INVESTIGATION OF FLOW CHARACTERISTICS OF COAL WATER SLURRY

A

Dissertation

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Submitted by

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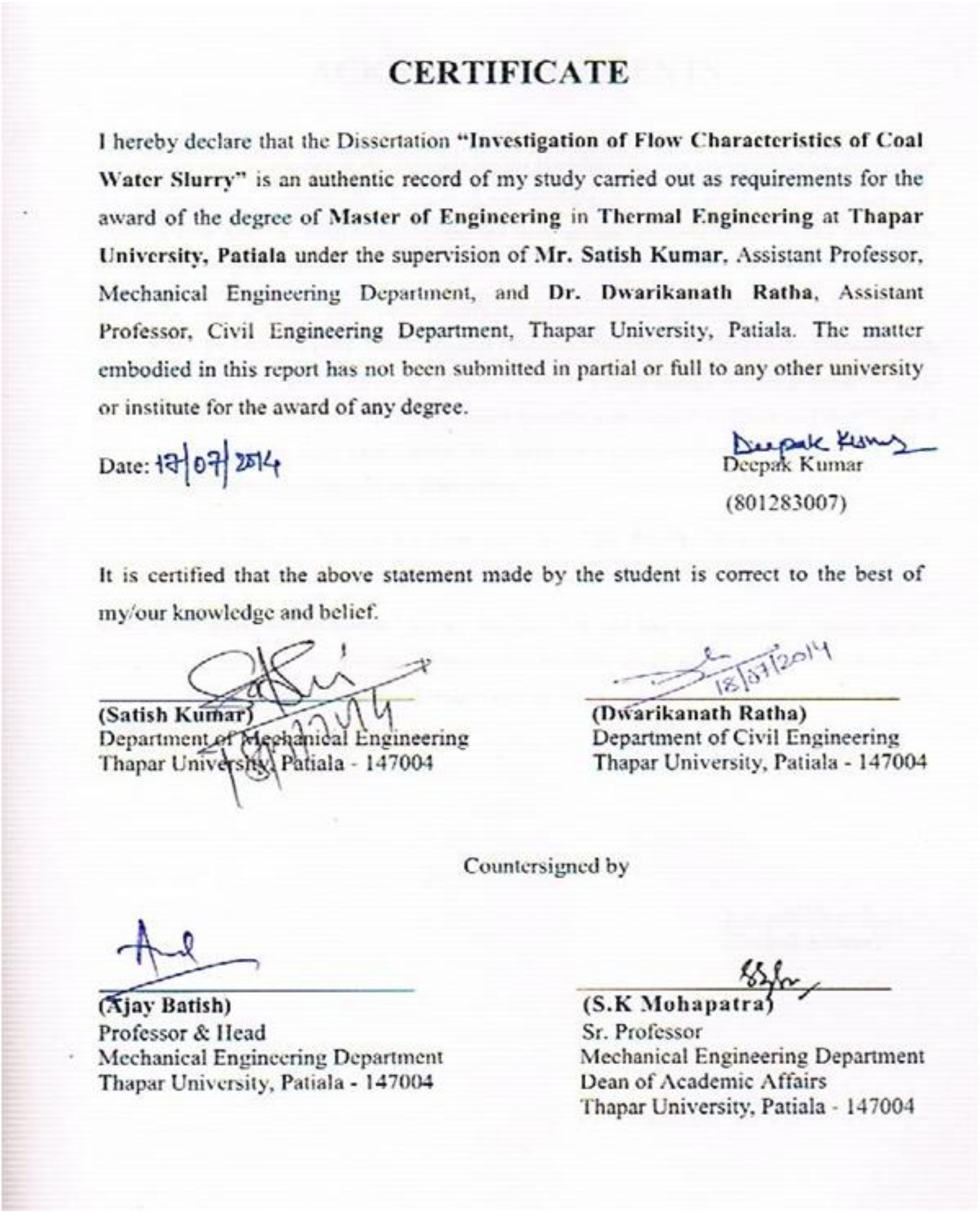

CERTIFICATE

I hereby declare that the Dissertation **"Investigation of Flow Characteristics of Coal Water Slurry"** is an authentic record of my study carried out as requirements for the award of the degree of **Master of Engineering** in **Thermal Engineering** at **Thapar University, Patiala** under the supervision of **Mr. Satish Kumar**, Assistant Professor, Mechanical Engineering Department, and **Dr. Dwarikanath Ratha**, Assistant Professor, Civil Engineering Department, Thapar University, Patiala. The matter embodied in this report has not been submitted in partial or full to any other university or institute for the award of any degree.

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ABSTRACT

The present study on the coal-water slurry rheology and its transportation performance was conducted at the Mechanical Engineering Department, Thapar University, Patiala. The rheological behaviour of Indian coal sample was investigated by using Anton Paar RheolabQC rheometer to generate extensive rheological data with a perspective to study the effect of solids concentration, temperature, and fraction of coarse particles. The rheological data obtained was used to evaluate the pressure drop of coal water slurry flowing through straight pipe using ANSYS FLUENT 14.5 computational fluid dynamics code. The slurry flow behaviour was found to be shear thinning above 30 % solids concentration (by weight) with viscosity decreasing with an increasing shear rate. The shear stress-strain rate data were fitted into the rheological models to calculate the model parameters for Power-Law fluid and Herschel-Bulkley fluid. The rheological study was conducted to investigate the effect of solids concentration, temperature, fraction of coarse particles in fine particles. It was found that the slurry viscosity increased with an increase in solids concentration. It was found that with increase in temperature the apparent viscosity of the slurry decreases.

The coarse particles were also added to relatively finer coal particles to determine the effect of addition of fraction of coarse particles and it was observed that the slurry viscosity decreased with the addition of coarse particles until an optimum ratio of coarse. An increase in slurry viscosity was found at coarse/fine ratio greater than the optimum coarse/fine ratio. It was also found that with increase in temperature the apparent viscosity decreases first but after a particular temperature the apparent viscosity increases with increase in temperature.

The rheological data generated were utilized in evaluating the pipeline flow characteristics of coal water slurry using numerical techniques. A straight pipe was modeled using ANSYS meshing tool with analysis performed using ANSYS FLUENT 14.5. It was found that for coal water slurry flowing through pipeline the pressure drop increases with increase in velocity and solid concentration.

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CHAPTER 1

INTRODUCTION

One of the most significant scientific challenges in the world today is to efficiently utilize a fuel to generate power at the most economic level. For this purpose various types of techniques of utilizing fuel in solid form (e.g. pulverized coal), liquid form (e.g. petroleum), and gaseous form (e.g. Compressed Natural Gas) have been utilized from the very beginning.

The first oil crisis in 1973 turned all interests on coal converge technologies. The aim was to replace the fossil carbon in mineral oil by the carbon in coal. From this time, extensive studies have been started particularly on coal gasification, liquefaction and combustion. In addition to these existing extensive studies, in recent years, research on coal-water mixtures (CWMs) was commenced.

A typical coal-water mixture consists of:

- 50-75% finely ground coal, with a top size of 250 to 300 microns.
- 25-50% water.
- Approximately 1% chemical additives.

However, when coal in a finely powdered form is mixed with water, the obtained slurry flow behavior generally gets altered depending on the concentration of coal (i.e. solid loading) and the interfacial properties in the water. Ideal CWS with maximum coal loading should be relatively stable at static state and dynamic state with a low viscosity. Rheological behavior will also affect the atomization of CWS to combustion chamber of power plant. The efficient utilization of coal water slurry is possible only when the slurry is prepared such that it permits maximum coal loading with appreciable viscosity and maintains a uniform concentration. Therefore, to study whether a particular coal water slurry is suitable to be inducted as a fuel, rheological studies are often conducted to determine the rheological parameters like viscosity, shear stress etc. by applying a rate of shear on the slurry and the rheograms (flow curves) and viscosity curves obtained thus are then fitted to the different rheological models that best describes the category of fluid in which the slurry in investigation falls in.

1.1 COAL

At various times in the geologic past, the Earth had dense forests in low-lying wetland areas. Due to natural processes such as flooding, these forests were buried under the soil. As more and more soil deposited over them, they were compressed. The temperature also rose as they sank deeper and deeper. Under high pressure and high temperature, dead vegetation was slowly converted to coal. As coal contains mainly carbon, the conversion of dead vegetation into coal is called carbonization. Coal is classified as a non-renewable energy source because it takes millions of years to form.

India is the third-largest producer of coal in the world with 589 million tones. Coal is one of the most abundant sources of energy in the country. Coal is accounted for 51 percent of the primary energy consumed in the country.

1.2 TYPES OF COAL

Coal is formed by biological, physical and chemical processes, governed by temperature and pressure, over millions of years on plant remains, deposited in ancient shallow swamps. The degree of alteration (metamorphism), caused by these processes, during the temporal history of development determine their position or rank in the coalification series which commence at peat and extend through lignite to bituminous coal and finally anthracite. The relative amount of moisture, volatile matter, and fixed carbon content varies from one to the other end of the coalification series. The moisture and volatile matter decrease with enhancement of rank while carbon content increases i.e., carbon content is lowest in peat and highest in anthracite.

- **Peat**, considered to be a precursor of coal, has industrial importance as a fuel in some regions, for example, Ireland and Finland. In its dehydrated form, peat is a highly effective absorbent for fuel and oil spills on land and water. It is also used as a conditioner for soil to make it more able to retain and slowly release water.
- **Lignite** is the lowest rank of coal, with a heating value of 4,000 to 8,300 British thermal units (Btu) per pound. Lignite is crumbly and has high moisture content Lignite is mainly used to produce electricity. It contains 25 to 35 percent carbon.
- **Sub-bituminous** coal typically contains less heating value than bituminous coal (8,300 to 13,000 Btu per pound) and more moisture. It contains 35 to 45 percent carbon.
- **Bituminous** coal is formed by added heat and pressure on lignite. Made of many tiny layers, bituminous coal looks smooth and sometimes shiny. Ir has two to three times the heating value of lignite. Bituminous coal contains 11,000 to 15,500 Btu per pound. Bituminous coal is used to generate electricity and is an important fuel for the steel and iron industries. It contains 45 to 86 percent carbon.
- **Steam coal** is a grade between bituminous coal and anthracite, once widely used as a fuel for steam locomotives. In this specialized use it is sometimes known as

sea-coal in the U.S. Small steam coal (dry small steam nuts or DSSN) was used as a fuel for domestic water heating.

- **Anthracite** is created where additional pressure combined with very high temperature inside the Earth. It is deep black and looks almost metallic due to its glossy surface. Like bituminous coal, anthracite coal is a big energy producer, containing nearly 15,000 Btu per pound. It contains 86 to 97 percent carbon.
- **Graphite**, technically the highest rank, is difficult to ignite and is not commonly used as fuel — it is mostly used in pencils and, when powdered, as a lubricant.

1.3 COAL-WATER SLURRY

The mixture of solids and liquids is known as slurry. The physical characteristics of slurry are dependent on many factors such as particle size and distribution, solid concentration in the liquid phase, turbulence level, temperature, conduit size, and viscosity of the carrier. Water is the most commonly used fluid.

Factors such as the continued rise in oil prices, the difficulties associated with a stable supply of Crude oil, increased fuel consumption, and the limited oil reserves in recent years have increased interest in and research related to the use of coal, which is relatively cheaper, plentiful, and widely distributed across the globe. Therefore, many studies pertaining to coal slurry as alternative fuel replacing petroleum oil in the liquid state have been carried out. Coal slurry fuel can be divided into CWS (coal-water slurry), COS (coal-oil slurry), COWS (Coal-oil-water slurry), CMS (coal methanol slurry), and CMWS (coal-methanol-water slurry) depending on the type of liquid mixed with the solid coal. Among these different types, CWS fuel is considered by some to have the greatest economic feasibility as a fuel source and the greatest potential for commercialization.

Coal-Water Slurry is slurry of powdered coal and water which maintains a stable state over a long period when a small amount of additive is added. The coal-water slurry can be used as a liquid fuel (CWSF) for boilers and can replace petroleum for energy conversion. These are non-flammable and eco-friendly with good comparable combustion efficiency with that of conventional fuels.

For maximum efficiency as fuel, the coal concentration in coal-water slurry should be as high as possible, maintaining its viscosity at the minimum level simultaneously so that it will be suitable for storage and transportation through pipelines. The primary factors responsible for the optimum stability of coal-water slurry depend on physicochemical properties of coal, such as its (i) surface hydrophobicity, (ii) particle size distribution, (iii) oxygen content, (iv) zeta potential (surface charge), (v) pH sensitiveness, (vi) shear rate-shear stress relation, (vii) porosity, (viii) temperature sensitiveness of the viscosity of the coal-water slurry, and (ix) surface chemistry of coal etc.

