is also one of the measure that signifies the quality of the coal. Table 2 shows the ultimate analysis of the coal sample as described in section 2.2.

| S.No | Composition | value    |
|------|-------------|----------|
| 1    | % C         | 54.55    |
| 2    | % H         | 3.37     |
| 3    | % N         | 1.36     |
| 4    | % S         | 0.44     |
| 5    | % O         | 5.68     |
| 6    | Gross calorific value | 4258 kcal/kg |

3.3. **Coal indices**

The free swelling index is an indication of its use as a coking coal. It is very significant in determining the plastic properties of the coal. Coking index is one of the significant indices that classifies bituminous coals in the classification of coals. It signifies the binding strength among coal particles and also the binding strength between the coal particles and inert particles present. Grindability index is a measure of grindability nature of the coal. The minimum grindability index implies the hardness of the coal and hence is less grindable. Specific gravity of the coal is one of the measure that is used to classify and quantify the coals available in the market. Table 3 shows the various indices that are measured using the methods described through Sections 2.3, 2.4 and 2.5.

| S.No | Indexing                              | value |
|------|---------------------------------------|-------|
| 1    | Free swelling Index                   | 1     |
| 2    | Caking index                          | 9     |
| 3    | Hard grove Grindability Index         | 81    |
| 4    | Specific gravity                      | 1.5   |

3.4. **Packing density of Coal sample with varying size parameter**

Packing density of particles is a measure of size and shape of the particles. Irregular particles often occupy packing densities less compared to the spherical particles. The packing densities of various sized particles were measured and presented in the Table 4 given below to approximate their similarities towards regular shapes.
Table 4: Proximate analysis of the coal sample

| Absolute size constant (K) | 50  | 60  | 70  | 80  | 90  |
|---------------------------|-----|-----|-----|-----|-----|
| Packing density (g/ml)    | 0.64| 0.67| 0.72| 0.75| 0.80|

3.5. Rheological analysis of coal water slurries

After the preliminary analysis of coal, for coal water slurries, it is important to analyze the flow behavior. The flow behavior analysis of CWS was carried out at various concentrations of coal, various size constants, various shearing times, and various temperatures. This analysis includes the dependency of shear rate with viscosity or shear stress.

3.5.1. Rheological properties of CWS at a value of absolute size constant and at different concentrations

At a given absolute size constant and varying concentrations of coal, the rheological analysis is done by varying shear rate of 0 to 1000 s$^{-1}$.

It is evident from Figure 1 that the CWS solutions at all values of absolute constant K exhibit shear thickening nature. At low shears these solutions have less tendency to obstruct the flow field. However, at high shears, these particles become reluctant to adopt to the flow field thereby exhibiting the resistance. Due to this fact the stresses will be developed in the flow resulting the shear thickening nature of the fluid.

At any value of K, an increasing trend of shear is evident with an increase in concentration of the CWS. At higher concentrations it is observed that the shear stresses exhibits non-trendy behavior with the shear rates. This might be due to the excessive concentration of the slurries that actually affect the flow behavior abnormally. Even with the increase in the value of absolute size constant K, the viscosities have almost remain unchanged with little change in their shear stress values, not to the order of magnitude. However, at all values of K and higher strains, the transformation from likely Newtonian to non-Newtonian behavior might be due to the spacial rearrangement of particles in the mixture when the voids are filled by the small particles present.

3.5.2. Rheological properties of CWS at a concentration with varied values of absolute size constant

To investigate the effect of K on rheological properties at a given concentration and varying absolute size constants of coal, the rheological analysis is done by varying shear rate of 0 to 1000 s$^{-1}$.

It is again very clear from the Figure 2 that all the samples shows shear thickening behavior at varied value of K and at different concentrations. It can be also seen that there is shift of stresses almost two orders of magnitude with an increase in concentration from 55 % to 70% of CWS. It is known the presence of solid particles effect the flow field by increasing the viscosity and shear, and hence the increase is proportional to the number density.

It is also evident from the Figure 2 that though the K values has no significant effect on the stresses, the variations of the K values however does not follow any any trend. It could be observed that at any concentration of the CWS, the variation of K never followed any trend as shown via Figures 2a to 2d. This nature of the CWS might be due to spacial arrangement of the particles with in the voids that determines the development of stresses when the fluid is under the influence of the shear strains. It is now important to know weather the size, shape, and density of the particles have effect in the determination of flow properties of the CWS by looking at the above results.
3.5.3. Effect of granularity on rheological properties of CWS. To test the effect of the granularity of the particles on the rheological properties of the coal water slurries, two different sizes of the particles were chosen. The one being the particles that pass through the 100 mesh screen in the Taylor’s standard screens and the other being the particles that pass through that of 200 mesh screen. The former sample contains a mixture of sizes that vary from a very large size of 0.149 mm to a smaller sizes up to microns. It is a mixture of different sized particles having different shapes. The later sample contains particles that has a maximum size of 0.074 mm to particles of micron sizes. The later size particles are more or less have similarity in shapes as their size is very less compared to the former sample.

