INVESTIGATION OF FLOW CHARACTERISTICS OF COAL AND WATER SLURRY

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In

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Submitted by

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CERTIFICATION

I hereby certify that this thesis entitled, **"Investigation of flow characteristics of coal and water slurry"** in fulfillment for the requirements for the award of Degree of Master of Engineering in Thermal Engineering submitted to Mechanical Engineering Department, Thapar University, Patiala, is an authentic record of my own work and is carried under the supervision of Dr. S.K. Mohapatra. The matter submitted via this thesis report has not been submitted for the award of any other degree to the best of our knowledge.

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Dedicated to

My parents and Sanjeev Singla

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Abstract

The present study on the coal water slurry fuels' (CWSFs) rheology was conducted at the Mechanical Engineering Department, Thapar University, Patiala. The influence of the coal particle size on the coal properties, rheological behavior of CWSFs, and packing characteristics of CWSFs was studied. Three Indian coal samples were procured from different thermal plants and were designated as S-I, S-II, and S-III and were investigated by using Anton Paar RheolabQC rheometer to generate extensive rheological data. The coal particle size was found to have a major influence on its proximate composition. It was observed that the inherent moisture was negatively correlated with particle size ranging from 53-106 μm. This implies that the inherent moisture does not cause coarsening of pulverized coal. It was also observed that a higher volatile content would favor coal pulverizing.

The rheological results indicated that the viscosity of the CWSFs is a function of particle size distribution. A mixture of coarse and fine particles must be used for the preparation of CWSFs. A comparative study of uni-modal, bi-modal and tri-modal distributed slurries were made. The best coarse : fine ratios for bi-modal slurries for the three coal samples for which the lowest viscosity was observed, were found out. They were 70:30 (30f) for S-I, 40:60 (60f) for S-II, and 60:40 (40f) for S-III. It was also observed that the tri-modal distributed slurries showed a much lower viscosity when compared to uni-modal and bi-modal slurries, implying that CWSFs must be prepared with a variation of coarse and fine particles to achieve appreciable viscosity. The viscosity is also a function of temperature. With increase in temperature, the viscosity of the slurry was found to decrease owing to an increase in kinetic energy of the particles and a decrease in cohesive forces between the particles. This result was found to be common for uni-modal, bi-modal, and tri-modal slurries.

Further, the Void fraction (ε) and bed density (λ) of CWSFs with bi-modal distribution were also evaluated. The results indicated that with the determination of λ and ε, optimal coarse : fine ratios for preparation of CWSFs with the lowest possible viscosity could be known. The future scope of work, reflections, publications, and references are stated at the end.

Key words: Bed density; particle size distribution; proximate composition; rheology; void fraction.

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Nomenclature

G	Hardgrove grind-ability index
W	Weight of coal in grams
C_w	Concentration
F(d)	Mass distribution function
d	Particle diameter
d_{max}	Size modulus
M	Distribution modulus
l	Mean particle size (d_{50})
ε	Void fraction
V_s	Volume of the slurry
CO_2	Carbon dioxide
H_2O	Water
CO	Carbon monoxide
CH_4	Methane
H_2	Hydrogen
N_2	Nitrogen
O_2	Oxygen

Greek Symbols

τ	Shear stress
η	Viscosity
γ	Shear strain

v	Velocity
τ_y	Yield stress
λ	Bed density
Φ	Volume of fraction of coal
Φm	Maximum attainable solids volume fraction

Acronyms

CWSFs	Coal Water Slurry Fuels
SEM	Scanning Electron Microscopy
EDS	Energy Dispersive Spectroscopy
PSDs	Particle Size Distributions
RR	Rosin-Rammler
GGS	Gates-Gaudin-Schuhmann

Chapter 1

Introduction

Coal is, and would continue to be one of the major sources of fuel for generation of power in the reckonable future. Out of a total of 861 billion tons of estimated coal resources globally, India accounts for 266 billion tones. One of the most significant achievements in twentieth century is the commercial perfection of methods for coal firing in pulverized form. The reason behind firing coal in pulverized form in a steam generator (boiler unit) is that, the pulverized coal burns like gas, and hence, fires can easily be ignited and controlled (Singer 1981). It is also assumed that if coal is divided into finer particles and burned like gas, it becomes an attractive fuel promising greater boiler efficiency and simplicity of combustion (Singer 1981). An alternate technique of utilizing pulverized coal is by forming a slurry fuel and use the coal slurry fuel for direct combustion in furnaces.

Coal slurry fuels comprises of pulverized coal particles suspended into one or more fluids such as oil, methanol, or water. Such fuels possess the benefits of possessing high energy density (Choudhury 1992) and being suitable to be used as liquefied fuel (analogous to heavy fuel oil). Coal slurry fuels have been found to be a possibly effective substitute for oil in steam generators and incinerators, oil in internal combustion engines, and lately, co-firing feedstock with coal fines in utility incinerators.

Coal slurry fuels had been inspected ever since the twentieth century, nevertheless due to economic restraints these fuels did not become a significant energy source at that time. Much of the work during the twentieth century aimed at coal oil slurry fuels (COSFs), which could eventually replace any liquid fuel or oil in steam generators. However, recently the research has been made to concentrate further on coal water slurry fuels (CWSFs) to cause the entire substitution of oil in industrialized steam generators, utility incinerators, diesel engines, blast furnaces, and process ovens (Lee 2005).

1.1 Coal Water Slurry Fuels (CWSFs)

CWSF is an ignitable dispersion of pulverized coal particles in water (carrier liquid). When a CWSF is combusted, over 99% of its carbon content is consumed. CWSF is fire proof as well as explosion proof. Figure 1.1 represents a pictorial view of a CWSF.

Figure 1.1: Coal water slurry fuel (Biletskyy et al. 2013)

CWSFs generally have higher solid (coal) loading ranging from 60-70% by wt. causing to more energy compactness (densities) per unit mass (Table 1.1).

Table 1.1: CWSFs densities (Kesavan 1985)

Fuel	**Density (lb/gal)**	**Btu/lb**	**Btu/gal**	**Btu/ft^3**
40% water/60% coal blend	9.8	8000	78,700	589,000
30% water/70% coal blend	10.2	9373	95,600	715,000

However, the physical properties of CWSFs are of greater significance in the dispensation and preparation of the fuel. CWSF ought to be steady and possess little viscidness in the deformation rates of atomization and pumping. The flow behavior of CWSFs is a function of the following factors:

- Chemical and physical possessions of coal.
- The volume fraction (Φ) of the suspended coal particles.
- Particle size distribution (PSDs).

- Inter-particle relations (pretentious by the nature of pH, electrolytes, surface groups, and chemical additives).
- Temperature of the slurry.

Slurry capability or slurriability is a measure of how well a coal will form slurry. In other words, it can be defined as the concentration of coal in water which at a given shear rate, gives a specified viscosity. It is a measure of the equilibrium moisture content of coal in the suspension. Usually, it indicates the maximum amount of coal that can be slurried, while maintaining a viscosity of 1000cP, measured after 50s of shear at a deformation rate of $100s^{-1}$ (Kissa 1999). It is the measure of hydrophilic nature of coal. If a coal is more hydrophilic then it will hold more water and therefore, it would not form highly concentrated slurry (Kawatra et al. 2002). Further, the viscosity of CWSFs increases with increase in hydrophilicity of coal. Therefore, for forming coal slurry with less viscosity and more solid loadings, hydrophobicity of coal is suitable. Higher rank coals, except Anthracite, are hydrophobic in nature as they lack acid groups and can form slurry up to 80% by wt. of solid loadings. Anthracite coal is less reactive and has less volatility, and hence has poor ignition characteristics (Kesavan 1985).

It is desirable to have higher coal content in the CWSFs for fuel efficiency. However, the maximum coal that can be loaded is limited by high viscosity of the highly concentrated CWSFs. The viscosity of CWSFs is a function of reduced volume fraction ($\emptyset/\emptyset_m$), where $\emptyset$ is the volume of fraction of coal, and $\emptyset_m$ is the maximum attainable solids volume fraction. If $\emptyset_m$is increased, the solid loadings could be increased and viscosity could be decreased. The way by which $\emptyset_m$can be increased is using polydisperse mixture of coal particles and optimizing particle size distribution. Other factors that could affect viscosity of CWSFs are electrolytes, nature of coal, temperature, composition of the liquid phase, and use of dispersants and stabilizers (Kissa 1999).

Another significant property in hydrodynamic characteristics of CWSFs is the ionic strength of water in the fuel. The ionic strength of water will affect the interaction of coal with water, as coal is a mixture of mineral matter and carbonaceous materials in lieu of a uniform homogenous substance. In a hydrophobic colloidal system i.e. CWSFs, suspended by electrically repulsive powers, the amount of water and its ionic strength has an enormous effect on the stability against agglomeration of coal particles. The amount of the cations increases the viscosity of the CWSFs with low pH. Electrolyte i.e. water, strongly affects the rate of particle dispersion and, hence the rheology of CWSFs using an anionic dispersant. The accumulation of water to CWSFs using non-ionic dispersants seemed to have no significant impact on the viscosity of the fuel (Williams 1992).

It is expected to have minimal settling of coal particles in highly concentrated CWSFs but addition of additives to cause low viscosity increases the coal particles' settling rate. Therefore, in order to alleviate the CWSF, agglomerating agents are provided which produces a emollient (Zakin et al. 2005).

1.2 Benefits of CWSFs`

- CWSF is a cheap energy resource or it is a cost effective fuel. Per unit cost of energy of CWSF may be 30% to 70% lesser than that of corresponding gas or oil. Due to low emissions, CWSF is an eco-friendly fuel for heat and power generation. The combustion temperature of CWSFs is 100-200°C lower than that of oil or gas, leading to a reduction in NO_x and SO_x emissions.
- CWSFs are easy to transport and store. They can be pumped through pipes, tank wagons, tank trucks, and barks.
- Existing oil or gas fired systems can be adapted for CWSF combustion without any significant modifications. CWSF also offers a simple load adjustment range, i.e. load range can be adjusted from 35% to 100%.
- CWSF is fire and explosion proof, it is easy and safe to store and to transport, causes no or less dust pollution, does not require any coal storage yard and slag yard, improves the usage ratio of land, save up-to 50% of land area.
- Ash after CWSF combustion is an ideal amendment to special concrete production. CWSF boiler fly ash emission concentration is about 100mg/Nm^3, which can be used as very valuable co-material of concrete production.
- Gas or oil/diesel still could be used as fuels for preheating of the system or for special "heat peak shocks".

1.3 Utilization areas of CWSFs

CWSFs are applied for wide range of different industries mentioned below:

- Local/district heating stations which produce a thermal energy for their customers. Typical size of the boilers – from 1MW and higher.
- Steam/heat productions for heating and industrial purposes. Industries like cement, sugar, soda, textile, chemical, petro-chemical refineries and many other productions require a heat in a form of steam or hot water. CWSF may substitute totally or partially existing expensive fuels like gas, oil or dirty-burned coal.
- Coal mines which have a plenty of coal wastes in a form of coal fines or small-sized grains.
- Pyrolysis units/factories which produce pyrolysis oil out of rubber, auto-tires and other and which have a carbon black (pyro-carbon, char) as a wastes. Such carbon could be successfully utilized in a form of CWSF.
- Power generation stations which already use coal powder as a fuel. Low-cost coal wastes could be used as an additional fuel for steam boilers reducing the cost of produced steam. Additionally usage of CWSF reduces NO_x emissions at least on 20-25% which might be significant reason to use CWSF as one of the fuels.
- Areas with no access to gas pipes.

1.4 Mechanism of combustion of CWSFs

While describing the CWS combustion process, the differences in inflammation and combustion processes of slurry drops caused by powdered solid fuel combustion should be taken into consideration (Mochalov et al. 2012). To describe the process of CWS drops combustion, the following physico-chemical model consisting of several independent parallel-serial stages can be suggested (Fig. 1.2).

- **On the drop surface:** instant heat and moisture evaporation from the surface, low-temperature activation of reaction surface of the fuel before the combustion, coal micro particle combustion on the surface of the drop.
- **Inside the drop:** gradual heat of the drop, moisture evaporation from the interior of the drop, devolatilization and combustion of volatiles near the CWS drop, coal micro

particles transfer to the drop surface with formation of hollow sphere, coal micro particles combustion in chemical reaction with air oxygen and water vapour.

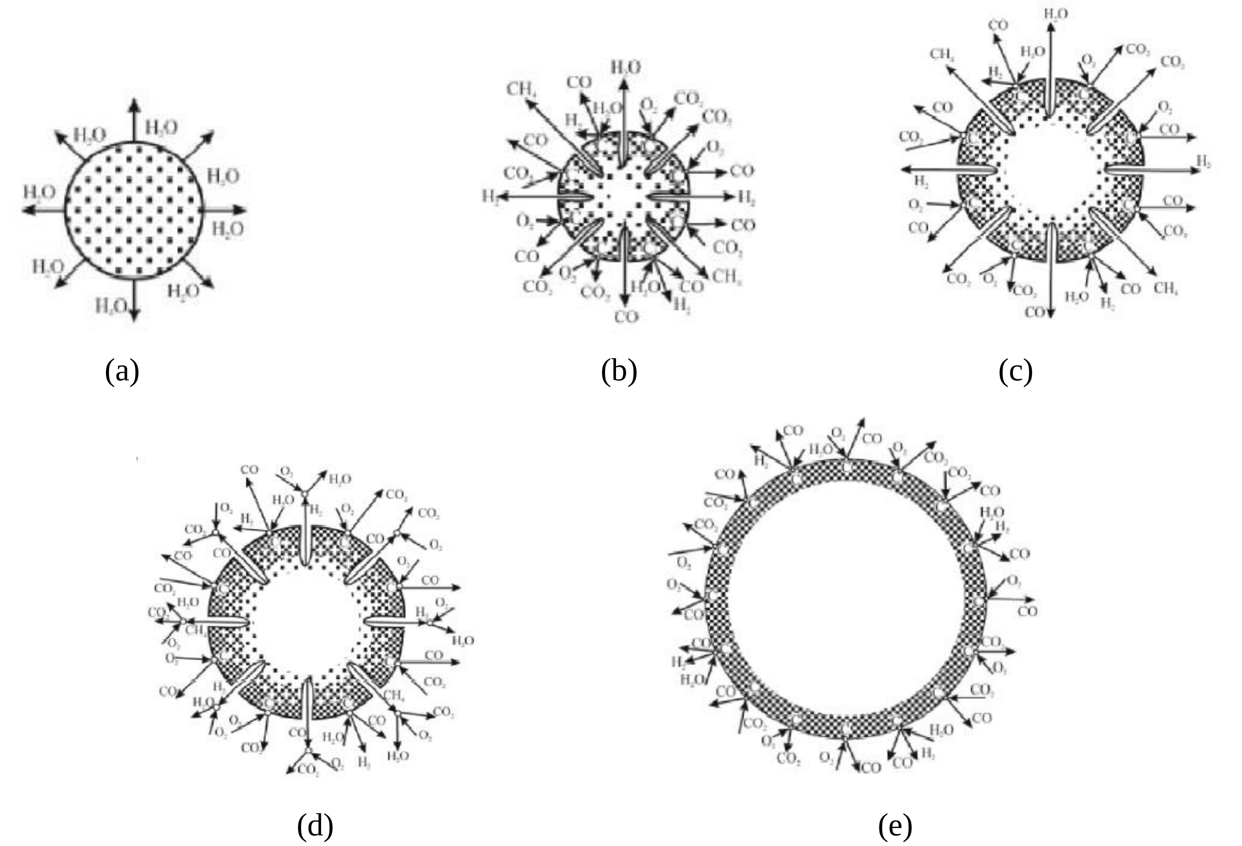


Figure 1.2: Physico-chemical model of CWS combustion: (a) moisture evaporation from the surface of CWS drop; (b) coal micro particle combustion on the surface of CWS drop, moisture evaporation from the interior of the drop; (c) coal micro particle combustion on the surface of CWS drop, devolatilization from the interior of the drop; (d) coal micro particle combustion on the surface of CWS drop, coal-volatile matter combustion; (e) coal micro particle combustion (Mochalov et al. 2012)

When a CWS drop gets in a hot combustion chamber, there is immediate warm-up of the drop surface and water evaporation from the drop surface. Inside the drop there is gradual warming and as the temperature is increasing the moisture evaporates from the interior of the drop. The process of water evaporation can be defined by the subsequent equation:

$$H_2O = \{H_2O\} \quad (1.1)$$

With the temperature increasing there is the process of thermal destruction (pyrolysis) of organic matter on the surface of CWS drop, accompanied by release of volatile substances. As the thermal front penetrates deep into the drop the release of volatile substances from the interior of the drop begins. These are the following equations describing the release of volatile substances:

$$CO = \{CO\} \quad (1.2)$$

$$CO_2 = \{CO_2\} \quad (1.3)$$

$$CH_4 = \{CH_4\} \quad (1.4)$$

$$H_2 = \{H_2\} \quad (1.5)$$

$$N_2 = \{N_2\} \quad (1.6)$$

Escaping combustible gaseous components react with air oxygen:

$$\{CO\} + \frac{1}{2}\{O_2\} = \{CO_2\} \quad (1.7)$$

$$\{H_2\} + \frac{1}{2}\{O_2\} = \{H_2O\} \quad (1.8)$$

$$\{CH_4\} + 2\{O_2\} = \{CO_2\} + 2\{H_2O\} \quad (1.9)$$

Because of water vapor generating as the result of water evaporation from the surface there is low-temperature activation of coal micro particles on the surface of CWS drop before its combustion that leads to substantial temperature drop of CWS combustion. In the process of volatiles combustions the surface of the drop gets warm and carbon residue of coal micro particles combusts on the drop surface. On the surface there are combustion reactions due to the interaction of carbon with air oxygen, water vapor and CO_2 obtained from volatiles release and partial volatiles and coke base combustion. Combustion can be described by following reactions:

$$C + \frac{1}{2}\{O_2\} = \{CO\} \quad (1.10)$$

$$C + \{H_2O\} = \{CO\} + \{H_2\} \quad (1.11)$$

$$C + \{O_2\} = \{CO_2\} \quad (1.12)$$

$$C + \{CO_2\} = 2\{CO\} \quad (1.13)$$

The process of combustion the surface of CWS drop takes place in parallel with the processes of water evaporation and release of volatile substances from the interior of the drop. In the processes of water evaporation and release of volatile substances coal micro particles transfer from drop interior to its surface resulting in CWS drop transformation into hollow sphere (Mochalov et al. 2012).