1.4 HISTORICAL DEVELOPMENT OF COAL-WATER SLURRY

The first combustion tests of CWS were conducted in the United States, Germany, and the Soviet Union in the 1960s. There was active development of CWMs in the United States in the 1980s, with emphasis on developing technologies to prepare mixtures with desirable physical and chemical properties, demonstrating retrofit in existing boilers, and developing specialized equipment for handling and transporting slurries. During this period, a number of private companies were actively involved in, or abandoned commercialization of slurries as oil prices declined in the early 1980s [Coal Energy for the Future, 1995].

Early efforts in CWS technology development mainly concentrated on the preparation of high energy concentrated on the preparation of high energy density liquid fuel from bituminous coals. The first attempts to utilize low rank coals (LRC) for this purpose consisted of simply mixing the pulverized LRC in its natural state directly with water. Chemical additives were not used and no changes were made to its surface characteristics. The result was that the utilization of LRC in its natural state was not economically feasible due to its extremely low energy content and unfavorable characteristics before and after burning [Witsee et al., 1986]. However the recent introduction of chemical additives has made LRC utilization as CWMs possible and feasible [Uyar et al., 1994].

The particle size distribution of the ground coal must be approximately adjusted to allow high solids loading of the CWM, and the chemical additives should match the interfacial properties of the coal particles, to lower the CWM viscosity and increase its stability. CWM with such properties behaves as a liquid fuel: it is pump able, can be atomized using a specially designed nozzle, ignited in a preheated environment, and hence stably combusted in a boiler or furnace [Wang et al., 1993].

Ideal CWS with maximum coal loading should be relatively stable at static state and during transportation, and exhibit good rheological behavior. Rheological behavior affects the atomization of CWM, which will influence the combustibility of CWM in boiler application. [Li and Li, 2000] The industrially expected value for the viscosity of a

CWM, even though not absolute, is Brookfield apparent viscosity of 1000 cp at 100 rpm. [Natoli et al., 1985]

1.5 UTILIZATION AREAS OF COAL-WATER SLURRY:

- CWS can be used in place of oil and gas in any size of heating and power station. CWS is suitable for existing gas, oil, and coal boilers.
- Since the 2004 Russia has continued the development and implementation of CWS technology for heating stations (for district heating) and power stations.
- Countries like China and Indonesia have been using coal water slurry for power generation successfully. More than 90 steam and power generating plants are utilizing CWS in China, with capacity ranging from 1.5 MW to 200 MW.
- CWS have been used in gas turbine and diesel engine for research and pilot plants only, as both of these applications require higher specification of coal than is currently used to produced CWS for boiler and heating applications.
- For gas turbine testing CWS particles five to ten micrometers in size have been used to demonstrate useful substitution for petroleum or natural gas in combined cycle gas turbine power plant applications.
- CWS can be used as fuel in coal gasification process to produce synthesis gas.

1.6 ADVANTAGES OF COAL WATER SLURRY

Ecology:

- WCF is a clean coal technology solution for big and small energy.
- WCF allows utilizing sewage water (from city canalization).
- WCF ash is an ideal additive to concrete mixtures.

Economy:

- Reduces cost price of Gcal and kWh.

Technology & Handling:

- WCF is an explosion-proof.
- WCF is easy to storage and pumping.
- WCF minimum number of non standard elements for preparing and combustion.

Autonomy:

- Fully autonomous energy source.
- Almost any type of coal could be used for WCF preparation
- WCF combustion reduces on 30-50% NO_x emission comparing to regular pulverized coal combustion.

Coal utilization while WCF combustion is about 99%. It means that only 1% of uncombusted coal exists in ash.

1.7 ROLE OF RHEOLOGY IN THE DESIGN OF COAL-SLURRY TRANSPORTATION SYSTEM

Rheology is the study of the flow of matter, primarily in the liquid state, but also as 'soft solids' or solids under conditions in which they respond with plastic flow rather than deforming elastically in response to an applied force. It applies to substances which have a complex microstructure, such as mud, sludge, suspensions, polymers and other glass formers (*e.g.,* silicates), as well as many foods and additives, bodily fluids (*e.g.,* blood) and other biological materials or other materials which belong to the class of soft matter.

Newtonian fluids can be characterized by a single coefficient of viscosity for a specific temperature. Although this viscosity will change with temperature, it does not change with the strain rate. Only a small group of fluids exhibit such constant viscosity, and they are known as Newtonian fluids. But for a large class of fluids, the viscosity changes with the strain rate (or relative velocity of flow) are called non-Newtonian fluids. Rheology generally accounts for the behavior of non-Newtonian fluids, by characterizing the minimum number of functions that are needed to relate stresses with rate of change of strains or strain rates. For example, ketchup can have its viscosity reduced by shaking (or other forms of mechanical agitation, where the relative movement of different layers in the material actually causes the reduction in viscosity) but water cannot. Ketchup is a shear thinning material, as an increase in relative velocity caused a reduction in viscosity, while some other non-Newtonian materials show the opposite behavior: viscosity going up with relative deformation, which is called shear thickening or dilatant materials.

The Rheological properties of particle suspensions are of great importance in numerous industrial applications including pipeline transportation of slurries. Rheological data can be used to find the relationship between flow rate and pressure drop. Rheological parameters can also be used to determine the power required to agitate the slurry in the tank, and to determine the wear rate and life of the pipeline. Knowledge of suspension rheology is also important to ensure a stable/energy efficient pipeline transportation system. The rheological characteristics of a slurry depends on several parameters such as shape, size and size distribution of particles, solids concentration, carrier fluid properties etc. By suitably manipulating the particle size distribution, if other parameters are same, it is possible to obtain a stabilized slurry suspension. The particle size is also important from the dewatering view point. If the solids are coarse then the cost of dewatering is less but the flow becomes more heterogeneous whereas if the particles are fine then the flow is homogenous but the slurry becomes non-Newtonian and the cost of dewatering also increases. Thus in a slurry transportation system, a compromise has to be made between the particle size and the cost of dewatering. The rheological behavior of the slurry is also required to predict the head requirement for pumping the slurry. The presence of solid particles in the slurry affects the performance characteristics of the pump. In addition, surfaces of the impeller and the walls of the casing wear more rapidly due to solid particles. The characterization of rheological behavior of slurry is complicated due to the fact that a large number of factors influence it. Historically, the rheology of suspension has been investigated mostly through experimentation on equalized particulate suspension. Correlations have been derived, on the basis of the above data, to predict the Newtonian viscosity of suspension. However, in commercial slurry, all the particles of the material will not be equalized and the ratio of the size of the largest particles to that of the smallest particles may be of the order of 1000 or even more.

Further, the particles of different materials will differ in various properties like density, shape etc. Thus the actual flow pattern that exists in a slurry pipeline will differ from material to material. Also the behavior of the slurries is generally non- Newtonian at the concentrations that are commercially used.

Non-Newtonian slurries make the principles of fluid mechanics more complex since the resistance to flow ‘viscosity’ now must be defined through a physical model reflecting process conditions. It is essential that a good understanding of the methods of characterizing rheological properties and extrapolating these characteristics to commercial slurries be obtained. In the absence of any suitable correlations for predicting the rheological parameters of non-Newtonian slurries contains large sized particles and wide particle size distribution, viscometric tests are unavoidable. For slurries containing large sized particles in a low viscosity carrier liquid, viscometric measurements are difficult because the large particles tend to settle down during measurements thus affecting the homogeneity of the suspension. Also the geometric interference of particles with the walls of the viscometer places a limit to the largest size particles that can be accommodated during tests. To overcome these problems the large sized/heavy particles may have to be scalped (removed) from the original sample and rheomtetric tests are performed with the remaining fine particulate slurries. At present, the effect of removal of large sized particles is not fully understood.

CHAPTER 2

LITURATURE REIVEW

Various studies on slurry rheology were carried out by many researchers in the past. Chapter reviews the previous published literatures, which lays foundation and basis for further work in this investigation. This helps to give a better understanding about the topic and also acts as a guideline for this thesis. The major focus of the following study is on the coal slurries and its applications in various areas. This section deals with literature review on rheology of coal slurries. The rheology of coal and coal ash slurries and their characterization has received attention in recent years because of widespread application in industry and academic interest. The focus of investigations has mostly been on viscosity of slurries and flow behavior and taming them to meet certain requirements such as ease of transportation and handling etc.

Roh N.S et al. [1994] investigated the effects of coal type, loading and particle size on the rheological behavior of coal water mixtures. Seven bituminous coals were used in the study with particle size distribution obtained by sieving for particle greater than 38 μm and Coulter counter for particles less than 38 μm. Rheological tests were conducted using Haake RV-12 viscometer. They found that all the slurries exhibited pseudoplastic behavior. The blending with coarse coal fraction was useful in reducing the viscosity and the static stability measurement by rod penetration test revealed that the stability was maximum when the same optimum coarse fine ratio was utilized.

Logos C et al. [1996] studied the effect of particle size on the flow properties of a South Australian coal water slurry. The coal used for the preparation of coal water slurry was a low rank Lochiel coal from South Australia. The particle size distribution was varied by introducing coarser fraction of coal to the finer fraction in different proportions. The rheological parameters were evaluated using concentric cylinder viscometer (HAAKE, Model RVI00). The solid loadings were in the range of 23 % to 50 % by weight. They found that the slurries prepared from only finer fraction i.e. under 45 µm were more viscous than the coal water slurries prepared from a mixture of coarse and fine particles with coarse particles varying from 208-279 µm. The optimum coarse to fine ratio was 40:60 that showed the least apparent viscosities with a Newtonian behavior of the slurry.

Nguyen et al. [1997] determined the rheological properties of coal-water slurries and studied the effects of the size distribution of coal particles on the rheological behavior of coal-water slurry. The coal studied were two raw lignite’s, Lochiel and Bowmans coal obtained from South Australia. The rheological properties were measured using HAAKE RV-100 viscometer. The coal-water slurry prepared consisted of 23 to 50 wt% for Lochiel coal and 40 wt% for Bowmans coal. They found that the solid concentration affected the nature of the slurry with 23 wt% as Newtonian and at higher concentration as shear thinning. Above 40 wt% the slurry showed viscoplastic behaviour with the presence of a yield stress .They found that addition of a coarser coal fraction to a suspension lowers the viscosity substantially. They did not use additives.

Usui et al. [1997] studied the sedimentation stability of coal-water slurry of a deashed coal with and without a stabilizer. Three coal-water mixtures were prepared that had equal apparent viscosities by controlling the coal concentrations. Polymethacrylate

(PMA) with a 0.3 wt% was used as a dispersing additive. Rhamsan gum was used as a stabilizing additive. They found that very small additions of rhamsan gum were good enough to prevent the sedimentation of coal particles.

Yavuz et al. [1998] studied the effect of Particle Size Distribution on the Rheology of Lignite - Water slurry. The lignite sample was sieved into six particle size fractions: 125-90, 90 - 75, 75 - 63, 63 - 53, 53 - 45, <45 μm. They used slurry with a solid concentration of 60% by weight. Experiments were carried out at 293 K. results showed that slurry having a fine particle size distribution is not suitable as the viscosity is very high. So they mixed different fractions of lignite powders in a given amount to obtain an optimum particle size distribution within the range of particle sizes < 125 pm. Also they investigated the sedimentation behavior of the slurries prepared. And they found the particle size increased, sedimentation was also increased. However, above a given particle size distribution (- 35 μm), the rate of sedimentation became slower.

Atesok et al. [2002] investigated the effect of coal properties on coal water slurry using two Turkish coals of different ranks and a Siberian bituminous coal with mean particle size of 50, 36 and 19μm. Sodium polystyrene sulphonate and sodium salt of carboxymethyl cellulose were used as dispersant agent and stabilizer. RVD2-Brookfield rotating type viscometer was used for the viscosity measurements. The pH value was varied from 7.05 to 7.25 for all tests and temperature was kept constant at 25 ± 2^{o}C. The pH was varied by HCl or NaOH. Zeta potential was measured by Zeta meter 3.0 between pH 2 and 11. It was observed that the value of zeta potentials decreases dramatically with addition of chemical additives.

Lu et al. [2002] discussed the resistance properties of coal-water paste flowing in pipes. Four steel tubes were used each being 5500 mm long, and with nominal bores of 25, 32, 40, and 62 mm and each test piece has two pressure tapping points at 3300mm centers. The loop was fitted with screw pump having a throughput of 16 m^3/h, driven by a 15 KW YCT motor. Coal water paste with different water content in range of 22.1-33.5 wt. % was prepared. Pressure drop was measured by electric differential manometer. The result obtained from the experiments show that the energy loss coefficient of CWP laminar flow in pipes has the same form as Newtonian fluid.