Figure 3 shows the variations of shear stresses with the varying shear rates. It is evident

Figure 1: Variation of shear stress with shear rate for various concentrations of CWS at (a) K=50 (b) K=60 (c) K=70 (d) K=80 (e) K=90
Figure 2: Variation of shear stress with shear rate for various K values at (a) 55% concentration (b) 60% concentration (c) 65% concentration (d) 70% concentration

Figure 3: Variation of shear stress with shear rate for granularity of the particles whose sizes are (a) less than 0.149 mm (b) less than 0.074 mm
Figure 4: Variation of shear stress with shear rate at shearing times of (a) 60 seconds (b) 180 seconds

from Figure 3a that the stresses varies abnormally with the variation in shear rates. This might be due to the inter particle interactions and self assembly during the straining of CWS as these mixtures have different sized and shaped particles varying from a larger size of 0.149 mm to micron size. This nature of trend is observed for both concentrations of 55 % and 60% of CWS. However, from Figure 3b shows that the variations of stresses are nullified. This nature could happen when there is more or less uniform sized and shaped particles, that particularly does not effect the self assembly of particles in the flow field. From the above results it can be concluded that the size and shape of the particles have its effect on the rheological properties of CWS.

3.5.4. Effect of shearing time on CWS
To investigate the effect of shearing time on coal water slurries, the CWS samples of 55% and 65% concentrations were chosen. These samples were kept under the influence of shear for a time period of 60 seconds and 180 seconds. Then they are subjected to the rheological analysis by varying the shear strain and measuring the corresponding shear stress. It is to be noted that the variations of viscosity with shear rate is analyzed at lower shear rates up to 300 s$^{-1}$.

It can be seen from Figure 4a and Figure 4b that the shear stresses are almost similar for both the concentrations of the CWS at 55% and at 65%. There is no significant interplay among the particles where the shearing effect is observed. Hence it can be said that the shearing has no effect on the rheological properties of CWS at almost any concentrations.

3.5.5. Effect of temperature on CWS
To investigate the effect of temperature on CWS, two different concentrations of CWS, 55% and 65% were chosen and the viscosity of these samples at temperature of 30°C, 50°C and 70°C were measured.

It can be seen from Figure 5a and Figure 5b that the viscosity is decreasing with an increase in the shear rate. The decrease is evident in both the cases with the two orders of magnitude. However, as the concentration of the CWS has its effect on viscosity, the 65 % concentration slurry have higher values of viscosity when compared to that of the 55 % concentrations of CWS. It is very clear from Figure 5a and Figure 5b that the viscosity is not a function of temperature rather it is function of concentration of CWS.

4. Conclusions
The proximate analysis of the coal showed a moisture content of 0.97%, volatile matter of 18.96%, ash content of 33.63% and fixed carbon of 46.43%. The ultimate analysis of the coal
Figure 5: Variation of viscosity with shear rate at temperatures of 30°C, 50°C and 70°C for (a) 55% CWS concentration (b) 65% CWS concentration

sample showed 54.55% C, 3.37%H, 1.36%N, 0.44%S, 5.68%O with a gross calorific value of 4958 kcal/kg. The analyzed coal sample showed a free swelling index of 1, caking index of 9, hard groove grindability index of 81 with a specific gravity of 1.5. The rheological analysis of CWS at a value of absolute size constant and at varied concentrations showed unchanged values of viscosity. However at higher strains near to 1000 s⁻¹, shift was observed from Newtonian nature to non-Newtonian nature which might be due to the self assembly of the particles of different sizes that were present in the sample. At a given concentration with varied absolute size constants, no significant effect on stresses variations were observed. However, no trend was observed with an increase in the absolute size constant which might be due to the self assembly of small particles within the voids of the bigger particles. The granularity of the particles has shown significant effect on rheological properties. Smaller particles due to their similarity in size and shape showed a complete Newtonian behavior. The shearing time of the CWS has no effect on the stress strain relation. The temperature has no significant effect on the rheology of the CWS. However, there is no trend of stress strain relation with temperature changes.

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