HYDRAULIC TRANSPORTATION OF ZINC SUSPENSION THROUGH PIPELINES

A Dissertation

Submitted in partial fulfillment of requirements for the degree

Master of Engineering

in

Thermal Engineering

By

Paras Verma

Registration No.: 801783010

Under the Supervision of

Dr. Kundan Lal
Assistant Professor
MED, T.I.E.T Patiala

Dr. Satish Kumar
Associate Professor
MED, NIT Jamshedpur

MECHANICAL ENGINEERING DEPARTMENT

THAPAR INSTITUTE OF ENGINEERING &TECHNOLOGY
PATIALA

Dedicated to my parents

&

Friends

CERTIFICATE

I hereby declare that the thesis entitled **"Hydraulic Transportation of Zinc suspension Through Pipelines"** is an authentic record of my work carried out as for the award of the degree of Master of Engineering in Thermal Engineering at Thapar Institute of Engineering and Technology, Patiala, Punjab under the supervision of **Dr. Kundan Lal,** Assistant Professor Mechanical Engineering Department, Thapar Institute of Engineering and Technology, Patiala and **Dr. Satish Kumar,** Associate Professor, Mechanical Engineering Department, NIT Jamshedpur.

The matter presented in thesis has not been submitted for the award of any other degree of this or any other university.

Paras Verma

Paras Verma

(801783010)

Date: 24.06.19

Place: Patiala

It is certified that the above statement made by the student is correct to the best of my/our knowledge and belief.

Dr. Kundan Lal
Mechanical Engineering Department
T.I.E.T, Patiala-147004

Dr. Satish Kumar
Mechanical Engineering Department
NIT, Jamshedpur-832109

ACKNOWLEDGEMENT

I am highly grateful to the authorities of Thapar Institute of Engineering and Technology, Patiala for providing this opportunity to carry out the thesis work.

I would like express a deep sense of gratitude and thank profusely to my thesis guide **Dr. Kundan Lal, Associate Professor, MED, T.I.E.T, Patiala** and **Dr. Satish Kumar, Associate Professor, NIT, Jamshedpur** for his sincere and invaluable guidance, suggestion and attitude which inspired me to submit thesis report in the present form.

I am also thankful to other faculty members of Mechanical Department, T.I.E.T, Patiala for their intellectual support. My special thanks are due to my family members and friends who constantly encouraged me to complete this study.

Paras Verma

PARAS VERMA

ABSTRACT

The present investigation was carried out to study the pressure drop characteristics of zinc tailing water slurry in 90˚ pipe bend. Zinc tailing sample was collected from Rampura Agucha mine situated in Rajasthan, India. Before the determination of pressure drop the physical characteristics of zinc tailing sample was determined by various bench scale tests. • It was observe from SEM micrograph that zinc tailing particles are non-spherical in shape and have knife edge structure. The specific gravity of the procured tailing sample was found as 2.87. The maximum static settled concentration of zinc tailing slurry was found as 52.61, 54.02, 61.99 and 65.62% for solid concentration of 25, 35, 45 and 55% respectively. The pH of slurry was lies within the range of 7-7.3. The rheological experiments were carried out to investigate the flow behaviour of zinc tailing water slurry for solid concentration range of 25-55% (by weight). It was found from results that slurry exhibits Newtonian flow behaviour for solid concentration range of 25-35%. Whereas, the increase in solid concentration from 35-55% results in change in flow behaviour to Bingham plastic flow nature. The addition of coarse particles 150-250 μm size results in appreciable decrease in apparent viscosity in fine (<53 μm) particulate slurry. The maximum percentage decrease in apparent viscosity was observed with 20% addition of coarse particles.

The pressure drop of slurry through pipe bend at high concentrations was determined using CFD technique. The geometry of pipe bends was varied by modifying the R/d ratio (1.0-3.0). The modeling results were validated with experimental data. The Standard k-ε model shows a most appropriate comparison with experimental results and hence used in the further investigation. The hexagonally shaped cooper type three-dimensional non-uniform grid was chosen to discretize the entire domain. The mesh was refined at the boundaries so as to achieve the y^+ value to 30. The contours of turbulence intensity, volume fraction and flow velocity were obtained at the various locations of bend geometry that have never been measured experimentally at such higher concentrations. The solid concentration was varied in the range of 25-55% for flow velocity range of 2-5 m/s. The pressure drop was found to be minimum for bend having R/d ratio 2.0 for low flow rates. For high flow rates pipe bend having R/d ratio 2.5 was optimum. From the results, it was observed that flow velocity dragged the solid particles from the bottom of the pipe along the outer periphery of bend wall.

KEY WORDS: Pressure drop, Zinc tailing, Pipe bend, CFD, Slurry, R/d ratio

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURES

Symbols	***Description***
C_W	Solid concentration (% by weight)
d	Diameter of solid phase
D	Pipe Diameter (mm)
g	Acceleration due to gravity (m^2/s)
K_b	Bend loss coefficient
S	Source terms
P	Pressure force
Q	Discharge (m^3/s)
r	Radius of curvature
Re	Reynolds number
$\vec{R}$	Interaction Force
V	Velocity (m/s)
$\vec{V}$	Terminal Velocity
W	Weight (grams)
Greek letters	
ϕ	Specularity coefficient
θ	Granular temperature
φ	Internal friction angle
λ	Bulk viscosity
μ	Shear viscosity
τ	Shear stress tensor
σ	Prandtl number
Abbreviations	
PSD	Particle size distribution
pH	Potential of Hydrogen
SEM	Scanning Electron Microscopy

Chapter 1
INTRODUCTION

Since the ancient time of civilization, mining industry plays important role in developing the social, industrial and economic development. Due to the rapid growth in the population, importance of mining industry increases suddenly over the last century. Nowadays mining industries contribute in many fields such as agriculture, transportation, construction, energy, health etc. With the increase in the demand of minerals depletion rate of high-grade minerals increased. This made the industries to develop finely disseminated low grade ore bodies.

Mining is considered as an endeavour of humankind. Although, if we consider fishing, lumbering and agriculture as one part, procuring and processing of oil and gas with mining similarly, then agriculture and mining are the primary source to fulfil all the basic needs of past and present civilization. From prehistoric time to present, mining industry plays crucial role in the advancement of human existence (Madigan1981). The term *mining* here is used for the extraction of naturally occurring mineral matters such as solids, (ores i.e. iron, aluminium, zinc, coal etc.) liquids, (petrochemical products such as gasoline) and gases (natural gas etc.) from the earth's crust or heavily bodies for utilitarian purposes.

There are only 1-2% valuable mineral is present in mineral ore. However, in exceptionally precious minerals like silver and gold, the presence of few grams per ton is also efficient. This means that a large amount of solid waste is left after processing of mineral ore. Slurry transportation is the method of conveying and processing the solid ore using pipelines. Water is the most commonly used carrier fluid in slurry preparation process. In recent years, the main focus of the researchers is to make the slurry transportations system more economic and efficient. By 1374, zinc was found in metallic form in India. From 12^{th} to 16^{th} century zinc metal was used for making brass and zinc oxide are used in medical purposes. Generally zinc ore is a mixture of copper, silver, gold, lead and other metals. Usually zinc ore contains 3-15% zinc. Ore containing higher percentage of hematite and magnetite called natural ore and it can be fed into blast furnace directly.

Mineral slurries are broadly categorised into two categories namely settling slurries and suspended slurries. The suspended slurries mainly consist for fine solid particles with high solid concentrations. Also, the rate of settling of fine particulate slurry is very slow. However, the slurry having coarse particle is termed as settling slurry. The rate of settling of coarser particles in solid liquid slurry is more than fine particle slurry.

1.1 MINERAL TAILING

Minerals are extracted from the earth's crust and from heavy rocks. Basically, minerals are founded in the form of different chemical compounds which is called ore. Tailings are the materials left after the extraction of valuable components from the ore. Mine tailings are usually produced in slurry form, which is the mixture of water and mineral particles. The deposit was originally an ore before experiencing a metamorphic event. 1 billion years ago, the high-grade metamorphic event is theorized to occur. There are a few sulphides and oxides present within the ore. Gahnite and rutile are the richest source of zinc ore. Tailings consist of ground rock and process effluents that are generated in mine processing plant. To extract the desired product from the mine ore mechanical and chemical process are used and the residual left behind is known as tailings. The extraction process is never 100% efficient. Then the uneconomic metals, minerals and process water are discharged in the form of slurry to the storage area which is known as Tailings storage facility (TSF).

1.2 TRANSPORTATION OF MINERAL TAILING

Tailings are conveyed to the storage area by different modes. Generally, tailings are transported through slurry pipelines. Mineral tailing properties and geographical locations play an important role in deciding the tailing disposal system.

The pipelines are generally used for slurry transportation. Centrifugal or positive displacement pumps are being to provide driving force to slurry. The gravitational slurry conveying systems are being used where the tailing disposal site is a lower elevation than processing plant. However, there is a need of chokes and drop boxes to prevent wear and high flow rates in pipelines. The other mode of transportation is with the help of channel as open concrete launder system. In this system the mineral tailing flows under the effect of gravity with a free surface. But this method is not appropriate for highly viscous tailing slurries.

1.2.1 Need of slurry pipeline

- As road and rail are expensive modes as well as these modes are already very much burdened. However, the roads and rail are also not capable for transporting fine tailings.
- It also causes environmental pollution as it contains sulphides. Tailings can only be transported through slurry pipelines.

- The cost of logistics is 12-13% approximately of GDP against 8-10% in developed world.
- As tailing cannot be transported directly, these can be transported in slurry form. So, slurry pipeline is one of the economical way of transportation.

1.2.2 Benefits of transportation of zinc-tailing through slurry pipeline

- It is environment friendly because bulk transportation of zinc tailing through slurry pipeline does not cause any noise, smoke and air pollution.
- This pipeline system of transporting tailing can be used for short as well as for long distances.
- Environmental conditions such as storm and inclement in weather has no effect on pipeline, tailing can be transported throughout the year.
- Transportation of ultrafine tailings requires special wagons, which can be easily avoided by slurry transportation mode.
- Due to its easy construction, low operational and maintenance cost make it very much effective as compare to the other mode of transport.

1.3 DESIGN PARAMETERS FOR THE OPTIMAL SLURRY CONVEYING SYSTEM

The efficiency and economy of slurry conveying system is site-sensitive. It is very hard to make generalizations for slurry pipeline system economics. However, the main parameter for comparing the slurry transport system with conventional modes of transport is the length. The pipelines often have a shorter route as compared to road and track routes. Also, the installation of pipelines is quite easier than a severe construction of road and railway tracks. Slurry pipelines are often laid in difficult and remote geographic areas. In mountains, it is very easy to install the pipeline a number of kilometers in a day by conventional construction techniques. It is quite simple and easy to maintain the slurry transportation system because the pipeline is buried and pumping stations are far apart. The slurry pipeline system becomes more competitive and significant among conventional transport modes because they are able to move more than million tons of solid products per year. Slurry pipelines are often laid in difficult and remote geographic areas. In mountains, it is very easy to install the pipeline a number of kilometers in a day by conventional construction techniques.

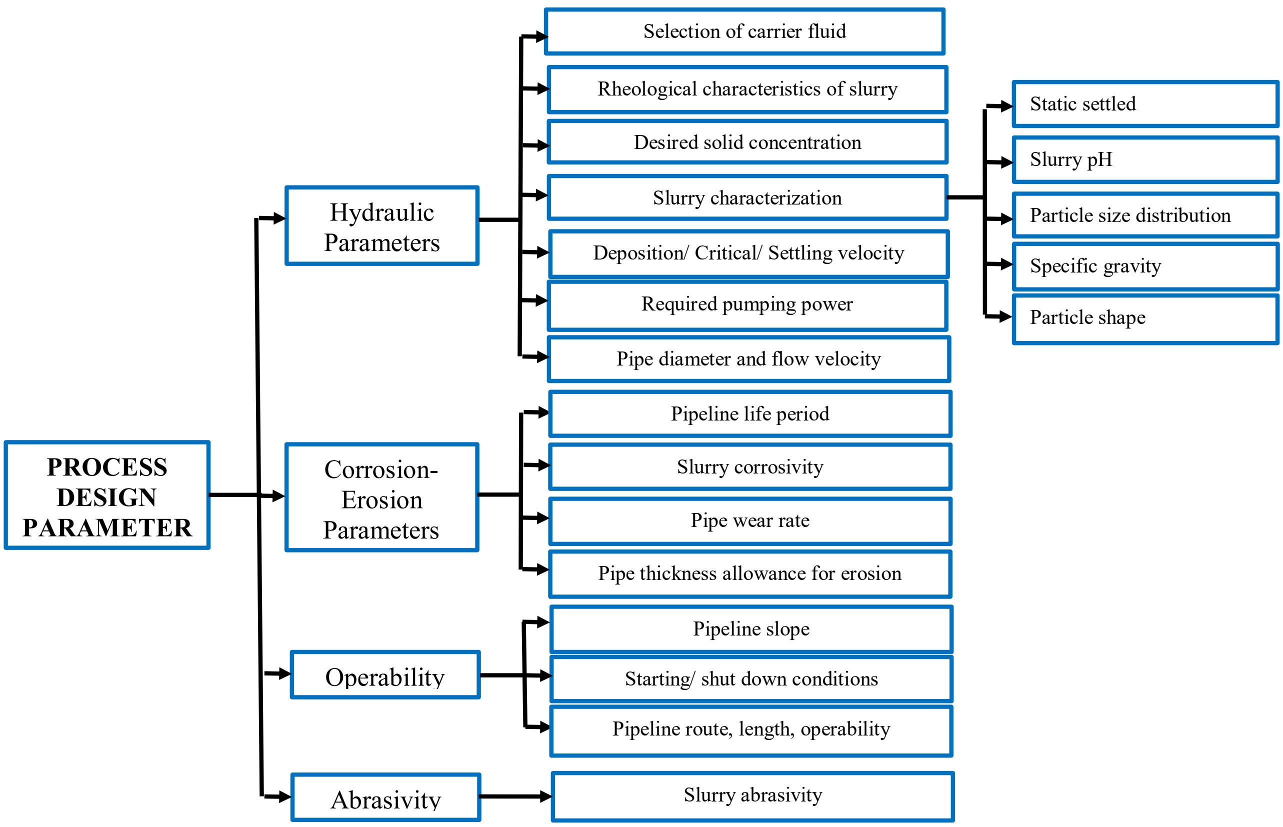

Figure 1.1: Process design parameter of a typical slurry transportation system

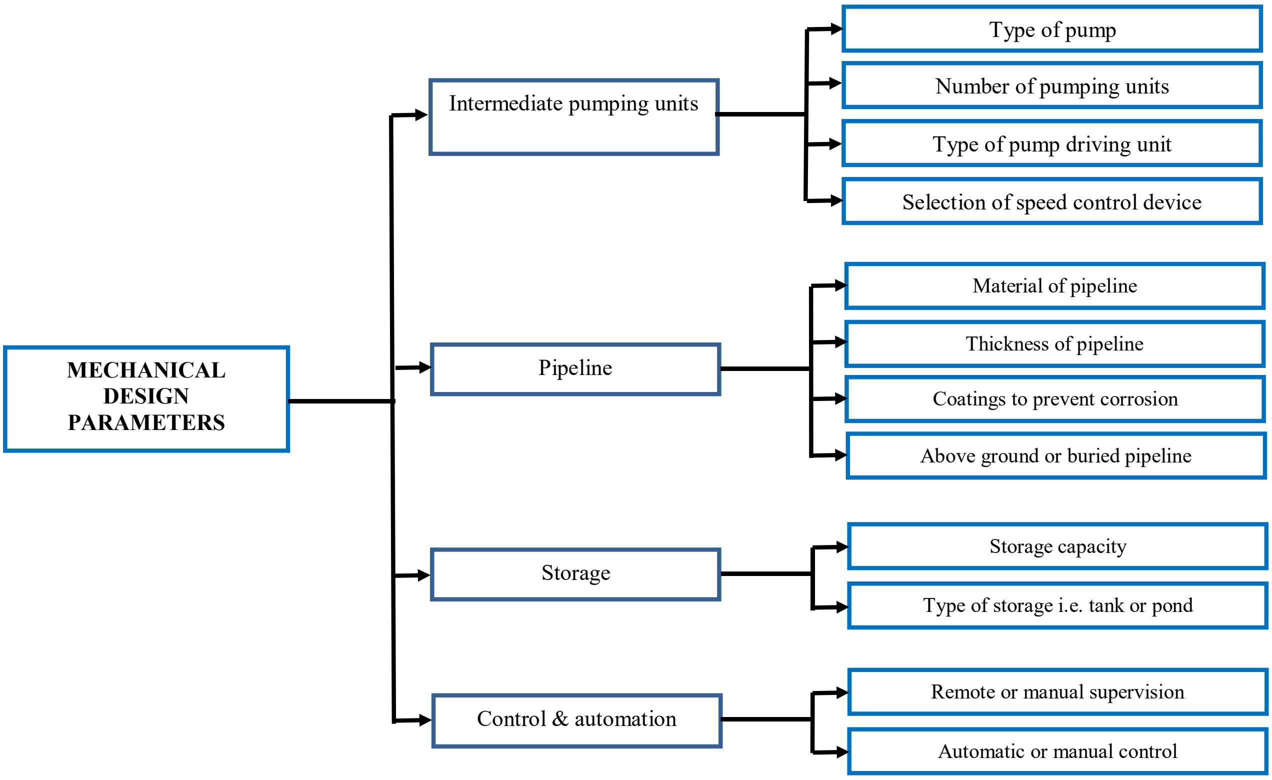

Figure 1.2: Mechanical design parameters for a typical slurry transportation system

Slurry pipelines are often laid in difficult and remote geographic areas. In mountains, it is very easy to install the pipeline a number of kilometers in a day by conventional construction techniques. It is quite simple and easy to maintain the slurry transportation system because the pipeline is buried and pumping stations are far apart. The slurry pipeline system becomes more competitive and significant among conventional transport modes because they are able to move more than million tons of solid products per year. The designing of slurry transportation systems is categorized into two design parameter namely process design and mechanical design. The process design parameter is further discretized into operability, abrasivity, erosion-corrosion, and hydraulic design as shown in Figure 1.1. On the other hand, the mechanical design parameter is classified into control-automation, pipeline design, storage, and pumping stations. The detailed overview of mechanical design parameters is illustrated in Figure 1.2.

The flow characteristics of all type of minerals and solid waste slurries are not possible to predict from available correlations. Therefore, the designing of a slurry pipeline is mainly based on the experimental data procured from pilot plant test loops and other lab scale testing results. In the present scenario, the minerals and solid wastes like coal, iron ore, zinc tailing, lead ore, coal ash etc. are transported at very lean solid concentrations of 5-20% (by weight). These attempts are resulted in consumption of large quantity of carrier fluid and energy. Hence, the whole system becomes inefficient as well as uneconomic. The technology of numerical simulation also provides great help in designing the slurry transportation system. The flow characteristics of different slurries have been studied by many researchers (Lin and Ebadian, 2007; Balakin et al. 2011; Gopala et al. 2011; Csizmadia and Hos, 2013) with the help of computational fluid dynamics (CFD) code. The post-processing part of CFD helps to make the virtual movie of all the designing parameters helpful for the design of efficient slurry transportation system.

1.4 STORAGE METHODS

The mineral tailings were disposed in down-stream flowing water. But this method has certain drawbacks like deposition of solid particles from slurry. Thus the use of tailing dams is come into play.