Mishra et al. [2002] investigated the rheological behavior of Indian coal-water slurry. In this investigation the effect of solid concentration, ash content, pH, and temperature on CWS was studied. Coals from the Talcher coal field, Orissa, India were used for the investigation. The rheological studies of CWS were carried out in HAAKE rotational viscometer RV30. A thermostatic temperature bath was used to maintain the temperature of the slurry. The pH of the CWS was adjusted using EDT research pH/Ion meter (model ECM 221). From the present study it was observed that CWS becomes more viscous with increase in ash content and solid concentration. The viscosity of CWS is high in acidic medium, being highest around pH 6 and lowest around pH 8.

Li et al. [2002] studied the rheological characteristics and sedimentation stability of the slurry with the addition of four kinds of stabilizing additives. Additives used in this study were rhamsan gums, carboxym ethylcellulose, and xanthan gum. The fly ash discharged from the Matsuura Power Station on Kyushu Island (Japan) was used in this study. Fly ash was mixed with deionized water to give a fly ash concentration of 68 wt. %. The concentration of dispersing additive (NSF) was set at 0.3 wt. %. The apparent viscosities of fly ash–water slurries with and without additives were measured using a rheometer (Iwamoto Seisakusho Co., Ltd. Model IR-200) with coaxial rotating cylinders. The temperature of the test samples was maintained at 298 K. The experimental results show that stabilizing additives are effective in increasing stability of fly ash–water slurry. The use of S-194 as a stabilizer, at a concentration of 0.2 wt. %, is recommended for preparation of stable fly ash–water slurry.

Dincer et al. [2003] studied the effect of chemicals on stability and viscosity of coal water slurries the effects of different chemicals that were used as dispersing agent and stabiliser on the stability and viscosity of coal–water slurries were investigated. In the experiments, anionic type of chemicals—polyisoprene sulphonic acid soda (Dynaflow-K), a derivative of carboxylic acid (AC 1320) and naphthalenesulfonate–formaldehyde condensate (NSF)—were used as dispersing agents and the stabiliser was the sodium salt of carboxymethyl cellulose (CMC-Na). The coal sample used was a bituminous coal (thermal code no. 434) of Turkish origin, with medium volatile matter. The found that polymeric anionic dispersing agents such as Dynaflow have much greater effect on the viscosity and the stability of coal water slurry.

Boylu et al. [2004] studied the effect of coal particle size distribution, volume fraction and rank on the rheology of coal water slurry. Experiments were conducted using two Turkish lignites from Soma and Istanbul – Agacli, and a bituminous coal from Sibria. The coal samples were prepared by mixing different coal particles size fractions to obtain desired d_{50} (19, 35, 50μm). The specific area of coal was measured by BET method. Zeta Meter 3.0 type instruments was used for the measurement of zeta potential. The pH of the sample was maintained by adding acid or base. The rheological experiments were performed on RVD2-Broolfield rotating viscometer. The measurements were taken using shear rate of 100 rpm. The pH value and temperature of slurry were kept constant at 7.0 and 25±2 ^{0}C respectively.

Boylu et al. [2005] studied the stabilization properties of Coal Water Slurry using carboxymethyl cellulose (CMC). The material chosen were two Turkish brown coals from Soma and Istanbul and a bituminous coal from Zonguldak. The coal particles were ground to less than 63 microns and the mixture prepared was 61, 55 and 52%. The stability was measured using rod penetration test method. The effect of changing the CMC concentration on penetration after 7 days was studied. They found that there was a negligible effect on changing the concentration of CMC on the stability of coal from Soma and Istanbul as the penetration remained the same after days and hydrophilic nature of lignite coals were attributed to this but they found that varying the concentration of CMC has a profound effect as a stabilizer on the bituminous coal-water slurry increasing the stability with penetration possible to 100 % from 60% due to the hydrophobic nature of bituminous coal and the optimum concentration of CMC was found to be of 0.01%.

Mosa et al. [2008] examined the effect of chemical additives or reagents on rheological characteristics of coal water slurry (CWS). Apparent viscosity and flow properties of coal water slurry are sensitive to the use of chemical additives (dispersants and stabilizers). Among studied dispersing agents, sulphonic acid recorded the best performance in modification and reducing CWS viscosity. The best dosage of all tested dispersants was found to be as 0.75 % by wt of solids. With regard to studied stabilizers, Na- CMC recorded better performance than xanthan gum. The best dosage of investigated stabilizers was found to be as 0.1 % by wt. from total solids.

Tian-ye et al. [2008] studied the effect of coal blending on the coal water slurry using three different coal samples from Daliuta (DLT), Linhuan (LH) and Yongcheng (YH). Maximum size of the coal was 300μm and 75% particles are smaller than 74μm. The dispersant used was Naphthalene sulfuric acid-formaldehyde condensate. LH and YH coal was mixed with the DLT with the weight percentage of 10-40%. It was observed that addition of coal with high rank can improve the slurryability of the low rank coal.

Senapati et al. [2008] studied the rheological behaviour of coal water slurry using a natural additive. Two types of coal having different ash contents were obtained from Talcher Coal Field, Orissa, India. The rheological measurements were carried out employing HAAKE RV 30 rotational viscometer. The coal water slurries were prepared with concentration by weight ranging between 55-63.7 %. The additive concentrations for coal water slurries were varied from 0.4–1.2 % by weight. The static stability was measured using rod penetration test. They found that the coal water slurry in the presence of natural additive exhibited bingham plastic behaviour. The static stability of the coal water slurries were found to be 3 to 4 weeks by employing the natural additive.

Das et al. [2009] prepared highly concentrated coal-water slurry employing three different low-rank coals of Indian origin having variable ash content. The formulation, rheology and stabilization of the slurry were investigated using saponin extracted from the seeds and pericarps (mods) of the Acacia concinna plant as a dispersant. The saponins extracted from both the seeds and pericarps of the plant are found to stabilize the slurry. They claim that the plant-based additive saponin from A. concinna (both pericarps and seeds) can be suitably substituted for a synthetic additive, such as SDS (Sodium Dodecly

Sulphate). A few pilot experiments with other commercially available additives, such as CMC and SDDBS, also yielded the same results.

Liu et.al [2009] investigated the local resistance characteristics of coal–water slurry flowing through three types of piping components, namely gradual contractions, sudden contractions and 90^0 horizontal bends, at a transportation test facility. Author came on to the result that coal water slurry exhibits different rheological behaviours, i.e., the shear-thinning, Newtonian, and shear-thicken, at different shear rates. Author observed that when cola water slurry flows through the gradual contractions, the local pressure loss firstly decreases to a minimum, and then increases as the gradual contraction angle increases. From the experiments performed by the authors they concluded that when the coal water flow through the sudden contractions, with the increase of pipe diameter ratio, the local pressure loss increases for the two kinds of coal water slurry, whose mass concentration range from 57% to 59% and 59% to 62%, respectively as Reynolds number increases, local resistance coefficients of the three fittings declines quickly at first. However, with further increase in Reynolds number, local resistance coefficients shows different behaviours for the three fittings due to the special rheological property of coal water slurry at higher shear rates.

Yong-gang et al. [2009] reported the effect of solvent ratio, particle granularity, solvent type, and temperature and shear time on the Shengli lignite coal-solvent slurries. Three hydrogen donor solvents were used: hydrogenated recycle solvent obtained from direct liquefaction pilot plant (REC), quartic-hydrogenated products of heavy oil from the Anqing Oilfield (HAR); and tetralin (THN, AR). The temperature was varied from 30-

70^0C. The results showed that the pseudo-plastic behavior changes to Newtonian behavior as temperature increases.

Lei et al. [2010] proposed a long distance pipeline transportation system with an additive feeding system suitable for restarting after more than a 24-hour shutdown. The aim of their investigation was to find suitable stabilizing additives for fly ash-water slurry to prevent sedimentation during an interrupted period of pipelining. Rheological characteristics and sedimentation stability of the slurry with the addition of four kinds stabilizing additives were measured. Additives used in this study were rhamsan gums (S-194, S-130), carboxymethyl cellulose (CMC), and xanthan gum (Vanzan). They confirmed that viscosity of the fly ash water slurries increases with increase in concentration of stabilizer. The concentration of stabilizing additives to give the same viscosity as untreated slurry were determined as 0.2 wt%, 0.2 wt%, 0.45 wt% and 0.3 wt% for S-194, S-130, CMC, Vanzan, respectively. As a dispersing additive, naphthalene sulfonate-formeldehyde condensate (NSF) was used to reduce the viscosity of fly-ash slurry. They mixed fly ash with deionized water .to give a fly ash concentration of 68 wt%. The concentration of dispersing additive (NSF) was set at 0.3 wt%/slurry. The viscosity of fly ash-water slurry with and without additives was measured using rheometer with coaxial rotating cylinders. They Concluded that stability of slurry with S-194 is better than that of other additive.

Lu et al. [2010] discussed the effect of particle size distribution on flow pattern and pressure drop in pipeline flow of slurries. Author observed three distinct flow patterns for different particle size distribution at different velocities. They are fully stratified, partial stratified and fully suspended. Particle size distribution effects flow patterns significantly.

Fine particles and medium particles which has smaller weight tend to be lifted up by the turbulent dispersive action of the carrier, therefore uniform flow pattern is easily obtained making the flow fully suspended. Whereas coarser particles are too heavy to be fully lifted. It is difficult for coarse particles to come into fully suspended even at high velocity of slurries. Solid particles contribute to the total friction of mixture flow in two ways, through mechanical friction and viscous friction.

Zhou et al. **[2010]** investigated the rheological properties of concentrated coal-water slurry by applying the Herschel-Bulkley model. The rheograms were obtained from HAAKE rheometer with shear rate range of $0s^{-1}$ - 200 s^{-1}. The slurry was dispersed with lignin-based dispersant (MSL). Two slurries were prepared with coal concentration of 64.0 wt% and dispersant dosage of 0.7 wt% and 1.5 wt%. They found that when the dispersant dosage was 0.7 wt%, the slurry showed shear-thinning characteristic and for 1.5 wt% dosage it showed shear-thickening characteristic. The affecting factors such as solid content of CWS and dispersant dosage on rheological property of CWS were also studied, and the results showed that the CWS tend to pseudoplastic characteristic with increasing coal concentration, while tend to dilatant flow characteristic with increasing dispersant dosage.

Bentz et.al [2012] investigated the influence of three variables (cement particle size distribution, fly ash particle size distribution, and ratio of fly ash to cement) at each of four levels on the yield stress and viscosity of blended paste. From the experiments author concluded that both particle densities and particle surface areas, determined from measured particle size distributions, are critical parameters that influences rheological properties. Their investigations reveals that yield stress is dominated by the particle density of the cement component, fly ash mainly acting as a diluent that effectively decreases the cement particle number density. Author also concluded that viscosities are influenced by both cement and fly ash particles, with approximate linear relationships between plastic viscosity values and either total particle surface area or total particle density being found

Buranasrisak et al. [2012] studied the effects of particle size distribution and packing characteristics on the rheological behaviour of coal-water slurry. A sub-bituminous coal of Indonesian origin was used to prepare the samples. The samples were classified into six particle size ranges. Naphthalene Sulfonate formaldehyde (NSF) and Na-CMC were utilized as the dispersing agent and stabilizer respectively. The viscosities of coal water slurries were measured using MV-2000 series II Cannon® Rotary Viscometer at different solid loadings ranging between 60 to 65 % by weight. The different packing characteristics of the coal samples were defined by making monomodal, bimodal and multimodal distributions at different coarse to fine ratios. They observed that maximum coal loading was possible when coal water slurry was made from bimodal particle size distribution.

CHAPTER 3

CHARACTERISATION STUDIES OF COAL SAMPLE

Coal from Assam Steam was used in this thesis. The sample was obtained from coal traders. The various characterization studies that were done on the coal sample included Scanning Electron Microscopy (SEM) analysis, Energy Dispersive X- ray Spectroscopy (EDS) analysis and proximate analysis. Also particle size distribution curves were generated for three coal samples in order to find the mass median diameter of coal samples.

3.1 PARTICLE-SIZE ANALYSIS

The particle-size analysis is an attempt to determine the different grain sizes that make up the sample. It is not possible to determine the individual particle sizes; however the test can only determine the approximate size range between two sieves.

A known weight of coal sample is taken and washed over a B.S. 200 mesh. Then the coal particulates were sieved through a set of British Standard sieves. The weight of the coal sample retained in each sieve was measured and the percentage retained was calculated. Using this data particle size distribution curve was obtained as shown in fig 3.1.