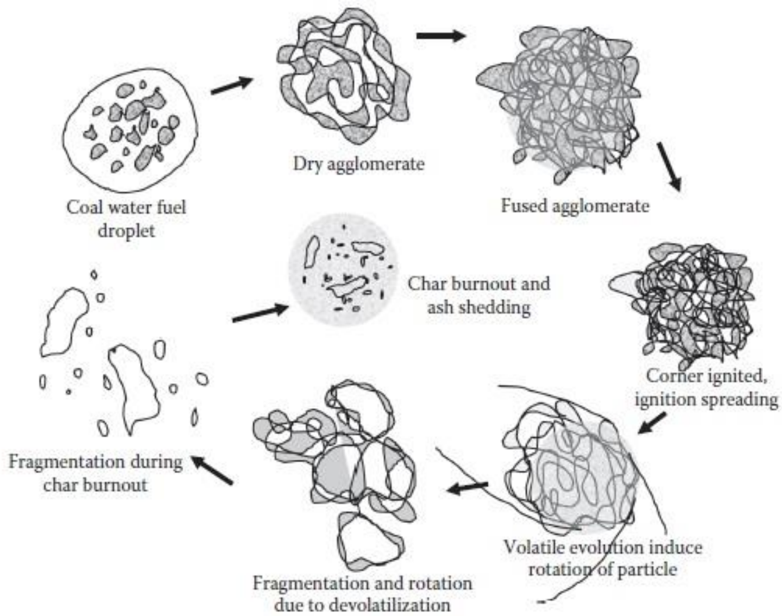


Figure 1.3: CWSF combustion mechanism (Miller et al. 1994)

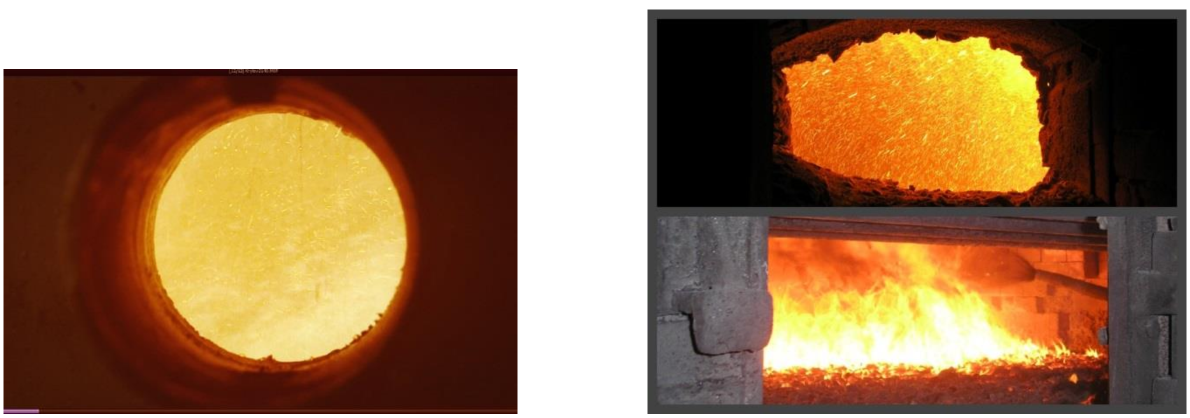


Figure 1.4: CWSF swirl combustion (Carbon slurry fuel technology, 2013)

1.5 Rheology and its significance

Rheology is generally defined as the study of movement of matter, mainly in liquid state, or as ‘soft solids’ i.e. solids that undergoes plastic flow in answer to a realistic force in lieu of being deformed elastically under certain conditions (Morrison 2001). In other words, it indicates the deformation of bodies under the influence of stresses. The term was obtained by the saying of Simplicius (often recognized to Heraclitus), *panta rhei*, "everything flows" (Beris et al. 2014), and was first used to describe the deformation of soft solids and the flow of liquids.

Flow is a continuous irreversible deformation inhibited by internal and external friction offered by the flowing matter. The internal resistance offered is referred to as viscosity, denoted by η. Viscosity (internal friction) is defined as the retarding influence of a stationary fluid layer on a parallel moving fluid layer. When a shear stress (force per unit area; τ), is applied to the fluid layers, each layer would move with a certain velocity depending upon the distance from the plane of applied force. Shear strain (γ) is defined as the velocity gradient perpendicular to the plane of applied stress. According to Newton's law (Kissa 1999),

$$\tau = \eta\left(\frac{dv}{dx}\right) = \eta\gamma \qquad (1.14)$$

The fluids conforming to Newton's law are termed as Newtonian fluids, with η being constant. However, for non-Newtonian fluids, the viscosities are not independent of shear rate and shear stress, and hence is not a persistent value. The one point measurement of their viscosity would provide the value of apparent viscosity at a particular shear rate.

Rheology generally reports about the trend of non-Newtonian fluids by determining the minimal expanse of functions required to develop a association amid deformation rate and shear stress. A plot amid deformation rate and shear stress is a straight line with slope indication the viscosity in case of Newtonian fluids. For non-Newtonian fluids, the shape of the curve reflects the category of the flow. The main categories include Power-Law, Herschel-Bulkley, Bingham, and Casson. The constitutive model equations for selected non-Newtonian fluids are stated in Table 1.2.

Table 1.2: Constitutive equations for non-Newtonian fluid models (Yong-Gang et al. 2009)

Type of non-Newtonian Fluid	**Constitutive equation**	**No. of parameters relating shear stress and shear rate**
Power-Law	$\tau = K\gamma^n$	Two parameter
Bingham	$\tau = \tau_y + \mu_P\gamma$	Two parameter
Herschel-Bulkley	$\tau = \tau_y + K\gamma^n$	Three parameter
Casson	$\tau^{1/2} = \tau_C^{1/2} + (\mu_C\gamma)^{1/2}$	Two parameter

Figure 1.5 represents a graphical representation of the shear stress versus shear rate behaviour plotted as a rheogram for a number of different continuum fluid models.

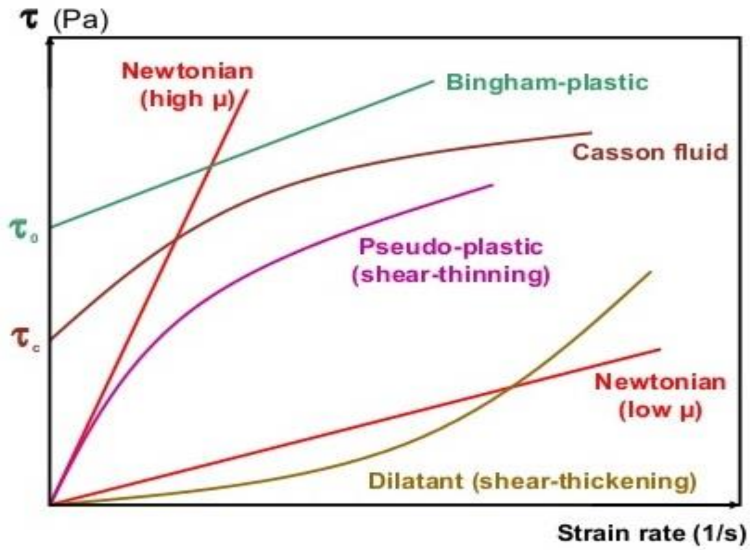


Figure 1.5: Rheogram of different fluid models (Yong-Gang et al. 2009)

1.6 Importance of CWSFs' rheology

The following points illustrate the importance and application of the rheology of CWSFs:

- Rheology controls the quality of coal by determining its rheological or flow properties. The coal material is to be accepted or rejected is estimated based on the rheological results.
- Rheology helps in estimation of the mixability and pumpability of CWSFs and helps in the designing of CWSF transportation systems.
- Rheology also helps in the estimation of the frictional pressure drop when CWSF flows in pipes.
- Rheology evaluates the capability of slurry to transport large particles. It also evaluates the surrounding temperature profile affecting the CWSF's flow behaviour.
- Rheological data helps in finding a relationship between the pump and flow in pipelines. It also helps in selecting a definite pump that would be required to supply enough power for CWSFs to flow over the desired distance.

1.7 International status on CWSFs

CWSFs originally advanced in Russia nearly 80 years back, and this fuel was then used in Europe in 1950. During that time, oil prices turned to be less due to presence of massive oil assets, leading to a halt in the expansion and the applications of the CWSFs technology. CWSFs made its appearance again in the 1970s, after the worldwide prices of oil increased and the oil resource became rare (Everett 1988).

In 1992, the US Army was asked to reduce the expenditure or utilization of petroleum (oil) fuel. The US Army then switched to using CWSFs as a substitute fuel to the dense fuel oil for steam generators (Hamich et al. 1993). Further, GPU Energy (PENELEC), Pennsylvania Electric Energy Development Authority (PEEDA). New York State Electric and Gas Corporation (NYSEG), Electric Power Research Institute (EPRI), and Pennsylvania Electric Energy Research Council (PEERC) inducted a mission to examine the consumption of CWSFs prepared from coal fines. The mission examined the full-scale and laboratory-scale co-firing of a 32 MW steam generator (Zang et al. 1993).

In the 2000's, CWSFs concern was revived in China in order to encounter the environmental challenges of the Beijing Olympics. CWSFs technology in China has advanced and mellowed hastily. It almost achieved the global level and efficiently conceded all the industrial examination's for its usage in steam generators as an alternative to heavy oil. Japan, where stowage spaces and natural resources are restricted and scarce, the advantage of ease in transference of CWSFs is now being utilized.

In 2014, Electricity Generating Authority of Thailand ("EGAT") studied the practicability to retrofit the 300 MW oil fired power plant at Krabi Province to utilize CWSFs. The 300MW oil fired power plant at Krabi Province was a stand by unit and it was expected that the plant would be converted to a mid-merit unit for energy communication by utilizing CWSFs. It was also expected of CWSFs that it would enhance fuel variety to the power generating plant that is presently utilizing about 70% of the natural gas. The combined practicability study of EGAT and Zhejiang University of China to utilize CWSFs as an alternative to the heavy oil might turn out to be a significant phase for energy expansion for Thailand (Daniel et al. 2014).

1.8 Organization of thesis

The organization of the thesis is such that, the latter is divided into different chapters. The first chapter presented a detailed knowledge about CWSFs, a major potential replacement of fuel oil in the near future. The second chapter states the literature review of work published by various researchers related to the CWSFs. This chapter also contains a brief summary in tabular form for all the discussed literature work. The third chapter presents the gaps in the literature, present scope of work (objectives), and the methodology flow chart for the same. The fourth chapter illustrates the characterization studies performed on the coal samples. It describes about the particle size distribution of coal, its grind-ability index, proximate analysis and the influence of coal particle size on proximate composition, chemical composition and morphological analysis of coal samples, and Rosin- Rammler (RR) and Gates-Gaudin-Schuhmann (GGS) mathematical modeling. The fifth chapter illustrates the rheological investigations on the CWSFs as a function of PSDs and temperature. The sixth chapter describes about the packing characteristics of coal particles in CWSFs by determining the bed density (λ) and void fraction (ε). It also describes how to find the optimal coarse : fine ratio for obtaining minimum viscosity and maximum coal loadings. The seventh chapter gives the conclusions and the future scope of work. The eight chapter provides the reflections and the publications made on the present work. At the end are then stated the references.

Chapter 2

Literature Review

2.1 Literature review

There is a considerable research work that has been done in the past to evaluate the CWSFs' rheology from various perspectives. Numerous factors that contribute in altering the CWSFs' rheology have been investigated by researchers and an optimum value that promotes an economic slurry transport with an appreciable viscosity in a particular shear rate range has been found.

Lorenzi et al. (2002) studied the impact of coal particle size distribution on the rheology of CWSFs. They used a surfactant during the preparation of slurry to cause an increase in the solid content. Higher the solid content, lesser is the settling of particles, helping in the storage of slurry fuel. A comparison of the slurry obtained was made using mono-modal and bimodal size distribution and the study indicated that the bimodal distribution should be preferred for the making of CWSFs for lesser viscidness. An optimal fine : coarse particle quotient was also determined for coal studied which came about to be nearly 55:45 (fine:corase) at which the minimum viscosity was observed. Presence of the surfactant resulted in entrapment of greater quantity of air during the coal water slurry preparation, resulting in the change of density and viscidness of the coal water slurry in the days following their preparation.

Senapati et al. (2002) investigated the flow behavior of coal-water slurry (CWS) by making use of a HAAKE RV30 viscometer. The major purpose of their study was to determine the influences of ash content, temperature, solid loadings, and pH on the flow behavior of the CWS. They predicted that the slurry exhibited the pseudo-plastic behavior. The apparent viscosity was found to be maximum around pH 6 and minimum around pH 8. The slurry showed an increment in viscosity with rise in ash content and solid concentration of the coal particles. The variation of temperature on the seeming viscidness of the slurry was illustrated using an Arrhenius relation. They found that with increase in the temperature, the viscidness tended to decrease. Nevertheless, the limits of the activation energy of the slurry were observed to be autonomous of the deformation rate and solid loadings.

Boylu et al. (2004) examined the impact of particle size distributions on CWSFs rheology. The slurries were prepared using three distinct categories of coals with varied ranks but similar particle sizes. Along with the estimation of the physic-chemical possessions of the coal sections, their zeta potentials were investigated too. The fractions consisting of varied proportions of solid loadings with d_{50} sizes of 19, 35 and 50 µm were utilized in order to estimate the influence of volume fraction on the apparent viscidness of the slurry. The d_{50} values of the coal particle sizes showed that despite having identical values of volume fraction, their values of apparent viscosities was found to increase from higher to lower rank of coals. Hence, slurries that were made by utilizing coals of high rank contained more amounts of solids. They also found out that the apparent viscidness of the slurries increased with raising the pulp compactness (by wt.) for different particle size distributions. The outcomes might be illustrated by the argument that different rank coals exhibit different physic-chemical possessions such as porosity and C/O ratio, etc.

Yuchi et al. (2005) collected sixteen Chinese coals each varying in rank and examined the influences of coal physiognomies on the flow possessions of coal water slurry (CWS). Multivariate progressive regression analysis was used by them to find out the relationship between coal possessions and CWS physiognomies. Slurry ability, flow behavior (rheology), and static stability were the three properties of CWS that were investigated in the study. On the other hand, coal rank, air equilibrium moisture (Mad), ash content, petrographic macerals, pore structure, extreme moisture holding capacity (MHC), surface possessions, and adsorption characteristics of dispersants were also investigated. It was observed that a positive correlation exhibited between the carbon content and grind-ability index of coal with the slurry ability, whereas surface area and air equilibrium moisture examined through Mercury Porosimeter exhibited negative correlations. The flow performance of CWS could be correlated positively with the soluble ions content, ash content, pore volume, and content of soluble ions measured through Mercury Porosimeter, whereas zeta potential possessions of the coal exterior exhibited negative correlation with the flow performance. The soluble ions contents displayed a positive correlation with the fixed constancy of CWS.

Mosa et al. (2007) studied the influence of temperature and pH on rheology of coal-water slurry (CWS). They conducted the experiments in a thermal cup at different temperatures ranging from 100 to 200 ◦F. The studied pH range of the slurry was from 2 to 12. The apparent viscosities and non-Newtonian properties were investigated using Power-Law model and a Chandler Engineering viscometer Model 3500LS+. It was observed that the apparent viscosity of the slurry and degree of pseudo-plasticity decreased with increasing the temperature. At temperatures greater than 180 ^{o}F, the coal slurry exhibited a Newtonian fluid behavior. The apparent viscidness was observed to rise with rise in pH, whereas the degree of pseudo-plasticity decreased with increasing pH from 1 to 6 and then increased from 7 to 12. At pH equal to 6, the slurry showed Newtonian fluid behavior. During the transportation of slurry, it was observed that the seeming viscidness also increased with increasing number of pumping cycles. This was attributed to changes in particle size distribution as a result of particle degradation which, in turn, increase pressure drop along the pipeline.

Shukla et al. (2008) conducted the experimental investigations to examine the rheology of coal–oil–water (COW) dispersion with coal particles having varied sizes. In their study, coal average particle sizes of 108 µm, 75.7 µm and 62.9 µm were used. . The solid concentrations were varied from 10% to 50% by wt. All the experiments were conducted in a bob and cup kind coaxial cylinder-shaped viscometer. Newtonian, dilatant and pseudo-plastic performance of the suspensions was examined depending upon the component content and the operating conditions. Their study showed the possibility to attain an optimal coal particle size for enhanced use of coal suspensions. A widespread relationship was also provided in order to calculate the viscidness of the dispersion including the solid loadings, concentration of oil, particle diameter and torque.