1.4.1 Tailings dams and ponds

Tailings in the slurry form are directly transported to the ponds through slurry pipeline system. The solid or refused waste left after the processing of the mineral ore is pumped through pipelines to tailing pond where deposition of mineral tailing takes place. These ponds are normally confiscated with a dam, which is called tailing dams. The main advantage of this storage system is that it prevents loss of fine tailings by heavy winds. These fine tailings contain toxic heavy metals that cause negative effect on human health.

1.4.2 Paste tailings

Paste tailings disposal technique is modification of tailings dam/pond system. In pond storage technique huge amount of water is used as compared to solid. During deposition phenomenon the solid phase settles down from water and seepage of water occurs. However, the percentage of solid phase in water is increased in paste tailing technique. This leads to decrease in consumption of water and the process of storage becomes more efficient and economic.

1.4.3 Dry stacking

Dry stacking also generally termed as filtered tailings. In this technique a dry cake of tailing is produced by high degree dewatering of tailing-water slurry. This type of tailing is not conveyed through pipeline because of very low moisture content. Therefore, the waste is mostly transported through belt conveying, wagons or trucks. A stable deposit without any storage infrastructure is produced in this type of mineral tailings storage system. The low moisture content of less than 20% is mainly achieved by using drum, stack plates and vacuum filters (Martin and Davies 2009). This type of tailing storage technique requires very low quantity of water. Thus dry stacking is more useful in dry areas where conservation of water is more critical.

1.5 MINERAL UTILIZATION

After Iron, aluminium and copper, zinc is 4th most consumed metal in world. Zinc is most commonly used as an anticorrosive agent. Nearly 50% of zinc production is consumed in zinc galvanizing. The process of covering the iron/steel materials with different layers so as to save them from rusting is known as galvanizing.

Another utilization of zinc is as alloy, the zinc is consolidated with copper and with different metals to shape materials that are utilized as a part of automobile, electrical parts, and household apparatuses. A third major utilization of zinc is in the generation of zinc oxide, which is utilized as a part of elastic assembling and as a protective skin ointment.

1.6 RHEOLOGY

Fluid is a substance which undergoes infinite deformation when force is applied on it. Rheology defined as the study of movement of matter, generally in aqueous state, or as 'soft solid' i.e. solid that undergoes plastic flow under the influence of realistic force and remained deformed under certain condition (Morrison, 2001; Antony N. Beris, 2014). In other words, it is defined as study of fluid behaviour under the influence of applied force. However, on fluid only normal compressible and shear stress can be applied whereas in rheology generally study of fluid behaviour is done under the influence of applied shear stress. Usually two plate model is used to study the behaviour of fluid. The schematic diagram of two plate model is shown in Figure 1.3.

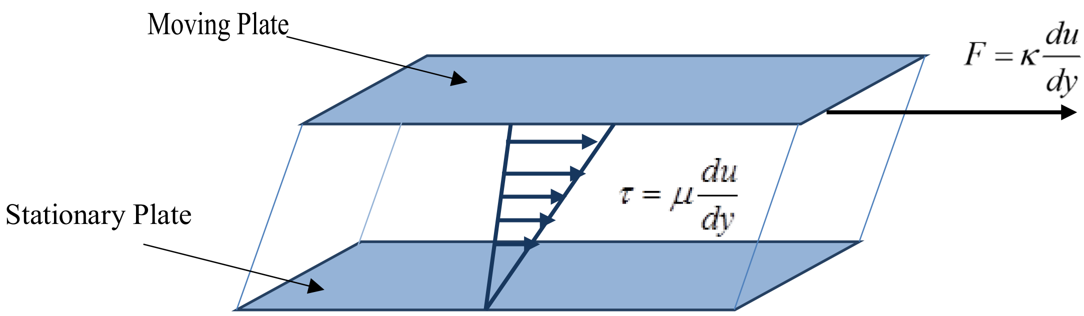

Figure 1.3: Parallel plate model of deformation of fluid under an applied force

Flow is defined as continuous irreversible deformation due to internal and external friction offered to the flowing matter. The property of matter that offers resistance to flow in a particular direction due to intermolecular interaction is known as viscosity. Under the impact of applied shear load, each layer of fluid would moves with different velocity depending distance from the plane of applied force. Shear strain is also known as velocity gradient which is perpendicular to the plane of applied stress. According to the Newton's law (Kissa, 1999),

$$\tau = \mu \frac{du}{dy} = \mu\gamma \qquad (1.1)$$

The fluid which obeys the Newton's law of viscosity is known as Newtonian fluids having constant viscosity (μ). However in non-Newtonian fluids, viscosity of fluid is function of flow parameters. The slope of plot between shear stress and shear rate indicate the type of fluid. As in case of Newtonian fluid, the slope of the graph is straight line whereas non-Newtonian fluid is further categorized based upon the shape of the curve reflects the category of the flow. The shapes of slope for different types non-Newtonian fluid is shown in Figure 1.4.

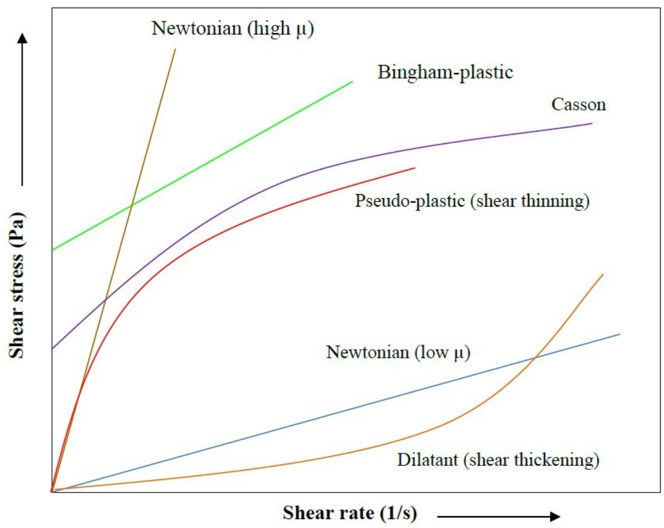

Figure 1.4: Rheograms of different fluid models

Table 1.1: Various rheological models with model equations

Type of non-Newtonian fluid	Model equation	No. of parameters relating shear stress and shear rate.
Bingham Law	$\tau = \tau_y + \mu\gamma$	Two parameter
Power-Law	$\tau = k\gamma^n$	Two parameter
HERSCHEL -Bulkley	$\tau = \tau_y + \mu\gamma^n$	Three parameter
Casson	$\tau^{1/2} = \tau_y^{1/2} + (\mu\gamma)^{1/2}$	Three parameter

Table 1.2: Classification of fluids

<table>
<tr><td rowspan="3">Newtonian fluids
$\tau = \mu \frac{du}{dy}$</td><td colspan="3">Non-Newtonian fluids
$\tau \neq \mu \frac{du}{dy}$</td></tr>
<tr><td colspan="2">Viscous fluids</td><td rowspan="2">Visco-elastic fluids</td></tr>
<tr><td>Time dependent</td><td>Time independent</td></tr>
<tr><td rowspan="3">• Fluids that obey Newton law of viscosity are Newtonian fluids.

• Water and air behaves like Newtonian fluids.</td><td>Thixotropic fluids
$\tau = \mu \left(\frac{du}{dy}\right)^n + f(t)$

• For thixotropic fluids n<1.
• Viscosity decreases with time.
• Examples: Enamels and inks.</td><td>Pseudo-plastic fluids
$\tau = \mu \left(\frac{du}{dy}\right)^n$

• For pseudo-plastic fluids n<1.
• Viscosity decreases with shear rate.
• Examples: Polymer solution, blood etc.</td><td rowspan="3">• Fluids that resist the applied force by viscous and elastic effect are known as visco-elastic fluids.

$\tau = \mu \frac{du}{dy} + \alpha E$

Where E is elasticity modulus.

• The example of visco-elastic fluids is polymerized fluids.</td></tr>
<tr><td rowspan="2">Rheopectic fluids
$\tau = \mu \left(\frac{du}{dy}\right)^n + f(t)$

• For thixotropic fluids n>1.
• Viscosity increases with time.
• Examples:Gypsum-water slurry.</td><td>Dilatant fluids
$\tau = \mu \left(\frac{du}{dy}\right)^n$

• For dilatant fluids n>1.
• Viscosity increases with shear rate.
• Examples: butter, sugar syrup etc.</td></tr>
<tr><td>Bingham plastic fluids

$\tau = \tau_0 + \mu \frac{du}{dy}$
• Examples: tooth paste, mud slurry etc.</td></tr>
</table>

1.6.1 Different rheological models

Rheology describes the trends of non-Newtonian fluid by determining the parameters required to develop relationship among the deformation rate and shear stress. The shape of curve reflects the category of the flow. In order to determine the various parameters, the different rheological models are used. The majorly used rheological models are listed in Table 1.1. Two parameter rheological models are widely used to study the fluid flow behaviour. As Bingham model is used to study the flow behaviour of petroleum drilling fluid and many different type muds whereas Power law is used study the rheology of soft solid such as coal and ash slurry. Casson model is used for visco-plastic fluids which have wide application to model the flow of blood. Similarly, Herschel-Bulkley is used to study the rheology of slurry formed by hard solids such as iron-ore but all of above-mentioned models have been found a good approximation for other fields like rheology of food product and polymer etc.

1.6.2 Importance of Rheology

- Rheology helps to estimate about mixability and pumpability of the slurry which helps in designing of iron-ore slurry transportation system.
- Rheology also helps evaluate the frictional pressure drop when slurry flows in pipes.
- Rheology evaluates the ability of slurry to transport the fine and large particles. It also studies the effect of surrounding temperature on the flow behaviour of suspension of iron.
- Rheological data is also very important to find relationship between the pump and flow in pipelines. It also helps us in selecting pump of enough power so as to transport slurry to the distance.
- Rheological data is primary raw data which is required for the computational analysis of slurry flow.

1.7 PRESSURE DROP

For designing of slurry transportation system, it is necessary to find out the pressure drop in pipe flow. In past years many researchers performed experiments to obtain correlations for the prediction of head loss in pipe line. The correlation developed depends on the rheological nature of slurry and experimental data of pressure using pilot test loops. But these correlations are applicable of certain size ranges with low solid concentrations. Therefore, it is beneficial to study the flow characteristics with the computational scheme resulting lowering the capital cost and time for study.

1.7.1 Losses in pipeline

The losses in the pipelines are mainly occurs due frictional loss and pipe fittings. These loss are named as major and minor losses.

Major losses:

The losses occur inside the pipeline due to friction are termed as major losses. The major losses in pipes are function of pipe length, flow velocity, diameter of pipe and friction factor. The friction factor is based on the type of flow inside pipeline i.e. laminar or turbulent and average roughness of pipe material. The most common mathematical equation used for the calculation of major head loss in pipelines is Darcy-Weisbach equation as written below:

$$h_f = \frac{flV^2}{2gD} \qquad (1.2)$$

Where, h_f =frictional head loss, f= friction factor, L=length, V=velocity, g= gravity, D=diameter.

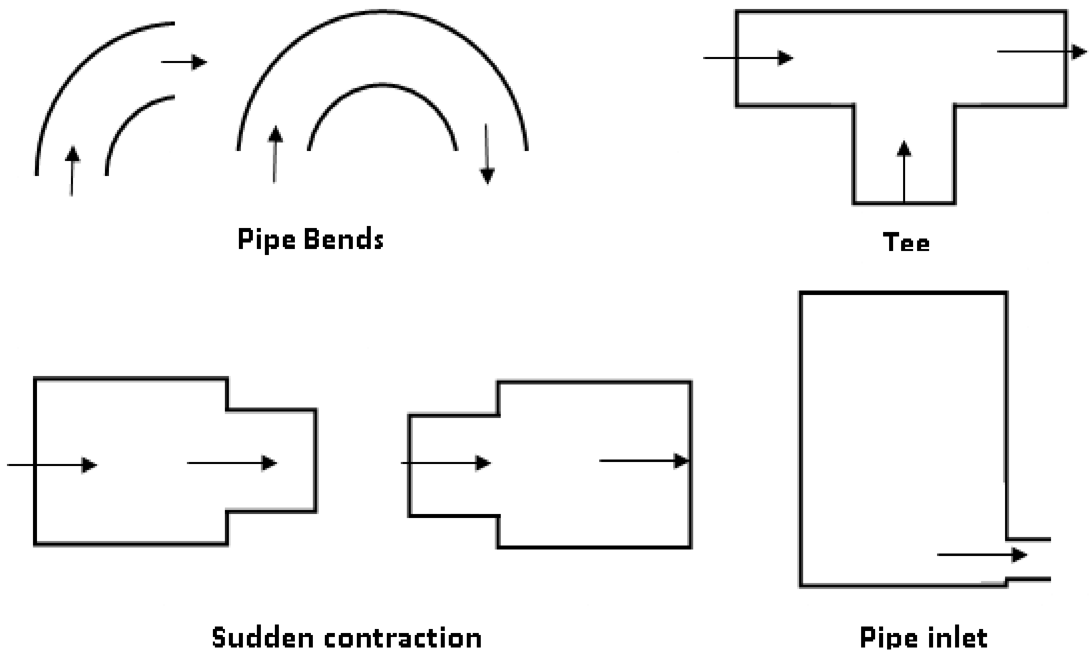

Figure 1.5: Various pipe fittings in pipeline system

Minor losses:

The pipeline circuit consists of considerably more number of fittings rather than straight pipe. Figure 1.5 shows the some common fittings used in pipeline system. These additional pipe fittings in pipeline system add to overall pressure drop in the whole system. The loss occurs due to pipe fitting is known as minor losses. In long pipelines or slurry conveying systems the losses occurs due to friction i.e. major losses are more as compared to minor losses. The minor losses occurs due to:

- Sudden contraction and expansion
- Pipe exit and entrance
- Tees, elbows, bends and other fittings
- Valves
- Gradual expansion and contraction

Table 1.3: Various types of losses

Sudden expansion	$h_e = \frac{(V_1 - V_2)^2}{2g}$
Sudden contraction	$h_c = 0.5\frac{V_2^2}{2g}$
Pipe inlet	$h_i = 0.5\frac{V^2}{2g}$
Pipe exit	$h_o = \frac{V^2}{2g}$
Bend	$h_b = \frac{KV^2}{2g}$
Valves	$\frac{KV^2}{2g}$

Chapter 2
LITERATURE REVIEW

A lot of research work is carried out in the past on the rheology of slurry suspension by many researchers, which sets roots and base for advance work in this investigation. This acts as a guideline for this thesis and give better understanding of the topic. Factors that affects the rheology of minerals have been inspected by many researchers and an optimum value for slurry transportation with viscosity in a specific shear rate has been found. The main emphasis of the following study is on the mineral slurries and its applications in several areas. In this study, earlier to the research work, a widespread review of the published works in mineral rheology field with factors like particle shape, size, its properties, temperature, pH, chemical additives etc were taken. The rheology of minerals and their characterization has received attention in recent years because of widespread application in industry and academic interest.
The transportation of bulk materials through pipelines is a developing technology in many countries. Now-a-days, the solid materials can be transported through pipelines at higher as well as lean concentration. There are many advantages of conveying these dense mixtures through pipelines as this system requires lesser space, low manpower and is environment-friendly. A typical hydraulic conveying system consists of pipeline circuit, a heavy-duty pump, and other devices like pressure transducers, flow meters, data acquisition system etc.

Kwak et al. (2005) studied the effect of concentration on flow behaviour and depositional geometry of tailings. Flume apparatus was used to simulate the deposition of the paste. They observed that the residual stress which was obtained from a stress profile (time) was not a suitable measure of yield stress. They also found that stress (measured at the transition between the viscoelastic and elastic region) along with the maximum stress are suitable measures due to independency of the vane size used in rheometer.

Yuchi et al. (2005) studied the multivariate regression analysis for sixteen samples acquired from different mines of China with various ranks of coal vary between Lignite to Anthracite to find the correlations between eighteen different parameters from forty coal properties. They concluded that the grindability index and carbon content of coal shows positive relation with the slurry ability on the other hand the moisture present in the air at equilibrium and surface area found by mercury porosimeter results in negative impact. The rheological behaviour of coal water slurry related positively with ash content, soluble ions and volume of pore examined by mercury porosimeter.

Verma et al. (2006) examined characteristics of pressure drop of fly ash slurry at higher concentration along a 90° horizontal bend. They compute the bend loss coefficient and relative pressure drop for slurry concentration ranging from 50 to 65% (by weight), particle size ranging from 300 µm to 3 µm. A huge number of particles i.e. 84.4% were less than 75 µm. The pilot test loop plant used for experimentation was having a pipe diameter of 53 mm with a length of 30 m with radius ratio of 5.6. They concluded that relative pressure drop first increased as there was increase in slurry velocity as well as reached to a constant value at higher velocities but there was decrease in bend loss coefficient as there was increase in slurry velocity.

Chen et al. (2009) studied about the flow characteristic of coal water slurry in straight pipeline using CFD. They used Eulerian multiphase approach with RNG k-ε turbulent model to evaluate the coal water slurry flow. They validated the numerical simulation model for the pressure drop data with previous studies available in literature. They investigated the effect of influx velocity and grain composition on pressure drop characteristics. They performed the experimentation on pilot plant test loop to evaluate the slurry flow characteristics inside different horizontal pipes. Results show that numerically simulated data hold good agreement with experimental data.

Eesa et al. (2009) investigated the slurry flow characteristics of coarser particulate slurry in pipeline by using Computational Fluid Dynamics (CFD) code ANSYS CFX with the help of Eulerian model to study the flow of coarser particles inside the pipe. The positron emission technique was used for tracking solid particles and particles in motion. They also studied the flow properties under the influence of slurry velocity, Particle size and efflux concentration. The concentration of particles varied from range of 5 to 40% (by volume) having mean particle size of 2 to 9 mm with the slurry velocity of 25 to 125 mms^{-1}. They found that that with the exception of smaller particles, they exhibited asymmetric velocity profile tending to increase with increasing particle size as well as increase in head loss was noticed due to increase in solid concentration.

Senapati et al. (2009) performed experiments to find out the rheological characteristics of lime-water slurry at different particle size, Slurry temperature and concentration (by volume). They concluded that the shear stress is a direct function of shear rate and for concentration below 30% by weight it behaves as almost Newtonian fluid elsewhere which slurry was highly pseudoplastic in nature. They also found that the viscosity of limestone mineral slurry decreases with temperature and the change can be defined by Arrhenius equation in terms of required activation energy.

Zhou et al. (2010) experiments were performed to study on the concentrated suspension of coal water slurry to examine the rheological characteristics. Firstly, they prepared slurry from coal using Haake rheometer and performed a regression analysis on experimental data to fit different rheological models. They found that at solid concentration 60 and 70% (by weight) the aqueous suspension coal-water exhibit pseudoplastic behaviour. Also, the experimental data found to be well fitted with two variable rheological model Herschel-Bulkely.

Lei et al. (2010) investigated the effect of additive for restart purpose of slurry pipeline after a shutdown of more than 24-hour. Their aim was to find the appropriate stabilizing agent for fly ash water slurry for the prevention of sedimentation. Suitability of four different additives were examined with the help of rheological and sedimentation stability experiments. Stabilizing additives labouring for the study were carboxymethyl cellulose (CMC), rhamsan gums (S-194, S-130), and xantham gum (Vanzan). As a result there was an increase in viscosity as the additives were added but the concentration of 0.2, 0.45 and 0.3% (by weight) had same viscosities as that of untreated fly ash slurry for additive S-194, S-130, CMC and Vanzan respectively. Naphthalene sulfonate-formaldehyde condensate (NSF) was used as a dispersing additive for reduction of viscosity and concentration of NSF was kept 0.3% (by weight). The rheological characteristics were measured using coaxial rotating cylinder rheometer. They found that S-194 was having the maximum stability as compared to others.