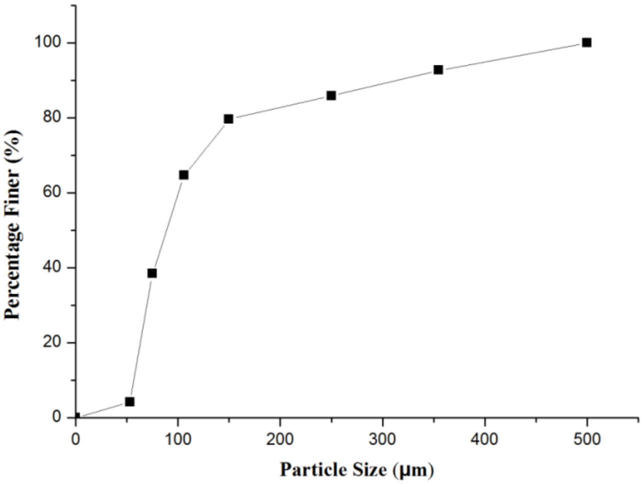


Figure 3.1 Particle size distribution of coal sample.

Fig. 3.1 shows that all of the coal particles are finer than 500µm and 38.39% particles are finer than 75µm.

3.2 SCANNING ELECTRON MICROSCOPY (SEM)

The scanning electron microscope (SEM) uses a focused beam of high-energy electrons to generate a variety of signals at the surface of solid specimens. The signals that derive from electron-sample interactions reveal information about the sample including external morphology (texture), chemical composition, and crystalline structure and orientation of materials making up the sample. In most applications, data are collected over a selected area of the surface of the sample, and a 2-dimensional image is generated that displays spatial variations in these properties. Areas ranging from approximately 1 cm to 5 microns in width can be imaged in a scanning mode using conventional SEM techniques (magnification ranging from 20X to approximately 30,000X, spatial resolution of 50 to 100 nm). The SEM is also capable of performing analyses of selected point locations on the sample; this approach is especially useful in qualitatively or semi-quantitatively determining chemical compositions (using EDS), crystalline structure, and crystal orientations (using EBSD). The design and function of the SEM is very similar to the EPMA and considerable overlap in capabilities exists between the two instruments.

SEM was performed on coal sample by 6510LV model SEM machine (JEOL made) installed in SAI Lab in Thapar University, Patiala.

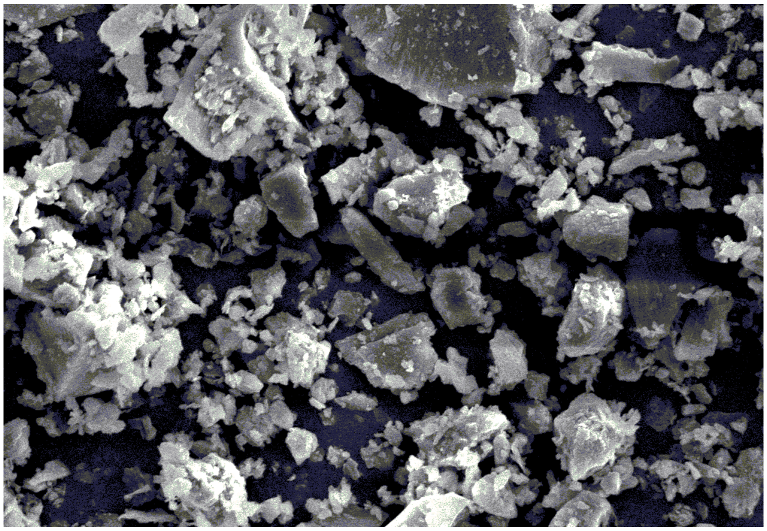


Figure 3.2: SEM Micrograph of coal sample

3.3 ENERGY DISPERSIVE X-RAY (EDX)

Energy Dispersive X-Ray Analysis (EDX), referred to as EDS or EDAX, is an x-ray technique used to identify the elemental composition of materials. EDX systems are attachments to Electron Microscopy instruments (Scanning Electron Microscopy (SEM) or Transmission Electron Microscopy (TEM)) instruments where the imaging capability of the microscope identifies the specimen of interest. INCA X- act model of EDX (OXFORD Instrument made) machine is used for the EDX analysis. The data generated by EDX analysis consist of spectra showing peaks corresponding to the elements making up the true composition of the sample being analyzed. Elemental mapping of a sample and image analysis are also possible. In a multi-technique approach EDX becomes very powerful, particularly in contamination analysis and industrial forensic science investigations. The technique can be qualitative, semi-quantitative, quantitative and also provide spatial distribution of elements through mapping. Qualitative analysis involves the identification of the lines in the spectrum and is fairly straight forward owing to simplicity of X-ray spectra. Quantitative analysis (determination of the concentrations of the elements present) entails measuring line intensities for each element in the sample and for the same elements in calibration standards of known composition. By Scanning the beam in a television-like raster and displaying the intensity of a selected X-ray line, element distribution images or 'maps' can be produced. Also, images produced by electrons collected from the sample reveal surface topography or mean atomic number differences according to the mode selected. The scanning electron microscope(SEM) , which is closely related to the electron probe, is designed primarily for producing electron images, but can also be used for element mapping, and even point analysis, if an X-ray spectrometer is added, There is thus a considerable overlap in the functions of these instruments.

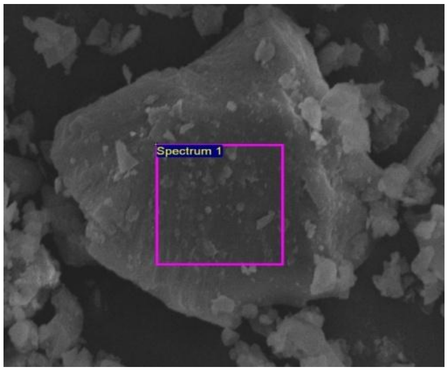


Figure 3.3: Portion selected for EDX of coal sample

Table 3.1 Elemental composition for coal sample

Element	Weight%
C	59.44
O	32.96
Al	0.69
Si	1.43
S	2.58
Cu	1.84
Zn	1.05

3.4 pH OF SLURRY AT DIFFERENT COAL CONCENTRATIONS:

The pH of coal water slurries were determined to observe the effect of coal loading on the pH value of coal water slurries. The pH was measured by a digital pH meter. The pH meter was first calibrated by dipping the electrode into the buffer solutions and then the electrode was cleaned with distilled water to ensure correct measurements

The pH value of the slurry determined at 30%, 40%, 50% and 60% wt. concentration was 6.11, 6.02, 5.94 and 5.81 respectively. The pH value of the slurry was found to be decreasing as the coal concentration increases.

3.5 PROXIMATE ANALYSIS OF COAL SAMPLE

Ash, inherent moisture, volatile matter and fixed carbon present in a coal sample was determined by proximate analysis of the sample. Table 3.2 shows the proximate analysis of the coal sample, conducted as per the prescribed testing method of IS: 1350

Table 3.2: Proximate analysis of coal samples

Parameters	S-I
Moisture,%	0.52
Ash, %	41.74
Volatile Matter, %	16.60
Fixed Carbon, %	41.14

CHAPTER 4

RHEOLOGICAL STUDIES ON COAL WATER SLURRY

During the transportation of coal-water mixture through pipelines, the estimation of energy required for pumping depends on the viscosity of the mixture. Therefore rheological studies are very useful for determining the viscosity and also for studying the effect of various parameters like solids concentration, temperature, particle size distribution, and properties of coal like ash and moisture content. In the present study, the rheological experimentation was carried out on coal-water mixtures. The rheological measurements were made with the help of Anton Paar RheolabQC rheometer.

4.1 DESCRIPTION OF THE EQUIPMENT

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 Figure 4.1. It is a rotational rheometer consisting of a high precision encoder and a highly dynamic EC motor. The measurements are obtained by selecting controlled shear rate test settings. It has wide speed and torque ranges and very short motor response time. The measuring systems can be detected automatically by the inbuilt Toolmaster™ system that ensures the exact measuring data to be used with more precision.

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 measuring system consists of a spindle having bob and a cup with a small annular gap in between them. The coal-water mixture 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.

Figure 4.1: Anton Paar RheolabQC rheometer

The slurry is subjected to shearing action in between the annular gap between the measuring cup and bob, and hence shear stress is measured as a function of shear rate. The output results are obtained on the Rheoplus software installed on a computer which is connected to the rheometer by LAN connection.

The temperature of the slurry was controlled with the help of water bath. The temperature of the water was controlled according to the temperature required of the slurry, with the help of water bath and the water was circulated around the cylinder cup and rotating bob fixed in the rheometer with the help of connecting pipes. The water was circulated for 5-10 minutes to reach the thermal equilibrium.

4.2 EXPERIMENTAL PROCEDURE

The rheological experiments were carried out using Anton Paar Rheolab QC rheometer. Two measuring systems DG42/SS/QC-LTD and CC27/QC-LTD were chosen for the rheological measurements. They were thoroughly cleaned and dried.

The coal water slurry sample was prepared by mixing known amount of coal with the water to obtain the required slurry concentration. The slurry was continuously stirred for 5 to 10 minutes by a glass rod and a proper care was taken to avoid attrition and spillage of coal water slurry. The required weight of the coal was weighted in an electronic balance with least count ±0.0001g. The rheological experiments were conducted with solid weight concentration of 30%, 40%, 50% and 60% by wt. the shear rate was applied from 0-600 s^{-1} for time interval of 2 minutes to measure the apparent viscosity and shear stress at a given shear rate.

4.3 RESULTS AND DISCUSSION

The rheological properties of coal slurries were measured at different concentrations of 30% - 60% by weight. The flow characteristics of coal sample having fine particle size and different particle size distributions were determined by the rheological study. The flow behavior obtained for fine particle size at different coal concentration (by weight) is presented in the rheograms.

4.4 EFFECT OF SOLIDS CONCENTRATION ON SLURRY RHEOLOGY

The flow curves obtained by the rheological experimentation revealed that the rheological behavior of coal water slurry is immensely affected by the variation in concentration of solids in the slurry.

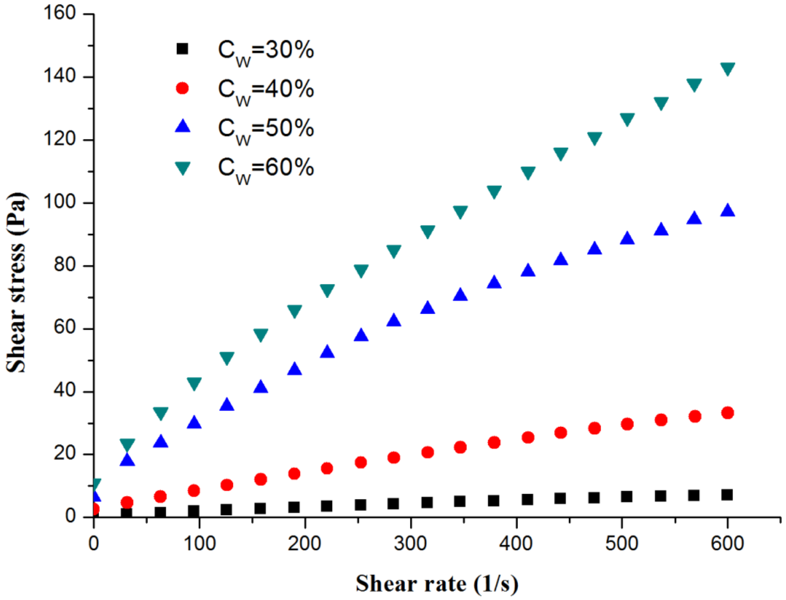


Figure 4.2: Rheogram of coal water slurry at different concentrations (% by weight)

After studying the graph in Figure 4.2, it was found that both solids concentration had a considerable effect on rheological behavior of coal-water mixture. As solid concentration was increased, the apparent viscosity of coal-water mixture increased. This can be attributed to the fact that when concentration increases, the density of coal particles in coal-water mixture also increases, which means that there are now more coal particles in same amount of volume. As a result of which particle to particle shear interactions increases and hence viscosity increases. It was also observed that the yield stress of coal-water mixture increased, with an increase in solids concentration.