Zhou et al. (2010) determined the flow properties of coal-water slurry (CWS) prepared from Datong coal using Haake rheometer, and the data obtained by rheology were formfitted using Power-law, Bingham-plastic, Herschel-Bulkley, Sisko, and Casson mathematical models, respectively. The fitted parameters indicated that the Herschel-Bulkley model had the extreme correlation constant; the model was chosen to examine the flow possessions of the made CWS. The results indicated that CWS that has higher solid concentration, exhibited pseudo-plastic behavior, and CWS that had excessive dispersant exhibited dilatant behavior. Further, the incorporation of high-valence cationic electrolyte increased the pseudo-plastic behavior of the slurry, while the incorporation of anionic agent, decreased the shear-thickening behavior.

Buranasrisak et al. (2012) studied the ramifications of coal particle size distribution and its packing characteristics on the rheology of CWSFs. They conducted the experiments for mono-modal and bimodal particle size distributions (PSD) using the coal samples with six particle size ranges; i.e. < 38 μm, 38-63 μm, 63-75 μm, 75-90 μm, 90-180 μm and 180-250 μm. It was found out that, at an adequate apparent viscosity, the bi-modal PSD with an optimal fine to coarse ratio can help in obtaining the slurry with highest coal loading.

Ganguly et al. (2012) examined the outcomes of particle size distribution of pulverized Alaska coal, which has higher volatile matter and is low rank coal, on its burning efficiency. Performance was detected by efficiency; $NO_{x,}$ SO_x emissions, and content of carbon of ash. Their study indicated that Alaska coal might be combusted at a grind as coarse as 50% falling through 76 µm, with none negative effect on the emissions and power generating capacity. The particle size distributions studied were in the assortment of 41 to 81% falling through 76 µm. No correlation was obtained amid particle size distribution, efficiency and the emissions. Further, two more tests were conducted where heap mercury (Hg) statistics was determined. They too did not illustrate any actual alteration in the emissions of mercury with particle size distribution. These plants possess a greater tendency to efficiently reduce plant capacity by crushing the coal less causing no effect of plant's efficiency or emissions and hence can increase marketability. Their study anticipated that the Alaska coal may be scorched at a particle size as coarse as that falling through 76 µm sieve, with no negative outcome on generation of power and emissions.

Alderliesten (2013) studied the statistical and physical possessions of the Rosin-Rammler (RR) mathematical model and its factors to determine their appropriateness in the any specific area. The author observed that the physical significance of the RR location parameter depended up on the measure of its spread parameter (m). Due to this reason, the location factor became physically unaccountable and hence became unsuitable for the advancement of physical models. The RR model was found to be still utilized for purposes like production control. It was also observed that the RR model with values of spread parameter less than 3 does not occur. The values of spread parameter could give a coarse explanation of particle size distributions inside the restrained size array but it could not determine the amount of minor particles outside the restrained size array. The spread parameter is not suitable for models pointing at determining the factors calculating the process factors or physical product. In the present study two statistics sets were made use of for authentication. RR spread parameters and mean particle diameters were found to be arithmetically correlated, but the association was invalid for mean factor values. It was also observed that it is impossible to predict mean particle diameter exhibiting a performance near to that of the RR location parameter. It was found out that for process control applications the RR location parameter could be replaced by a mean particle diameter. The type of mean particle diameter to be taken was found to be the function of the RR spread parameter occurring in the process.

Panda (2014) explained that the coal water slurry could be an auxiliary for fuel oil in India. Indian coals in general are lower in rank, have adequately pulverulent mineral material mostly of quartz and silicate origin with low sulphur. Since most of the studies have been done with coals available in the western countries having low ash content, therefore, an attempt was made to study certain facets of the flow behavior of coal slurries prepared out of coals available in India. An empirical relationship was established among shear stress, percentage of ash by weight and concentration of solid in coal water mixture. The coal water slurry will go a long way as an alternate source of fuel considering the rheological studies in designing pipelines for transportation of slurry with optimum solid concentration.

Ulusoy et al. (2016) used mechanical sieving (MS) and dynamic image analysis (DIA) for determining the particle size distribution (PSD) of coal (mainly lignite) that were pulverized by Gy-Ro and ball mills. The PSD statistics of pulverized coal particles were studied on DIA and MS by log-normal scattering plots. The PSD statistics were also modeled using the two widely used mathematical models namely Gaudin-Schuhmann (GS) and Rosin-Rammler (RR). Generally, it was observed that the particle sizes below 100 μm showed analogous PSD, for both DIA and MS methods. On mathematical modeling, the RR model was found to fit well on the complete array of particles sizes provided by Gy-Ro and ball mills in comparison to GS model. It was also found out that DIA could estimate the particle size arrays under 100 μm, while MS could not. Moreover, the results provided by DIA were found to be more accurate than those obtained by MS especially for particle sizes of 38 μm and below. Consequently, RR and DIA model was suggested for PSD investigation of fine coal particles.

Singh et al. (2016) studied the rheology of CWSFs of an Indian coal. The rheological behavior of the CWSF was examined by preparing the slurry samples by mixing fine and coarse particles, resulting in bimodal distributed slurry. A particle size small than 75 mm was made use for investigation of flow performance of coal slurry and they observed that the increment in the solid loadings caused the rise in the viscidness of the coal-water dispersion. It was also detected that with rise in the solid loadings, the coal-water dispersion converted to a non-Newtonian fluid. The bimodal dispersion was prepared by mixing fine particles (ranging between 53–75 μm) and coarse particles (ranging between 106–150/ 150–250 µm) in varied amounts. The optimal portion in bimodal dispersion was found to be 30% where the apparent viscosity was found to be lowest.

Yang et al. (2016) studied a two-grade fractal model to cause improvement in the packing characteristics of coal particles in brown coal water slurry (BCWS). The two grade model was based on the fractal theory and improvised by distinguishing the coal particle size into two different grades. Further packing efficiency (PE) of coal particles in BCWS was analyzed. In addition to this, various reversion stages of the model in numerous particle arrangements were also investigated. It was found out that the PE of BCWS was a function of fractal characteristics of sizes below 74 µm and further PE could be improved by setting fractal dimension to be near 2.6-2.7. Further, the fractal model was also found to fit the particle size distributions with varied ratios of coarse (CS) to fine (FS) to ultra-fine (UFS) coal. It was observed that the maximum value of PE was obtained when the ratio of varied particle sizes was 7:0:3 (CS:FS:UFS) with the fractal measurement being 2.7080. Utilizing the above mentioned fractal dimension, it was found out that the BCWS prepared with this dimension had an increment in its solid loadings by 2.9 %.

Zhu et al. (2017) investigated the impact of particle size distribution on the flow and steadiness possessions of bio-char- water slurry fuels. They prepared slurries with varied D_{50} values of bio-char having uni-modal and bimodal distribution with different dimension fine : coarse ratios (λ) and diverse fine portion (ξ). The yield stress of the prepared dispersions was determined using a Brookfield vane viscometer whereas the dependence of the viscidness and the shear stress up on the deformation rate was characterized using a Haake VT550 cone and plate viscometer. The bimodal distributed slurry was found to have a decreased viscidness and improved solid loadings. The viscidness was found to decrease more with decreased λ, and was more reflective at reduced ξ. The slurry made with finer bio-char was found to be steadier.

2.2 Tabular summary

S. NO.	REFERENCE	INVESTIGATION	APPARATUS AND MATERIAL USED	KEY RESULTS
1.	Lorenzi et al. (2002)	The Impact of Particle Size Distribution and Non -ionic Surfactant on the Flow Performance of CWFs Formed By Iranian and Venezuelan Coals	HAAKE VT 550 Rheometer	It was found that at higher values of deformation rates, the flow performance of bi-modal CWFs was pseudo-plastic, whereas the flow performance tended to be dilatant in case of uni-modal CWFs. Further when a coarse : fine ratio of 45:55 was used for preparation of bi-modal CWFs, the viscosity of the slurry was found to be minimum.
2.	Senapati et al. (2002)	Flow Performance of Coal-Water Slurry	HAAKE RV30 Viscometer	It was detected that the CWS prepared revealed shear thinning or pseudo-plastic behavior. It was also observed that the viscidness of the slurry increased with rise in the coal loadings and ash content. It was also found out that the slurry pH had a significant effect its viscosity. The viscosity was found to be maximum at of pH 6 for all 3 kinds of coal and was minimum at pH 8.
3.	Boylu et al. (2004)	Influence of Coal Particle Size Distribution, Volume Fraction and Rank on the Flow Performance of Coal–Water Slurries	Zeta Meter 3.0 Type Instrument RVD2-Brookfield Rotating Viscometer	It was found that the CWS prepared by coal of high rank could hold a greater quantity of solid loadings. It was detected that the slurry viscidness was directly proportional to the pulp density for various PSDs.

4.	Yuchi et al. (2005)	Influence of Coal Physiognomies on the Possessions of Coal Water Slurry	Mercury Porosimeter Nxs-11 Rotation Viscosimeter	It was found out that the amount of carbon and grind-ability index exhibited a positive association with the slurry-ability, whereas surface area and air equilibrium moisture and surface area exhibited negative correlations. It was also observed that the flow performance of CWS was positively associated with the pore volume and content of ash while zeta potential had negative impact.
5.	Mosa et al. (2007)	A Study on the Influence of Slurry Temperature, Particle Degradation and Slurry pH on Flow Performance and Pressure Drop of Coal Water Slurries	Chandler Engineering Viscometer Model 3500LS+	It was detected that the seemed viscidness and degree of pseudo-plasticity sharply declined with increasing slurry temperature. It was also observed that the viscidness was enlarged with increasing numeral of pumping cycles, owing to the particle degradation, leading to an increase in pressure drop along the pipeline.
6.	Shukla et al. (2008)	Coal-Oil-Water Multiphase Fuel: Flow Performance and Estimation of Optimal Particle size	Coaxial Cylindrical Viscometer	It was detected that the viscidness of COWMs slurry rose with rise in particle size for both COMs and COWMs.
7.	Zhou et al. (2010)	Flow Performance Analysis of Coal-Water Suspension With High Solid Loadings	The Haake Rheometer	It was indicated that CWS comprising of higher solid loadings exhibited shear thinning while the slurry prepared using excessive dispersant exhibited dilatant behavior. It was also found out that the yield value and shear thinning behavior could be increased by adding high-valence cationic electrolyte, whereas dilatant behavior could be increased by adding anionic agent.

8.	Buranasrisak et al. (2012)	Influence of Particle Size Distribution and Packing Features on the Formation Coal Water Slurry With High Solid Loadings	MV-2000 Series II Cannon Rotary Viscometer	It was observed that solid loadings in preparation of CWS could be increased by using bi-modal distribution with optimum coarse : fine ratio.
9.	Ganguly et al. (2012)	Correlation amid Particle Size Distribution of Pulverised Coal of Low Rank and Performance of a Power Plant	Rheotest-2 Instrument	NO_x, SO_x, and CO emissions were found to same between the groups, however they were found to vary inside every trial cluster. The array was found to be greater for CO considering the coarse cluster.
10.	Alderleisten (2013)	The Rosin-Rammler (RR) Size Distribution: Physical and Arithmetical Properties and Interactions to Moment-Ratio Defined Mean Particle Diameters	Rosin-Rammler Distribution Function	RR density distribution was found to be indistinguishable from Weibull density distribution illustrating quantifiable failure and low energy occurrences. It was also observed that the mean particle diameters and RR spread and location factors are correlated arithmetically, but the association was found to be invalid for mean factor limits of an array of size distributions.
11.	Panda (2014)	Coal Water Slurry as an Alternative for Fuel Oil in India	HAAKE 30 viscometer	It was observed that the slurries upto 30% concentration by weight for coals behaved like Newtonian fluid and thereafter the transition was found to occur. It was also observed that the relation between yield stress and ash content was linear. The yield stress increased with the increase in ash content.
12.	Ulusoy et al. (2016)	Particle Size Distribution Modeling of Milled Coals by Mechanical Sieving (MS) and Dynamic Image Analysis (DIA)	Quantachrome instruments, Florida, USA	It was observed that RR model fitted appropriately the PSD data for the complete array of coal particle sizes grounded by Gy-Ro and ball mills in comparison to GS model. It was also observed that the results obtained from DIA were more accurate than MS

				for size of 38µm and below.
13.	Singh et al. (2016)	Impact of Particle Size Distribution and Temperature on Flow Performance of Coal Slurry	Anton Paar Rheolab QC Rheometer	It was observed that a rise in solid loadings caused an increment in the viscidness of coal water slurry and transformed it into a non-Newtonian fluid.
14.	Yang et al. (2016)	Optimization of Packing State in Brown Coal Water Slurry Based on the Two Grade Fractal Model	Viscometer (NXSI 1-B)	It was observed that the maximum value of PE was obtained when the ratio of varied particle sizes was 7:0:3 (CS:FS:UFS) with the fractal measurement being 2.7080.
15.	Zhu et al. (2017)	Flow Performance and Constancy Features of Biochar-Water Slurry Fuels (BCWFs): Influence of Particle Size and Particle Size Distribution	HAAKE VT550 cone and plate viscometer	It was observed that the biochar bimodal distributed slurry possessed a lesser viscidness and more solid loadings. The slurry fuels made from finer biochar were steadier.

Chapter 3

Gaps in Literature and Objectives of the Thesis

3.1 Gaps in literature

A lot of research work has been done in the past to investigate the rheological behavior of CWSFs from different perspectives, few of which were discussed in the previous chapter. Various factors that affect the rheology of CWSFs that have been studied by various researchers are the effects of additives and stabilizers, highly concentrated CWSFs, zeta potential, etc. However, a gap in study reveals that there is still a lot of work to be done in determining the effects of fraction of coal fines, particle size distribution (PSDs) and packing fraction density on the flow (rheological) performance of CWSFs in order to get efficient combustion and transportation of CWSFs with appreciable viscosity.

3.2 Objectives of the thesis

The present scope of study lies in the investigation of flow characteristics of CWSFs prepared from three dissimilar grades of Indian coal, procured from varied locations across India as a function of particle size distribution, varied coarse/fine ratio, temperature and packing fraction density. The coal samples were obtained from Guru Nanak Dev Thermal Plant, Bathinda, Punjab (S-I), Trident limited, Madhya Pradesh (S-II), and Deenbandhuchotu Ram Power Plant, Yamuna Nagar, Haryana (S-III). The objectives of the present study are stated as follows:

- Analysis of rheological/flow behaviour of CWSFs as a function of particle size distribution (PSDs): A comparative study of uni-modal, bi-modal, and tri-modal particle size distributed slurries.
- Analysis of rheological/flow behaviour of CWSFs as a function of temperature: A comparative study of uni-modal, bi-modal, and tri-modal particle size distributed slurries.
- Determination of bed density/ packing fraction density and void fraction of the coal particles in the slurry.

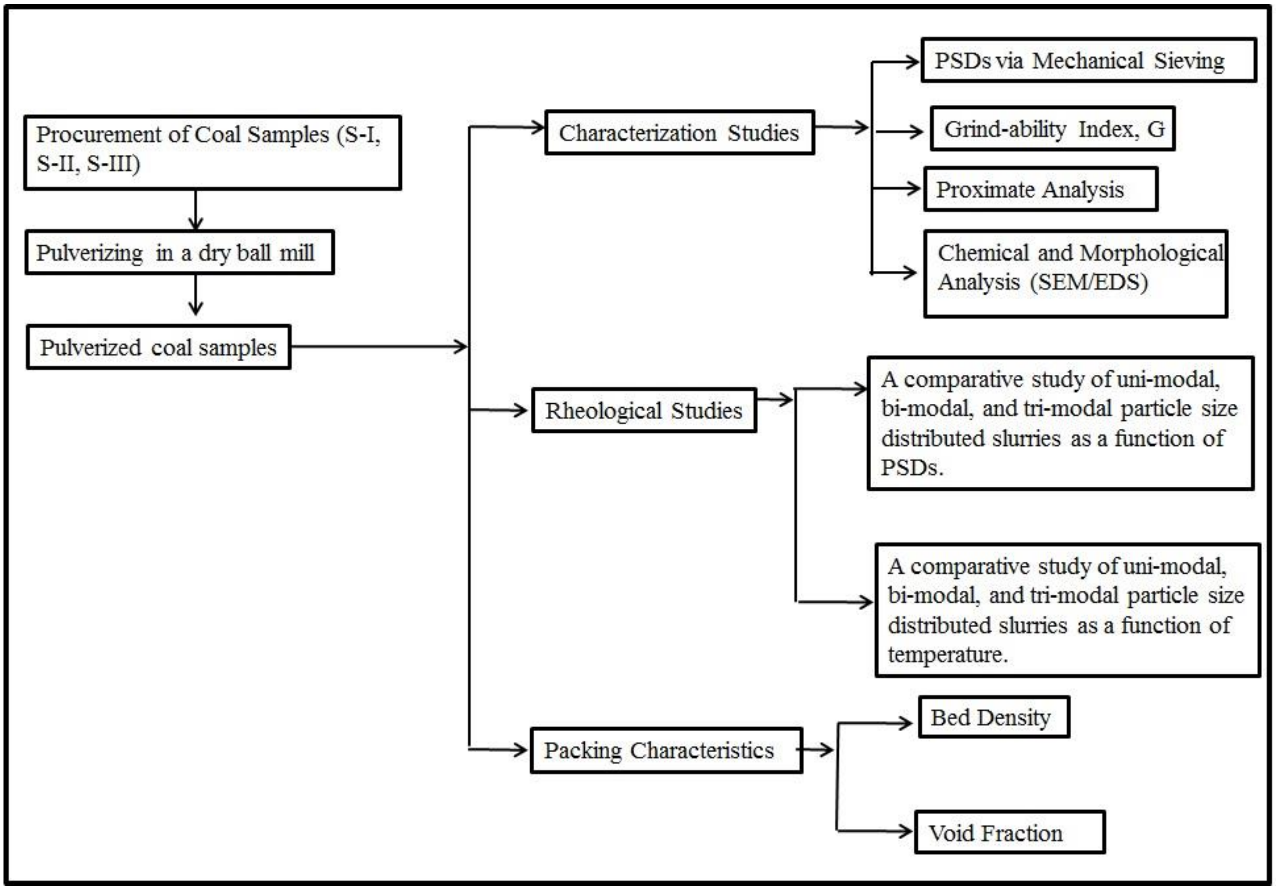


Figure 3.1: Detailed flow chart of the methodology

Chapter 4

Characterization Studies on Coal Samples

Three different Indian coal samples, each varying in ash content, were procured from different sources. The coal samples were obtained from:

- Guru Nanak Dev Thermal Plant, Bathinda, Punjab (S-I)
- Trident limited, Madhya Pradesh (S-II)
- Deenbandhuchotu Ram Power Plant, Yamuna Nagar, Haryana (S-III).