Hossain et al. (2011) examined the flow behaviour of solid particles in a straight horizontal pipeline of four bends. Numerical simulations were carried out with the help of commercial CFD code FLUENT 6.2. They solved the multiphase phenomenon for the flow of different solids with varying particle size diameters. Mixture model was used to solve the governing equations. Results show that particle deposition is a function of particle diameter and flow velocity. It was also observed that deposition occurs along the circumference of the pipe. High magnitude of solid concentration was observed at bottom of pipeline near the bend upstream and at 60° from the bottom of pipeline for bend downstream.

Buranasrisak et al. (2012) examined the impacts of distribution of particles and packing qualities on the rheological behaviour of coal-water slurry. A sub-bituminous coal of Indonesian origin was used to set up the experiment. The examples were grouped into six particle size ranges < 38, 38-63, 63-75, 75-90, 90-180 and 180-250 μm. Naphthalene Sulfonate formaldehyde (NSF) and carboxymethyl cellulose (CMC-Na) were used as the dispersive agent and stabilizer respectively. The viscosities of coal water slurries were measured using MV-2000 arrangement II Rotary Viscometer at different solidconcentration between 60 to 65 % by weight. The different packing properties of the coal specimens were characterized by making monomodal, bimodal and multimodal appropriations at different course to fine proportions. They observed that most extreme coal stacking was conceivable when coal water slurry was produced.

Mazumder et al. (2012) examined the effect of elbow ratio on pressure drop characteristics with the help of CFD. With the help of 90° elbow the numerical simulations were performed on the air-water flow. The diameter of the elbow pipe was taken as 12.7 and 6.35 mm. The radius ratio of the elbow was varied from 1.5-3 with velocity of air varying from 15.24-45.72 m/s and for water was 0.1-10 m/s. The hexahedral method was used for discretization. The results showed a close agreement with the experimental and empirical results those were intended by using Chisholam and Azzi-Friedel model.

Nabil et al. (2013) achieved a numerical simulation study of solid-liquid slurry flow in a pipeline. They used CFD code FLUENT to simulate the slurry flow by employing Eulerian-Eulerian scheme and k-ε model. They used square pipeline of dimension 26.8×26.8 mm. The pipeline mesh was discretized by using tetrahedral method. They used different particle size diameter (0.2, 0.7 and 1.4 mm) of water-sand slurry with solid concentration ranges of 5-30% (by volume) flowing at different velocities ranges 0.5–5 m/s. Governing equations were discretized by utilizing first order upwind approach to solve the turbulent kinetic energy, momentum equation, volume fraction, and turbulent dissipation rate. Numerical simulated results were very close to the experimental data for medium and coarse slurry flow at low concentration (5-10%) and fails for the flow of coarser slurry at higher concentration.

Gheshlaghi et al. (2013) numerical study was performed by using two-phase Eulerian approach and k-ε turbulence scheme through combining the population balance models at steady-state. They designed a CFD code for settled-bed of tailing thickeners having a thickness of 120 m diameter. They found that massive increase of turbulence results in breakage of particle-aggregate and reduces the torque range of the tailing thickeners.

Vieira and Peres (2013) studied the effect of regrinding of iron-ore concentrate on dispersion along with rheological characteristics of slurry. The tests for regrinding were performed under various pH value i.e. 7.3, 8.5 and 10.0 of dispersion along with addition of lime at concentration of 300g/t. As the Ph varies from 7.3 to 10.0 the degree of slurry dispersion increases, However the values of apparent viscosity and yield stress noticed to be lower as well as the specific energy consumption reduced by 17.4%.

Trahana et al. (2014) invesigated the effect of head loss and particle sphericity experiments were performed on air-rock bed thermal energy storage system. The head loss characteristics of packed bed thermal energy storage system were investigated by selecting irregular shaped solid particles and keep the ratio of tank to the diameter of particle constant that is 10.4. With the help of experimental data they derived an empirical relation to find the pressure losses in bed of irregular shape particles.

Panda et al. (2014) numerically investigated the pressure drop characteristics for the coal-ash slurry flow through 90° pipe bend. The ratio of fly ash and bottom ash was maintained as 6:4, 8:2 the additive was also introduced in bottom ash slurry which was maintained at 4 and 6%. The flow velocity was varied from 1.5-3 m/s and the solid concentration of slurry was varied from 20-50%. It was observed that as the flow velocity and concentration were increased there was an increase in the pressure drop. The mixing of additives was having more effect on the head loss when compared with addition of bottom ash in fly ash slurry flow.

Hashemi et al. (2014) investigated the solid velocity and concentration profiles for concentrated sand-water slurry in horizontal pipeline. The particle size and solid concentration was taken as (d_{50}) of 100 μm and 20-35% (by volume) respectively. The flow velocity was varied in the range of 2-5 m/s flowing through a 52mm diameter pipe. The concentration of the solid was greater at the boundary and increases with flow velocity. The variations in concentration were largely due to particle-fluid interactions as compared to fluid-fluid or particle-particle interactions. They compared the concentration fluctuations with results collected for fluidized bed flows on basis of stokes number.

Slatter et al. (2015) studied the rheological behaviour of different types of tailings (coarse and fine). They added two different types of flocculants in slurries during the experiments. They concluded that from the sample B (fine slurry), the rheological behaviour was essentially very similar for both the flocculants. On the other hand, the sample A (coarse slurry) was sensitive to both the flocculants. Hence, this material showed evidence of structural rebuild of polymeric agglomerates.

Assefa and Kaushal et al. (2015) examined the rheological behavior of coal ash slurry at high concentration ranges from 50-70% (by weight). They selected a model from experimental results by considering viscosity as dependent variable whereas solid volume fraction, mean particle diameter and coefficient of uniformity as independent variable and for optimization nonlinear least square method was used. Regression analysis on experimental data was performed by using an empirical rheological model for viscosity as a function of solid volume fraction, mean particle diameter and coefficient of uniformity and optimized. They found that the proposed model shows close agreement with experimental data and able to predicted viscosity of multi-sized Bingham slurries at higher concentration.

Singh et al. (2016) studied the rheological properties of the slurry with the help of blended coal samples with the mixture of fine and coarse particles, as then they created a bimodal particle-size distribution and they concluded that as the quantity of coarser particles was increased then the slurry viscosity was decreased continuously until on optimum ratio of coarse to fine particles. Hence, they concluded that the optimum fraction was 30% up to which point the apparent viscosity decreases.

Chen et al. (2017) numerically studied the backfill pipeline transport model (three-dimensional) was developed with the help of computational fluid dynamics (CFD) technique, which was used to study the pipeline transport possessions and they concluded that TFSB (three phase foam slurry backfill) can uphold a steady state during pipeline transport.

Mishra et al. (2017) numerically investigated the flow characteristics of coal and copper-ore slurry flow through pipeline. The model used was 3-D ASM along with RNG k-$\boldsymbol{\varepsilon}$ turbulence model for study of coal and copper-ore slurry flow. The particle size was varied for both coal and copper ore from 70.5-275.5 μm and 40.1-278.5 μm respectively. The specific gravity of coal was 1.98 whereas specific gravity of copper ore was 2.84 with volume fraction of slurry varying from 0.08 to 0.19. For copper-ore slurry flow of coarse particle size i.e. 275.7 μm the pressure drop was maximum but for coal slurry it was for 70.5 μm. The pressure was having an increasing trend with volume fraction loading.

Kumar et al. (2017b) performed the experimentation and computational investigation on iron ore slurry on horizontal pipeline and reported that Computational methods were used to predict the head loss and flow behaviour of multiphase flow. They performed study on 12 μm particle sized iron-ore slurry flow through 105 mm pipe with flow velocity range 1.35-5.11 m/s and concentration from 2.63%-31%. RNG k-ω turbulence model was used to find out the head loss and turbulent quantities. Head loss per metre and local solid concentration across pipe cross-section at outlet have been presented along with *CFD* validation.

Li et al. (2017) investigated the chemical composition and thermal behaviour of tailing and soil. The DTPA-available content of Pb and Zn were calculated as 6.16 and 10.61 respectively. The chemical composition, Phase composition, thermal behaviour of the lead-zinc tailing tailing and contaminated soil were investigated by XRF, XRD, FTIR and TGA-DSC. They found that the contents of Zn and Pb were 0.191 wt.% and 0.044 wt.% respectively, while for the lead-zinc tailing these were 0.190 wt.% and 0.031 wt.% for contaminated soil.

Nayak et al. (2017) investigated the thermo-fluidic behaviour of fly ash slurry through 180° return pipe bend. The slurry concentration was changed with in the range of 10 to 50% with velocity ranging from 1 to 5 m/s. Particle size of fly ash was taken as 13 μm. It was noted that as the flow velocity and particle volume concentration increases the head loss through the pipeline also increases as well as they found that as the radius ratio decreases from 5.6 to 2.98 the pressure drop changed from 14 to 83% for change in concentration from 10 to 50%. The concentration profile depicted the formation of secondary flows at the inner side of pipe bend which starts at an angle of 45° and increased up to 180°.

Merrill et al. (2017) performed a feasibility-study on hyperspectral characterization to estimate rheological properties of mineral suspensions. They performed a set of rheology tests for slurries having different compositions. They combined three minerals (from five minerals) and observed that bentonite suspension viscosity (15% vol.) decreases by addition of bentonite from another source.

Tebowei et al. (2017) numerically investigated the flow characteristics of sand slurry flow through V-inclined bend. They used two fluid Eulerian-Eulerian model. The K-ε turbulence model was used for the turbulence study of the flow. They calculated the results for slurry flow at 10D, 2.5D and 15D away from pipe dip for both upstream and downstream flow. They found that the correlations used for predicting minimum sand transport were not valid for V-inclined bends. They found that for efficient pipeline design the critical mass transport equation should be used for study of slurry and to enable unhindered slurry flow through bend sections.

2.1 MOTIVATION BEHIND THE PRESENT STUDY

The transportation of mineral slurries through pipeline is accomplished by planning slurry transportation components that advances economic transport with a minimum pressure drop. At low concentration, slurry behaves Newtonian and the flow in the pipelines keeps up a consistent consistency at the different shear rate. Likewise, in mineral slurry, highly concentrated slurry is needed in atomized structure that is subjected to high shear rates. These highly concentrated slurry normally shows non-Newtonian flow behaviour with viscosities fluctuating with the rate of shear. Along these, before planning a slurry transportation framework, it is of principal significance to focus the rheological behaviour of mineral slurries to know the different parameters like the viscosity at different concentrations, flow behaviour, the pressure drop etc. The present study is directed to create broad rheological information and focus the mineral slurry rheological behaviour that best describe the mineral specimens at different solid concentration, particle size distribution, and mineral fines.

2.2 GAPS IN LITERATURE

Based on literature review, following gaps in knowledge on the flow characteristics of the Zinc tailing slurry suspension is observed.

- Due to incomplete understanding of complex solid-liquid flow phenomenon in the pipeline and limited data base, there is no well-established method available to predict the pressure drop in the pipeline for the flow of solid-liquid mixtures at different concentrations.

- The empirical correlations developed experimentally for the prediction of the pressure drop are applicable to the particular slurry and cannot predict reasonable pressure drop with the same slurry collected from different locations and other type of slurries.
- Limited investigations have been carried out to establish the effect of higher concentration of slurry on the different energy losses in the pipeline.

2.3 OBJECTIVES

Limitations of the available experimental and numerical data have motivated to undertake the present study. Here are the objectives of the present study:

- To investigate the physical and chemical properties of zinc tailing slurry suspension.
- To investigate the rheological characteristics of zinc tailing slurry
- To investigate the pressure drop characteristics of zinc tailing slurry suspension in pipe bend at high concentrations using CFD.

Chapter 3

PHYSICAL AND CHEMICAL CHARACTERIZATION OF ZINC TAILING

The hydraulic characteristics of slurry are function of various geometric and dynamic parameters. The designing of the slurry transportation system is directly or indirectly depends upon these parameters. From the extensive literature review carried out in the previous chapter it is observed that very few studies were carried out to study the flow characteristics of zinc tailing-water slurry. Therefore it is very important to establish a database so that the designing of pipeline system become easier and fast. Large amount of solid waste in form of mineral tailing in being generated after the processing of minerals from mineral ore. This waste is disposed off to the tailing dams at very low solid concentration. This leads to consumption of large amount of water and pumping cost is also increased. In previous chapter it is revealed that flow of two phase slurry is influenced by different parameters like particle size, specific gravity of solid, type of carrier fluid, slurry pH, chemical composition and static settled concentration. In this chapter the detailed investigation to examine the chemical and physical characteristics of zinc tailing slurry suspension by using different bench scale tests is carried out.

3.1 SAMPLE COLLECTION

The zinc tailing sample was procured from the tailing dam of Rampura Agucha mine, Rajasthan, India. Figure 3.1 represents the geographical view of Rampura Agucha mine.

Figure 3.1:Geographical view of Rampura Agucha mine, Rajasthan, India

3.2 PARTICLE SIZE DISTRIBUTION (PSD)

In order to obtain, the variation of particle size in zinc tailing sample the particle size distribution was carried out. Initially, the inhered moisture from sample was removed with the help of oven so as to break the agglomeration of solid particles. The sample was placed in an oven at 120°C temperature for one hour. A motorized table top sieve shaker was used for sieving with sieves size of 1000, 710, 500, 355, 250, 150, 106, 75 and 53 µm, as shown in Figure 3.2.

Figure 3.2: Photographic view of mechanical sieve shaker

A known weight of sample was passed over series British standard sieves. The sieve shaker was run for 30 minutes so that exact particle size distribution was obtained. After 30 minutes the sample weight which was retained on the sieve (each) and bottom pan was measured by using weighing machine. The results obtained after sieving is listed in Table 3.1. It was observed from results that collected zinc tailing sample in very fine in nature. All the particles in zinc tailing sample were finer than 300 µm size. It was found that 14.5% particles were less than 53 µm. Whereas 3.9, 5.4, 16.6, 29.7 and 29.9% were lie in the range of 250-300, 150-250, 106-150, 75-106, 53-75 µm respectively.

Table 3.1: Particle size distribution

Sieve size (µm)	Mesh size (mm)	Fraction (gm)	Cumulative weight % (under)
<53	0.053	14.5	14.5
53-75	0.075	29.9	44.4
75-106	0.106	29.7	74.1
106-150	0.15	16.6	90.7
150-250	0.25	5.4	96.1
250-300	0.3	3.9	100

3.3 SURFACE MORPHOLOGY AND CHEMICAL COMPOSITION

SEM/EDS method is used to study the surface and chemical characteristics of materials. Both of the analysis are done on the same equipment as SEM equipment is equipped with an EDS. With the help of this method we can obtain analytical results of coarse or fine particles. It is also used for the chemical analysis of collected sample. SEM micrographs are mainly used to study the surface characteristics of the specimen. One can easily interpret the micrographs which are obtained from the SEM. The instrument used for testing was SEM-JSM-6510LV JEOL. In this technique highly energetic and accelerated electron beam is made incident on the sample to be analysed. These energetic electrons then interact with the atoms and produce variety of emissions which are detected by sensors. On the other hand, EDS analysis sensor is used to differentiate the energy spectrum and preinstalled EDS software is used to analyse and to find out the elements which are present in sample. The EDS spectrum gives the composition of the several elements and compounds which are present in the sample.

SEM and EDS are commonly used to study the surface morphology and chemical characteristics to realize the elements present in the sample. In SEM analysis high resolution images are produced that is because of narrow electron beam which results in 3-D appearance which is very helpful in configuring out the surface analysis of the sample. The SEM images of the zinc tailing sample is shown in Figure 3.3. From the SEM images it was noticed that all the particles were irregular in shape. The solid particles have knife edge structure. It was also seen that number of fine particles were more as compared to coarser. The irregularity and knife edged shape of solid particles results in decreased drag forces during the transportation of slurry in pipelines.

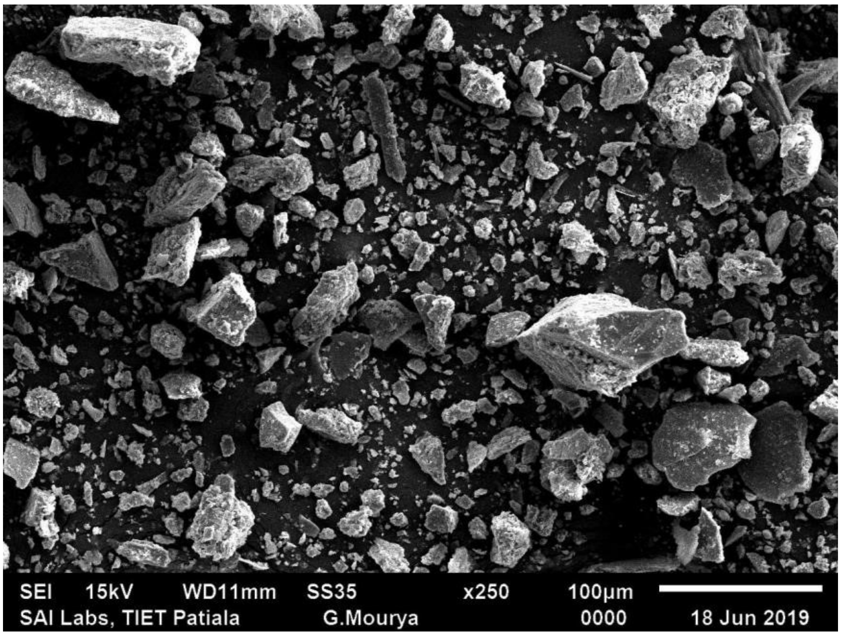

Figure 3.3: SEM micrograph of zinc tailing

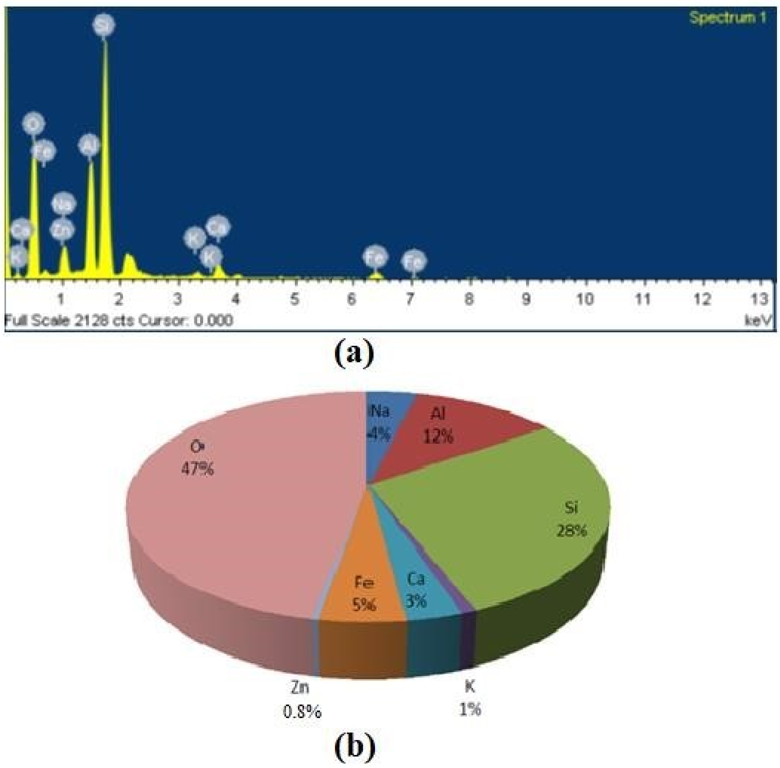

Figure 3.4: (a) EDS spectrum of zinc tailing (b) Elemental composition of zinc tailing

Figure 3.4 represents the EDS spectrum and elemental composition of the zinc tailing sample. From results it was observed that alumina and silica is present in major proportion as compared to the other elements. The oxygen is present in the oxide form. Whereas iron, calcium and sodium was present in minor proportion. The iron, calcium, sodium, oxygen and aluminium was found as 5, 3, 4, 47 and12% respectively.