4.5 EFFECT OF TEMPERATURE ON SLURRY RHEOLOGY

To study the effect of temperature on coal-water mixture rheology, flow curves of shear stress vs. shear rate (rheograms) were generated for coal-water mixtures at different temperatures. Rheograms for coal-water mixtures made for coal sample are shown in Figure 4.2-4.13

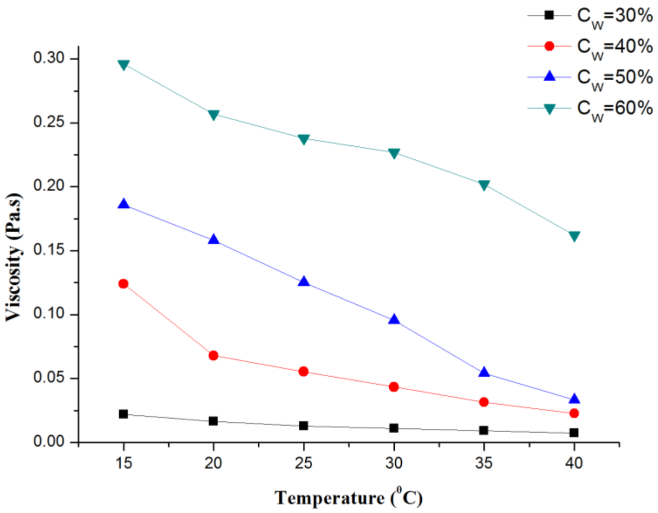


Figure 4.3: Variation of viscosity of coal water slurry with temperature.

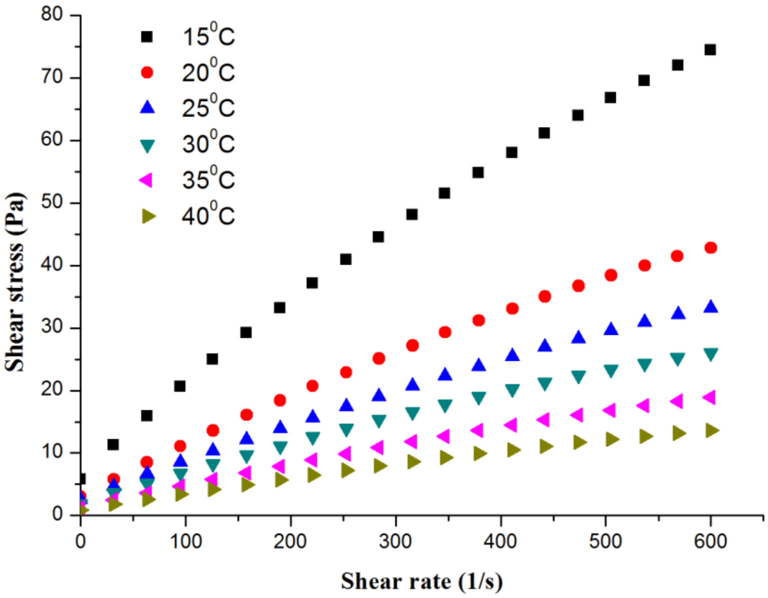


Figure 4.4: Variation of viscosity of coal water slurry with temperature for C_W=40%

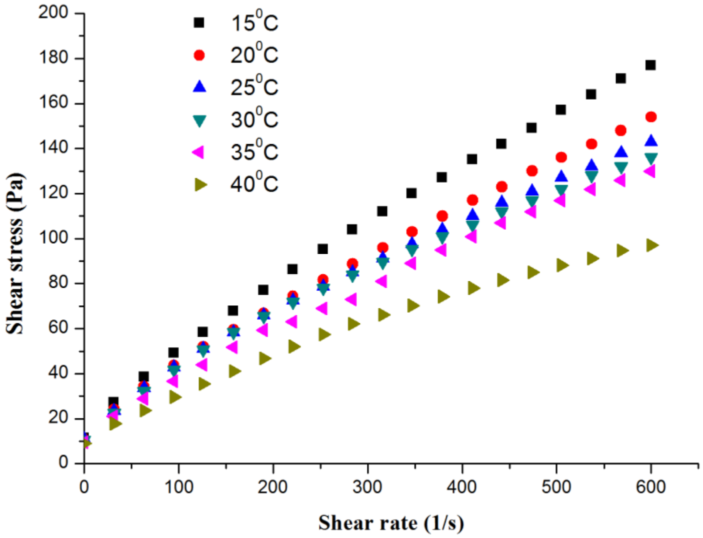


Figure 4.5: Variation of viscosity of coal water slurry with temperature for C_W=60%

After studying the graphs in Figure 4.3-4.5, it was found that temperature had a considerable effect on rheological behavior of coal-water mixture. As temperature was increased, the slope of the curve decreased indicating that apparent viscosity decreased. The decrease in apparent viscosity with increase in temperature can be attributed to the fact that with increase in temperature, the kinetic energy of molecules increases. With increase in kinetic energy, the magnitude of attractive forces between molecules decreases and molecules can now move more freely with respect to one another, hence resulting in lesser viscosity.

4.6 VARIATION OF APPARENT VISCOSITY WITH SHEAR RATE

Variation of apparent viscosity as a function of shear rate for coal-water mixtures is shown in Figure 4.6-4.8. The effect of temperature on apparent viscosity of coal sample was also studies.

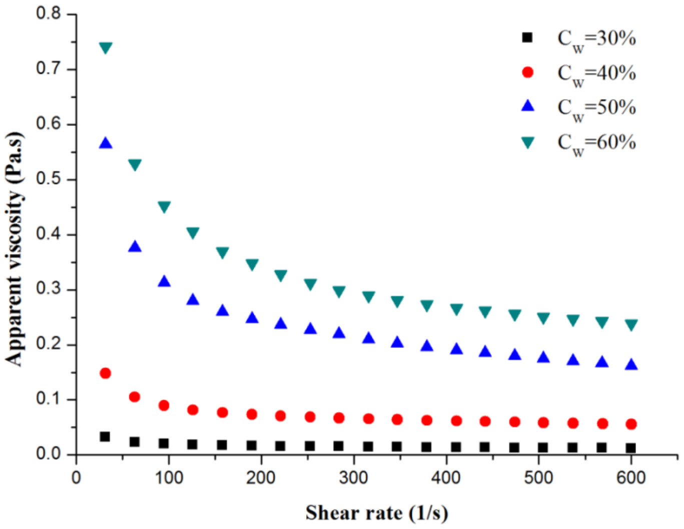


Figure 4.6: Variation of apparent viscosity with shear rate.

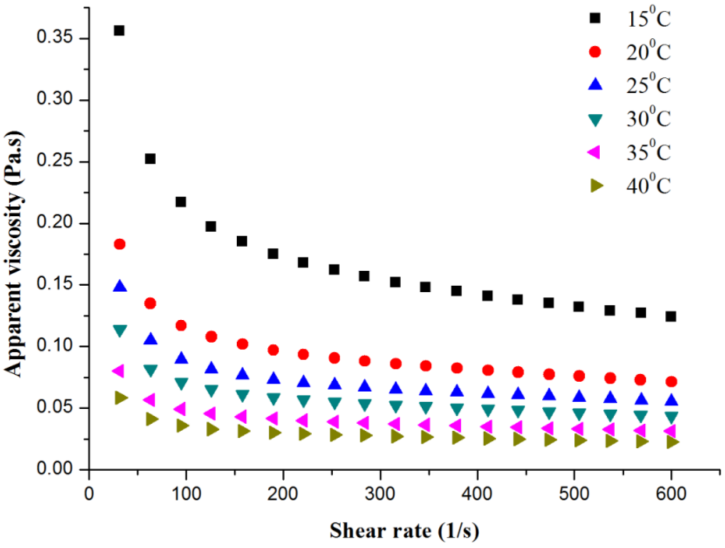


Figure 4.7: Variation of apparent viscosity with shear rate at C_w = 40 %

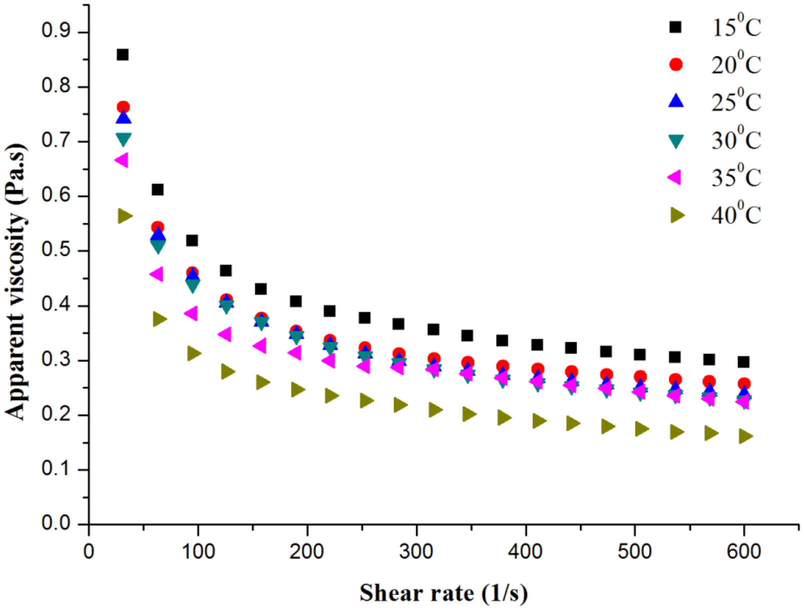


Figure 4.8: Variation of apparent viscosity with shear rate at C_w = 60 %

From the graphs shown in Fig. 4.6-4.8, it was observed that up to 30 % solids concentration, coal-water mixtures behaved as a Newtonian fluid having apparent viscosity independent of shear rate. It was also observed that above 40 % solids concentration, the coal-water mixtures behaved as yield pseudo plastic fluid having a decrease in apparent viscosity with increase in shear rate. The pseudoplastic behaviour of coal water slurries indicated by the rheograms and viscosity curves of coal water slurries at higher solids concentration (i.e. above 30 % by weight) can be attributed to the viscous forces that dominate at higher shear rates and causes a breakdown of the slurry structure which causes a decrease in the slurry viscosity with an increasing shear rate. Also, the increase in solid loading causes an increase in the viscosity and shear stress of coal water slurry as the interparticle interaction among the coal particulates highly increases and the effective area under shear also increases. The result of both of these is to cause a steep rise in viscosity and shear stress.

4.7 EFFECT OF TEMPERATURE ON YIELD STRESS.

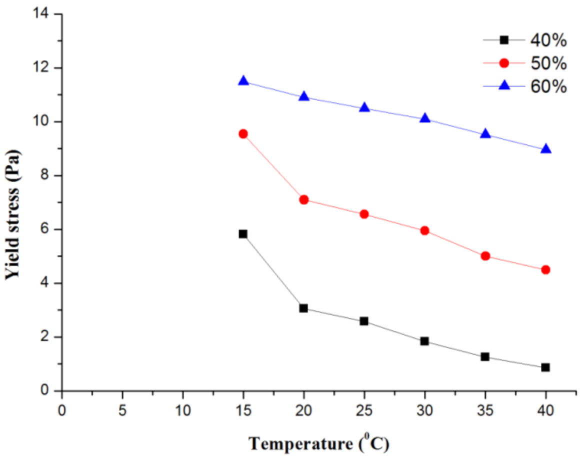


Fig. 4.9: Variation of yield stress with temperature.

From Figure 4.9 it was observed that with increase in temperature the yield stress of slurry decrease

4.8 EFFECT OF FRACTION OF COARSE ON SLURRY RHEOLOGY

It is reported by many authors that the viscosity of the coal water slurries could be reduced by blending the coal samples with a fraction of coarse and hence making a bimodal particle size distribution. A bimodal slurry sample was prepared by mixing the two size of coal. A fraction of coarse particles was blended in fines particles. The fine particles used had the particles size of 53-75 μm and the coarse particles used had particle size of 106-150 μm.

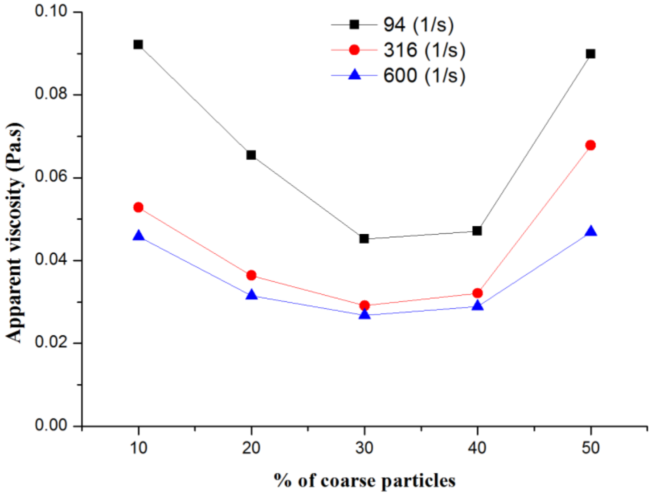


Figure 4.10: Effect of fraction of coarse particles on the apparent viscosity of coal

The effect of coarse particle on the apparent viscosity of the slurry is shown in Figure: 4.9. From the figure it is clear that the apparent viscosity of the slurry decreases with increase in fraction of the coarse particle upto a fixed fraction. After a this fraction the apparent viscosity increases with the increase in fraction of coarse particle. Similar trend was observed by the Logos C et al. (1996).