The coal samples procured were pulverized in a dry ball mill (in the presence of air) of sizing as diameter 32 cm and length 30cm using approximately 3kgs of cast iron balls (make - AS Enterprise, Calcutta). The coal samples were run at a constant speed of 90- 100 rpm for a period of 12 hrs. The filling rate of balls and coal were around 40 % by volume. The grinding conditions used were as per the standard ISO: 9931.

Figure 4.1: Pictures of dry ball mill (make AS Enterprise, Calcutta)

The characterization studies were done on the three coal samples in order to determine their particle size distribution, grind-ability index, proximate composition, and chemical and morphological properties.

4.1 Particle Size Distribution (PSDs)

The diversity in the size of the coal particles and the fraction of coal particles present in varied size ranges were calculated in order to obtain PSDs. A recognized quantity of each coal sample was considered and pounded on B.S. 200 mesh. MS (Mechanical Sieving) tests were then performed using a sieve shaker and set of 1000, 710, 500, 355, 250, 150, 106, 75, and 53µm British standard sieves with an amplitude of 40 on a scale of 0-100 with the frequency setting being continuous. The mass of coal particles retained on each sieve was procured, calculated and expressed in percentages. The MS test gives the mass distribution of varied sizes of coal particles acquired from sieve aperture diameters (Ulusoy et al. 2016). The values of weights of varied particle sizes acquired from MS tests for the three coal samples are enumerated in Table 4.1.

Table 4.1: PSDs analysis of the coal samples

Ranges of size (mm)	**Mesh Size (mm)**	**Fraction (gm)**			**Cumulative weight % (under)**			**Cumulative weight % (over)**		
		S-I	**S-II**	**S-III**	**S-I**	**S-II**	**S-III**	**S-I**	**S-II**	**S-III**
<0.053	0.053	1.50	3.70	5.60	0.19	0.82	0.65	99.80	99.18	99.36
0.053-0.075	0.075	2.10	114.60	344.90	0.47	26.07	40.40	99.53	73.93	59.61
0.075-0.106	0.106	11.00	20.60	171.30	1.90	30.41	60.13	98.10	69.59	39.87
0.106-0.150	0.150	51.10	59.80	104.20	8.57	43.79	72.14	91.43	56.20	27.86
0.150-0.250	0.250	379.80	88.30	200.90	58.08	63.26	95.23	41.92	36.74	4.77
0.250-0.355	0.355	289.50	123.90	16.50	95.83	90.57	97.20	4.17	9.43	2.81
0.355-0.500	0.500	17.60	34.50	13.30	98.12	98.17	98.73	1.88	1.83	1.27
0.500-0.710	0.710	13.30	6.30	9.65	99.86	99.56	99.84	0.14	0.44	0.16
0.710-1.00	1.000	1.10	2.00	1.40	100	100	100	0	0	0

S-I (Guru Nanak Dev Thermal Plant, Bathinda, Punjab); S-II (Trident limited, Madhya Pradesh); S-III (Deenbandhuchotu Ram Power Plant, Yamuna Nagar, Haryana)

Figure 4.2 depicts the PSDs curves of the three coal samples studied viz S-I, S-II, S-III, obtained from the data enumerated in Table 4.1.

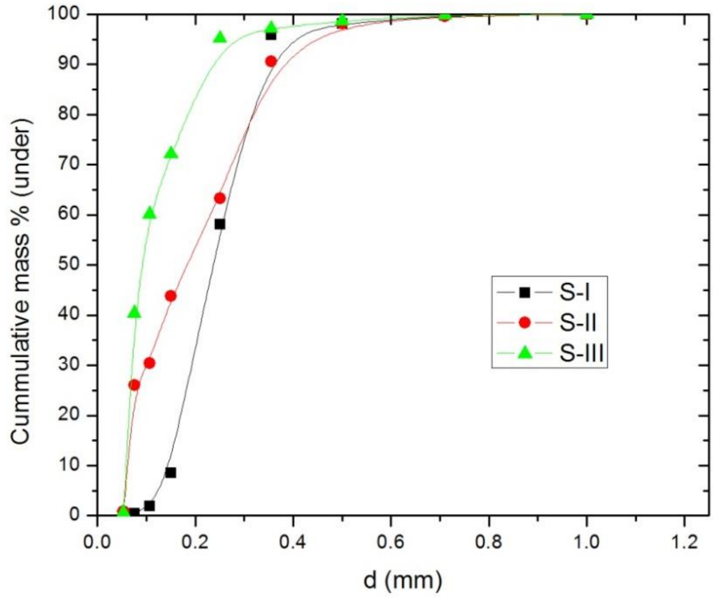


Figure 4.2: PSD curves for the three coal samples (S-I, S-II, and S-III) obtained by MS tests

The PSDs curves obtained indicates a continuous distribution of varied coal particle sizes for each coal sample. Table 4.2 indicated the mass-median diameter (D_{50}) values of the three coal samples obtained from the PSDs curves.

Table 4.2: Mass median diameters of the three coal samples

Coal Samples	**S-I**	**S-II**	**S-III**
D_{50} (mm)	0.235	0.180	0.085

S-I (Guru Nanak Dev Thermal Plant, Bathinda, Punjab); S-II (Trident limited, Madhya Pradesh); S-III (Deenbandhuchotu Ram Power Plant, Yamuna Nagar, Haryana)

The obtained values of D_{50} (mass-median diameters) for the three coal samples (S-I, S-II, and S-III) are in agreement with the values of D_{50} of the coal samples being utilized in the respective thermal power plants. Though, the values are quite different from those mentioned theoretically (Singer 1981), but the values obtained matches completely with those being used in respective thermal power plants for coal firing.

4.2 Grind-ability index, G

The grind-ability of coal samples was determined using the Hardgrove scheme that accounts for the increment in the surface area formed by the application of a certain amount of work and expresses the result as Hardgrove grind-ability index, G (Sarkar 1990)).

$$G = 13 + 6.93W \qquad (4.1)$$

Where, W represents the weight of coal in grams passing through a 200 mesh sieve after 50g of coal of size 16 to 30 mesh are ground in a standard mill for 60 revolutions.

A soft and easily grind-able coal generally has a higher value of G. The general trend illustrates that the value of G is initially directly proportional to the rank of coal (i.e. with rise in the rank, the G value also rises), reaching the highest value of around 105 for bright coals (89% to 90% carbon) and then sharply decreases to around 35 for anthracites (Sarkar 1990). The results are represented in Table 4.3.

Table 4.3: Grind-ability index for all the three coal samples

Hardgrove grindability index	**S-I**	**S-II**	**S-III**
G	60	54	63

S-I (Guru Nanak Dev Thermal Plant, Bathinda, Punjab); S-II (Trident limited, Madhya Pradesh); S-III (Deenbandhuchotu Ram Power Plant, Yamuna Nagar, Haryana)

4.3 Proximate analysis of coal samples

The proximate analysis of the three coal samples was conducted as per the recommended analysis practice stated in IS: 1350 (I) to obtain the amount of inherent moisture, volatile matter, ash, and fixed carbon in the coal samples. The outcomes of the same are stated in Table 4.4.

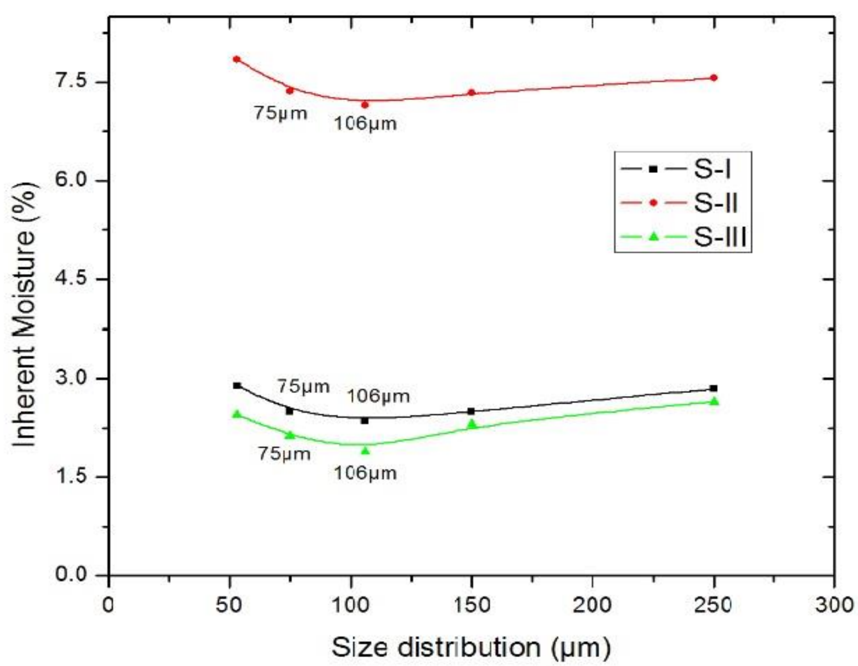
Table 4.4: Proximate analysis of coal (air dried basis)

Parameters	**S-I**	**S-II**	**S-III**
Total Moisture %	4.0	7.5	2.5
Volatile Matter %	22.0	32.5	21.5
Ash %	32.5	16.5	43.0
Fixed Carbon %	41.5	43.5	33.0

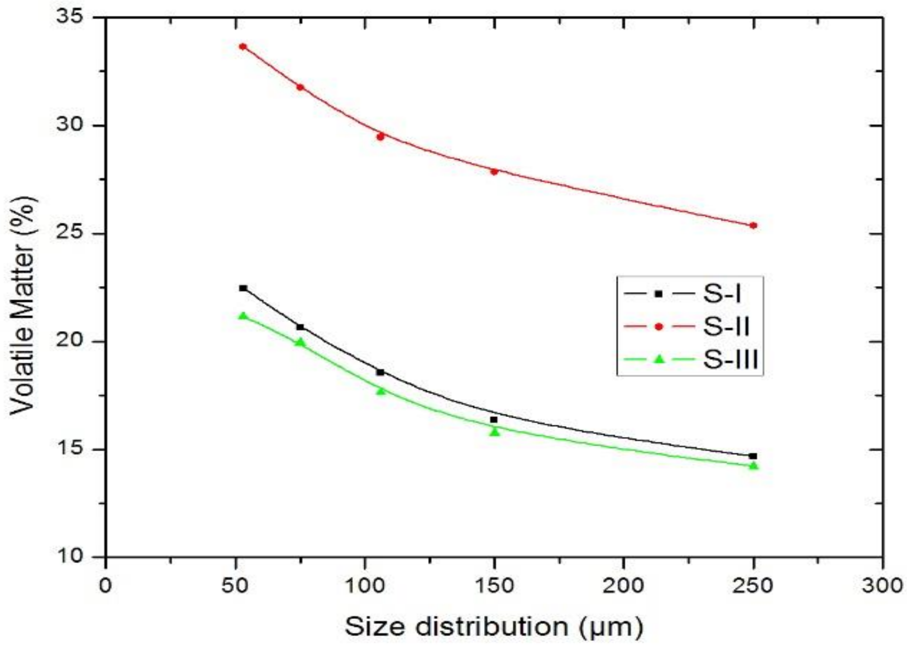
S-I (Guru Nanak Dev Thermal Plant, Bathinda, Punjab); S-II (Trident limited, Madhya Pradesh); S-III (Deenbandhuchotu Ram Power Plant, Yamuna Nagar, Haryana)

The proximate analysis of the three coal samples revealed that all the three coal samples had different ash content with S-II (Madhya Pradesh) having the least ash content in comparison to S-I and S-III. The results also indicated that the inherent moisture is least in S-III.

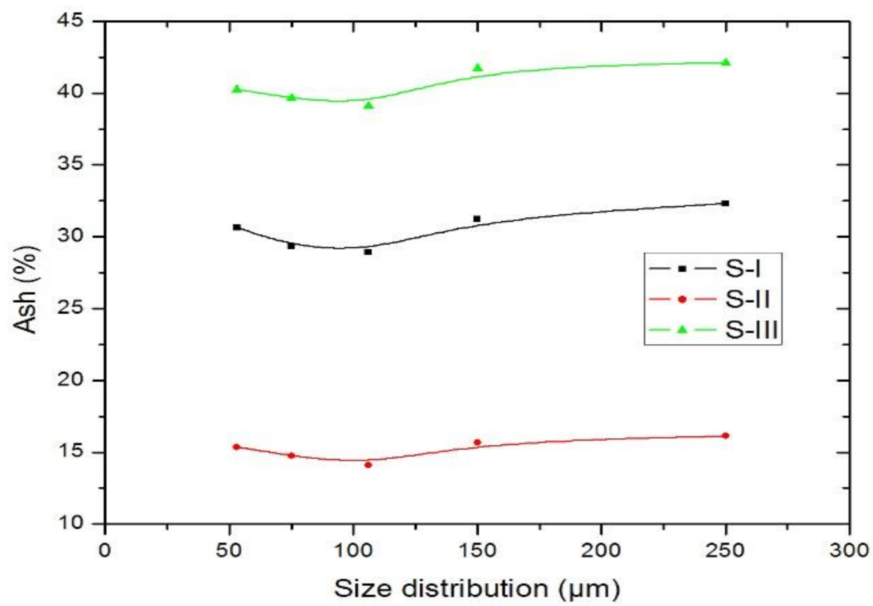
Jayaweera et al. (1989) proposed that varied fractions of sizes prepared from a single coal sample by mechanical sieving might not necessarily have the same proximate composition. They also stated that the coarser particles may have more mineral content associated with them. Xu et al. (2005) also observed that the ash content of different fractions of sizes from bituminous coals first decreased and was then found to rise with decrease in coal particle size. To analyze the same, five different size fractions of each coal sample (S-I, S-II, and S-III) were prepared and were tested for their proximate composition. The five size fractions used were 53µm, 75 µm, 106 µm, 150 µm, and 250 µm. The results of proximate composition obtained are shown in Fig. 4.3.



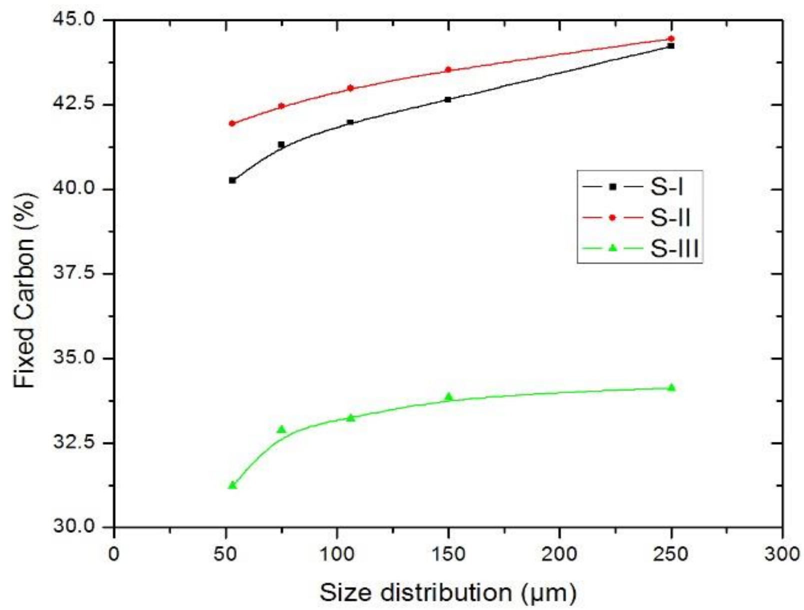
(a) Variation of inherent moisture with the particle size distribution (PSDs)



(b) Variation of volatile matter with the particle size distribution (PSDs)



(c) Variation ash content with the particle size distribution (PSDs)



(d) Variation of fixed carbon content with the particle size distribution (PSDs)

Figure 4.3: Effect of coal particle sizes on the proximate composition of all the three coal samples

Generally, pulverized coal fired boilers utilizes a size less than 106μm for its combustion (Singer 1981). Therefore, it is observed from the Fig. 4.3(a) that inherent moisture is negatively correlated with particle size ranging from 53-106 μm. This implies that the coarsening of the pulverized coal is not affected by the inherent moisture content of coal. This can be explained as inherent moisture is adhered by the capillarity inside the interstices of coal structure or is associated with minerals and, hence, can be associated with the coal porosity, which favors the pulverization of coal particles. Similar kind of result was also obtained by Xue et al. 2013.