3.4 POTENTIAL OF HYDROGEN (pH) OF SLURRY

The pH test was used to study about the aqueous solution of the slurry whether the slurry is acidic or alkaline in nature. The pH in chemistry is the negative log of the hydrogen ions in a solution. The pH value 7 is for pure water, called as neutral solution. Aqueous solution with a pH value less than 7 and greater than 7 are said to be acidic and alkaline in nature respectively. The pH was measured with the help of a digital pH meter as shown in Figure 3.5.

Figure 3.5: Photographic view of digital pH meter

Initially, with the help of buffer solutions the pH meter was calibrated. The buffer solution of pH 4 and 8 was prepared by mixing the buffer capsule in 100 ml demineralized water. After calibration the pH testing of the slurry at different concentrations was done. The pH value of the slurry was determined for solid concentration range of 25-55% concentration (by weight). The variation in the pH value of zinc tailing slurry with solid concentration is represented in Figure 3.6. From results it was observed that the solid concentration has very little impact on pH of slurry. The increase in solid concentration results in very small increase in pH value.

The pH value of solid concentration range of 25-55% lies within the range of 6.99-7.30. It was observed from results that zinc slurry is alkaline in nature.

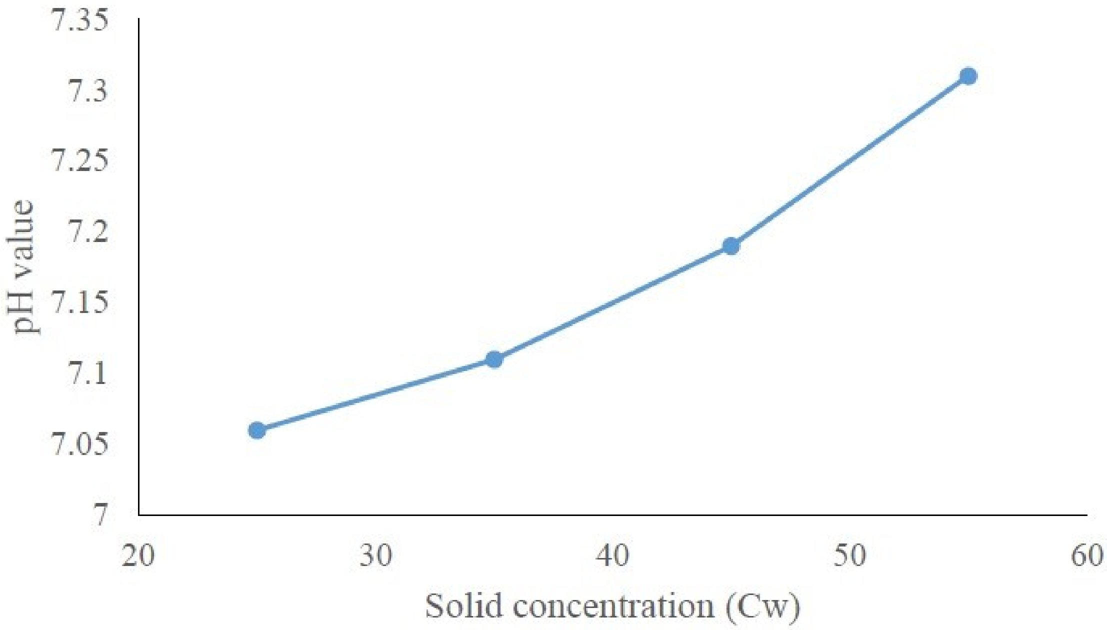

Figure 3.6: Variation of pH with solid concentration

3.5 SPECIFIC GRAVITY

Specific gravity is the ratio of density of a substance to the density of a reference substance. The reference substance in most of the cases is always water (at 4° C) but for gases it is air at room temperature i.e. (20° C). The density of water always varies with pressure and temperature as does the density of the sample. So, it is mandatory to specify the temperature and pressure at which the weights were determined. The specific gravity of Zinc tailing sample was determined with the help of pycnometer approach. Determination of specific gravity helps in calculation of other properties including degree of saturation and void ratio. The specific gravity of zinc tailing sample was calculated with the help of following equation.

$$\text{Specific Gravity } (\sigma) = \frac{(W_{CS} - W_B)}{(W_{CW} - W_{CSW}) + (W_{CS} - W_B)} \quad \text{...........................(3.1)}$$

Where W_C = Weight of measuring cylinder (gram), W_{CS} = Weight of flask and solid (gram), W_{CW} = Weight of flask with water (gram) and W_{CSW} = Weight of flask with solid and water (gram). The specific gravity of the sample is found to be 2.87.

3.6 MAXIMUM STATIC SETTLED CONCENTRATION

It is defined as the measure of the maximum possible static settled concentration of suspension. The static settled concentration of slurry was obtained by placing the slurry undisturbed for specific time range of 20-40 hours. It is denoted by C_w^{max}, it is also a function of specific gravity of the material along with the solid concentration of the suspension. For economical design of slurry pipeline it is necessary to study the C_w^{max} value. In present study, gravitational method was used to calculate the maximum value of the static settled concentration of zinc tailing water slurry. The specific energy consumption increases as the solid concentration reaches to maximum value of sttled concentration. For this, the slurry was prepared ranging from 25-55% was (by weight) and was allowed to settle down in measuring cylinder till there was no further settling. C_w^{max} was computed with the help of following relation as given below.

$$C_w^{max} = \frac{w_s}{w_l + w_s} \qquad \text{……………………………………………(3.2)}$$

Where, W_s denotes the weight of the solid in settled mass, W_l denotes weight of water in the settled mass.

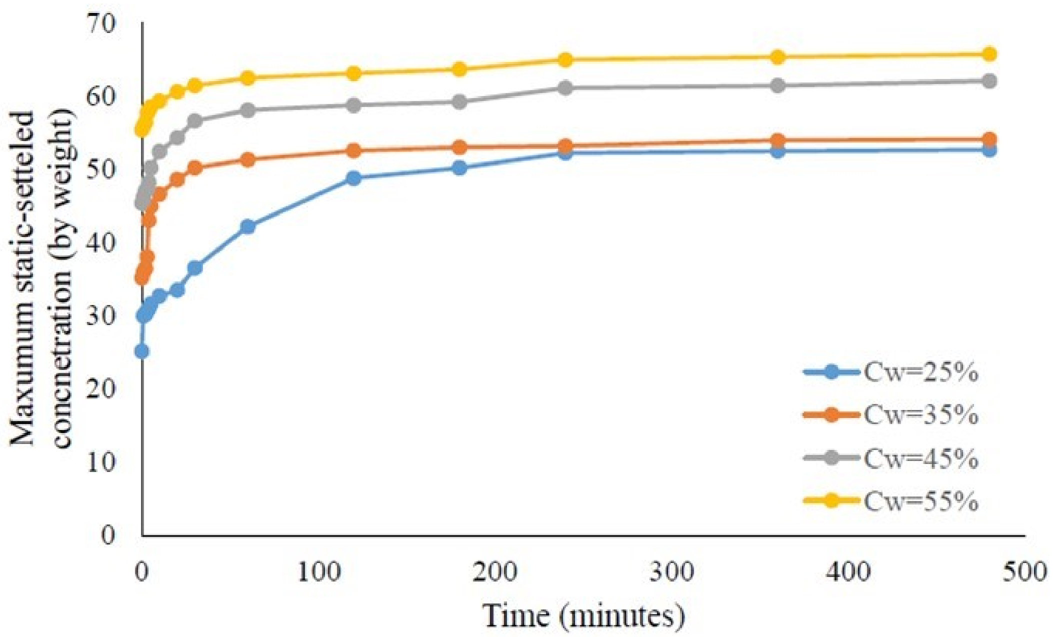

Figure 3.7: Effect of solid concentration on static-settled concentration for zinc tailing slurry

Before reaching to static settlement level, the settling was very rapid at the early stage and the difference in the level of slurry in measuring tank is very less after fixed time interval. The variation in the C_w^{max} with solid concentration is signified in the Figure 3.7. It was observed from the results the settling rate of the solid particles increases up to 200 minutes after that further settling was ceased. The increase in solid concentration form 25-55% results in increase in settling of solid particles. This was observed due to the increase in the number of solid particles per unit volume of the slurry. The maximum static settled concentration of zinc tailing slurry for solid concentration of 25, 35, 45 and 55% (by weight) was found as 52.61, 54.02, 61.99 and 65.62% respectively.

Chapter 4

RHEOLOGY OF ZINC TAILING SUSPENSION

The flow characteristics of the slurry are highly influenced by rheological behaviour of solid-liquid suspension. The efficiency of the slurry transportation system depends upon amount of solid conveyed and pumping cost. The pumping cost or energy required for conveying a solid is depends upon the viscosity of slurry. Slurry is defined as the mixture of solid and liquid, it goes under plastic deformation when external forces are applied on it. Due to presence of solid particles, the flow characteristics study of the slurry suspension becomes a complex phenomenon. As the physical properties of solid particles also effect the flow behaviour of the slurry suspension. The flow characteristic of slurry suspension relies on many factors such as volume fraction, viscosity of slurry and the solid physical properties. As the solid concentration increases in the slurry suspension the flow behaviour shifts from Newtonian behavior to non-Newtonian behaviour as well as the viscosity increases. There are various parameters which plays an important role to determine the rheological characteristics of solid suspension like viscosity, particles size and solid concentration etc. Therefore, it is required to study the rheological characteristics of zinc tailing-water slurry so as to design economical slurry conveying system. In this chapter the rheological characteristics as collected zinc tailing sample was investigated for solid concentration range of 25-55% (by weight). However, the experiments were also extended to the decrease the viscosity of slurry by adding coarser particles in finer slurry at high solid concentration of 55%. The details of experiments and apparatus used are described in further sections.

4.1 RHEOMETER

Rheometer is a device which is used to study the flow characteristics of the liquids and slurries as shown in Figure 4.1. It helps to calculate approximate way of deformation under the effect of applied shear stress. To investigate the fluid behaviour such as Newtonian/non-Newtonian, deformation rate, viscosity, shear stress and elongation viscosity etc, various types of rheometers are available. The most common among them is the cone plate concentric cylinder type rheometer which was used to determine the rheological characteristics of solid-liquid suspension. The measurements were obtained by selecting controlled shear rate.

4.1.1 Working principle of rheometer

A constant torque motor is connected to the Rheometer which works through the various arrangements of the Rheometer. A sensor which is used to measure the angular position or movement of the system is connected with the shaft. It has wide speed and torque ranges. The measuring system consists of a spindle having a bob and cup with a small annular gap between them. Firstly, the mixture is prepared and after that it is poured in the measuring cup. The measuring cup is then inserted into a measuring cylinder and is coupled to the rotating spindle.

Figure 4.1: Photographic view of Rheolab QC rheometer

The slurry is subjected to shearing action in between the annular gap and hence shear stress is measured as a function of the shear rate. Results are obtained on the Rheoplus software on a computer. The product of angular velocity and torque with the "form factors" C1 and C2 to find out the shear stress, τ and shear rate γ, respectively

Shear Stress $$\tau = C_1 \times M \quad (4.1)$$

Shear rate $$\gamma = C_2 \times \omega \quad (4.2)$$

Viscosity $$\eta = \tau \times \gamma \qquad (4.3)$$

Whereas M denotes the torque and ω represents the angular velocity.

In some measuring systems the arrangements like parallel plates, the gap between the measuring systems is adjustable and can be set by the user. In this case the equation used is:

$$\gamma = \frac{C_2 \times \omega}{L} \qquad (4.4)$$

Where, L denotes the gap.

4.2 SAMPLE PREPARATION

A 50 ml of slurry samples of varying solid concentration range of 25-55% was prepared to perform rheological tests. By mixing known amount of solid along with water the zinc tailing slurry was prepared. The zinc tailing slurry was prepared by mixing known amount of solid with water. Electronic type single pan balance with least count of ±0.001 mg was used to measure the weight of zinc tailing sample. A stirrer was used to ensure the uniform mixing of aqueous suspension of slurry. Concentric cylinder type rheometer was used to perform the experiment. The tests were conducted by varying shear rate value from 0-600 s-1 by changing solid concentration however the temperature remains constant i.e. 25°C. Every experiment was repeated two times and average value was taken to ensure repeatability.

4.3 RHEOLOGICAL CHARACTERICTICS OF ZINC TAILING-WATER SLURRY

Rheological experiments were performed on zinc tailing slurry sample as to investigate the flow characteristics of slurry and the slurry was prepared from as collected random sample. The rheological experiments were performed at different solid concentrations varying from 25-55% (by weight). The shear rate was varied in range of 0-600 s-1 at constant temperature of 25°C. The variation of shear stress with shear is shown in Figure 4.2. From the results it was detected that zinc tailing water slurry exhibits Newtonian flow behaviour for solid concentration range of 25-35%. On the other hand, when the solid concentration increases from 35-55% results in change in flow behaviour to Bingham plastic flow nature. When the solid concentration was increased from 35-55% the initial yield stress was observed.

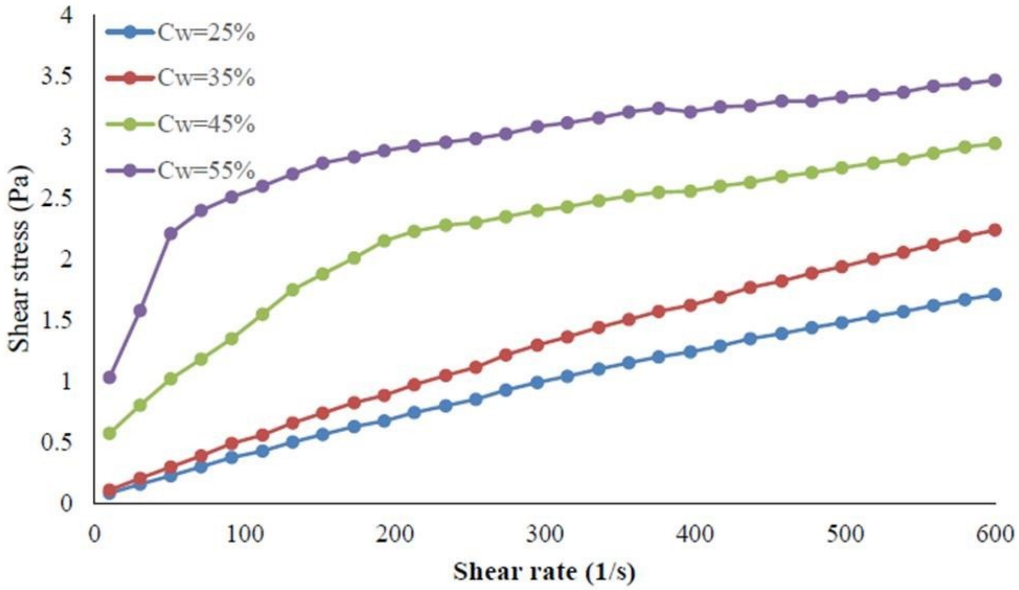

Figure 4.2: Variation of shear stress with shear rate

Figure 4.3 tells about the variation in apparent viscosity of zinc tailing water slurry with shear rate. It apparent viscosity of the zinc tailing water slurry was highly affected by solid concentration. The increase in the solid concentration results in increase in apparent viscosity. The increase in apparent viscosity with solid concentration is because of increase in number of solid particles per unit volume of water. As the solid concentration increases the solid particles forms clusters and cause resistance to flow.

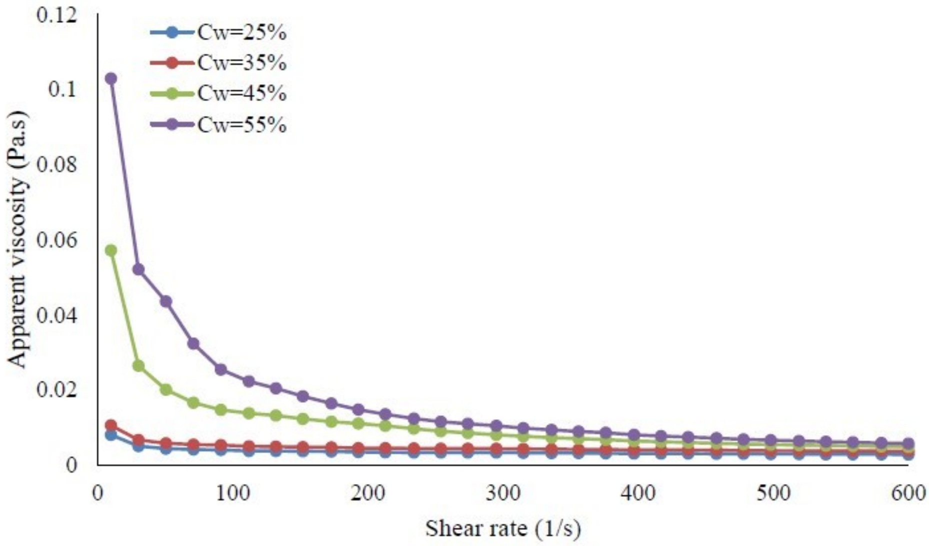

Figure 4.3: Variation of apparent viscosity with shear rate

Hence viscosity of the slurry is increased. It was also observed from results that increase in shear rate results in decrease in apparent viscosity. This is due to the fact that as the shear rate increases the clusters of solid particles breaks down as apparent viscosity of the slurry decreased. The apparent viscosity of slurry was increased by 27.21, 46.24 and 72.59% as the solid concentration of slurry was increased from 25-35, 35-45 and 45-55% respectively for shear rate of 91 s-1. At a shear rate of 295 s-1 the apparent viscosity was increased by 34.24, 85.62 and 28.75% as the solid concentration was increased from 25-35, 35-45 and 45-55% respectively. Gandhi et al. 2005 and Singh et al. 2017 also reported the similar observations.

4.4 EFFECT OF BI-MODAL PARTICULATE SLURRY ON RHEOLOGICAL CHARACTERISTICS OF ZINC TAILING-WATER SLURRY

The experiments were also performed to examine the effect of bi-modal slurry in rheological characteristics of zinc-tailing water slurry. The addition of coarse particles was done in fine particulate slurry so as to decease the apparent viscosity of slurry. The main focus was to decrease the pumping cost by reducing the slurry viscosity at higher solid concentrations. The slurry of fine having particle size >53µm was prepared for solid concentration of 55%. The addition of coarse particles (150-250 µm) was done in fine particulate slurry. The variation in shear stress with shear rate after the addition of the coarse particles in fine particulate slurry is shown in Figure 4.4. It was observed from results that the flow behaviour was remained unchanged with the addition of coarse particles i.e. Bingham flow.