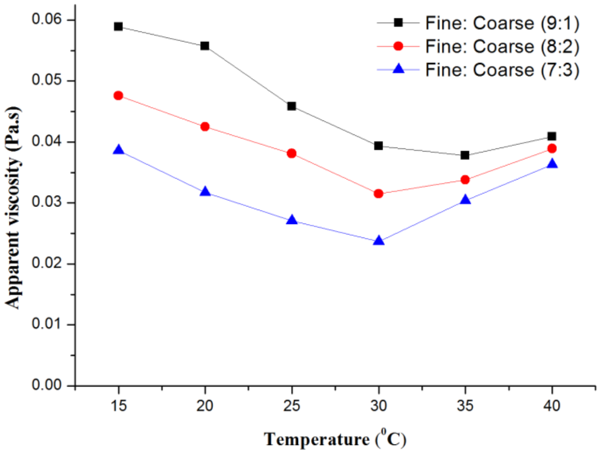


Figure 4.11: Effect of temperature on the apparent viscosity of coal with different coarse fraction

The effect of the temperature on the apparent viscosity of the slurry with different coarse fraction was also studied. Figure 4.10 shows the effect of temperature on the apparent viscosity of coal with different coarse fraction. From figure it is clear that with increase in the temperature the apparent viscosity decreases. But after a certain temperature the apparent viscosity of coal slurry increases with increase in the temperature. The reason for this change in trend can be further studied in future studies.

4.9 RHEOLOGICAL MODEL FITS

The rheological data obtained from the experimentation was fitted into rheological models to calculate the model parameters for determining the flow behavior of coal-oil mixtures at different concentrations and temperatures. Coal-water mixtures without yield stress were analyzed with Power-Law model and those having yield stress were analyzed with Herschel-Bulkley model.

The relation for Power-Law model is:

$$\tau = \dot{K}\,\gamma^{\dot{n}} \tag{4.1}$$

Taking logarithm on both sides of Eq. (4.1) gives:

$$\ln\tau = \ln\dot{K} + \dot{n}\ln\gamma \tag{4.2}$$

A linear regression of $\ln\tau$ as a function of $\ln\gamma$ was performed to calculate the model parameters $\dot{n}$ and $\dot{K}$.

The relation for Herschel-Bulkley model is:

$$\tau = \tau_y + \dot{K}\,\gamma^{\dot{n}} \tag{4.3}$$

The Herschel-Bulkley is a three parameter model. The yield stress corresponding to zero shear rate was estimated by curve fitting. Then, the Herschel- Bulkley model was reduced to a two parameter model by taking the yield stress at the left hand side of Equation 4.3 and taking logarithms on both sides.

Rearranging and taking logarithm on both sides of Eq. (4.3) gives:

$$\ln(\tau - \tau_y) = \ln\dot{K} + \dot{n}\ln\gamma \tag{4.4}$$

A linear regression of $\ln(\tau - \tau_y)$ as a function of $\ln\gamma$ was performed to calculate the model parameters $\dot{n}$ and $\dot{K}$. The model parameters i.e Flow behaviour index ($\dot{n}$) and consistency coefficient ($\dot{K}$) are shown in Table 4.1

Table 4.1: Rheological model parameters for coal samples.

Solid concen-tration (% C_W)	**Tempera-ture (^{0}C)**	**Yield stress (Pa)**	**Rheological model used**	**Flow behaviour index (ṅ)**	**Fluid type**
30	15	0	Power-Law	1	Newtonian
	25	0	Power-Law	1	Newtonian
	25	0	Power-Law	1	Newtonian
	30	0	Power-Law	1	Newtonian
	35	0	Power-Law	1	Newtonian
	40	0	Power-Law	1	Newtonian
40	15	5.81	Herschel-Bulkley	0.86	Yield pseudo plastic
	20	3.06	Herschel-Bulkley	0.88	Yield pseudo plastic
	25	2.58	Herschel-Bulkley	0.89	Yield pseudo plastic
	30	1.84	Herschel-Bulkley	0.90	Yield pseudo plastic
	35	1.26	Herschel-Bulkley	0.92	Yield pseudo plastic
	40	0.86	Herschel-Bulkley	0.93	Yield pseudo plastic

50	15	9.54	Herschel-Bulkley	0.79	Yield pseudo plastic
	20	7.1	Herschel-Bulkley	0.83	Yield pseudo plastic
	25	6.56	Herschel-Bulkley	0.85	Yield pseudo plastic
	30	5.95	Herschel-Bulkley	0.88	Yield pseudo plastic
	35	5.01	Herschel-Bulkley	0.90	Yield pseudo plastic
	40	4.49	Herschel-Bulkley	0.91	Yield pseudo plastic
60	15	11.488	Herschel-Bulkley	0.70	Yield pseudo plastic
	20	10.985	Herschel-Bulkley	0.73	Yield pseudo plastic
	25	10.918	Herschel-Bulkley	0.75	Yield pseudo plastic
	30	10.55	Herschel-Bulkley	0.78	Yield pseudo plastic
	35	9.52	Herschel-Bulkley	0.80	Yield pseudo plastic
	40	8.95	Herschel-	0.83	Yield pseudo

CHAPTER 5

NUMERICAL STUDY ON PIPE FLOW CHARACTERISTICS

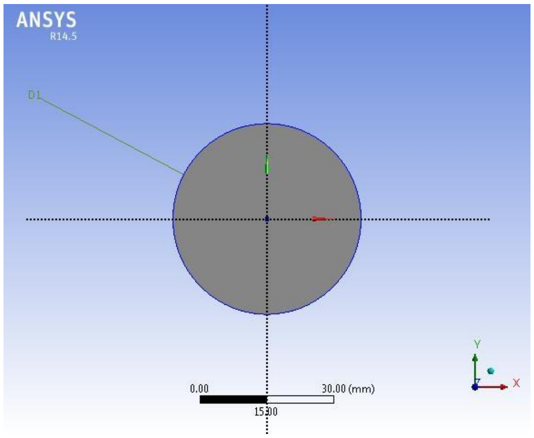
The design of slurry pipeline is a complex process and requires that the design should be optimised that permits highly concentrated slurry transport with minimum pressure drop and wear. Computational Fluid Dynamics (CFD) is a powerful tool that uses numerical methods and algorithms to model the real life behavior of fluids. It allows the optimization of design parameters without the need for the costly testing of multiple prototypes. The rheological study done on coal sample was useful in generating the slurry viscosity data that can be utilized to determine the pressure drop in coal water slurry pipelines. In the present study, pressure drop characteristics of 50 mm diameter slurry pipeline were numerically evaluated using ANSYS FLUENT 14.5 code.

5.1 NUMERICAL EVALUATION

Numerical evaluation for pipeline of different geometries for pressure drop characteristics was carried out by computational fluid dynamics (CFD). CFD is the analysis of systems involving fluid flow, heat transfer and associated phenomena by means of computer-based simulations. Computational power is used to perform the calculations required to simulate the interaction of fluid with object surfaces defined by proper boundary conditions.

5.2 MODELING AND MESHING

ANSYS Design Modeler (DM) is used to construct geometry. Geometry consists of pipe with internal diameter of 50 mm and length of 7 m shown in Figure 5.1 and 5.2. Length of the pipe is large enough, so that the flow is fully developed.



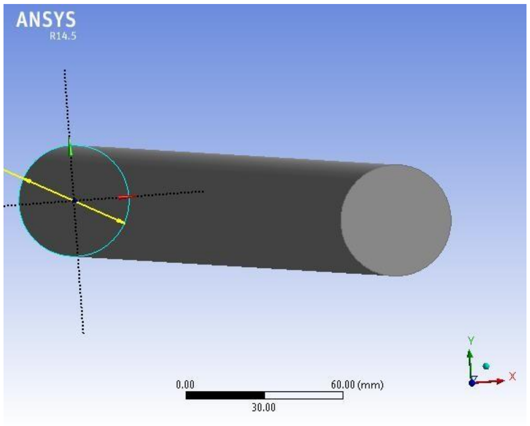


Figure 5.1 Crossectional View of Pipe **Figure 5.2 Isometric view of Pipe**

A grid independence test was conducted for straight pipe to choose the most suitable grid size. Different numbers of elements were obtained for different grid sizes and the simulation results for pressure drop of coal water slurry flow at fixed solids concentration of 50 % by weight and flow velocity of 2.5 m/s for straight pipe were compared.

Complete domain is discretized or mesh or grid is generated using Ansys ICEM tool. Four different geometries having different number of elements (230000, 332000, 415670, 565322, 630558) is generated to make the solution grid independent. Initially carrier liquid (water) is used to simulate the fluid flow from the pipe with different mesh size geometries and it is observed that after 415000 elements the solution becomes grid independent.

Before obtaining the grid test results for coal water slurry flow, the pressure drop was theoretically calculated at mean flow velocity of 2.5 m/s for water flowing in straight pipe by using Darcy-Weisbach equation.

The theoretical results of pressure drop for water flowing in straight pipe were validated with the simulated results at different grid sizes of 1.5, 2, 2.5 and 3.0. It was found that the pressure drop obtained by simulation in ANSYS FLUENT 14.5 with 415000 elements was the same as obtained by Darcy-Weisbach equation.

Hence, it was ensured that the pressure drop obtained by simulating the flow of water in pipeline 415000 elements was the same as obtained theoretically. After conducting these tests, the coal water slurry flow was simulated and a grid independence test was performed to choose the most accurate grid size.

5.3 PROBLEM SETUP

There were three faces bounding the calculation domain, the inlet, the pipe wall and the outlet. In ANSYS FLUENT 14.5 code, the mixture model was chosen for the study of coal water slurry flow which is a multiphase flow. Phase 1 was considered as the carrier liquid which was water and Phase 2 was considered as coal powder. The rheological data obtained earlier were used to compute the pressure drop in the slurry pipeline.

k-ε turbulence model was chosen as the turbulence model. The pressure-velocity coupling was achieved by utilizing Coupled SIMPLE algorithm that caters to the need of multiphase flows. The boundary conditions were given as velocity inlet (inlet condition) and pressure outlet (outlet condition) with pipe wall as the wall domain.

5.4 COMPUTATIONAL RESULTS

The pressure drop measurements were predicted at different mean flow velocities of 1.0 m/s 1.5 m/s, 2.0 m/s, 2.5 m/s, 3 m/s and 3.5 m/s for 30 %, 40 %, 50 % and 60 % solid concentration (by weight) of coal water slurry.