On the other hand, it is observed that the influence of coal particle size on volatile content (Fig. 4.3(b)) and fixed carbon (Fig. 4.3(d)) are opposite, whereas is weak on the ash content (Fig. 4.3(c)). The volatile matter is negatively correlated to particle size implying that a higher volatile content would favor coal pulverizing. Fixed carbon has a positive but insignificant correlation with particle size above 100 μm i.e. with coarser particles. The increase in coal particle size led to a decrease in the ash content initially but later the particle size and the ash content were found to be directly proportional to each other. The reason behind such a trend can be thought of the different friability of minerals.

4.4 Chemical composition and morphological analysis

The morphological characteristics and the chemical composition of the coal samples were obtained by SEM (Scanning Electron Microscopy) and EDS (Energy Dispersive Spectroscopy) techniques respectively. SEM is the technique of great resolution superficial imaging using an electron ray. SEM micrographs are found to possess a greater depth of field because of the narrow electron ray/beam, resulting in a distinctive 3-d appearance beneficial for understanding the surface arrangement of the coal samples (Roy et al. 2015). For SEM imaging, the coal samples must be electrically grounded in order to prevent scanning faults caused due to electrostatic charge at the surface, therefore the coal samples gets coated with an ultrathin coating, usually gold (Au). This process is known as sputter coating. The coating increases the signal and surface resolution (Loureiro et al. 2016). The SEM micrographs obtained for the three coal samples (S-I, S-II, and S-III) are shown in Fig. 4.4(a), 4.5(a), and 4.6(a) respectively.

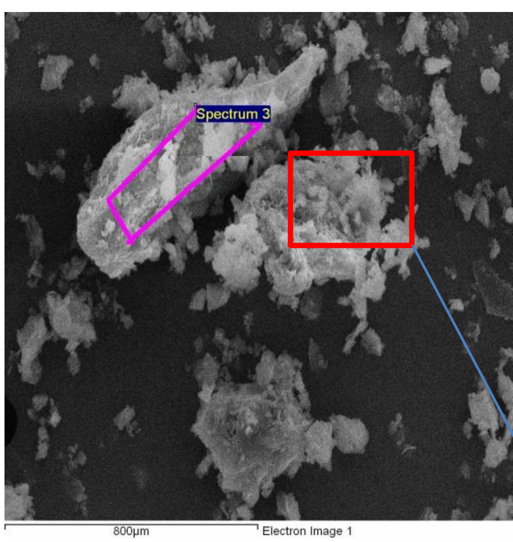


Figure 4.4(a): SEM micrograph for S-I

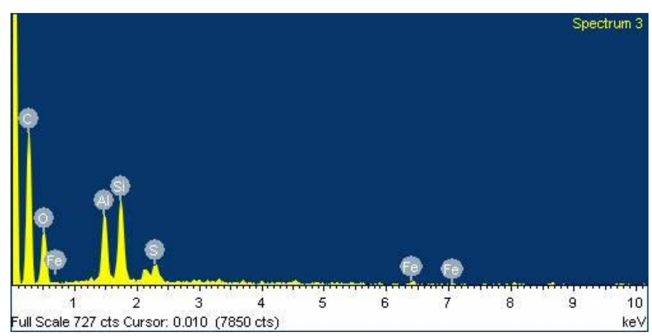


Figure 4.4(b): EDS output of S-I

Soot, carbonaceous, and minerals giving a rough surface

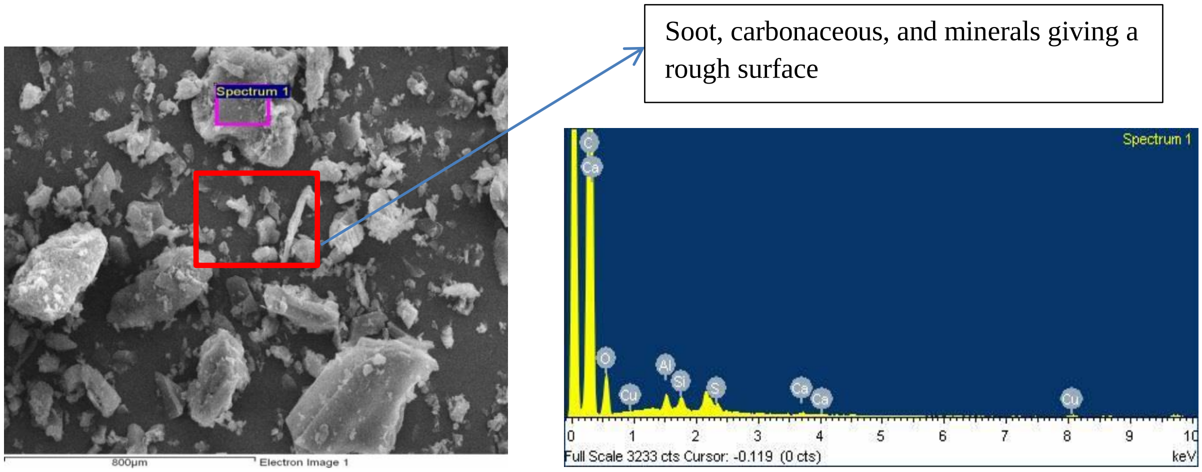


Figure 4.5(a): SEM micrograph for S-II

Figure 4.5(b): EDS output of S-II

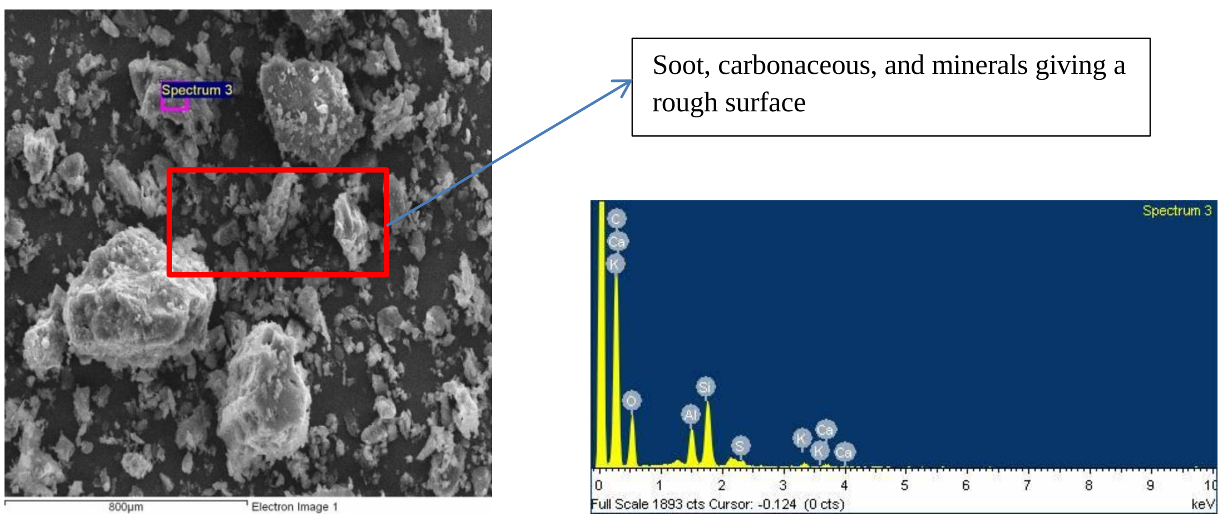


Figure 4.6(a): SEM micrograph for S-III

Figure 4.6(b): EDS output of S-III

The SEM micrographs showed that the coal samples were mainly irregular in shape and mirrored the presence of the grime, carbonaceous bits, alumino-silicates, etc. The small asymmetrical particle deposition was detected due to ash and soil attrition. The white blistering spots were the results of mine fire. There was a significant difference in the distribution of the coal particles of all the three samples. This might explain that why the coal water slurry have much higher viscosity as compared to fly ash slurry at same concentration which have round shape providing ball bearing action manifesting as reduction in viscosity. As seen from the SEM micrograph, the sample S-III contained more fines than any other coal sample. While the S-I tends to be more distributed towards the coarser side with a few fraction of fines. The S-II exhibited a mixture of coarse and fine particles.

Figures 4.4(b), 4.5(b), and 4.6(b) depicts the EDS output of the coal samples. EDS is an investigative practice used for fundamental study of chemical composition of a coal sample (Roy et al. 2015). The chemical composition of the three coal samples as obtained by the EDS output peaks are stated in Table 4.5.

Table 4.5: Chemical composition of the coal samples as obtained by the EDS

Coal Samples	**Chemical Composition**							
	C	O	Al	Si	S	Ca	Cu	Fe
S-I	60.4	28.72	3.88	4.96	1.04	…….	1.19	0.99
S-II	81.51	16.71	0.48	0.38	0.1	0.13	0.68	…….
S-III	57.9	3.58	2.68	4.83	0.23	0.38	1.29	0.94

S-I (Guru Nanak Dev Thermal Plant, Bathinda, Punjab); S-II (Trident limited, Madhya Pradesh); S-III (Deenbandhuchotu Ram Power Plant, Yamuna Nagar, Haryana)

4.5 Rosin-Rammler (RR) and Gates-Gaudin-Schuhmann (GGS) mathematical modeling

Mostly, mathematically modeled distribution functions are formfitted to size dispersals to develop a precise size stricture for modeling purposes. The most extensively used distribution models are those anticipated by Rosin-Rammler (RR) and Gates-Gaudin-Schuhmann (GGS). Therefore, a comparative study of the distribution functions F(d) (mass fraction) obtained by smearing RR and GGS mathematical models to the records procured by the PSD curves plotted as a result of mechanical sieving of the pulverized coal samples, was made. The comparison of the two models would provide the method for accurate segregation of divergent particle sizes in order to increase the boiler efficiency.

The GGS model (Schuhmann 1940) represents the mass distribution function by a simple power law, defined by the equation:

$$F(\mathrm{d}) = \left(\frac{d}{dmax}\right)^{m} \qquad (4.2)$$

Where F(d) is the portion of section finer than the size d; d is the particle diameter (mm); d_{max} is the largest diameter of the coal particle of the distribution (size modulus) (mm), that localizes the dissemination in global size range; and m is the distribution modulus measuring the wideness of the size distribution.

In GGS model, the data are schemed alongside sieve orifice diameter on log-log graph, resulting in a fairly straight contour with a slope identical to m, finding the equation:

$$logF(d) = mlog(d) - mlog(dmax) \qquad (4.3)$$

Therefore, a plot of the logarithm of F(d) and the logarithm of the d i.e. the diameter of the coal particles, would provide a straight line if the experimental data of PSDs curve fits the GGS model.

The RR model (Rosin and Rammler 1934) has extensively been used to define the PSDs of numerous concentrates attained by milling, crushing, and grinding operations. The RR model is defined as:

$$F(d) = 1 - exp\left[-\left(\frac{d}{l}\right)^m\right] \qquad (4.4)$$

Where F(d) is the distribution function; d is the particle size (mm); l is the mean particle size (mm) (i.e. D_{50}); and m is the amount of spread of the particle sizes. The expression could be rephrased as:

$$\ln\{-ln[1 - F(d)]\} = mln(d) - mln(l) \qquad (4.5)$$

A plot of principal term of this manifestation with the natural logarithm of d, would give a straight line with a slope equal to m, if the data of the PSD curve fits the RR model. Figure 4.7 represents the distribution function F(d) (mass fraction) of the three coal samples (S-I, S-II, and S-III), attained from fitting the investigational outcomes of Fig. 4.2 to Eq. (4.4). The value of the distribution function at a specified loaction is the portion of the quantity of particles (mass) which is under a specified size.

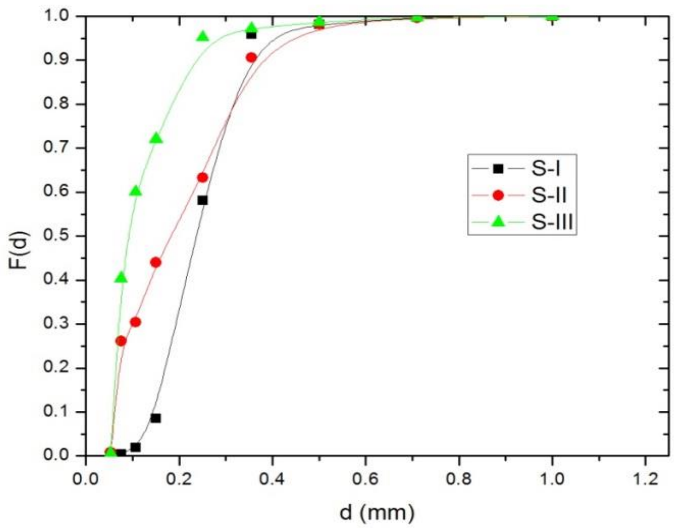


Figure 4.7: Plot of distribution function vs. particle size

The experimental results obtained from the PSDs curves of the three coal samples revealed in Fig. 4.2, are represented in tabular form for each coal sample in Tables 4.6, 4.7, and 4.8 respectively. These experimental results were then used to implement and compare the two mathematical models viz RR model and GGS model.

Table 4.6: Fits to RR and GGS model for S-I

Cumulative weight % (under)	**F(d)**	**d (mm)**	**Log F(d)**	**Log d**	**ln{-ln[1-F(d)]}**	**ln d**
0.1956	0.00196	0.053	-2.71	-1.28	-6.236	-2.94
0.4694	0.00469	0.075	-2.33	-1.13	-5.359	-2.59
1.9035	0.01904	0.106	-1.72	-0.97	-3.951	-2.24
8.5658	0.08566	0.150	-1.07	-0.82	-2.413	-1.89
58.0834	0.58083	0.250	-0.24	-0.60	-1.520	-1.38
95.8279	0.95828	0.355	-0.02	-0.45	-1.006	-1.04
98.1225	0.98123	0.500	-0.01	-0.30	0.987	-0.69
99.8566	0.99857	0.710	-0.001	-0.15	1.879	-0.35
100	1	1.000	0	0	0	0

S-I (Guru Nanak Dev Thermal Plant, Bathinda, Punjab)

Table 4.7: Fits to RR and GGS model for S-II

Cumulative weight % (under)	**F(d)**	**d (mm)**	**Log F(d)**	**Log d**	**ln{-ln[1-F(d)]}**	**ln d**
0.8155	0.0082	0.053	-1.24	-1.28	-2.799	-2.94
26.0745	0.261	0.075	-0.58	-1.25	-1.196	-2.59
30.4138	0.304	0.106	-0.52	-0.98	-1.015	-2.24
43.7954	0.44	0.150	-0.36	-0.82	-0.545	-1.89
63.2577	0.633	0.250	-0.19	-0.60	0.002	-1.38
90.5664	0.906	0.355	-0.04	-0.45	0.86	-1.04
98.1706	0.982	0.500	-0.008	-0.30	1.391	-0.69
99.5592	0.996	0.710	-0.002	-0.15	1.709	-0.35
100	1	1.000	0	0	0	0

S-II (Trident limited, Madhya Pradesh)

Table 4.8: Fits to RR and GGS model for S-III

Cumulative weight % (under)	**F(d)**	**d (mm)**	**Log F(d)**	**Log d**	**ln{-ln[1-F(d)]}**	**ln d**
0.6453	0.0065	0.053	-0.76	-1.28	-3.588	-2.94
40.3918	0.404	0.075	-0.55	-1.25	-2.599	-2.59
60.1325	0.601	0.106	-0.35	-0.98	-1.469	-2.24
72.1406	0.721	0.150	-0.14	-0.82	-1.111	-1.89
95.2324	0.952	0.250	-0.09	-0.60	0.969	-1.38
97.1939	0.972	0.355	-0.01	-0.45	1.198	-1.04
98.7266	0.987	0.500	-0.005	-0.30	1.469	-0.69
99.8387	0.998	0.710	-0.0005	-0.15	1.827	-0.35
100	1	1.000	0	0	0	0

S-III (Deenbandhuchotu Ram Power Plant, Yamuna Nagar, Haryana)

The linear regression fits were obtained for each coal sample using the two models and are depicted in Fig. 4.8 and 4.9 respectively.