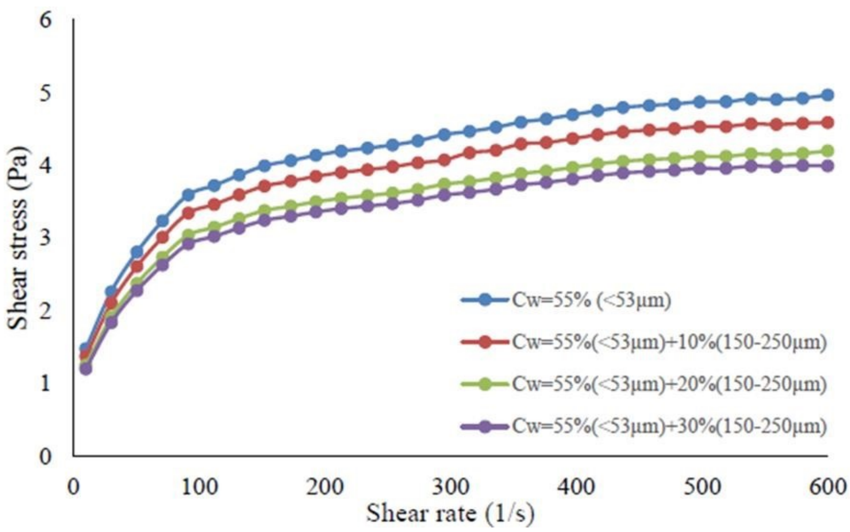

Figure 4.4: variation in shear stress with shear rate after the addition of coarse particles in fine particulate slurry

Figure 4.5 displays the variation in apparent viscosity with shear rate with and without addition of coarse particles. From results appreciable decrease in apparent viscosity was observed with addition of coarse particles in fine particulate slurry as the dosage percentage was increased from 10-30%. However the maximum percentage decrease in apparent viscosity was noticed with 20% addition of 150-250 µm sized particles. Further increase in addition of coarse particles results in decrease in apparent viscosity but the percentage decrease is very less. The apparent viscosity of slurry was decreased by 7, 15.45 and 16.41% as the percentage addition of coarse particles was increased by 10, 20 and 30% respectively at shear rate of 112 s-1. At the shear rate of 600 s-1 the apparent viscosity was decreased by 6.54, 16.85 and 17.32% as the addition of coarse particles was increased by 10, 20 and 30% respectively. The maximum percentage decrease in apparent viscosity was observed with 20% addition of coarse particles.

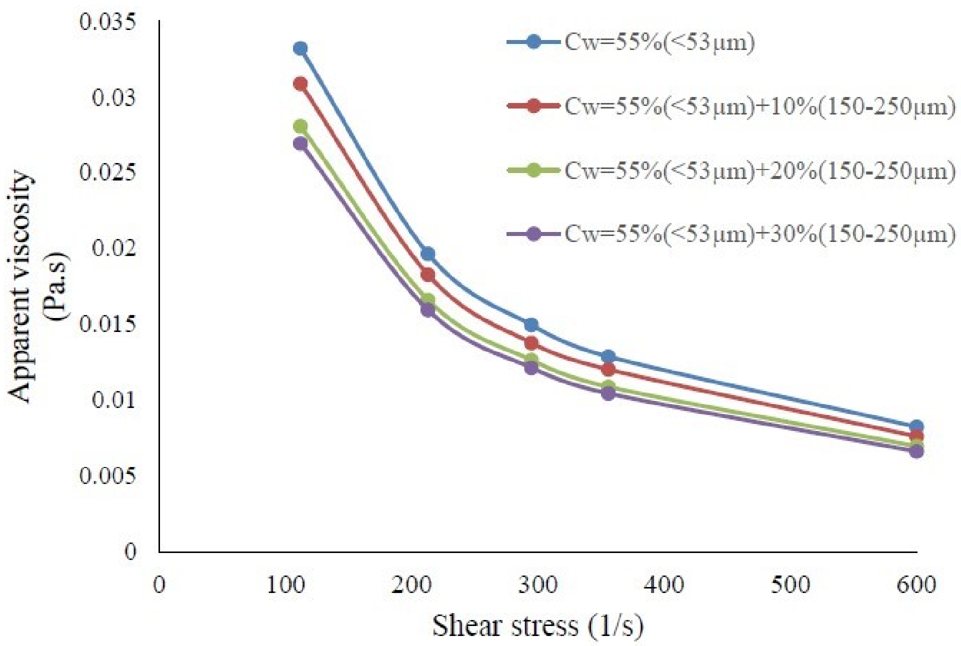

Figure 4.5: Variation in apparent viscosity with shear rate with and without addition of coarse particles

Chapter 5
NUMERICAL SIMULATION OF SLURRY FLOW THROUGH PIPE BEND

Computational Fluid Dynamics (CFD) uses numerical algorithms and methods to predict the real-life behaviour of fluids. CFD helps us in designing the parameters without using the prototype testing facility. CFD is one of the most powerful tool, which helps to visualize the internal flow characteristics along with the physics. Governing equations are used to model flow behaviour, but these equations cannot be applied to many complex flow patterns directly due to many unknown variables. First of all, the domain geometry is divided into integrated small elements to create manageable discrete sections. After that the governing equations are applied to each small element. However, the effect of neighboring elements are also considered. So, by this technique we obtain a full solution for the entire fluid flow by solving governing equations on all elements. The accuracy is function of various factors including the quality of mesh, the interpretation of results, and accuracy of boundary conditions. In case of CFD integrals and derivatives are replaced by governing equations with discretized algebraic equations. Many different models are used as per requirement, results are obtained after repetitively simulations.

5.1 DISCRETIZATION TECHNIQUES

Discretization technique is basically used to convert integral and differential equations into discrete parts. It is a process of converting differential equations into linear and non-linear equations, which can be solved. It is regarded as an infinite continuous value of the entire domain, and the approximation is a quasi-expression that values only for discrete points.

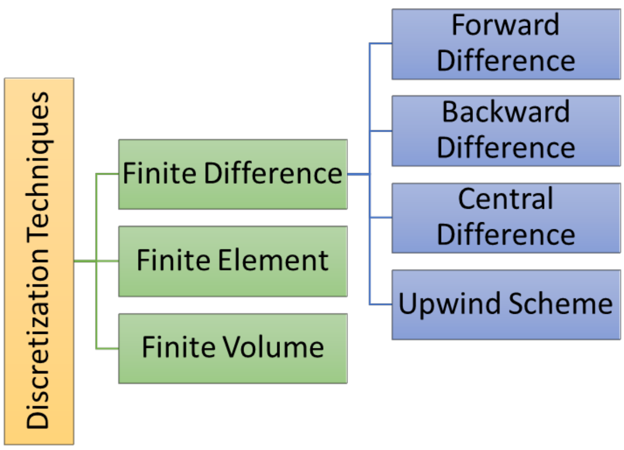

Figure 5.1: Discretization Techniques

There are a several number of techniques used for the solution of partial differential equations. Figure 5.1 shows various techniques of discretization. These methods can be chosen according to the application. As finite volume technique is commonly used for fluid flow problems whereas for structural and mechanics study finite element method is used. For present study FLUENT was used which uses finite volume method for discretization.

5.2 CFD METHODOLOGY

The CFD methodology is basically divided into three main categories as discussed below

Pre-Processing

Solver

Post-Processing

5.2.1 Pre-Processing

First step is to generate process geometry or flow domain. Then, the mesh generation should be done on the domain of interest and the final step in case of pre-processing is to explain the properties of matter, inlet and outlet boundary conditions in flow field.

5.2.2 Solver-

Once the fluid properties along with inlet and outlet boundary conditions are introduced to solve the problem. After that, we have to select the flow equations and numerical schemes. Then iterations are performed for convergence of the solution. Finally, compiling and exporting results for post-processing.

5.2.3 Post-Processing

-Before post-processing we got the results. Then under this category, we have to analyse the results with different techniques such as by plotting contours, vector, streamlines etc. These should be done to get appropriate graphical representation.

In case of Zinc-tailing, firstly the sample was collected, then SEM and EDS were performed on the sample to know the physical characteristics and chemical composition. Then rheological experiments were performed to know about the flow characteristics of zinc tailing-water slurry. The numerical investigation of pressure drop characteristics of two phase flow at different velocities, particle size and concentration was done.

5.3 APPLICATIONS OF CFD

CFD has a wide range of applications. Some of the prominent applications are listed below:

- CFD is used to study the heat transfer and fluid flow problems.
- These days designing industries are using CFD for analysing the pipe line systems, energy analysis etc.
- CFD is also used in aerodynamic and modelling industries.
- It is also used to study the aerodynamic structure of automobiles CFD is used in automobile industry.

5.4 ADVANTAGES AND DISADVANTAGES OF CFD

CFD has more advantages over disadvantages. It has a wide range of applications in industries. Those advantages are very important and have helped the engineers to solve the problems whose analytical solution is impossible. Some of the advantages and disadvantages of CFD are given below:

Advantages

- To solve the problems experimentally is very much expensive as well as less accurate as compared to solving problems with the help of CFD.
- Also, there are many problems whose analytic and experimental solutions are very difficult as well as dangerous but with the help of CFD one can analyse the results easily.
- CFD has also helped the designers to visualize the flow characteristics of complex geometry and boundary conditions.

Disadvantages

- To achieve accuracy the input and boundary conditions need to be chosen with care.
- There may be some numerical errors which are due to the type of hardware used and complexity of the problem.
- Computation time may also be extended for large models.
- If the validation of the experimental results with numerical data is wrong than the cost may be much higher.

5.5 MULTIPHASE MODELING

For multiphase modeling two techniques are used with different approaches. The two approaches which are used for multiphase modeling are discussed below:

- Euler-Euler approach
- Euler-Lagrange approach

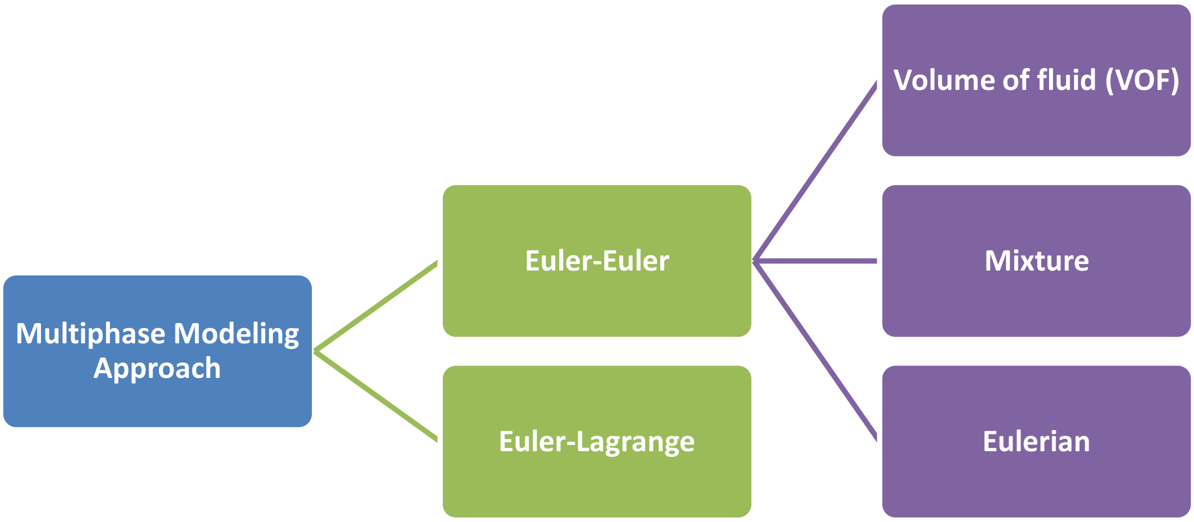

Figure 5.2: Multiphase modeling approaches

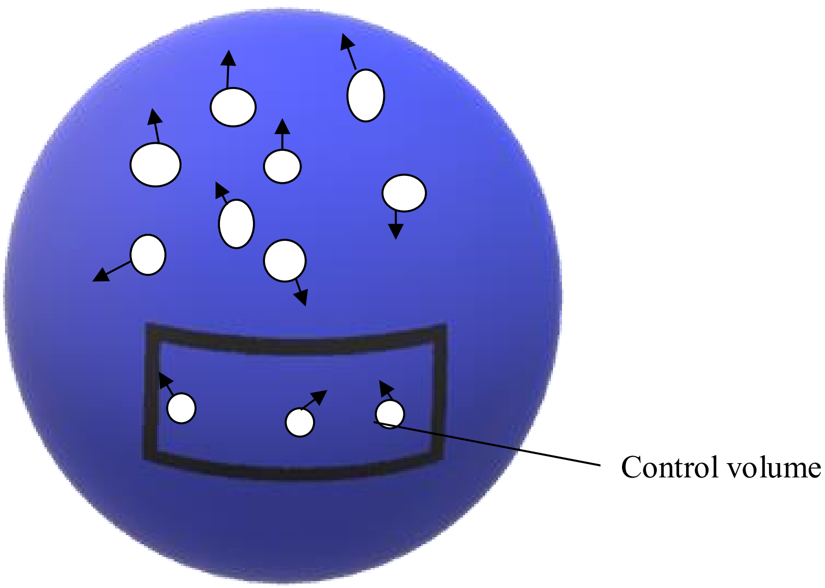

Figure 5.3: Schematic diagram of Euler-Euler approach

5.5.1 Euler-Euler Approach

Euler-Euler approach is generally based on both the solid and liquid phase can be solved with the help of governing equations. On the other hand, the lagrangian approach is not suitable for solid phase because it was in Euler-Lagrange approach. In this Euler-Euler approach the dispersed phase and fluid phase are modelled using governing equations which are solved with in the control volume defined. Figure 5.3 shows the liquid phase as well as the dispersed phase. In this figure the liquid phase is shown in blue colour whereas dispersed phase is denoted by white spheres.

The flow velocities and volume fractions of both the phases are obtained in the control volume using the above approach for both solids and liquids. The Euler-Euler models are categorized into three models that are available in the fluent.

Volume of fluid (VOF) model-This model is applied to the flow in which the phase is separated from the continuum phase. Therefore, this model is applicable for separated flows. This model solves the conservation equations for both phases with the help of combined solid-liquid mixture properties. There are various applications of this model which includes stratified flows, free surface flows, filling and the motion of large bubbles within the fluid.

Eulerian model-This model has 'n' number of governing equations for every phase. This model is the most complex model as compared to others. The coupling is accomplished by pressure and interphase exchange coefficient. These models can be successfully applies to the bubble columns, risers and fluidized bed flows.

Mixture model-This model is applicable to the solid-liquid containing two or more phases. Where ever the velocity differs from different phase, then mixture model is used. Alongside, this model is also applicable for homogeneous solid-liquid flow with strong coupling.

5.5.2 Euler-Lagrange approach

In this approach the motion of the continuum phase affects the motion of dispersed phase as well as of continuum phase in the flow. This model, solves conservation momentum equation to treat the fluid phase as continuum. Figure 5.4 shows the continuum of blue colour in which the small white particles are dispersed as secondary phase. One can solve the solid phase for solid-liquid flow by tackling particles in flow fields. Whereas, this approach always neglects the particle to particle interactions for the simplification of the flow problem. But this model is not applicable for multiphase flow in which the volume fraction of solid phase cannot be neglected as in modeling of liquid to liquid, fluidized bed flows.

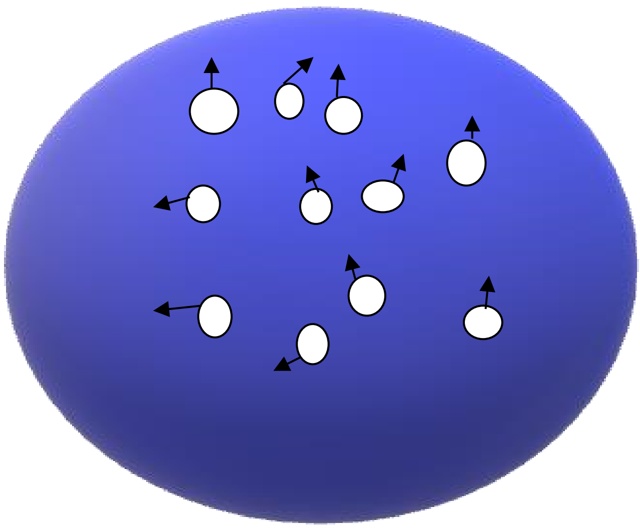

Figure 5.4: Schematic diagram of Euler-Lagrangian approach

5.6 CRITERIA FOR MULTIPHASE MODEL SELECTION

It always depends upon flow under consideration to select the appropriate multiphase scheme. The various types of flows and multiphase models which were used for the study are tabulated in the Table 5.1. From the table it is vivid that the selection of multiphase flow approach always depends on the nature of the flow. In case of solid-liquid flow with volume fraction of dispersed medium less than or equal to 10%, then the Discrete phase model (DPM) IS USED. For the flows having mixed phase or separate or flow having dispersed phase volume fraction greater than 10%, then Mixture and Eulerian models were applied. However, the Eulerian model was much accurate than the mixed model.

Table 5. 1: Multiphase flow with multiphase model

Dispersed phase volume fraction <10%	• Discrete Phase Model (DPM)
Dispersed phase volume fraction >10%	• Mixture model • Euleria model
Pneumatic Transport	• For homogeneous flow-Mixture model • For granular flow-Eulerian model
Hydraulic transport of solids	• Mixture model • Eulerian model

Here, we used Eulerian model with granular form for the study, because the mixture model for homogeneous pneumatic flow and Eulerian for granular based pneumatic flow as well as the study of slug flows and free surface flow can be done by using VOF model. The study slurry flow and fluidized bed can be made with the application of Eulerian model.

5.7 TURBULENCE MODELING

To simulate and model disturbances which were caused by turbulence in flows, turbulence modeling was used. Averaged form of Navier-stokes equation which is also known as Reynolds average Navier-stokes equation (RANS) was used for modeling the turbulence. The averaging may be time or space or both. To remove the small fluctuations resulting ease in modeling of turbulence, the averaging N-S equation was used. The first turbulence model is named as Prandtl mixing length theory.

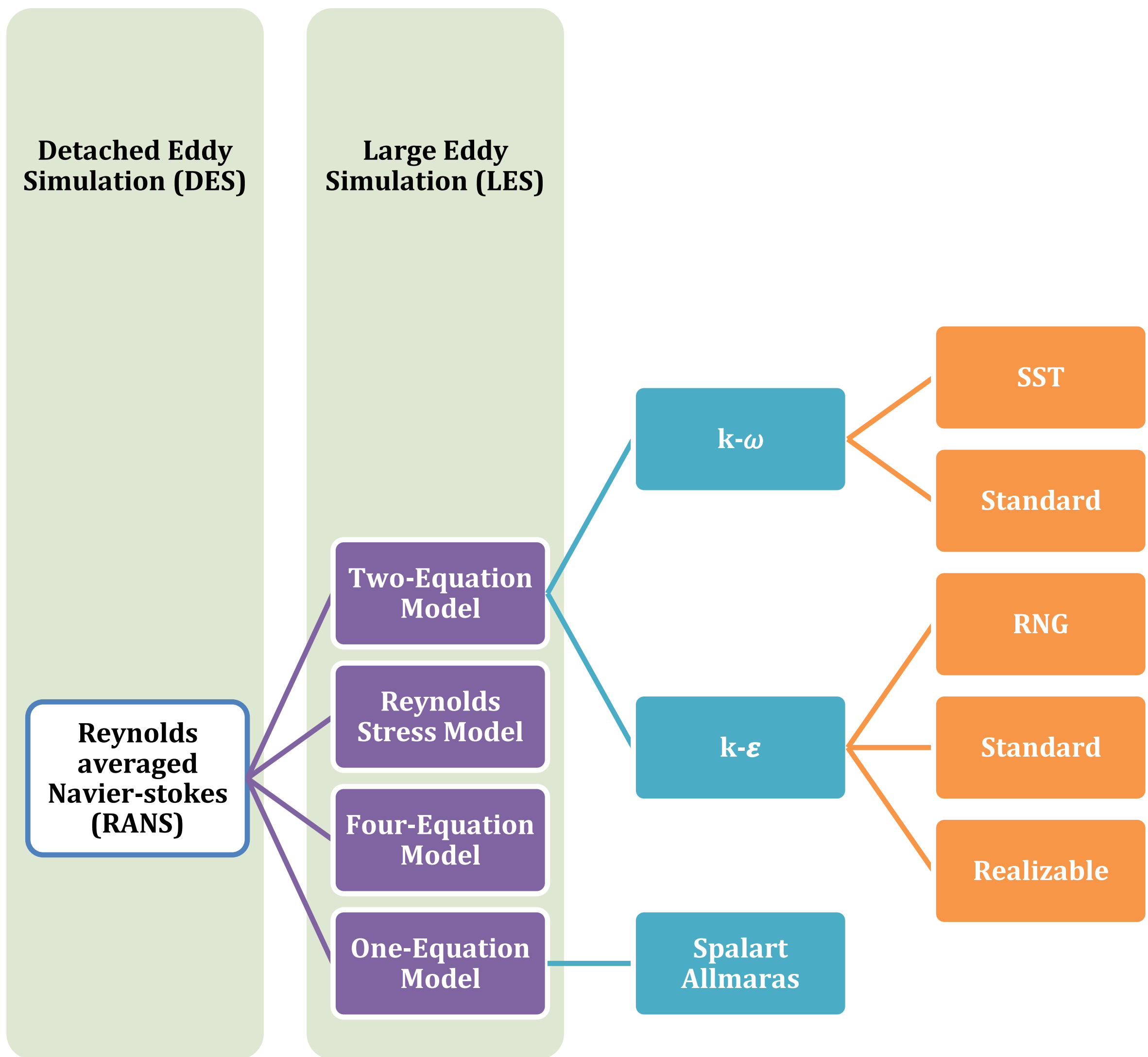

Figure 5.5: Different Turbulence Models

Classification of turbulent modeling

There are various approaches to accomplish the turbulent flows. These turbulence models contain one to seven equations turbulence models. RANS is used for modeling of the turbulence with suitable model or by computing them directly. Figure 5.5 shows the different turbulence models which are used for modeling.