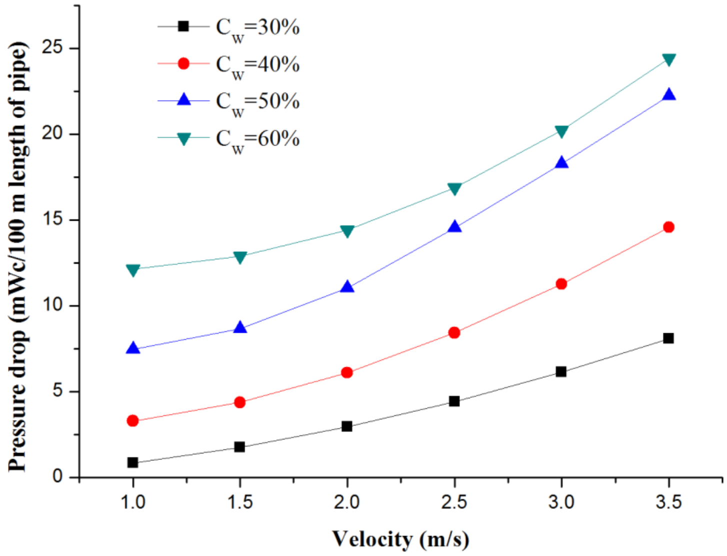
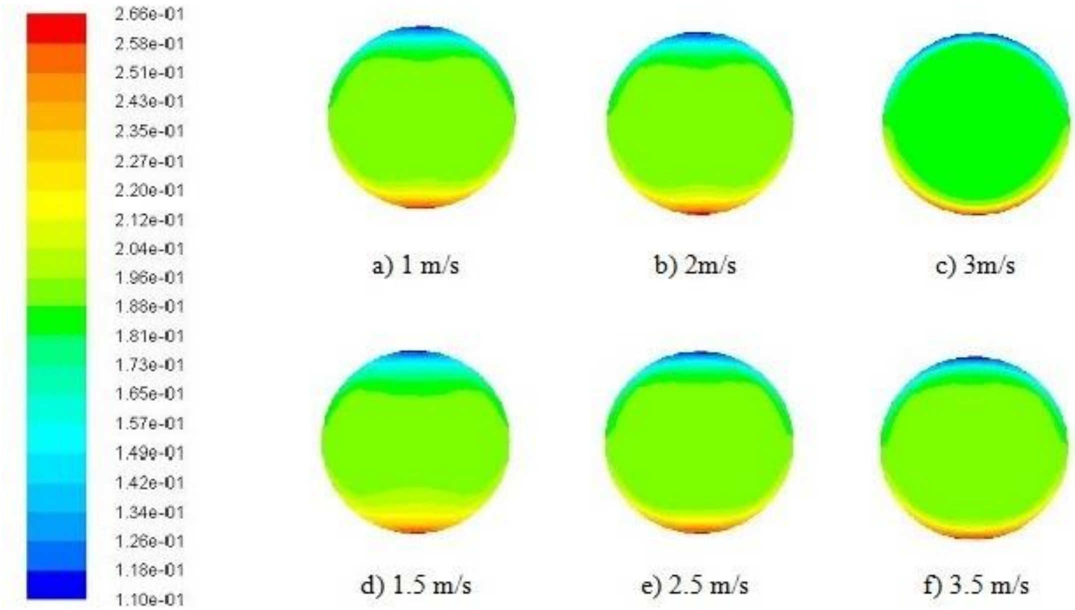


Figure 5.3: Pressure drop at different solids concentration of coal sample

It was observed that the pressure drop in straight pipe increased as the mean flow velocity increased. The pressure drop also increased with an increase in solids concentration of coal water slurry which was due to the increase in apparent viscosity of coal water slurry at increasing solids concentration by weight.

5.5 Concentration Profile

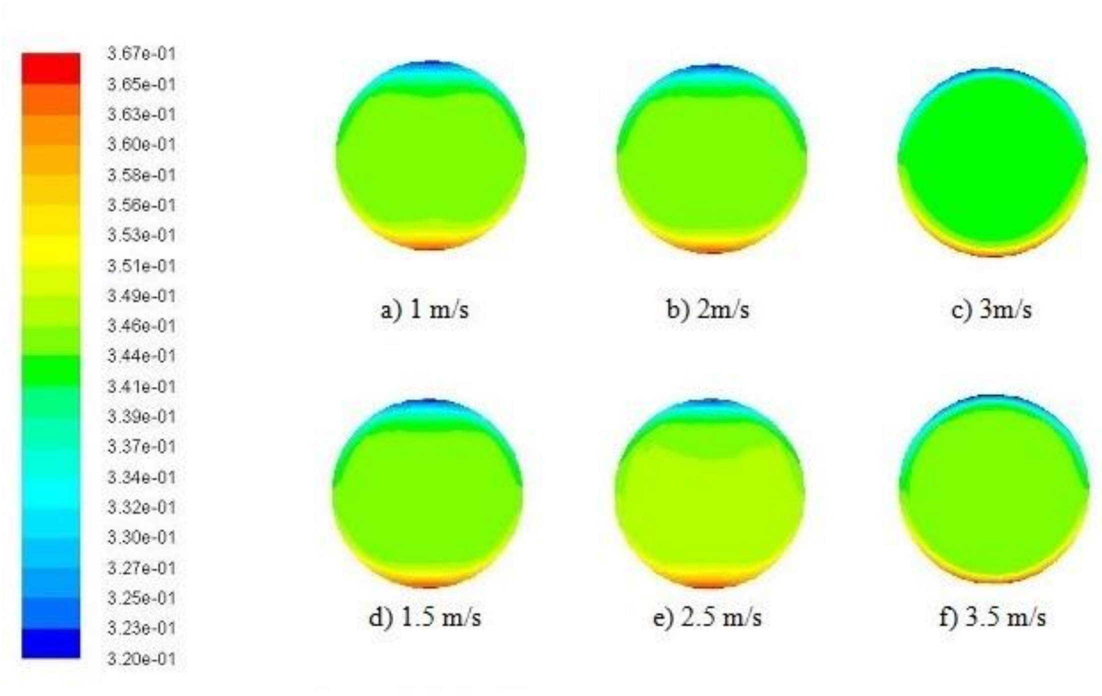
The CFD predicted vertical concentarion profile of coal slurry at the outlet of the pipe at various velocities and concentrations is shown in Figure 5.4-5.5. As the particle size used in present simulation for the zinc is below 75µm the flow is homogenous flow in which solid particle are fully mixed with carrier fluid as shown in below figures only small proportion of the solid particle are settled at low velocities which are again lifting up with increase in the velocity of the flow due to increase in turbulent energy which make particles suspended.



a) 1 m/s b) 2m/s c) 3m/s

d) 1.5 m/s e) 2.5 m/s f) 3.5 m/s

Figure 5.4: CFD predicted solid volume fraction contour at 40% concentration by weight at different velocities



a) 1 m/s b) 2m/s c) 3m/s

d) 1.5 m/s e) 2.5 m/s f) 3.5 m/s

Figure 5.5: CFD predicted solid volume fraction contour at 60% concentration by weight at different velocities

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

6.1 SUMMARY AND CONCLUSION

The present research work entitled “Investigation of flow characteristics of coal water slurry” was carried out using coal sample of Indian origin. The characterization studies were done prior to the rheological study to determine the ash content, particle size distribution, morphology, coal-water mixture pH. The pH of coal water slurry was found to decrease with an increase in solids concentration. After the characterization studies, the rheological data were generated for the coal sample to determine the coal water slurry flow behaviour. The slurry flow behaviour was found to be shear thinning above 30 % solids concentration (by weight) with viscosity decreasing with an increasing shear rate. The shear stress-strain rate data were fitted into the rheological models to calculate the model parameters for Power-Law fluid and Herschel-Bulkley fluid. The rheological study was conducted to investigate the effect of solids concentration, temperature, fraction of coarse particles in fine particles. It was found that the slurry viscosity increased with an increase in solids concentration. It was found that with increase in temperature the apparent viscosity of the slurry decreases.

The coarse particles were also added to relatively finer coal particles to determine the effect of addition of fraction of coarse particles and it was observed that the slurry viscosity decreased with the addition of coarse particles until an optimum ratio of coarse. An increase in slurry viscosity was found at coarse/fine ratio greater than the optimum coarse/fine ratio. It was also found that with increase in temperature the apparent viscosity decreases first but after a particular temperature the apparent viscosity increases with increase in temperature.

The rheological data generated were utilized in evaluating the pipeline flow characteristics of coal water slurry using numerical techniques. A straight pipe was modeled using ANSYS meshing tool with analysis performed using ANSYS FLUENT 14.5. It was found that for coal water slurry flowing through pipeline the pressure drop increases with increase in velocity and solid concentration.

6.2 FUTURE SCOPE

The various works that can be done in future are:

1. Validation of results by computing slurry flow behavior and pressure drop characteristics in an experimental pipeline loop setup.
2. Erosion wear studies of slurry pipeline for different solid weight concentration of coal water slurries.
3. Reason for the increase in apparent viscosity with increase in temperature for slurry with mixture of fine and coal particles.

REFERENCE

1. Atesok, G., Boylu, F., Sirkeci, A.A., Dincer, H., 2002, The Effect of Coal Properties on the Viscosity of Coal-Water Slurries, Fuel, 81, 1855-1858.
2. Boylu, F., Atesok, G., Dincer, H., 2005, The Effect of Carboxymethyl Cellulose (CMC) on the Stability of Coal-Water Slurries, Fuel, 84, 315-319.
3. Boylu, F., Dincer, H., Atesok, G., Effect of Coal Particle Size Distribution, Volume Fraction and Rank on the Rheology of Coal–Water Slurries, Fuel Processing Technology, 85, 241–250.
4. Buranasrisak, P., and Narasingha, M.H., 2012, Effects of Particle Size Distribution and Packing Characteristics on the Preparation of Highly-Loaded Coal-Water Slurry, International Journal of Chemical Engineering and Applications, 3, 31-35.
5. Das, D., Panigrahi, S., Senapati, P.K., Misra, S.K., 2009, Effect of Organized Assemblies. Part 5: Study on the Rheology and Stabilization of a Concentrated Coal-Water Slurry Using Saponin Of The Acacia Concinna Plant. *Energy & Fuels.* v.23, pp. 3217–3226.
6. Dincer, H., Boylu, F., Sirkeci, A.A., Atesok, G., 2003, The Effect of Chemicals On the Viscosity and Stability of Coal Water Slurries. International Journal of Mineral Processing, 70, 41-51.
7. Gao, X.R., Chang, H.H., Wei, W.L., Wang, L.Z., Zhang, Z.L., Wang, Z.Z., 2010, The Influence of the Amount of Dispersants and Slurry Content on The Slurryability of Coal Pitch Water Slurry, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 33, 194-201.

8. Gürses, A., Açıkyıldız, M., Doğar, C., Karaca, S. and Bayrak, R., 2006, An Investigation on Effects of Various Parameters on Viscosities of Coal–Water Mixture Prepared with Erzurum–Aşkale Lignite Coal, Fuel Processing Technology, 87, 821-827.
9. Lei, L., Usui, H., Suzuki, H., 2010, Study of Pipeline Transportation of Dense Fly Ash-water Slurry, Coal Preparation, 22(2) 65-80.
10. Li, L., Usui, H., Suzuki, H., 2002, Study of Pipeline Transportation of Dense Fly Ash-Water Slurry, Coal Preparation, 22(2), 65-80.
11. Li, Y., Li, B., 2000, Study on the Ultrasonic Irradiation of Coal Water Slurry, Fuel, 79, 235-241.
12. Logos, C., Nguyen, Q.C., 1996, Effect of Particle Size on the Flow Properties of a South Australian Coal-Water Slurry, Powder Technology, 88, 55-58.
13. Lu P., Zhang M., 2002, Resistance Properties of Coal–Water Paste Flowing in Pipes, Fuel, 81, 877-881.
14. Lu, H., Yin, J., Yuan, Y., Wang, J., 2010, Effect of Particle Size Distribution on Flow Pattern and Pressure Drop in Pipeline Flow of Slurries, 2nd Conference on Environmental Science and Information Application Technology
15. Mishra, S.K., Senapati, P.K., Panda, D., 2002, Rheological Behavior of Coal-Water Slurry. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 24, 159-167.
16. Natoli, J., Mahar, R.C., Bobsein, B.R., 1985, Polycrylate Thickeners for Coal Water Slurries: Slurry Formation, Stability and Rheology, International Chemical Engineering Symposium Series, 95, 17-36.

17. Nguyen, Q.D., Logos, C., Semmler, T., 1997, Rheological Properties Of South Australian Coal-Water Slurries, Coal Preparation, 18, 185-199.
18. Ongsirimongkol, N. and Narasingha, M.H., 2012, Effects of Stabilizing Agents on Stability and Rheological Characteristics of The Highly-Loaded Coal-Water Slurry, International Journal of Chemical Engineering and Applications, 3,49-52.
19. Roh, N., Shin, D.H., Kim, D.C. Kim, J.D., 1994, Rheological Behaviour of Coal-Water Mixtures 1. Effects of Coal Type, Loading and Particle Size, Fuel, 74, 1220-1225.
20. Senapati, P.K., Das, D., Nayak, A., Mishra, P.K., 2008,. Studies on Preparation of Coal Water Slurry Using a Natural Additive, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 30, 1788-1796.
21. Usui, H., Saeki, T., Hayashi, K. Tamura, T., 1997, Sedimentation Stability and Rheology of Coal Water Slurries, Coal Preparation, 18, 201-214.
22. Uyar, T. S., Özil, Ö. Erdönmez, G., 1994, Preparation of Low-Rank Coal-Water Mixtures, Coal, 271-278.
23. Wang, Z., Zhang, R., Jiang, Z., Jiang, S., 1993, Preperation of Coal-Water Fuels from Coal Preperation Plant Fines, Paper G3, Proceedings of the Sixth Australian Coal Preperation Conference, in Davis, J.J. (ed.), 418-427.
24. Witsee, G.A., Mass, D.J., Hammond, T.K., Goodman, R.M., 1986, Low-Rank Coal/Water Fuels, Third USA-Korea Joint Workshop on Coal Utilization Technology, Pittsburg, Pennsylvania, USA.
25. Yavuz, R., Küçükbayrak, S., 1998, Effect of Particle Size Distribution on Rheology of Lignite-Water Slurry. Energy Sources, 20, 787-794.