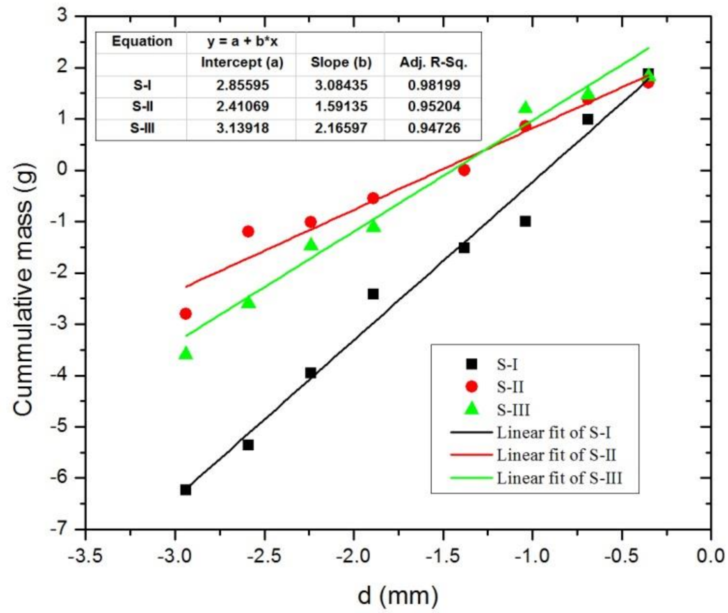


Figure 4.8: Fit to RR model for the three coal samples (S-I, S-II, and S-III)

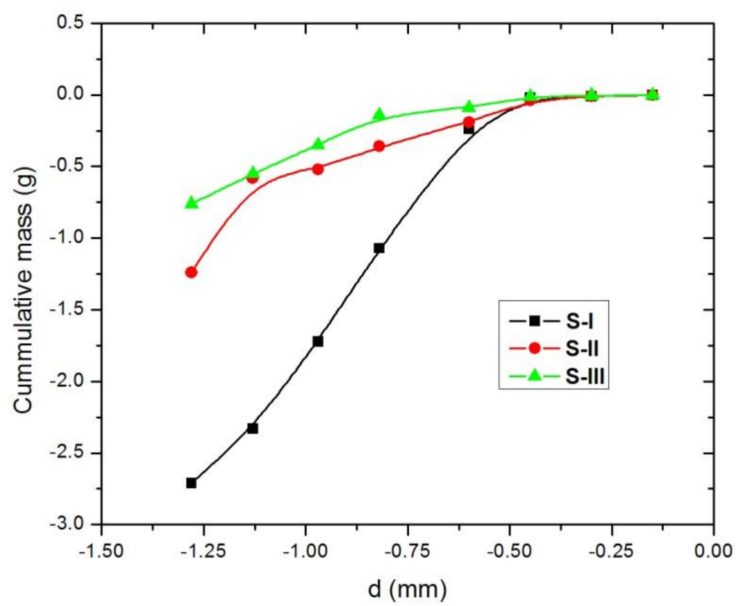


Figure 4.9: Fit to GGS model for the three coal samples (S-I, S-II, and S-III)

From the observations of the above Fig. 4.8 and 4.9, it can be seen that the RR models developed using the experimental results from PSDs curves show good calculated performance

($0.94 \leq R^2 \leq 0.99$) compared to the GGS models with all the three coal samples. The plots obtained by applying RR model provided the straight lines while the plots obtained by applying GGS model did not fit accurately i.e. the plots obtained were curves in lieu of straight lines implicating the RR model to be the chosen model for evaluating the appropriate value of the spread parameter m.

The subsequent distribution functions attained by the application of RR model for the three coal samples are as follows:

$$F(d) = 1 - exp\left[-\left(\frac{d}{0.154}\right)^{3.015}\right] \qquad \text{S-I (4.6)}$$

$$F(d) = 1 - exp\left[-\left(\frac{d}{0.080}\right)^{1.591}\right] \qquad \text{S-II (4.7)}$$

$$F(d) = 1 - exp\left[-\left(\frac{d}{0.047}\right)^{2.166}\right] \qquad \text{S-III (4.8)}$$

The application of the above expressions Eqs. (4.6, 4.7, and 4.8) to the PSDs curves permits one to anticipate the fraction of particles lesser than a definite diameter of particles (d) at the locations which do not conform to the MS method used, thereby procuring facts at the limits of the PSDs curves (Rosin and Rammler 1934).

The value of the spread parameter m is generally ≤ 3 (Alderliestein 2013). The smaller the value of m, the wider will be the size distribution of the coal samples and vice versa. This would lead to a decrease in the viscidness of the slurry fuels made by the coal samples. The reason that might explain the widening of the size distribution and a decrement in the viscosity is that the smaller particles would occupy the interstices of the coarser particles and apparently do not occupy any volume. In other words, the effective volume of the slurry fuels would be less than the actual volume owing to the above mentioned phenomena. Therefore, determination of the spread parameter using the most appropriate numerical method would provide the accurate segregation of the divergent particle sizes and hence the PSDS curves obtained would affect the coal properties and would influence the coal combustion process leading to an increase in the boiler efficiency.

Therefore, using AIC, the performance parameter (R^2) suitably chooses the proficient model, indicating the best model to depict PSDs of the coal samples to be RR model compared to GGS model. This is in settlement with the formerly reported study (Ulusoy and Igathinathane 2016, Macı´as-Garcı´a 2004, Grady and Kipp 1987, Delagrammatikos and Tsimas 2004, and Tasdemir and Tasdemir 2009), where R^2 was chosen to be the performance criterion.

Chapter 5

Rheological Studies on CWSFs

During the transportation of solid particles through pipelines, the estimation of energy required for pumping depends upon the viscosity of the slurry. The presence of solid particulates in the carrier fluid alters the viscosity of carrier fluid depending on the concentration of solids present, their particle size distribution, etc. The rheological studies are very useful for determining the viscous characteristics of slurry with respect to the particle size and particle size distributions. In the present study, the rheological experimentation was carried out on coal water slurries made from three diverse coals (S-I, S-II, and S-III) varying in their respective ash contents. The rheological data was generated using an Anton Paar Rheolab QC rheometer.

5.1 Experimental setup

The Anton Paar (Model: RheolabQC) rheometer used for the rheological study was supplied by Anton Paar, Germany. A pictorial view of the Anton Paar (RheolabQC) rheometer installed in the Mechanical Engineering Department of Thapar University, Patiala is shown in Fig. 5.1.

It is a rotational rheometer consisting of a high precision encoder and a extremely active 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 petite 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. Two different measuring systems can be utilized as per need of the study. These systems are DG42/SS/QC-LTD (for lower concentrations) and CC27/QC-LTD (for higher concentrations). The rheometer component consists of concentric bob and cup with a small annular gap in between them (Fig. 5.1(b)). The coal water slurry is prepared for each measurement and is filled up to the mark in the measuring cup. The measuring cup is then inserted into the measuring cylinder and the system is coupled to the rotating spindle by pushing down the flanged coupling. The slurry is subjected to shearing action in between the annular gap between the measuring cup and bob, and hence shear stress is determined as a function of deformation rate (Schramm 2000). The output results are obtained on the Rheoplus software installed on a computer which is connected to the rheometer by LAN connection (Fig. 5.1(a)).

(a) (b)

Figure 5.1(a): Anton Paar rheometer; (b) Cylindrical cup and rotating bob

5.2 Experimental procedure

For rheumatic tests, 50ml of the dispersion is made by mingling the essential amount of coal with the purified water to attain the anticipated concentration (C_w). An electronic weighing scale having a steadfastness of 10^{-4} gm is utilized for measuring the coal samples precisely. The dispersion was blended softly and thoroughly by hand shaking for 15-20 minutes in order to elude abrasion of the coal particles. The whole dispersion was emptied in the cup. The preferred speed of spinning was designated by altering the gear ratios. The deformation rate was implemented from 0 to 500 s^{-1} for a period of 125 seconds to measure the conforming shear stress and the viscidness below well-ordered deformation rate.

5.3 Preparation of CWSFs samples

5.3.1 For the comparative study of uni-modal and bi-modal distributed CWSFs

The coal water slurry samples (Fig. 5.2) were prepared at a concentration of 40% by weight of the solid loading. The uni-modal slurry samples were made by considering the coal particles in the size range of 75-106µm (coarse) and the bi-modal slurry samples were made by varying the concentration of the coal particles in the size ranges of 75-106µm (coarse) and 53-75µm (fine).

Figure 5.2: Coal water slurry sample

A total of 10 (1 mono-modal + 9 bi-modal) samples for each coal sample (S-I, S-II, and S-III) respectively, were prepared (Table 5.1) and tested for their rheological behavior on Anton Par Rheometer. The rheological investigations were also performed at varied temperatures, viz. $20 \pm 0.5°C, 30 \pm 0.5°C, 40 \pm 0.5°C, 50 \pm 0.5°C, and\ 60 \pm 0.5°C$, in order to study the impression of temperature variation on the viscosity of CWSFs.

Table 5.1: CWSFs samples for the comparative study of uni-modal and bi-modal PSDs

S. No.	Slurry Samples	Concentration (% by wt.)	Composition (% by wt.)		Nomenclature
1	Mono-modal	40 %	75-106 µm	**100%**	**Mono-modal**
2	Bi-modal		Coarse (75-106 µm) Fine (53-75 µm)	90% **10%**	**10f**
3	Bi-modal		Coarse (75-106 µm) Fine (53-75 µm)	80% **20%**	**20f**
4	Bi-modal		Coarse (75-106 µm) Fine (53-75 µm)	70% **30%**	**30f**
5	Bi-modal		Coarse (75-106 µm) Fine (53-75 µm)	60% **40%**	**40f**
6	Bi-modal		Coarse (75-106 µm) Fine (53-75 µm)	50% **50%**	**50f**
7	Bi-modal		Coarse (75-106 µm) Fine (53-75 µm)	40% **60%**	**60f**
8	Bi-modal		Coarse (75-106 µm) Fine (53-75 µm)	30% **70%**	**70f**
9	Bi-modal		Coarse (75-106 µm) Fine (53-75 µm)	20% **80%**	**80f**
10	Bi-modal		Coarse (75-106 µm) Fine (53-75 µm)	10% **90%**	**90f**

Experiments have been carried out to study the comparison of uni-modal and bi-modal particle size slurries and the effect of temperature variations on the flow properties like viscosity, shear stress, etc. The rheological results were obtained on a computer screen.

5.3.2 For the comparative study of uni-modal, bi-modal, tri-modal distributed CWSFs

The CWSF samples were formed at a constant concentration of 40% by weight of the solid loading. The mono-modal slurry samples were prepared using the coal particles in the size range of 75-106μm (coarse), the bi-modal slurry samples were made by varying the concentration of the coal particles in the size ranges of 75-106μm (coarse) and 53-75μm (fine), and tri-modal slurry samples were made by considering the particles in the size ranges of 53-75μm (very fine), 75-106 μm (fine), and 106-250 μm (coarse).

A total of 5 samples (tri-modal) for each coal sample (S-I, S-II, and S-III) respectively, were prepared (Table 5.2) and tested for their rheological behavior on Anton Par Rheometer. The rheological investigations were also performed at varied temperatures, viz. $20 \pm 0.5℃, 30 \pm 0.5℃, 40 \pm 0.5℃, 50 \pm 0.5℃, and\ 60 \pm 0.5℃$, in order to study the impression of temperature variation on the viscosity of CWSFs.

Table 5.2: CWSFs samples for the comparative study of uni-modal, bi-modal, and tri-modal PSDs

S. No.	Slurry Samples	Concentration (% by wt.)	Composition (% by wt.)		Nomenclature
1	Tri-modal	40 %	Coarse (106-250 μm) Fine (75-106 μm) Very Fine (53-75 μm)	60% 20% **20%**	**20vf**
2	Tri-modal		Coarse (106-250 μm) Fine (75-106 μm) Very Fine (53-75 μm)	50% 20% **30%**	**30vf**
3	Tri-modal		Coarse (106-250 μm) Fine (75-106 μm) Very Fine (53-75 μm)	40% 20% **40%**	**40vf**
4	Tri-modal		Coarse (106-250 μm) Fine (75-106 μm) Very Fine (53-75 μm)	30% 20% **50%**	**50vf**
5	Tri-modal		Coarse (106-250 μm) Fine (75-106 μm) Very Fine (53-75 μm)	20% 20% **60%**	**60vf**

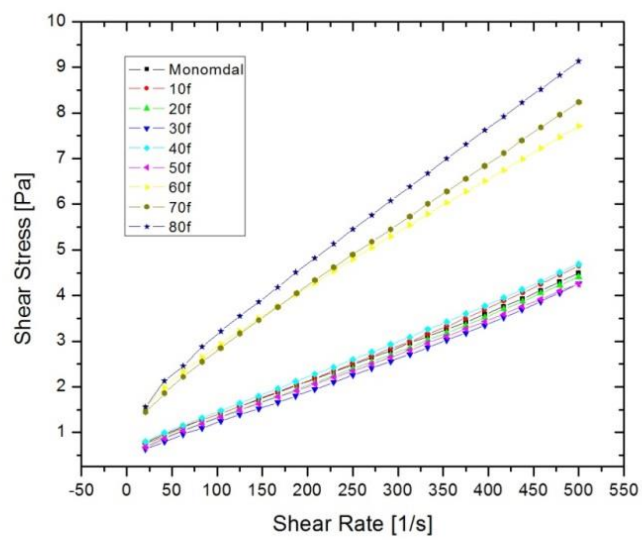
Experiments have been carried out to study the comparison of uni-modal, bi-modal, and tri-modal particle size slurries and the effect of temperature variations on the flow properties like viscosity, shear stress, etc. The rheological results were obtained on a computer screen.

5.4 Results and Discussions

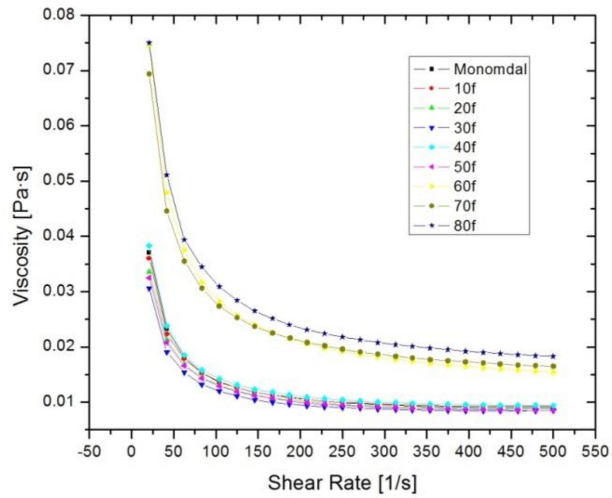
The coal water slurry concentration was kept steady at 40% by weight of solid loading and samples were prepared with varied coarse : fine ratio to study the outcome of particle size distribution (PSD) on the flow behavior of the slurry. Further, the work has been extended to study the impact of temperature variations on the flow performance of the slurry. The results obtained are represented in the rheograms.

5.4.1 Effects of coal PSDs on slurry rheology: a comparative study of uni-modal and bi-modal CWSFs

The results of the data obtained by the rheological analysis of the coal samples [S-I (Bathinda power plant), S-II (Madhya Pradesh), and S-III (Yamuna Nagar power plant)] are shown in Fig. 5.3-5.5 respectively.

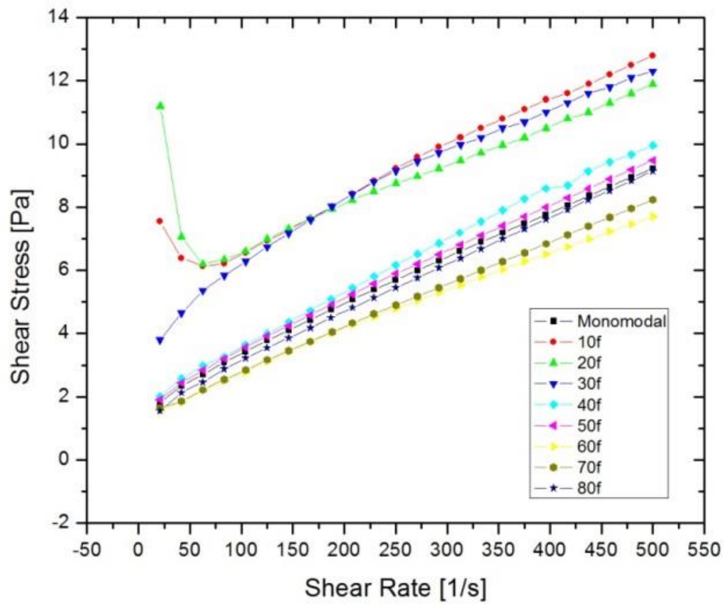


(a)

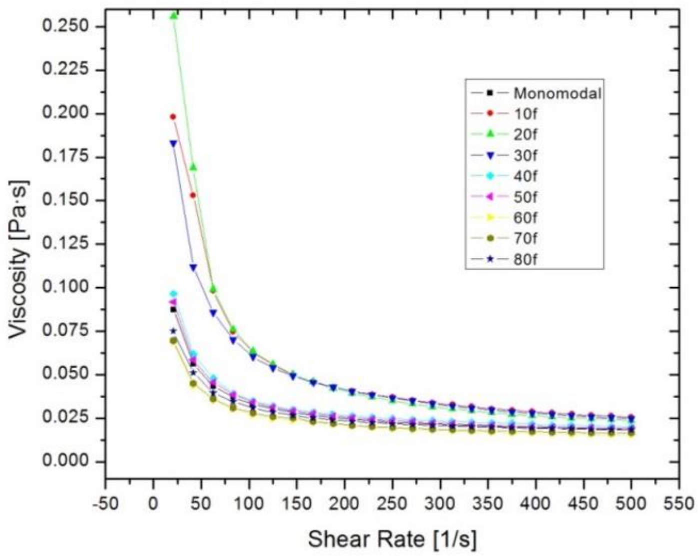


(b)

Figure 5.3: (a) Shear stress vs. shear rate; (b) Viscosity vs. shear rate, of S-I at a concentration of 40% by wt. for different coarse and fine particle size ratios