5.8 COMPUTATIONAL MODEL FORMATION

Present study is basically focused on CFD simulation of 90° pipe bend for flow of zinc tailing-water slurry. The effect of variation in solid concentration, velocity of the flow, radius to diameter ratio for pipe bend on slurry flow characteristics was investigated. Experimental results of pressure drop of zinc tailing flow are validated with a mathematical technique. For this study, discrete, mixture model and Eulerian model was used. This particular model was selected on the basis of characterization of the momentum depends upon volume fraction. We cannot use discrete phase model directly as the slurry flow is not a dilute system, therefore both Eulerian and Mixture models are applicable in slurry flow systems. For the present study the flow was modelled using granular Euler method.

5.8.1 Eulerian Model

As, Eulerian model uses the concept of phase volume fraction, which is described as one phase cannot occupied by another phase. This approach pleasures different phases mathematically. The volume fraction is defined by α_p and α_c, whereas 'p' is the particulate in the form of fine powder along with carrier fluid which is denoted by 'c' in the solid-liquid suspension. It is supposed that these volume fractions are in continuum with both space and time and the addition is equal to one. Conservation laws are applied here for each phase but these are of similar structure. Each and every fluid particle bears a number of forces which are described below.

- Force generated as a result of static pressure gradient, which is denoted by "∇P".
- Force generated as a result of solid pressure gradient, which is denoted by "∇P_p".
- The force generated with in the body, which is denoted by "ρg".
- Drag forces as a result of difference between velocities of two phases, $K_{pc}(\vec{v}_p - \vec{v}_c)$.
- Forces as a result of mass, $C_{vm}.\alpha_p.\rho_c.(\vec{v}_c.\nabla\vec{v}_c - \vec{v}_p.\nabla\vec{v}_p)$, here the value of C_{vm} = 0.5.
- The viscous force and the lift force,which are given as, $\nabla.\overline{\overline{\tau_c}}$ and $C_l.\alpha_p.\rho_c.(\vec{v}_c - \vec{v}_p)$ X (∇ X$\vec{v}_c$), where the value of $C_l = 0.5$ respectively.

5.8.2 Governing Equations

This section includes the numerical governing equations, mesh details and boundary conditions involved in numerical study.

Mass conservation equation:-

$$\nabla . (\alpha_a \rho_a \vec{v}_a) = 0 \tag{5.1}$$

Where, a can be either c or p.

Momentum Equations:-

For carrier fluid phase

$$\nabla . (\alpha_c \rho_c \vec{v}_c \vec{v}_c) = -\alpha_c \nabla P + \nabla . (\bar{\bar{\tau_c}} + \overline{\overline{\tau_{t,c}}}) + \alpha_c\, \rho_c \mathrm{g} + K_{pc}(\vec{v}_p - \vec{v}_c) + C_{vm} . \alpha_p . \rho_c . (\vec{v}_c . \nabla \vec{v}_c - \vec{v}_p . \nabla \vec{v}_p) + C_l . \alpha_p . \rho_c . (\vec{v}_c - \vec{v}_p) \text{ X } (\nabla \text{X } \vec{v}_c) \tag{5.2}$$

For solid particulate phase

$$\nabla . (\alpha_p \rho_p \vec{v}_p \vec{v}_p) = -\alpha_p \nabla P - \nabla P_p + \nabla . (\overline{\overline{\tau_p}}) + \alpha_p\, \rho_p \mathrm{g} + K_{cp}(\vec{v}_c - \vec{v}_p) + C_{vm} . \alpha_p . \rho_c . (\vec{v}_c . \nabla \vec{v}_c - \vec{v}_p . \nabla \vec{v}_p) + C_l . \alpha_p . \rho_c . (\vec{v}_p - \vec{v}_c) \text{ X } (\nabla \text{X} \vec{v}_c) \tag{5.3}$$

To model the values of terms comprising of drag forces, drift velocity is used for both the phases that is liquid phase and the solid phase Turbulent fluctuations in volume fraction are result of this velocity. The solid pressure is given by P_p.

$$P_p = \alpha_p\, \rho_p \theta_p + 2\rho_p(1 + e_{pp})\alpha_p^2 .\, g_{o,pp} .\, \theta_p \tag{5.4}$$

Where, $g_{o,pp}$ is Distribution function signifies the probability of collision of particulates and is given by:

$$g_{o,pp} = \left[1 - \left(\frac{\alpha_p}{\alpha_{p,max}}\right)^{\frac{1}{3}}\right]^{-1} \tag{5.5}$$

The terms used in the equation (5.2) and (5.3) $\overline{\overline{\tau_{t,c}}}$ is the Reynolds stress tensor, where individually $\bar{\bar{\tau_c}}$ and $\overline{\overline{\tau_p}}$ is the viscous stress tensor and particulate solid respectively. Which are given as,

$$\overline{\overline{\tau_{t,c}}} = -\frac{2}{3}(\rho_c k_c + \rho_c \mu_{t,c} \nabla \vec{U}_c)\bar{\bar{I}} + \rho_c \mu_{t,c}(\nabla \vec{U}_c + \nabla \vec{U}_c^{tr}) \tag{5.6}$$

$$\overline{\overline{\tau_p}} = \alpha_p \mu_p (\nabla \vec{v}_p + \nabla \vec{v}_p^{tr}) + \alpha_p(\lambda_p - \frac{2}{3}\mu_p)\, \nabla \vec{v}_p \bar{\bar{I}} \tag{5.7}$$

$$\bar{\bar{\tau_c}} = \alpha_c \mu_c (\nabla \vec{v}_c + \nabla \vec{v}_c^{tr}) \tag{5.8}$$

5.8.3 Shear stress on Solids

It was noted earlier that the shear and bulk viscosities of suspension were increased, this is because of exchange of momentum due to collision between solid particulate. $\mu_p$in equation 5.7 represents the shear viscosity of particulate solid is given by:

$$\mu_p = \mu_{p,col} + \mu_{p,fr} + \mu_{p,kin} \quad (5.9)$$

where $\mu_{p,col}$, $\mu_{p,fr}$and $\mu_{p,kin}$ are the collision, friction and kinectic viscosities which are given as

$$\mu_{p,col} = \frac{4}{5}\alpha_p \rho_p d_p g_{o,pp}\left(1 + e_{pp}\right)\left(\frac{\theta_p}{\pi}\right)^{\frac{1}{2}} \quad (5.10)$$

$$\mu_{p,fr} = \frac{Ppsin\varphi}{2\sqrt{I_{2D}}} \quad (5.11)$$

$$\mu_{p,kin} = \frac{10\rho_p d_p \sqrt{\theta_p \pi}}{96\alpha_p (1+e_{pp}) g_{o,pp}} + \left[1 + \frac{4}{5}\alpha_p \rho_p d_p \left(1 + e_{pp}\right) g_{o,pp}\right]^2 \alpha_p \quad (5.12)$$

5.8.4 Standard K-ε turbulence model

The standard k-ε turbulence model is based on the equations of dissipation rate (ε) and turbulent kinetic energy (k). The assumption for k-ε model is that the flow is turbulent and negligible molecular viscosity. This model is the combination of two turbulence models i.e. RNG k-ε and realizable k-ε. The equations for standard k-ε turbulence model are as follows.

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon - Y_M + S_k \quad (5.13)$$

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_i}(\rho\varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon \quad (5.14)$$

5.8.5 RNG k-ε Model

The k-ε RNG model is derived from Navier-Stokes equation by using Renormalization group methods (RNG) mathematical technique. Various terms of k-ε RNG model are same as in k-ε standard model. However, k-ε RNG model includes some of the additional terms which refine its accuracy. Following are the equations of k-ε RNG model:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left(\alpha_k \mu_{eff}\frac{\partial k}{\partial x_j}\right) + G_k + G_b - \rho\varepsilon - Y_M + S_k \quad (5.15)$$

and

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_j}\left(\alpha_\varepsilon \mu_{eff}\frac{\partial \varepsilon}{\partial x_j}\right)+C_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}-R_\varepsilon+S_\varepsilon \tag{5.16}$$

5.8.6 Realizable k-ε Model

The Realizable k-ε model is different from k-ε standard model. In Realizable k-ε model, term 'realizable' denotes the reliability of Reynolds stresses. The Realizable k-ε model includes two different terms for the turbulent viscosity and a modified transport equation for the dissipation rate. The transport equations for Realizable k-ε model are given as:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_j)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon-Y_M+S_k \tag{5.17}$$

and

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_j)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+\rho C_1 S\varepsilon-\rho C_2\frac{\varepsilon^2}{k+\sqrt{v\varepsilon}}+C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b+S_\varepsilon \tag{5.18}$$

Where

$$C_1=\max\left[0.43,\frac{\eta}{\eta+5}\right],\eta=S\frac{k}{\varepsilon},S=\sqrt{2S_{ij}S_{ij}}$$

C_2 *and* $C_{1\varepsilon}$, are constants.

5.8.7 k-ω Model

The *k*-ω model is a two-way transport model that solves the kinetic energy and turbulent frequency of particles. The turbulent frequency is denoted by symbol ω. This model is applicable to solve the fluid flow at low Reynolds number such as near wall region. Turbulence kinetic energy and turbulent frequency relation is given as:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left(I_k\frac{\partial k}{\partial x_j}\right)+G_k-Y_k+S_k \tag{5.19}$$

and

$$\frac{\partial}{\partial t}(\rho\omega)+\frac{\partial}{\partial x_i}(\rho\omega u_i)=\frac{\partial}{\partial x_j}\left(I_\omega\frac{\partial \omega}{\partial x_j}\right)+G_\omega-Y_\omega+S_\omega \tag{5.20}$$

Where, G_k represents the generation of turbulence kinetic energy, G_ω is the generation of ωI_k and I_ω represents the effective diffusivity of k and ω due to turbulence. S_k and S_ε are sources terms.

5.8.8 SST k–ω Turbulence Model

The term 'SST' denotes the shear-stress transport. Mentor (1994) developed SST k–ω model by solving the standard k–ω and standard k–ε model which capable to accurate formulation of turbulence flow in pipeline. SST k–ω Turbulence Model is effective in solving the equations near wall region at higher accuracy. The transport equations are given by

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left(I_k\frac{\partial k}{\partial x_j}\right)+G_k-Y_k+S_k \tag{5.21}$$

and

$$\frac{\partial}{\partial t}(\rho \omega)+\frac{\partial}{\partial x_i}(\rho \omega u_i)=\frac{\partial}{\partial x_j}\left(I_\omega\frac{\partial \omega}{\partial x_j}\right)+G_\omega-Y_\omega+D_\omega+S_\omega \tag{5.22}$$

In these equations, G_k represents the generation of turbulence kinetic energy due to the mean velocity gradients. G_ω represents the generation of ω, calculated as described for standard k-ω model. I_k and I_ω represent the effective diffusivity of k and ω, respectively. Y_k and Y_ω represents the dissipation of k and ω due to turbulence. D_ω represents the cross-diffusion term. S_k and S_ε are sources terms.

5.9 FLOW DOMAIN AND GRID INDEPENDENCY TEST

The modelling of the bend geometry was done in ANSYS-15.0. The diameter of pipe was taken as 50 mm. In order to have a fully developed flow at inlet of bend the pipe length was extended to 1000 mm. The material of pipe was taken as mild steel. Flow domain was discretized into tetrahedral type mesh. The refinement of the mesh at the boundary was done by applying inflation. A boundary wall was refined by taking 10-layer region possessing growth rate of 20% as shown in Figure 5.6. The value of the wall y+ was found to be 30. In order to optimize the number of elements and nodes in flow domain mesh independency test has been performed. The flow domain was discretized into 3, 4, 5, 6 and 7mm mesh size.

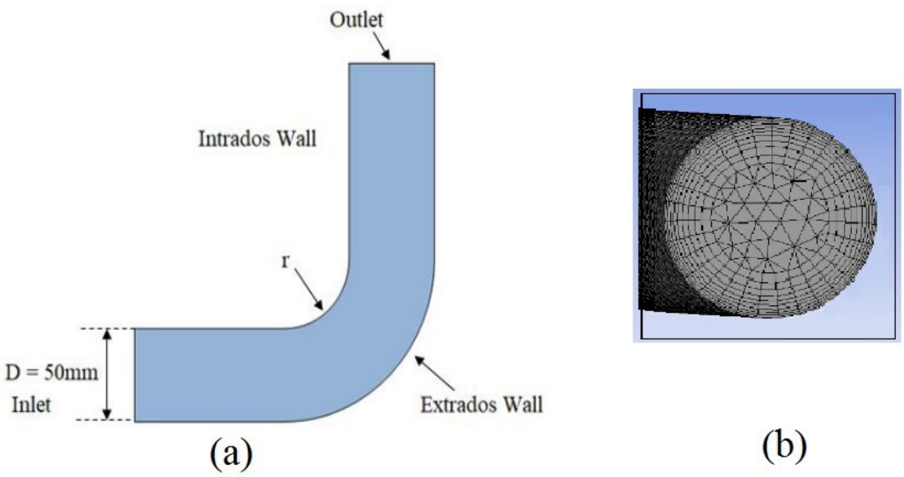

Figure 5.6: (a) Schematic diagram of pipe bend (b) Meshing of bend geometry

The variation in pressure drop with different mesh size of flow domain is shown in Figure 5.7. The simulations for pressure drop were carried out at solid concentration of 35% and flow velocity of 5 m/s. It was observed from the results that the variation in values of pressure drop was very less as the mesh size was decreased from 5 to 4 mm. The 5 mm mesh size was found to be optimum and used in further simulation.

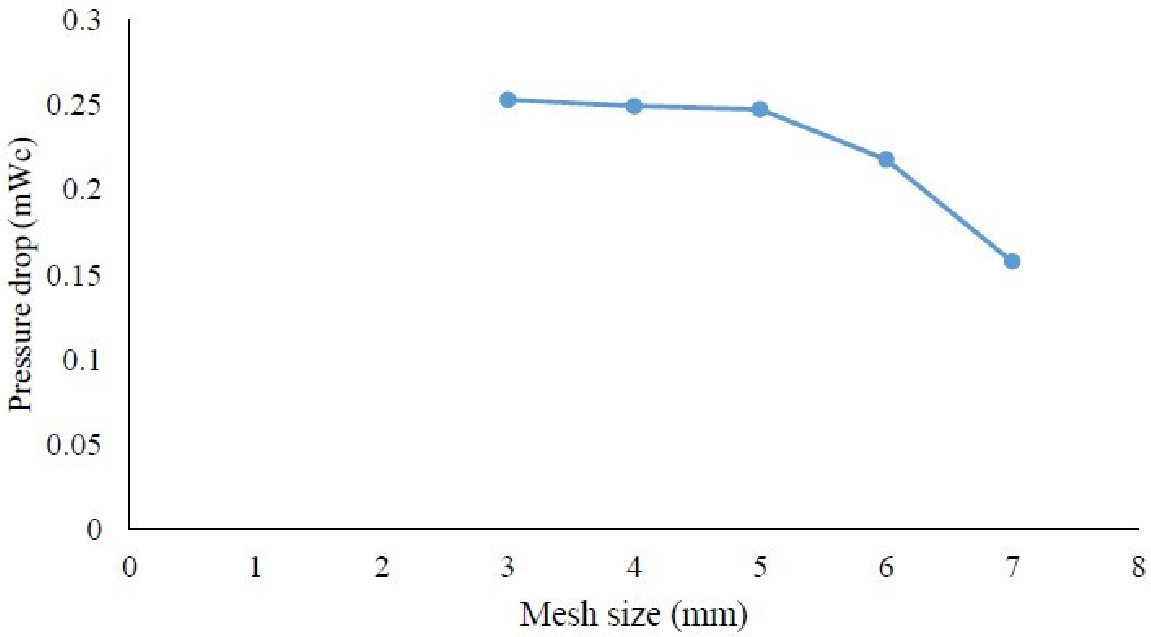

Figure 5.7: Variation in pressure drop with mesh size of flow domain

5.10 BOUNDARY CONDITIONS

The governing equations applied on flow domain were solved by applying boundary conditions at inlet, outlet and wall of pipe. The flow velocity and volume fraction of the solid phase was applied to the inlet section of bend geometry. The hydraulic diameter was used as 50 mm. However, the wall was subjected to no slip condition and roughness factor of pipe wall was taken as 0.4. At the outlet section zero Pascal pressure boundary condition was applied. The SIMPLE scheme was adopted to couple pressure and velocity. The window-based Intel® Core™ i7-6700 machine with 3.41 GHz processor was used to perform whole simulation study. The convergence criteria was taken as 10^{-4}.

5.11 VALIDATION OF EXPERIMENTAL RESULTS WITH NUMERICAL METHODS

5.11.1 Experimental test loop

The experiments were aimed to determine the pressure drop characteristics of zinc tailing-water slurry at varying flow rate and fixed solid concentration. The zinc tailing sample used in present study is procured from Rampura Agucha Mine, Rajasthan, India. Pressure drop experiments were conducted on pilot plant test loop established at MED, TIET, Patiala, Punjab, India as shown in Figure 5.8.