26. Zhou, M., Pan, B., Yang, D., Lou, H. Qiu, X., 2010, Rheological Behavior Investigation of Concentrated Coal-Water Suspension. Journal of Dispersion Science and Technology, 31, 838-843.

C1: Rheology of coal-water slurry at C_w = 40 % by weight.

Table C1.1: Rheology of coal water slurry at 15^0C

Shear Rate (1/s)	Shear Stress (Pa)	Apparent Viscosity (Pa.s)
0	5.8173	####
31.7	11.3	0.356
63.2	15.9	0.252
94.8	20.6	0.217
126	25	0.197
158	29.2	0.185
190	33.2	0.175
221	37.1	0.168
253	40.9	0.162
284	44.5	0.157
316	48.1	0.152
347	51.5	0.148
379	54.8	0.145
411	58	0.141
442	61.1	0.138
474	64	0.135
505	66.8	0.132
537	69.5	0.129
569	72	0.127
600	74.4	0.124

Table C1.2: Rheology of coal water slurry at 20^{0}C

Shear Rate (1/s)	Shear Stress (Pa)	Apparent Viscosity (Pa.s)
0	3.0689	####
31.7	5.8	0.183
63.2	8.5	0.135
94.8	11.1	0.117
126	13.6	0.108
158	16.1	0.102
190	18.4	0.0971
221	20.7	0.0935
253	22.9	0.0907
284	25.1	0.0883
316	27.2	0.0861
347	29.3	0.0842
379	31.2	0.0824
411	33.1	0.0807
442	35	0.0791
474	36.7	0.0775
505	38.4	0.076
537	40	0.0744
568	41.5	0.0729
600	42.8	0.0714

Table C1.3: Rheology of coal water slurry at 25^{0}C

Shear Rate (1/s)	Shear Stress (Pa)	Apparent Viscosity (Pa.s)
0	2.5895	####
31.7	4.68	0.148
63.2	6.63	0.105
94.8	8.5	0.0897
126	10.3	0.0817
158	12.1	0.0767
190	13.9	0.0733
221	15.6	0.0707
253	17.4	0.0687
284	19	0.0669
316	20.7	0.0654
347	22.3	0.0641
379	23.8	0.0629
411	25.4	0.0618
442	26.9	0.0608
474	28.3	0.0597
505	29.6	0.0586
537	30.9	0.0576
569	32.1	0.0565
600	33.2	0.0554

Table C1.4: Rheology of coal water slurry at 30^{0}C

Shear Rate (1/s)	Shear Stress (Pa)	Apparent Viscosity (Pa.s)
0	1.84	####
31.6	3.62	0.114
63.2	5.17	0.0818
94.8	6.71	0.0708
126	8.24	0.0652
158	9.7	0.0614
190	11.1	0.0588
221	12.6	0.0568
253	13.9	0.0551
284	15.3	0.0537
316	16.6	0.0524
347	17.8	0.0513
379	19	0.0502
411	20.2	0.0492
442	21.3	0.0482
474	22.4	0.0472
505	23.4	0.0462
537	24.3	0.0453
568	25.2	0.0443
600	26	0.0434

Table C1.5: Rheology of coal water slurry at 35^{0}C

Shear Rate (1/s)	Shear Stress (Pa)	Apparent Viscosity (Pa.s)
0	1.2687	####
31.6	2.53	0.0801
63.2	3.6	0.0569
94.8	4.69	0.0495
126	5.77	0.0456
158	6.84	0.0433
190	7.88	0.0416
221	8.9	0.0402
253	9.9	0.0392
284	10.9	0.0383
316	11.8	0.0374
347	12.7	0.0366
379	13.6	0.0359
411	14.5	0.0352
442	15.3	0.0346
474	16.1	0.0339
505	16.8	0.0333
537	17.6	0.0327
569	18.3	0.0321
600	18.9	0.0315

Table C1.6: Rheology of coal water slurry at 40^{0}C

Shear Rate (1/s)	Shear Stress (Pa)	Apparent Viscosity (Pa.s)
0	0.8689	####
31.7	1.85	0.0584
63.2	2.61	0.0413
94.8	3.39	0.0358
126	4.18	0.0331
158	4.96	0.0314
190	5.74	0.0303
221	6.5	0.0294
253	7.24	0.0286
284	7.95	0.0279
316	8.63	0.0273
347	9.29	0.0267
379	9.92	0.0262
411	10.5	0.0256
442	11.1	0.0251
474	11.7	0.0246
505	12.2	0.0241
537	12.7	0.0237
568	13.2	0.0232
600	13.6	0.0227

C2: Rheology of coal-water slurry at C_w = 50 % by weight.

Table C2.1: Rheology of coal water slurry at 15^0C

Shear Rate (1/s)	Shear Stress (Pa)	Apparent Viscosity (Pa.s)
0	9.54	####
31.7	13.1	0.412
63.2	17.9	0.282
94.8	22.5	0.237
126	26.6	0.211
158	30.3	0.192
190	33.6	0.177
221	36.6	0.166
253	39.4	0.156
284	41.8	0.147
316	44	0.139
347	46.3	0.133
379	48.3	0.127
411	49.9	0.122
442	51.6	0.117
474	53.4	0.113
505	55.2	0.109
537	56.8	0.106
568	58.2	0.102
600	59.6	0.0993

Table C2.2: Rheology of coal water slurry at 20^0C

Shear Rate (1/s)	Shear Stress (Pa)	Apparent Viscosity (Pa.s)
0	7.1	####
31.6	8.71	0.275
63.2	11.1	0.175
94.8	13	0.137
126	14.8	0.117
158	16.6	0.105
190	18.3	0.0965
221	19.9	0.0898
253	21.3	0.0844
284	22.7	0.0799
316	24.1	0.0763
347	25.4	0.0732
379	26.7	0.0706
411	28.2	0.0688
442	29.8	0.0674
474	31.4	0.0662
505	32.8	0.065
537	34.4	0.0641
568	35.9	0.0631
600	37.4	0.0624

Table C2.3: Rheology of coal water slurry at 25^{0}C

Shear Rate (1/s)	Shear Stress (Pa)	Apparent Viscosity (Pa.s)
0	6.56	####
31.6	7.47	0.236
63.2	9.42	0.149
94.8	11.1	0.117
126	12.6	0.0997
158	14.1	0.0895
190	15.6	0.0826
221	17	0.0769
253	18.2	0.0719
284	19.2	0.0675
316	20.4	0.0644
347	21.4	0.0617
379	22.6	0.0597
411	23.9	0.0583
442	25.3	0.0572
474	26.6	0.0561
505	27.9	0.0552
537	29.2	0.0544
568	30.5	0.0536
600	31.8	0.0531

Table C2.4: Rheology of coal water slurry at 30^0C

Shear Rate (1/s)	Shear Stress (Pa)	Apparent Viscosity (Pa.s)
0	5.95	####
31.7	6.88	0.217
63.2	8.62	0.136
94.8	10	0.106
126	11.4	0.0902
158	12.8	0.0809
190	14.2	0.0749
221	15.6	0.0704
253	16.9	0.067
284	18.2	0.0641
316	19.5	0.0616
347	20.8	0.06
379	22.3	0.0587
411	23.7	0.0577
442	25.2	0.0569
474	26.5	0.056
505	27.9	0.0552
537	29.3	0.0546
568	30.6	0.0539
600	32	0.0533

Table C2.5: Rheology of coal water slurry at 35^0C

Shear Rate (1/s)	Shear Stress (Pa)	Apparent Viscosity (Pa.s)
0	5.01	####
31.6	2.09	0.0662
63.2	2.74	0.0434
94.8	3.33	0.0351
126	3.86	0.0305
158	4.45	0.0282
190	4.99	0.0263
221	5.49	0.0248
253	5.97	0.0236
284	6.46	0.0227
316	7.03	0.0223
347	7.62	0.0219
379	8.2	0.0216
411	8.98	0.0219
442	9.55	0.0216
474	10	0.0212
505	10.6	0.021
537	11.2	0.0209
568	11.8	0.0208
600	12.5	0.0208

Table C2.6: Rheology of coal water slurry at 40^{0}C

Shear Rate (1/s)	Shear Stress (Pa)	Apparent Viscosity (Pa.s)
0	4.49	####
31.6	8.71	0.0662
63.2	11.1	0.0434
94.8	13	0.0351
126	14.8	0.0305
158	16.6	0.0282
190	18.3	0.0263
221	19.9	0.0248
253	21.3	0.0236
284	22.7	0.0227
316	24.1	0.0223
347	25.4	0.0219
379	26.7	0.0216
411	28.2	0.0219
442	29.8	0.0216
474	31.4	0.0212
505	32.8	0.021
537	34.4	0.0209
568	35.9	0.0208
600	37.4	0.0208

C3: Rheology of coal-water slurry at C_w = 60 % by weight.

Table C3.1: Rheology of coal water slurry at 15^0C

Shear Rate (1/s)	Shear Stress (Pa)	Apparent Viscosity (Pa.s)
0	11.488	####
31.7	27.2	0.858
63.2	38.6	0.611
94.8	49.2	0.519
126	58.5	0.463
158	67.9	0.43
190	77.1	0.407
221	86.3	0.39
253	95.3	0.377
284	104	0.366
316	112	0.356
347	120	0.345
379	127	0.336
411	135	0.328
442	142	0.322
474	149	0.315
505	157	0.31
537	164	0.305
568	171	0.301
600	177	0.296

Table C3.2: Rheology of coal water slurry at 20^{0}C

Shear Rate (1/s)	Shear Stress (Pa)	Apparent Viscosity (Pa.s)
0	10.985	####
31.7	24.2	0.763
63.2	34.3	0.543
94.8	43.6	0.46
126	52	0.411
158	59.5	0.377
190	66.8	0.353
221	74.4	0.336
253	81.7	0.323
284	88.7	0.312
316	95.9	0.303
347	103	0.296
379	110	0.289
411	117	0.284
442	123	0.279
474	130	0.274
505	136	0.27
537	142	0.265
568	148	0.261
600	154	0.257

Table C3.3: Rheology of coal water slurry at 25^{0}C

Shear Rate (1/s)	Shear Stress (Pa)	Apparent Viscosity (Pa.s)
0	10.918	####
31.6	23.5	0.742
63.2	33.5	0.529
94.8	42.9	0.453
126	51.1	0.405
158	58.4	0.37
190	65.9	0.348
221	72.5	0.328
253	78.8	0.312
284	85.1	0.299
316	91.3	0.289
347	97.6	0.281
379	104	0.273
411	110	0.267
442	116	0.262
474	121	0.256
505	127	0.251
537	132	0.247
568	138	0.243
600	143	0.238

Table C3.4: Rheology of coal water slurry at 30^{0}C

Shear Rate (1/s)	Shear Stress (Pa)	Apparent Viscosity (Pa.s)
0	10.55	####
31.7	22.4	0.707
63.2	32.3	0.511
94.8	41.7	0.439
126	50.7	0.401
158	58.5	0.37
190	65.5	0.345
221	71.8	0.325
253	77.9	0.308
284	83.8	0.295
316	89.6	0.284
347	95.3	0.274
379	101	0.265
411	106	0.258
442	112	0.253
474	117	0.247
505	122	0.242
537	128	0.237
568	132	0.232
600	136	0.227

Table C3.5: Rheology of coal water slurry at 35^{0}C

Shear Rate (1/s)	Shear Stress (Pa)	Apparent Viscosity (Pa.s)
0	9.5283	####
31.7	21.1	0.666
63.2	29	0.458
94.8	36.6	0.386
126	44	0.348
158	51.7	0.327
190	59.4	0.314
221	66.4	0.3
253	73.4	0.29
284	81.5	0.287
316	89.7	0.284
347	95.9	0.276
379	102	0.268
411	108	0.262
442	113	0.255
474	118	0.249
505	123	0.243
537	127	0.236
568	131	0.23
600	135	0.225

Table C3.6: Rheology of coal water slurry at 40^0C

Shear Rate (1/s)	Shear Stress (Pa)	Apparent Viscosity (Pa.s)
0	8.95	####
31.7	17.9	0.564
63.2	23.7	0.376
94.8	29.7	0.313
126	35.4	0.28
158	41.1	0.26
190	46.8	0.247
221	52.1	0.236
253	57.4	0.227
284	62.2	0.219
316	66.2	0.21
347	70.3	0.202
379	74.3	0.196
411	78.1	0.19
442	81.6	0.185
474	85.1	0.18
505	88.2	0.175
537	91.1	0.17
568	94.7	0.167
600	97.1	0.162