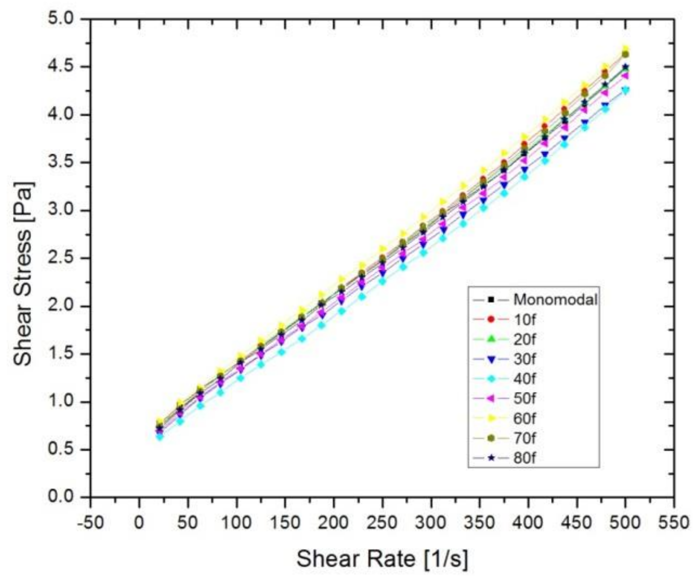


(a)

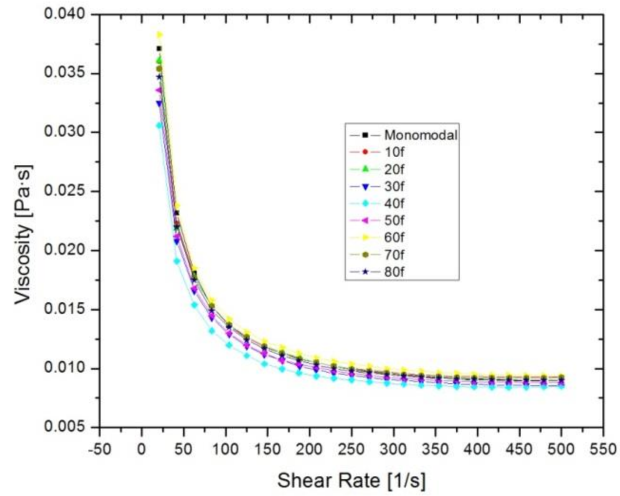


(b)

Figure 5.4: (a) Shear stress vs. shear rate; (b) Viscosity vs. shear rate, of S-II at a concentration of 40% by wt. for different coarse and fine particle size ratios



(a)

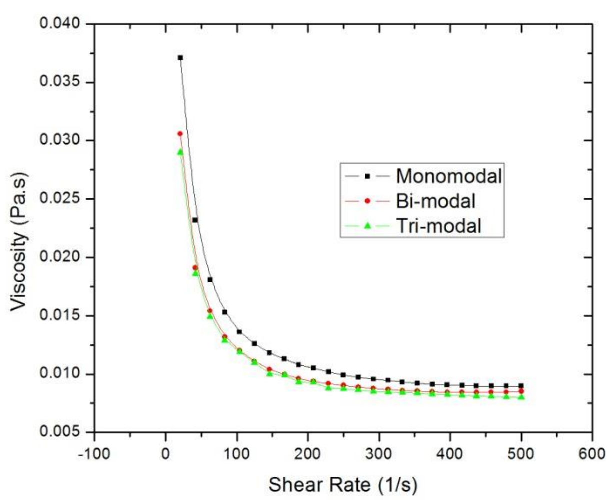


(b)

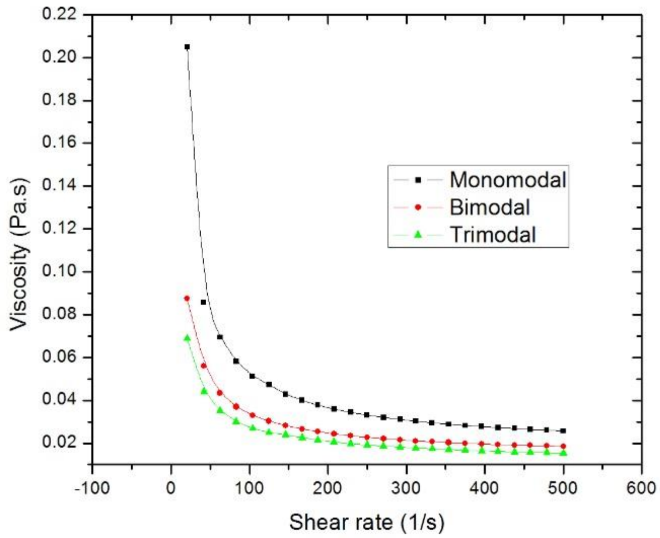
Figure 5.5: (a) Shear stress vs. shear rate; (b) Viscosity vs. shear rate, of S-III at a concentration of 40% by wt. for different coarse and fine particle size ratios

5.4.2 Effects of coal PSDs on slurry rheology: a comparative study of uni-modal, bi-modal, and tri-modal CWSFs

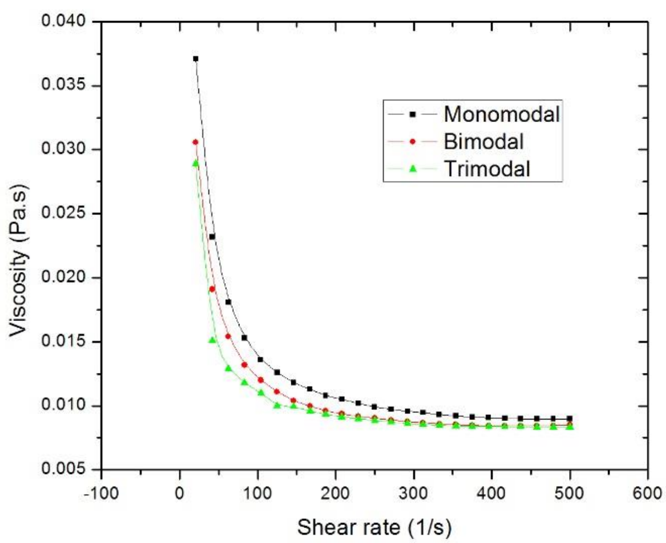
The results of the data obtained by the rheological analysis of the coal samples [S-I (Bathinda power plant), S-II (Madhya Pradesh), and S-III (Yamuna Nagar power plant)] are shown in Fig. 5.6.



(a)



(b)



(c)

Figure 5.6: Viscosity vs. shear rate of (a) S-I; (b) S-II; (c) S-III at a concentration of 40% by wt. for different coarse and fine particle size ratios

A close analysis of rheograms (Fig. 5.3-5.6) revealed the following critical points:

- All the three coal samples presented a varied distinction in terms of different coarse (75-106µm) : fine (53-75µm) ratios, when the comparison was made between uni-modal and bi-modal slurries (Fig. 5.3-5.5). It was found out that the viscidness of the slurry decreases with rise in the fraction of fine particles to a definite fraction and then rises with a rise in the fraction of fine particles. The shear stress and viscosity of the slurry was found to be lowest at a coarse : fine ratio of 70:30 **(30f) for S-I**, 40:60 **(60f) for S-II**, and 60:40 **(40f) for S-III** respectively. Lorenzi et al. 2002, Lee et al. 2015, and Zhu et al. 2017 have also obtained similar results in their study but restricted to bi-modal slurries.

- Similarly, when uni-modal, bi-modal, and tri-modal slurries were compared (Fig. 5.6), it was observed the apparent viscosity and shear stress were found to decrease more when more of very fine particles were added to the slurry. Usage of tri-modal, and further multi-modal slurries would help in the utilization of coal fines that are wasted during pulverizing. The method for obtaining the optimal coarse : fine ratios is discussed in the next chapter.
- For dispersions comprising of coarse and fine particles, it was recognized that the lessening of the viscidness may be purely due to a 3-D reorganization of the particles in the blend, with the finer/smaller particles entering the interstices amid the coarser ones (Fig. 5.7), making a higher concentrated complex of particles. This clue to a rise in particle kinesis and a reduction in the viscidness dissipation rate of the dispersion under shear. These particles behave like a emollient, resulting in a lesser viscidness (Lee et al. 2015). The identical reason supports the additional reduction of viscosity on adding very fine particles to the slurries.

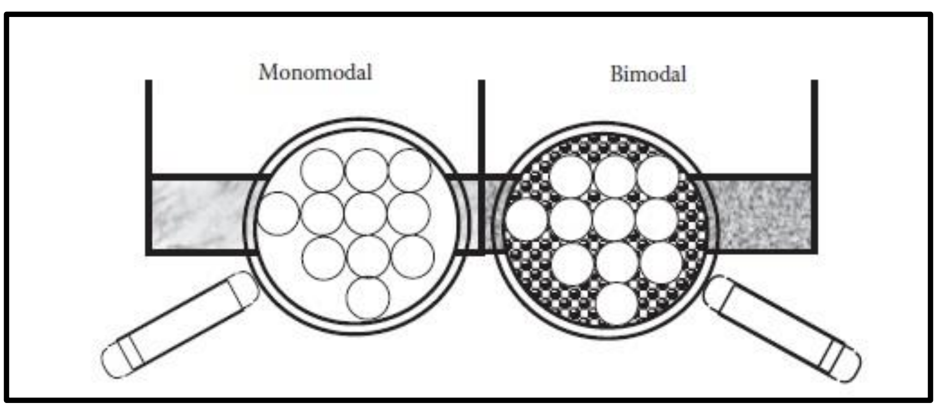
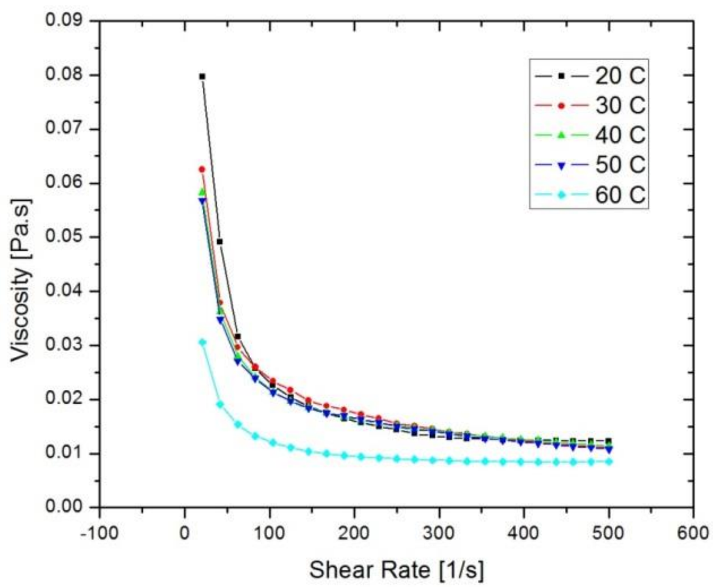


Figure 5.7: PSDs for uni-modal and bi-modal distributions (Lee et al. 2015)

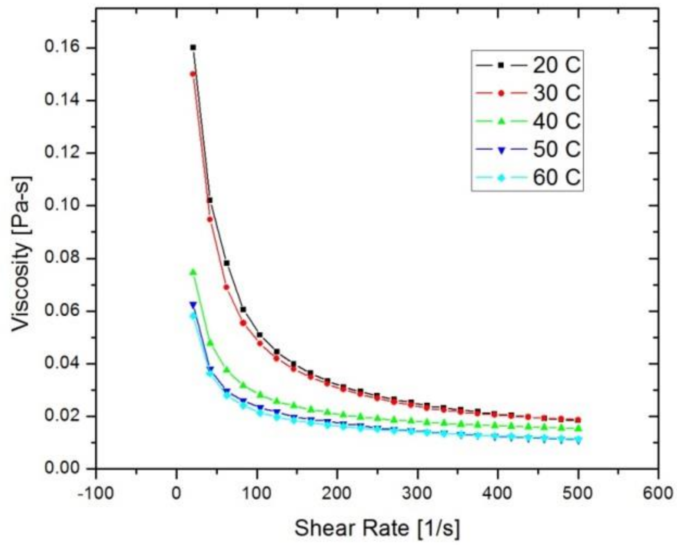
- Once the fine particles completely occupy the interstices of the coarser particles, further addition of fine particles causes an increase in viscosity, thereby presenting a difficulty in pumping the slurry through pipelines.

5.4.3 Effects of temperature on the rheology of CWSFs: a comparative study of uni-modal, bi-modal, and tri-modal CWSFs

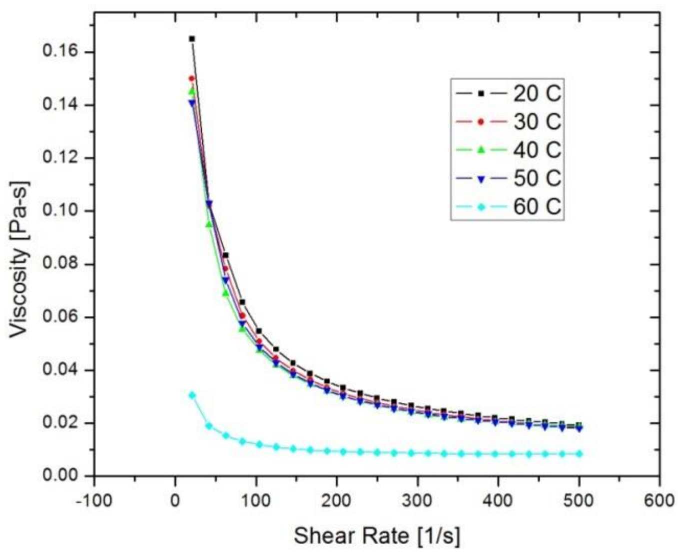
The rheological investigations were performed at varied temperatures viz. $20 \pm 0.5℃, 30 \pm 0.5℃, 40 \pm 0.5℃, 50 \pm 0.5℃, and\ 60 \pm 0.5℃$ for uni-modal, bi-modal and tri-modal slurries. The results obtained by the rheological data for all the three coal samples (S-I, S-II, and S-III) are shown in Fig. 5.8 and 5.9 respectively.



(a)

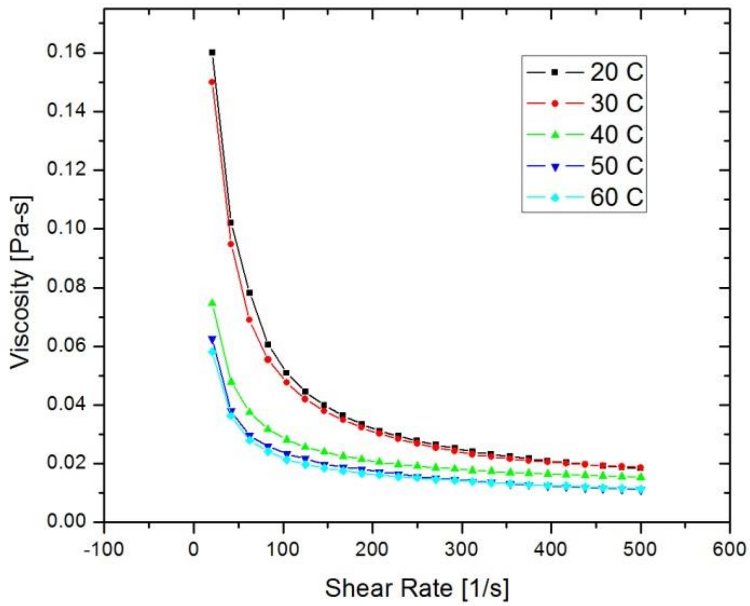


(b)



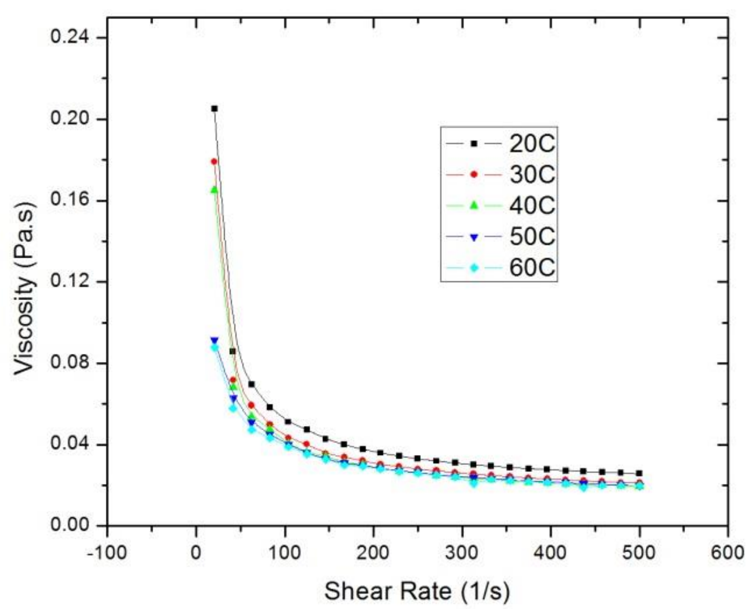
(c)

Figure 5.8: Viscosity vs. shear rate of (a) S-I; (b) S-II; (c) S-III at a concentration of 40% by wt. at varied temperatures viz. 20℃, 30℃, 40℃, 50℃, and 60℃ (bi-modal slurries)



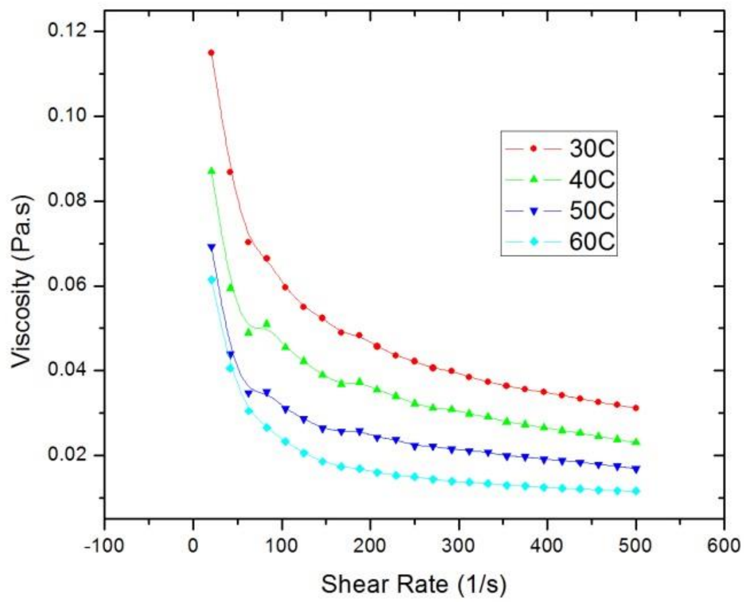
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Viscosity [Pa-s]
-100
0
100
200
300
400
500
600
Shear Rate [1/s]
20 C
30 C
40 C
50 C
60 C

(a)



0.24
0.20
0.16
0.12
0.08
0.04
0.00
Viscosity (Pa.s)
-100
0
100
200
300
400
500
600
Shear Rate (1/s)
20C
30C
40C
50C
60C

(b)



(c)

Figure 5.9: Viscosity vs. shear rate of (a) S-I; (b) S-II; (c) S-III at a concentration of 40% by wt. at varied temperatures viz. 20℃, 30℃, 40℃, 50℃, and 60℃ (tri-modal slurries)

A close analysis of the rheograms (Fig. 5.8 and 5.9) revealed the following critical points:

- A similar trend was observed for all the three coal samples (S-I, S-II, and S-III) in terms of variation with temperatures for both the bi-modal and tri-modal distributed slurries. The apparent viscosity was observed to decrease with increase in the temperatures.
- The reduction in the viscosity is in agreement with the momentum transmission mechanism in fluid by elemental impact, i.e., the resistance of the carrier fluid (water) decreases with temperature increase. In other words, with rise in temperature the kinetic energy of the coal particles increases with a reduction in the cohesive forces between the liquid molecules.