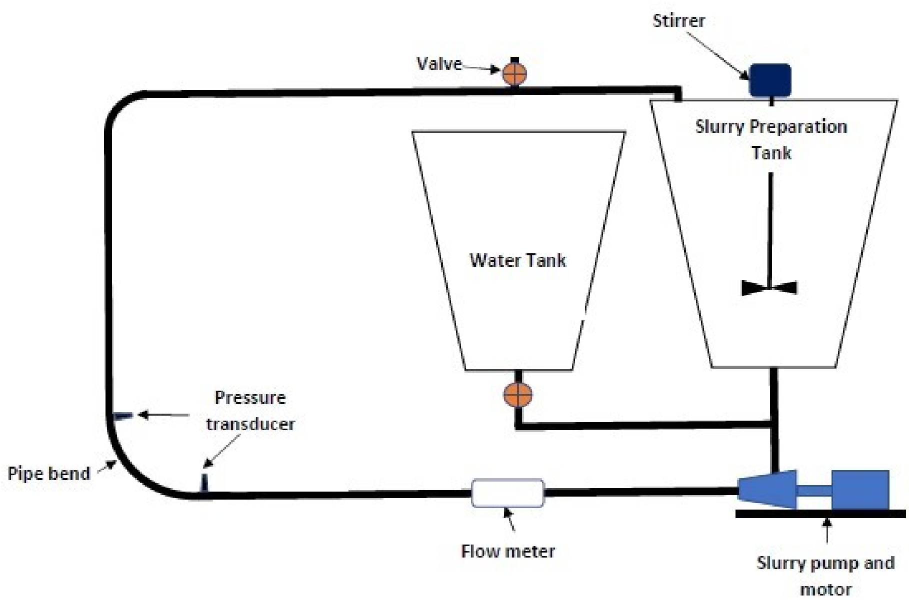

Figure 5.8: Schematic diagram of pilot plant test loop

The test loop is equipped with a slurry tank, slurry pump, flow meter, pressure transducers, data acquisition system and 60 m long pipeline having diameter of 50 mm. The slurry of desired concentration is prepared in slurry tank. The required driving force to slurry is provided with slurry pump. The inlet of pump is connected to slurry tank while the outlet section is allied with slurry pipeline. The rpm of the pump is controlled by varying the frequency from variable frequency device. The flow velocity of slurry is measured with flow meter installed in pipeline. The diaphragm type pressure transmitters are installed at various location of pipeline to measure pressure drop. The slurry after circulation is dumped into the slurry tank so as to provide continuous supply of slurry to pump. The system also consists of a transparent observation chamber (0.5 m long) made of acrylic pipe to observe the settling/choking of pipeline. The flushing of the whole loop is done after experimentation. The data stored in data acquisition system was taken with the help of pen drive. The validation of the experimental data obtained from pilot plant test loop was done with various turbulence models available in Fluent. The experiments of pressure drop were performed for flow of 55% (by weight) zinc tailing-water slurry suspension. The flow velocity of the slurry was kept in the range of 2-5 m/s. For solid concentration of 55% the pressure drop was increased by 1.32 times for increase in flow velocity from 2-3 m/s. However, increase in flow velocity from 3-4 m/s and 4-5m/s results in increase in pressure drop by 95 and 53.84% respectively.

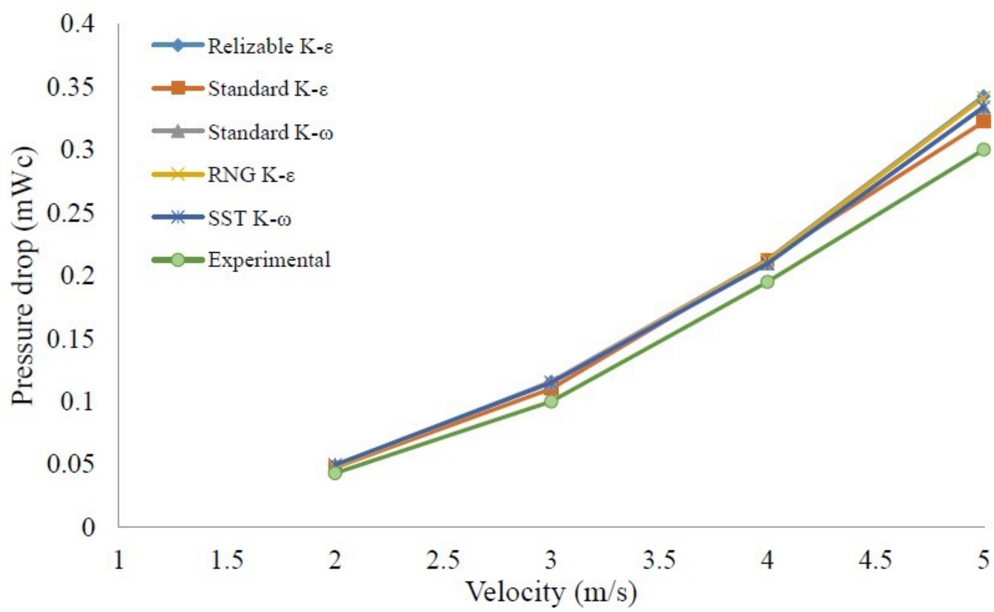

Figure 5.9: Validation of numerical modelling techniques

5.11.2 Validation of numerical results with experimentation data

A series of numerical simulations were carried out to study pressure drop across the 90˚ bend by using various turbulence models namely realizable k-ε, Standard k-ε, Standard k-ω, RNG k-ε and SST k-ω. The variation of pressure drop among various turbulence models and experimental results are plotted in Figure 5.9. The deviation of experimental results from Realizable k-ε, Standard k-ε, Standard k-ω, RNG k-ε and SST kω was found as 12.36, 7.65, 11.95, 11.65 and 10.96% respectively. The results depict that experimental data shows good agreement with Standard k-ε turbulence model with minimum deviation of 7.65%. In further investigation all simulations were performed by using Standard k-ε turbulence model.

5.12 EFFECT OF SOLID CONCENTRATION ON PRESSURE DROP

The effect of solid concentration on pressure drop across pipe bend was studied by carrying out numerical simulations. Solid concentrations of zinc tailing- water slurry were kept in the range of 25-55%. The ratio of radius of curvature to pipe diameter (R/d) was taken as 1.0. The flow velocity was varied within the range of 2-5 m/s. Figure 5.10 shows the variation in pressure drop with varying flow velocities at different solid concentrations. From the results it was observed that pressure drop increases with flow velocities as well as with solid concentration. As the flow velocity is increased from 2-3, 3-4 and 4-5 m/s the pressure drop was increased by 131.54, 92.99 and 51.64% for solid concentration of 55%.

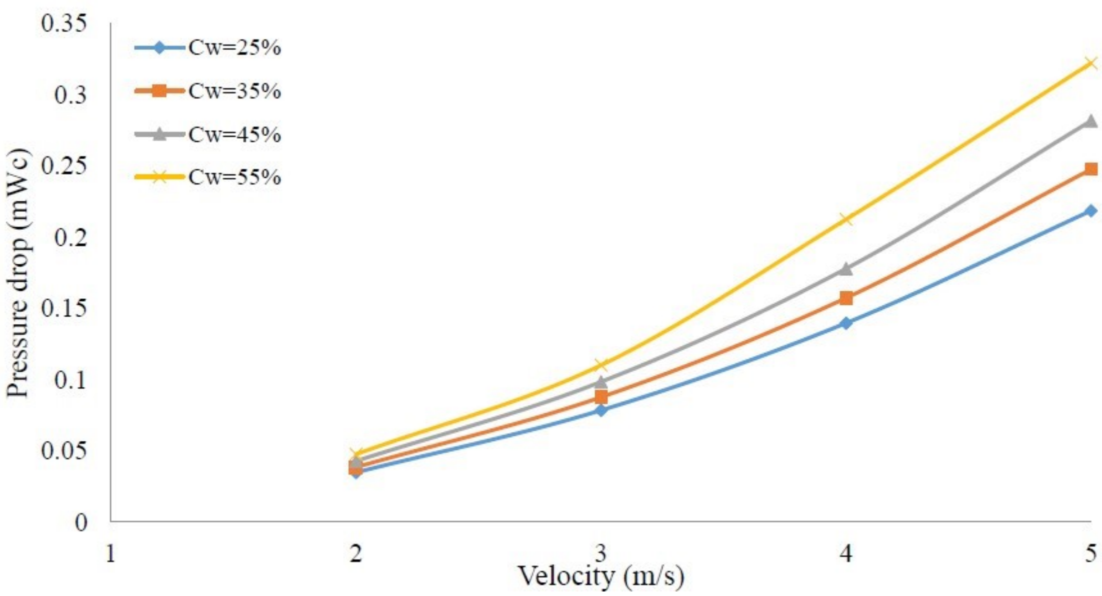

Figure 5.10: Effect of solid concentration on pressure drop

For the flow velocity of 5 m/s the pressure drop was increased by 13.29, 13.73 and 14.98% as solid concentration was increased from 25-35, 35-45 and 45-55% respectively. This increase in the pressure drop with flow velocity was noticed due to increase in the turbulence in flow. Also, the increase in turbulence leads to formation of flow separation and secondary flow phenomenon inside the pipe bend. As the velocity increases the intensity of flow separation and secondary flows also increases. Hence losses inside the bend increases and this result in higher pressure drop. The viscosity of zinc tailing-water slurry was increased with solid concentration. As the number of solid particles in fixed volume of water is increased more restriction to flow occurs. This leads to higher pressure drop as concentration was increased.

5.13 EFFECT OF BEND CURVATURE ON PRESSURE DROP

In present study, the effect of bend curvature on pressure drop across 90˚ bend was also studied. The R/d ratio was changed within the range of 1.0-3.0 by taking pipe diameter of 50 mm. All the numerical simulations were carried out on solid concentration of 55% and flow velocity was kept in range of 2-5 m/s. The variation in values of pressure drop with flow velocities and R/d ratios is plotted in Figure 5.11. From the results it is seen that the pressure drop is also a function of bend curvature. As the R/d ratio was increased from 1.0 to 3.0 remarkable decrease in pressure drop was observed. The minimum pressure drop for zinc tailing-water slurry was observed across pipe bends have R/d ratio 2.0 and 2.5. It was noticed from the result data that pressure drop is minimum for flow velocity range of 2-4 m/s across pipe bend having R/d ratio of 2.0. Whereas at higher flow velocity of 5 m/s the minimum pressure drop was observed at pipe bend possessing R/d ratio of 2.5. Further increase in R/d ratio from 2.5-3.0 the pressure drop was increased. The decrease in pressure drop by increasing the R/d ratio was observed due to decrease in flow separation and secondary flows. As the curvature of bend increased the passage for flow becomes smoother and turbulence was decreased. The decrease in turbulence also leads to suppression of secondary flows and flow separation phenomenon. Increase in R/d ratio from 2.5-3.0 further results in high pressure drop. Although the turbulence and secondary flows were decreased but the increase in effective length of pipe bend add-on to higher frictional losses. These frictional losses result in increase in pressure drop at higher R/d ratios. As the R/d ratio was increased from 1.0-1.5 and 1.5-2.0 the pressure drop was decreased by 13.56 and 4.60% respectively; whereas the pressure drop was increased by 1.5 and 6.62% when the R/d ratio was increased from 2.0-2.5 and 2.5-3.0 respectively for flow velocity of 2 m/s. At the flow velocity of 5 m/s the pressure drop was decreased by 12.96, 2.07 and 3.12% as R/d was increased from 1.0-1.5, 1.5-2.0 and 2.0-2.5 respectively; however, as the R/d ratio was increased from 2.0-2.5 the pressure drop was increased by 8.23%.

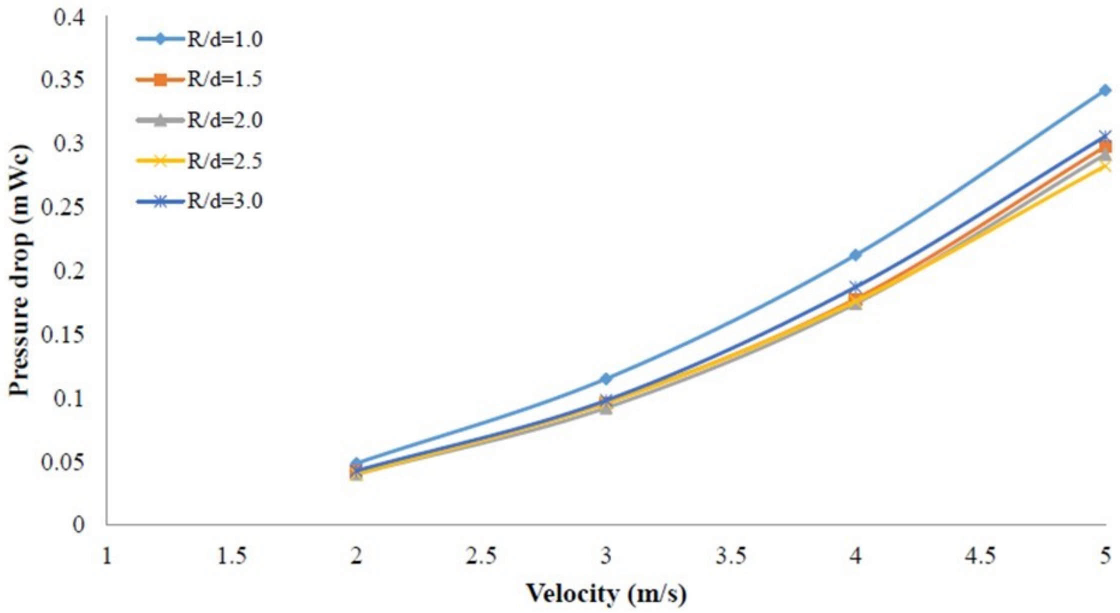

Figure 5.11: Effect of bend curvature on pressure drop

5.14 VOLUME FRACTION DISTRIBUTION FOR ZINC TAILING-WATER SLURRY

The volume fraction distribution of the solid phase inside the bend geometry was studied with help of contours obtained from CFD. Figure 5.12 (a) shows the effect of velocity (C_w=55%) on variation of solid phase at various locations of bend geometry. The red colour indicates highest accumulation whereas the blue colour indicates least of solid phase. It was seen from the results that maximum settling of solid phase at inlet was observed at the bottom of bend section. Also, as the flow velocity increased from 2-5 m/s this aggregation of solid phase decreases. However, this region of maximum accumulation start moves from bottom of pipe to outer periphery of bend section as flow proceeds to outlet of bend. This happens due to centrifugal forces acting to slurry in flow field. It was also noticed that as the velocity decreases more will be the settling of solid phase which can cause choking of the pipeline. Figure 5.12 (b) depicts the volume fraction contours at different solid concentrations for flow velocity of 5 m/s.

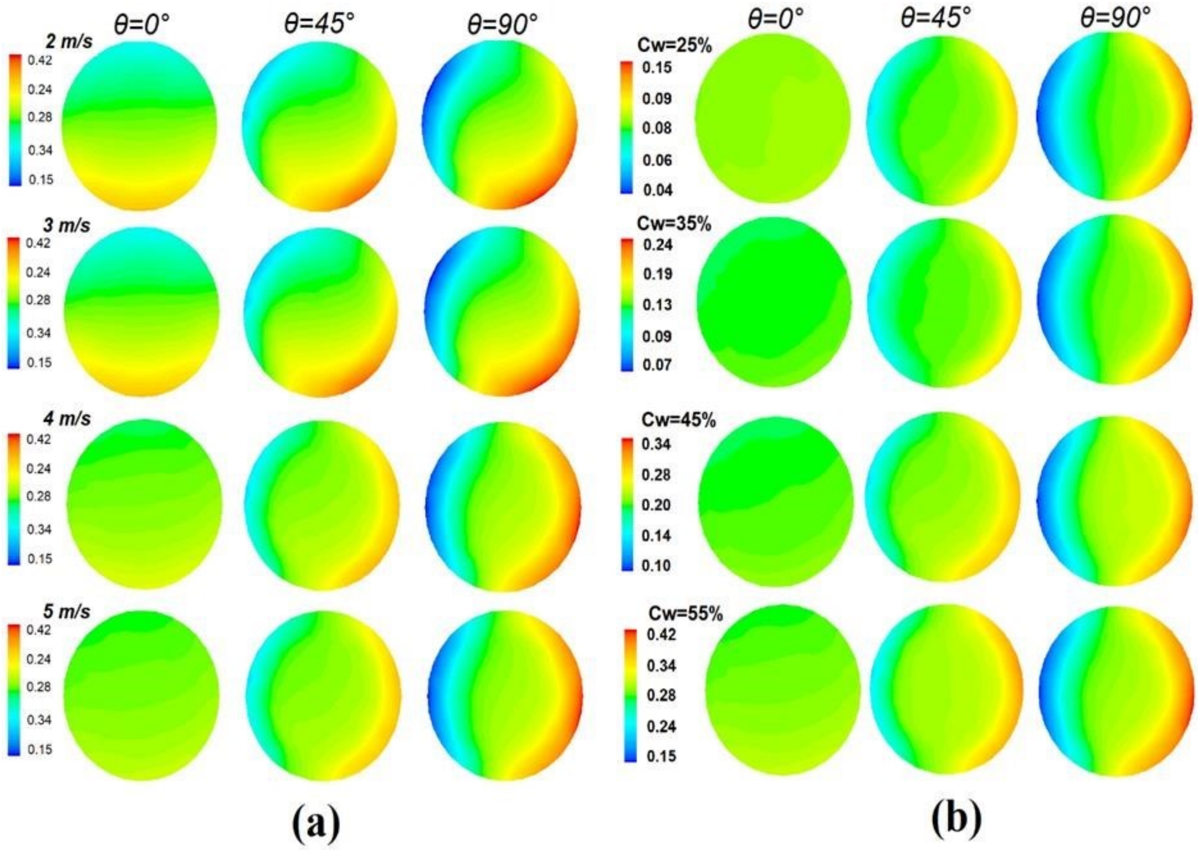

Figure 5.12: Variation in volume fraction with flow velocity and solid concentration (a) and (b)

It has been revealed from contours that increase in solid concentration leads to more aggregation of solid phase. This was observed because of the fact that as the number of solid particles in fix volume of water increases the settling increases. The flow velocity for high concentrated slurry should be kept high to avoid blockage of pipeline. The effect of R/d ratio on volume fraction distribution is shown in the Figure 5.13. The solid concentration was kept 55% and flow velocity of 5 m/s. It has been seen from the contours that with the increase in curvature of bend the accumulation of solid phase on the bottom and at the periphery of bend decreases. As the R/d ratio was increased from 1.0-3.0 the width of high concentrated zone is goes on decreasing and was minimum for bend having R/d ratio 3.0. The flow becomes more stable as the curvature of bend becomes smoother.

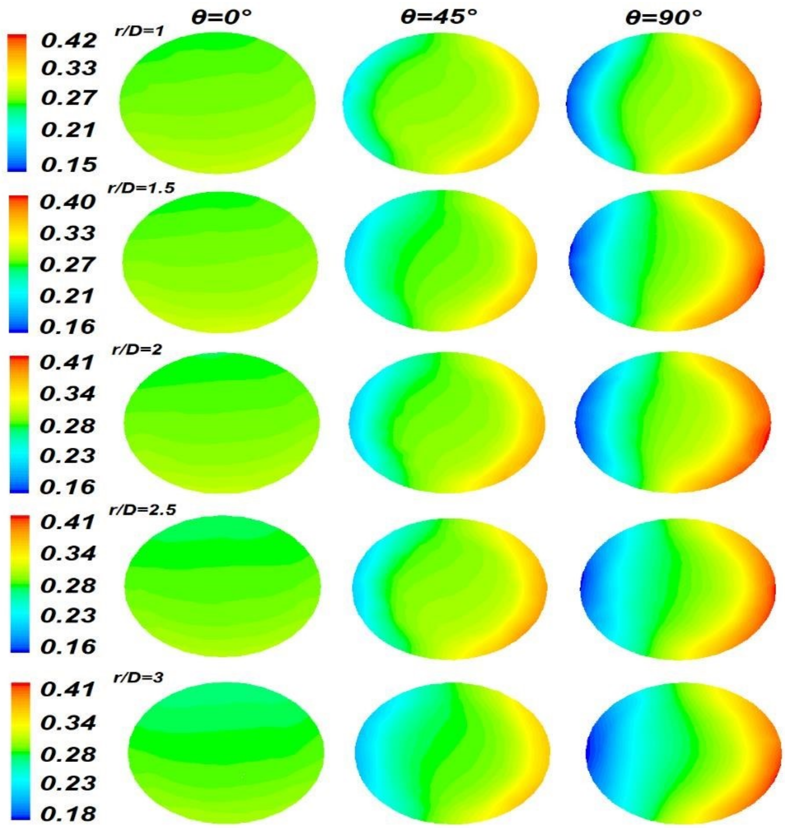

Figure 5.13: Variation in volume fraction with R/d ratio

5.15 TURBULENCE INTENSITY CONTOURS FOR ZINC TAILING-WATER SLURRY

The contours of turbulence intensity obtained from multiphase approach have been shown in Figure.5.14 and 5.15. The influence of flow velocity on turbulence at 55% solid concentration is shown in Figure 5.14 (a). It has been observed that maximum turbulence at the inlet section of bend in found at the circumference of pipe. The turbulence goes on decreasing and minimum at the centre of pipe. As the flow proceeds from the inlet to outlet of bend the maximum turbulent region shifts towards the internal periphery of bend section. Whereas the minimum turbulence region was decreased and shifted towards outer periphery. Also increase in turbulence was observed at the outlet section of bend.

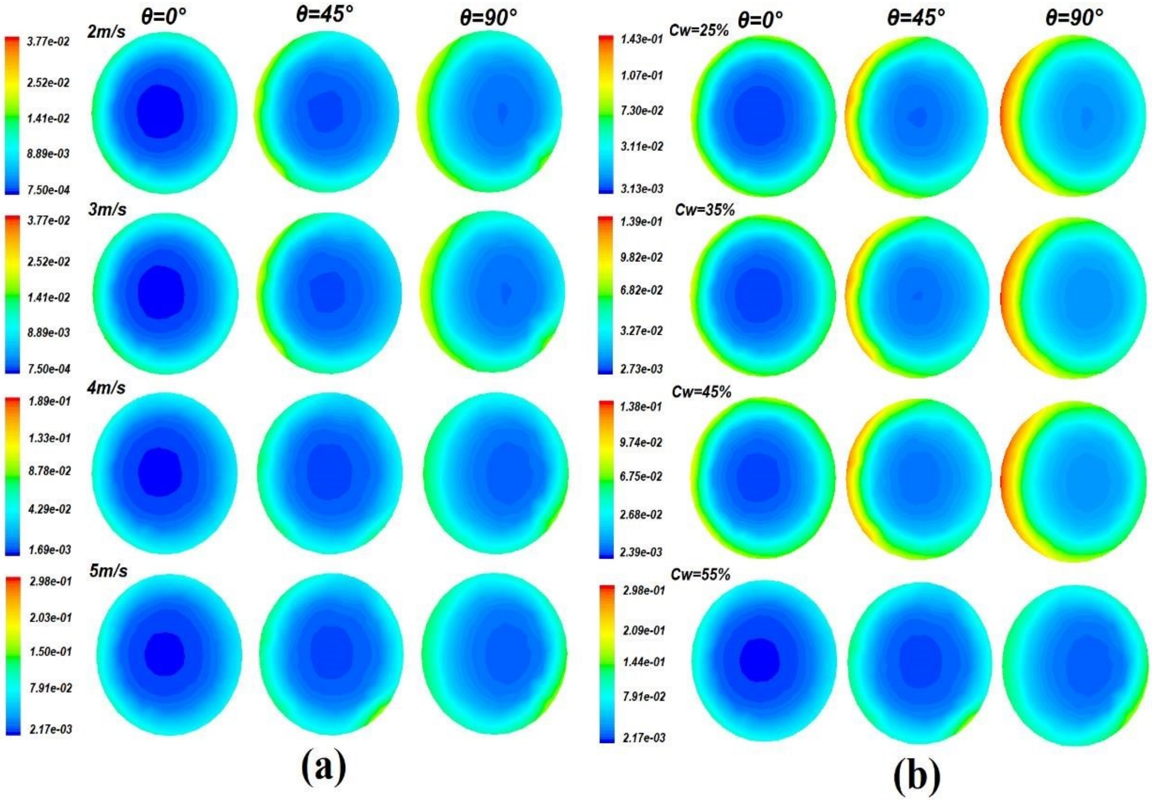

Figure 5.14:Variation in turbulence intensity with flow velocity and solid concentration (a) and (b)

As the flow velocity was increased from 2-5 m/s abrupt increase in the turbulence was observed from contours. Figure 5.14 (b) depicts the effect of solid concentration on turbulence for flow velocity of 5 m/s. From the turbulence contours it was seen that as the concentration was increased the turbulence inside the bend decreases. This decrease in turbulence was noticed because the flow becomes more homogenous as concentration was increased. Also, the intermolecular collisions between the liquid phase decreases. The variations of turbulence with bends having different R/d ratio is shown in Figure 5.15. It has been noticed from turbulence contours that as the R/d ratio was increased from 1.0-3.0 the turbulence decreases at all the positions of pipe bend. This shows that as the bend curvature was increased the flow separation and secondary flows in pipe bend decreases. This indeed leads to lower losses in bend occurs due to turbulence. The flow becomes smoother and more stable.

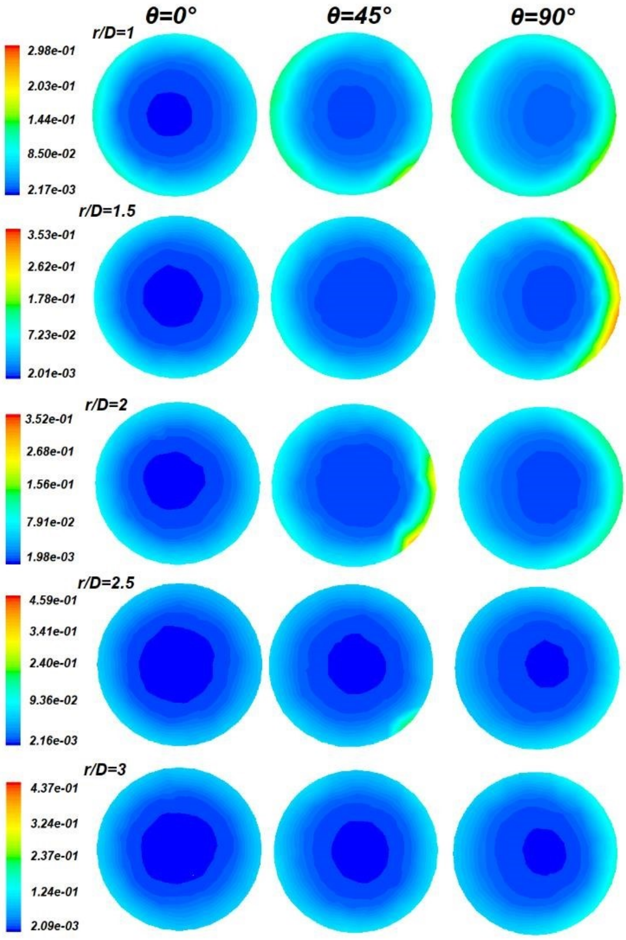

Figure 5.15: Variation in turbulence intensity with R/d ratio

5.16 VELOCITY CONTOURS FOR ZINC TAILING WATER SLURRY

The variation of the R/d ratio on the velocity across the various positions of the bend section is shown in the Figure 5.16 with the help of contours. The concentration of the zinc tailing-water slurry was kept constant i.e. 55% for flow velocity of 5 m/s. It has been noticed from the contours that maximum velocity region was stick to the internal periphery of bend whereas minimum velocity region seen at the outer periphery. The maximum variation in velocity was seen in contours of bend having R/d ratio 1.0. As the R/d ratio is increased from 1.0-3.0 the uniformity of velocity distribution increases. This means that with the increase in R/d ratio the flow becomes more uniform. Also, at lower bend curvatures the disturbance was more. The disturbance was the result of secondary flow and flow separation phenomenon. Hence more loses are there at lower R/d ratio that result into higher pressure drop.

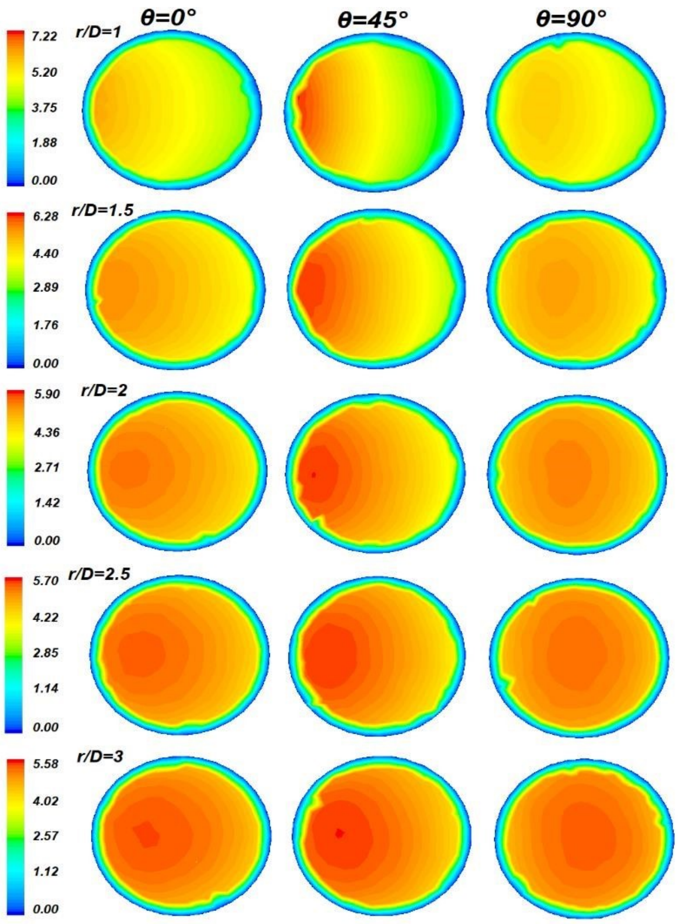

Figure 5.16: Effect of R/d ratio on velocity contours

Chapter 6
CONCLUSION

In present investigation, the pressure drop characteristics of zinc tailing-water slurry flowing in a 90° pipe bend have been studied. The experimental results were validated with different turbulence models. Numerical simulations were performed on range of solid slurry concentrations. The solid concentration is kept in the range of 25-55% (by weight). The velocity of the slurry is retained within the range of 2-5 m/s. The following conclusions based on results and discussion are made,

- Zinc tailing particles are non-spherical in shape and have knife edge structure. The maximum static settled concentration of zinc tailing slurry was found as 52.61, 54.02, 61.99 and 65.62% for solid concentration of 25, 35, 45 and 55% respectively. The pH of slurry was lies within the range of 7-7.3.
- The slurry exhibits Newtonian flow behaviour for solid concentration range of 25-35%. Whereas, the increase in solid concentration from 35-55% results in change in flow behaviour to Bingham plastic flow nature.
- The addition of coarse particles 150-250 μm size results in appreciable decrease in apparent viscosity in fine (<53 μm) particulate slurry. The maximum percentage decrease in apparent viscosity was observed with 20% addition of coarse particles.
- The Standard k-ε model provides better agreement with experimental data with percentage deviation of 7.65%.
- Pressure drop is increased with solid concentration and flow velocity. At the flow velocity of 5 m/s the pressure drop is increased by 13.29, 13.73 and 14.98% as solid concentration is increased from 25-35, 35-45 and 45-55% respectively.
- An increase in curvature of pipe bend leads to enhance the pressure drop characteristics of zinc tailing-water slurry. The minimum pressure drop is observed in pipe bend having R/d ratio of 2.0 for low flow rates. Whereas at high flow rates the optimum R/d ratio is noticed for pipe bend possessing R/d ratio 2.5.

6.1 FUTURE SCOPE

Present study was focused on rheological characteristics of zinc tailing water slurry by considering the influence of particle size only. The effect of additives or stabilizers can also be studied to improve rheological characteristics of slurry. Also, the pressure drop characteristics was only investigated for 90° bend. Further study can be extended for different geometrical configurations like 45° bend, 135° bend, and converging/diverging sections.

REFERENCES

1. Assefa, K. M., and D. R. Kaushal. "Experimental study on the rheological behaviour of coal ash slurries." *Journal of Hydrology and Hydromechanics* 63, no. 4 (2015): 303-310.
2. Buranasrisak, Patnaree, and Monpilai H. Narasingha. "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, no. 1 (2012): 31-35.
3. Chen, Xin, Jian Zhou, Qiusong Chen, Xiuzhi Shi, and Yonggang Gou. "CFD simulation of pipeline transport properties of mine tailings three-phase foam slurry backfill." *Minerals* 7, no. 8 (2017): 149-160.
4. Gheshlaghi, Majid Ebrahimzadeh, Ataallah Soltani Goharrizi, Alireza Aghajani Shahrivar, and Hadi Abdollahi. "Modeling industrial thickener using computational fluid dynamics (CFD), a case study: Tailing thickener in the Sarcheshmeh copper mine." *International Journal of Mining Science and Technology*23, no. 6 (2013): 885-892.
5. Hashemi, S. A., A. Sadighian, S. I. A. Shah, and R. S. Sanders. "Solid velocity and concentration fluctuations in highly concentrated liquid–solid (slurry) pipe flows." *International Journal of Multiphase Flow* 66 (2014): 46-61.
6. Hossain, Alamgir, Jamal Naser, and Monzur Alam Imteaz. "CFD investigation of particle deposition in a horizontal looped turbulent pipe flow." *Environmental Modeling & Assessment*16, no. 4 (2011): 359-367.
7. Kumar, K., S. Kumar, M. Gupta, H. C. Garg, and G. Singh. "Measurement of flow characteristics for multiparticulate bottom ash-water suspension with additives." *Journal of Residuals Science & Technology* 14, no. 1 (2017): 1011-1017.
8. Kwak, Minkyung, David F. James, and Katherine A. Klein. "Flow behaviour of tailings paste for surface disposal." *International journal of mineral processing* 77, no. 3 (2005): 139-153.
9. Li, Lei, Hiromoto Usui, and Hiroshi Suzuki. "Study of pipeline transportation of dense fly ash-water slurry." *Coal preparation*22, no. 2 (2002): 65-80.
10. Liu, E. J., K. V. Cashman, A. C. Rust, and A. Höskuldsson. "Contrasting mechanisms of magma fragmentation during coeval magmatic and hydromagmatic activity: the Hverfjall Fires fissure eruption, Iceland." *Bulletin of Volcanology* 79, no. 10 (2017): 68-81.

11. Mazumder, Quamrul H. "CFD analysis of the effect of elbow radius on pressure drop in multiphase flow." *Modelling and Simulation in Engineering* 2012 (2012): 37-51
12. Merrill, Javier, Leandro Voisin, Victor Montenegro, Christian F. Ihle, and Angus McFarlane. "Slurry rheology prediction based on hyperspectral characterization models for minerals quantification." *Minerals Engineering* 109 (2017): 126-134.
13. Nabil, Tamer, Imam El-Sawaf, and Kamal El-Nahhas. "Computational fluid dynamics simulation of the solid-liquid slurry flow in a pipeline." In *Proc. 17th International Water Technologies Conference IWTC17*, vol. 57. 2013
14. Nayak, Bibhuti Bhusan, Dipankar Chatterjee, and Amar Nath Mullick. "Numerical prediction of flow and heat transfer characteristics of water-fly ash slurry in a 180 return pipe bend." *International Journal of Thermal Sciences* 113 (2017): 100-115.
15. Ofei, Titus Ntow, and Aidil Yunus Ismail. "Eulerian-Eulerian simulation of particle-liquid slurry flow in horizontal pipe." *Journal of Petroleum Engineering* 2016 (2016):1-10
16. Panda, D., and B. Pradhan. "Hydraulic transport of fly ash and fly ash-bottom ash mixtures at high concentrations." *International Journal of Chemical Engineering and Applied Sciences* 4, no. 1 (2014): 1-4.
17. Rawat, Anubhav, S. N. Singh, and V. Seshadri. "Computational methodology for determination of head loss in both laminar and turbulent regimes for the flow of high concentration coal ash slurries through pipeline." Particulate Science and Technology 34, no. 3 (2016): 289-300.
18. Senapati, Pradipta Kumar, Dibakar Panda, and Ashutosh Parida. "Predicting viscosity of limestone–water slurry." *Journal of minerals and materials characterization and Engineering* 8, no. 03 (2009): 203-221.
19. Singh, Mani Kanwar, Dwarikanath Ratha, Satish Kumar, and Deepak Kumar. "Influence of particle-size distribution and temperature on rheological behavior of coal slurry." *International Journal of Coal Preparation and Utilization* 36, no. 1 (2016): 44-54.
20. Slatter, P. T., and K. D. Seddon. "Evaluation of the rheology of pipehead flocculated tailings." In *Proceedings of the 18th International Seminar on Paste and Thickened Tailings*, pp. 131-137. Australian Centre for Geomechanics, 2015.
21. Tarodiya, Rahul, and Bhupendra K. Gandhi. "Hydraulic performance and erosive wear of centrifugal slurry pumps-A review." *Powder Technology* 305 (2017): 27-38.
22. Trahan, Jamie, Alessandro Graziani, D. Yogi Goswami, E. Stefanakos, Chand Jotshi, and Nitin Goel. "Evaluation of pressure drop and particle sphericity for an air-rock bed thermal energy storage system." *Energy Procedia* 57 (2014): 633-642.

23. Tebowei, Roland, Mamdud Hossain, Sheikh Zahidul Islam, Mohamad Ghazi Droubi, and Gbenga Oluyemi. "Investigation of sand transport in an undulated pipe using computational fluid dynamics." *Journal of Petroleum Science and Engineering* 162 (2018): 747-762.
24. Verma, Abhai Kumar, S. N. Singh, and V. Seshadri. "Pressure drop for the flow of high concentration solid-liquid mixture across 90º horizontal conventional circular pipe bend." (2006):477-483.
25. Vieira, Marcos Gomes, and Antonio Eduardo Clark Peres. "Effect of rheology and dispersion degree on the regrinding of an iron ore concentrate." *Journal of Materials Research and Technology* 2, no. 4 (2013): 332-339.
26. Wu, Di, Baogui Yang, and Yucheng Liu. "Pressure drop in loop pipe flow of fresh cemented coal gangue–fly ash slurry: experiment and simulation." *Advanced Powder Technology*26, no. 3 (2015): 920-927.
27. Yuchi, Wei, Baoqing Li, Wen Li, and Haokan Chen. "Effects of coal characteristics on the properties of coal water slurry." *Coal Preparation* 25, no. 4 (2005): 239-249.
28. Zhou, Mingsong, Bing Pan, Dongjie Yang, Hongming Lou, and Xueqing Qiu. "Rheological behavior investigation of concentrated coal-water suspension." *Journal of Dispersion Science and Technology* 31, no. 6 (2010): 838-843.

PUBLICATIONS

- Paras Verma, Satish Kumar, Jatinder Pal Singh, and Kundan Lal. "Prediction of pressure drop for the flow of zinc ore-water suspension in horizontal pipeline." In IOP Conference Series: Materials Science and Engineering, vol. 455, no. 1, p. 012135. IOP Publishing, 2018.
- Paras Verma, Satish Kumar, Jatinder Pal Singh, and Kundan Lal "CFD simulation of 90° pipe bend for multiphase flow of zinc-tailing water slurry".TFEC-2019, Las Vegas USA. (Accepted).