Chapter 6

Packing Characteristics of Coal Particles in CWSFs

Void fraction (ε) and bed density (λ) were calculated to study the influence of packing characteristics of the coal particles in coal water slurry fuel. Bed density is expressed as the ratio of the total volume occupied by coal particles to the total volume of the coal slurry, while the void fraction is defined as the porosity of coal particle bed where the voids are occupied with water and is expressed as (Hensterson et al. 1978)

$$\varepsilon = \frac{V_s - V_c}{V_s} \tag{6.1}$$

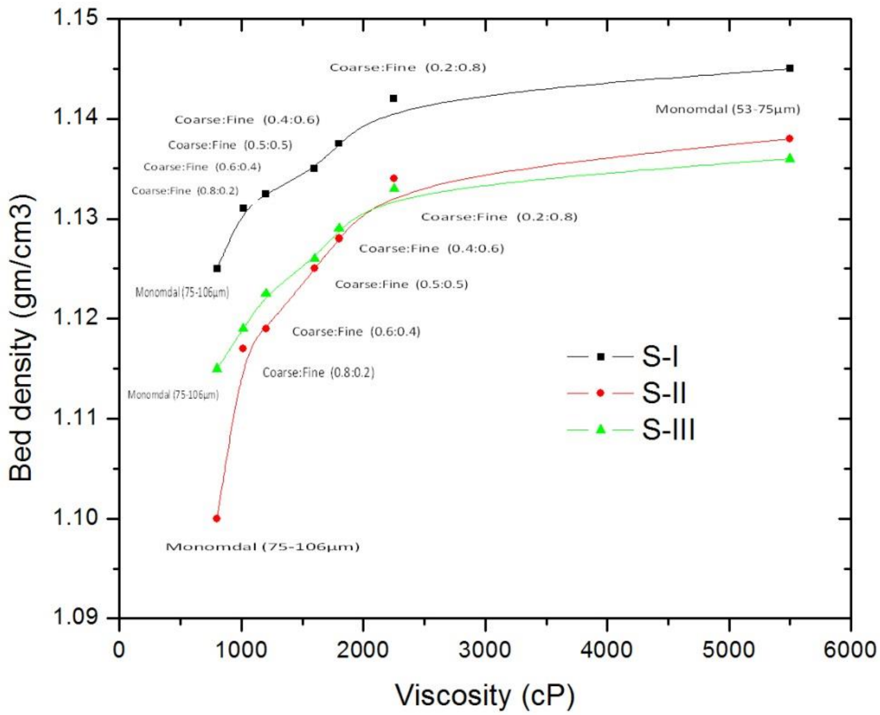
Where ε, V_s, and V_c are known as void fraction, slurry volume and coal volume. For the present work, it was presumed that the coal particles were in spherical shape, with different packing distributions viz. mono-modal (75-106 µm) and bi-modal (53-75 µm (fine) and 75-106 µm (coarse)) distributed coal water slurries at a concentration of 40% by weight of solid loading with varying coarse to fine ratios.

The apparent viscosity was found to be related to the λ, and ε as shown below in Fig. 6.1. Figure 6.1 (a) indicates that if λ increases, then an increase in the viscosity of CWSF can be observed. Figure 6.1 (b) also depicts that the λ and ε are inversely correlated. For heavily loaded CWSFs, the effective viscosity is about 1000-1200cP at a shear rate of 100rpm (Buranasrisak et al. 2012). Therefore, at an effective viscosity of 1200cP, it can be observed that the λ of the coal particle bed with bi-modal distribution is lesser than the mono-modal (53-75µm (fine)) distribution, and hence have higher ε. This provides the possibility of higher coal loading in bi-modal particle size distribution, when considering the effective apparent viscosity. At the effective apparent viscosity, λ and ε values for all the three coal samples are stated in Table 6.1

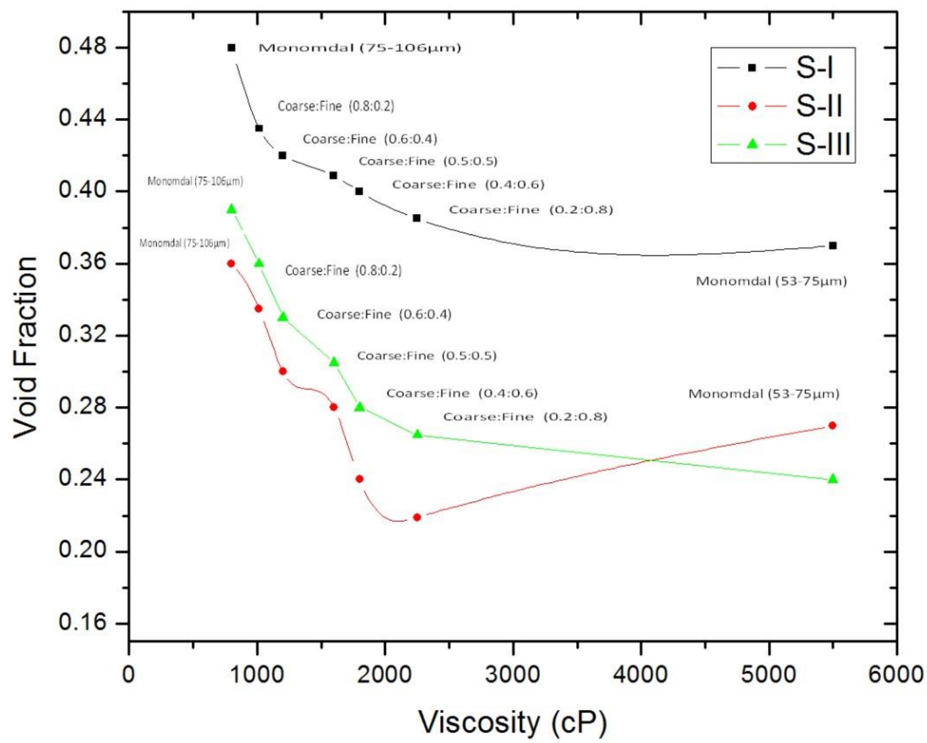
Table 6.1: Bed density (λ) and void fraction (ε) of the coal samples

Coal Sample	Bed density (λ) (gm/cm^3)	Void fraction (ε)
S-I	1.132	0.42
S-II	1.117	0.31
S-III	1.123	0.32

The above stated values of bed density and void fraction (Table 6.1) are for a solid loading of 40% by weight. These values indicate that to achieve 40% by wt. of solid loading, maximum bed density and void fraction must exceed or be equal to these values.



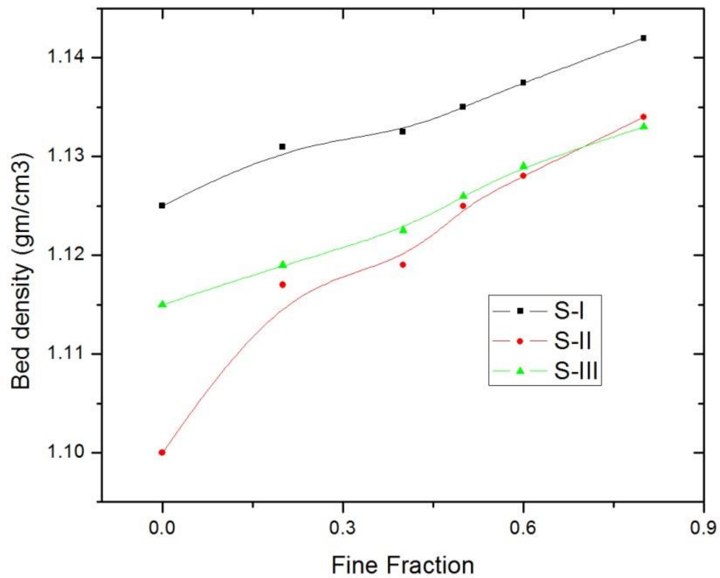
(a)



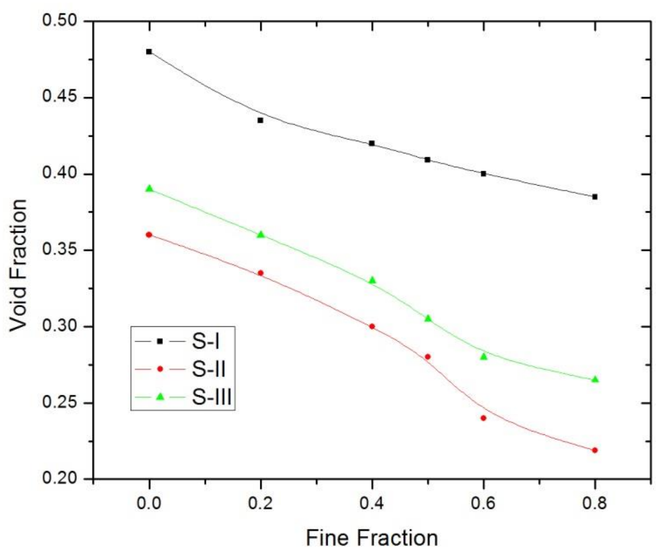
(b)

Figure 6.1: Relation between (a) bed density and viscosity; (b) void fraction and viscosity of CWSF at a solid loading of 40% by wt. for all the three coal samples (S-I, S-II, and S-III)

Since one of the factors that have a major influence on the void fraction and the coal bed density/packing fraction density is the fine portion of coal particle size bed, therefore, the influence of fine portion on packing physiognomies of CWSFs was also examined in the present study. The CWSFs with solid loadings at 40% by wt. were made by considering the coal particle sizes in the array of 75-106 μm for coarser particles and 53-75 μm for finer particles, and fluctuating the fine portion as; 0 (monomodal), 0.2, 0.4, 0.6, and 0.8.



(a)



(b)

Figure 6.2: Effect of fine fraction on (a) bed density; (b) void fraction of CWSFs for all the three coal samples (S-I, S-II, and S-III)

Figure 6.2 represents the influence of fine fraction on the bed density and void fraction of CWSFs for all the three coal samples (S-I, S-II, S-III). It is the general trend that more of fine fraction leads to a rise in the viscidness of CWSFs. This trend could be illustrated through the detail that additional fine particles have a habit of forming new agglomerates or dense configuration in the abysses amongst the comparatively coarse particles and lessen the flow-ability of CWSFs (Buranasrisak et al. 2012). Consequently, the fine fraction ought not to be above certain percentage in order to keep the viscosity of CWSFs in the range 1000-1200 cP at 100 rpm. As depicted in the Fig. 6.2 (a) and 6.2 (b), the fine fraction of the three coal samples studied at 40% concentration by wt., 0.3 is associated to the extreme packing fraction density/bed density at 1.132 g/cm^3 and the lowest void fraction at 0.42 for the coal sample S-I, 0.6 is associated to the extreme packing fraction density/ bed density at 1.117 g/cm^3 and the lowest void fraction at 0.31 for the coal sample S-II, and 0.4 is found to be associated to the extreme bed density at 1.123 g/cm^3 and the lowest void fraction at 0.32 for the coal S-III. The above results obtained were found to be in agreement with those obtained by the rheological studies discussed in the chapter 5. On the basis of this study, the optimal particle size distribution for multi-modal, the optimal fine : coarse ratio for bi-modal, and maximum coal loading could be determined with ease.

Chapter 7

Conclusions and Future Scope of Work

7.1 Conclusions

From the present work, it is found that the coal particle size have a major influence on the proximate composition of coal, rheological behavior of the CWSFs and packing characteristics of CWSFs. The following conclusions were observed:

- Proximate analysis of five different size fractions of each coal sample was carried out and it was found that inherent moisture was negatively correlated with particle size ranging from 53-106 µm. This implies that the coarsening of the pulverized coal is not affected by the inherent moisture. It was also observed that a higher volatile content would favor coal pulverizing.
- The viscidness of the coal water slurry is a function of particle size distribution. Too coarse particles may settle in the pipeline during transportation, while too fine particles are very viscous, causing pumping problems. Therefore, a compromise is made in order to overcome the above mentioned problems. A mixture of coarse and fine particles must be used for the coal water slurry preparations.
- The best coarse : fine ratios for the three coal samples for which the lowest viscosity was observed, were found out. They were 70:30 (30f) for S-I, 40:60 (60f) for S-II, and 60:40 (40f) for S-III.
- Similarly, when uni-modal, bi-modal, and tri-modal slurries were compared, it was observed the apparent viscosity and shear stress were found to decrease more when more of very fine particles were added to the slurry. Usage of tri-modal, and further multi-modal slurries would help in the utilization of coal fines that are wasted during pulverizing.
- The viscosity is also a function of temperature. With rise in temperature, the viscidness of the slurry falls owing to the rise in kinetic energy of the coal particles and a reduction in cohesive forces amongst the particles.

- Void fraction (ε) and bed density (λ) of CWSFs with bi-modal distribution were also evaluated. The results indicated that with the determination of λ and ε, optimal coarse : fine ratios for preparation of CWSFs with the lowest possible viscosity could be known.

7.2 Future scope of work

The present study presented an understanding of the impact of coal particle sizes on the proximate composition, flow (rheological) behavior of CWSFs, and the packing characteristics coal particles in CWSFs. The present study focused only on the influence of coal particle sizes at a particular concentration of coal i.e. at 40% by wt., without considering any effects of additives and stabilizers, or increasing the coal loadings. The present study can be further extended by adding additives and increasing the solid loadings to have a better understanding of rheology of CWSFs and its packing characteristics. Further, the slurries with multi-modal distributions could be made in order to study the result of coal fines, as more of fines could agglomerate decreasing the viscosity of CWSFs. The slurries could be prepared in huge amounts and can be used to fire in a boiler or steam generating unit, to understand the combustion phenomenon of the CWSFs with varied PSDs. There is still a large scope for further research work that lies in the field of coal water slurry technology for its efficient utilization and transport.

Chapter 8

Reflection and Publications

8.1 Reflection of the present work

- The outcome of coal particle size on its proximate composition has been determined by considering five different size fractions. After, determination of moisture content, the crucible is generally placed in a desiccator before placing them into the muffle furnace. During the transfer of crucible from desiccator to muffle furnace, there are chances of errors in the readings due to inclusion of external moisture.
- There are chances of occurrence of errors during rheological studies. Due to pre-shear interval, certain coal particles may settle down in the cylindrical cup, altering the rheological readings.
- The bed density (λ) was calculated manually using a flask for volume measurement and weighing machine. There are chances of occurrence of experimental errors.

8.2 Publications

- **Conference paper**: Vishnoi, N., and Mohapatra, S.K. 2016. Analysis of rheological behaviour of coal-oil slurry fuel with additives. *Journal of Basic and Applied Engineering Research* 3 (12): 1052-1056.
- Vishnoi, N., and Mohapatra, S.K. 2017. Study of Particle Size Distribution of Pulverized Coals in Utility Boilers. *Particulate Science and Technology*. DOI 10.1080/02726351.2017.1334731.
- Vishnoi, N., and Mohapatra, S.K. 2017. Study of the influence of pulverized coal particle sizes on proximate composition and rheology of coal water slurry fuels (CWSFs). *Korean Journal of Chemical Engineering:* - under review.

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