FLOW CHARACTERISTICS STUDY OF FLY ASH SLURRY IN HYDRAULIC PIPELINES USING COMPUTATIONAL FLUID DYNAMICS

Thesis Submitted in partial fulfillment of the Requirements for the degree of

MASTER OF TECHNOLOGY

IN

MINING ENGINEERING

BY

SHARON A BADARUDEEN

212MN1463

Under the Guidance of
Prof. HRUSHIKESH NAIK

DEPARTMENT OF MINING ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY

ROURKELA-769008

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Dedicated to My Parents

Department of Mining Engineering
National Institute of Technology
Rourkela-769 008, Odisha, India.

CERTIFICATE

This is to certify that the work in the thesis entitled, "**Flow characteristics study of fly ash slurry in hydraulic pipelines using computational fluid dynamics**" submitted by **Sharon A Badarudeen** is a record of an original research work carried out by him during 2013 - 2014 under my supervision and guidance in partial fulfillment of the requirements for the award of the degree of Master of Technology in Mining Engineering, National Institute of Technology Rourkela. Neither this thesis nor any part of it has been submitted for any degree or academic award elsewhere.

Prof. Hrushikesh Naik

Head of the Department

Department of Mining Engineering

National Institute of Technology, Rourkela

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In pursuit of this academic endeavor, I feel singularly fortunate. Inspiration, direction, cooperation, love and care all came in my way in abundance and it seems almost an impossible task for me to acknowledge the same in adequate terms. Yes, I shall be failing in my duty if I do not record my profound sense of indebtedness and heartfelt gratitude to my supervisor Prof. ***Hrushikesh Naik*** *who guided and inspired me in pursuance of this work. His association will remain a beacon light to me throughout my career.*

Next I have to thank my senior and brotherly ***Shaibu V B*** *for his suggestions and support throughout my work. I would like to thank all my friends especially Vishal, Akhil, Shince, Sandeep, Arjun and Midhun for their endless support for the betterment of the work.*

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I would like to thank whole heartedly my parents and family members whose love and unconditional support, both on academic and personal front, enabled me to see the light of this day.

Finally, I humbly bow my head with utmost gratitude before the God Almighty who always showed me a path to go and without whom I could not have done any of these.

Sharon A Badarudeen

ABSTRACT

Transportation of fly ash slurry via pipelines has been recognized as a potential economical and dependable mode of solid transportation. It also bids various other advantages over the conventional means of transportation. For improved understanding of the flow characteristics of these pipelines, investigators throughout the world have been analyzing the flow experimentally numerically and theoretically. Slurry pipeline systems are regularly used crosswise the world for the transportation of fly ash from the power plant to the ash ponds. These pipeline are very much energy exhaustive and also leads to disproportionate and inordinate wear of pipelines and wastage of water.

Objective of the present work is to conduct a methodical and logical study of fly ash slurry transportation in a pipeline at higher concentrations by the use of computational fluid dynamics and study the flow characteristics and pressure drops. An effort has been made in this study to develop comprehensive slurry flow model using CFD and utilize the model to predict pressure drop and validating the results with the calculated results. A broad computational fluid dynamics (CFD) model was established in the current study to gain understanding into the solid liquid slurry flow in pipelines.

The approach adopted in here is studying and solving the problem by mathematical modeling method. In this work, the solid suspension in a fully developed pipe flow was simulated and analyzed

A 20m pipe with a diameter of 0.5m is modeled, through which flow is conducted where modelling and meshing is done using ANSYS Fluent. High viscosity fly ash slurry with five different concentrations, 50%, 60%, 65%, 68% and 70% by weight of fly ash is passed and for each concentration five different velocities like 3, 3.5, 4, 4.5 and 5 m/s are used and pressure drops are calculated. Other characteristics studied are volume fraction, eddy viscosity and turbulence kinetic energy.

Keywords: Computational fluid dynamics, Eulerian-Eulerian approach, pressure drop, fly ash, viscosity.

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ABBREVIATIONS

CCR	Coal Combustion Residuals
CCP	Coal Combustion Products
FGD	Flue Gas Desulfurization
HCSD	High Concentration Slurry Disposal
CFD	Computational Fluid Dynamics
GPS	Global Positioning System
LDS	Leak Detection System
CTAB	Cetyltrimethyl Ammonium Bromide
NaSal	Sodium Salicylate
PEPT	Positron Emission Particle Tracking
DEM	Discrete Element Method
ASM	Algebraic Slim Mixture
DNS	Direct Numerical Simulations
VOF	Volume of Fluid Model
RNG	Renormalization Group
Re	Reynolds Number
St	Stokes Number
TKE	Turbulence Kinetic Energy

NOMENCLATURES

ε	Epsilon
ω	Omega
ρ	Density of the fluid
u	Velocity of fluid
p	Pressure
τ	Viscous stress tensor
g	Gravity vector.
α	Volume fraction
S_{mass}	Mass source term between phases
S_p	Momentum source term between phases
F	Force
U	Mean Velocity field
P	Mean pressure of the phases
l	Length of the pipe
d	Diameter of the pipe
μ	Dynamic viscosity of the fluid
λ	Pipe friction coefficient
Cw	Concentration by weight

CHAPTER 1

INTRODUCTION

In a thermal power station or a thermal power plant steam is the prime mover. Every day a huge quantity of coal is burned which produces ash, now and again being as much as 10 to 20% of the total amount of coal burned. Ash is present in all available forms of coal. Whenever coal is burnt in thermal power plant or in a boiler furnace it gives ash as a share of 10 to 20% of coal burnt. As the modern thermal power plants and large steam power plants where abundant amount of coal is burnt, the share of ash may go up to a range of thousands of tons per year. When we consider the case of India we can see that of the total electrical energy is produced from the thermal power plant which in turn produces a share of 170 million tons of fly ash as solid leftover yearly. Ash handling and disposal has always been a task for any industries using coal as the prime fuel. Figure 1.1 depicts a schematic view of ash production in power plants.

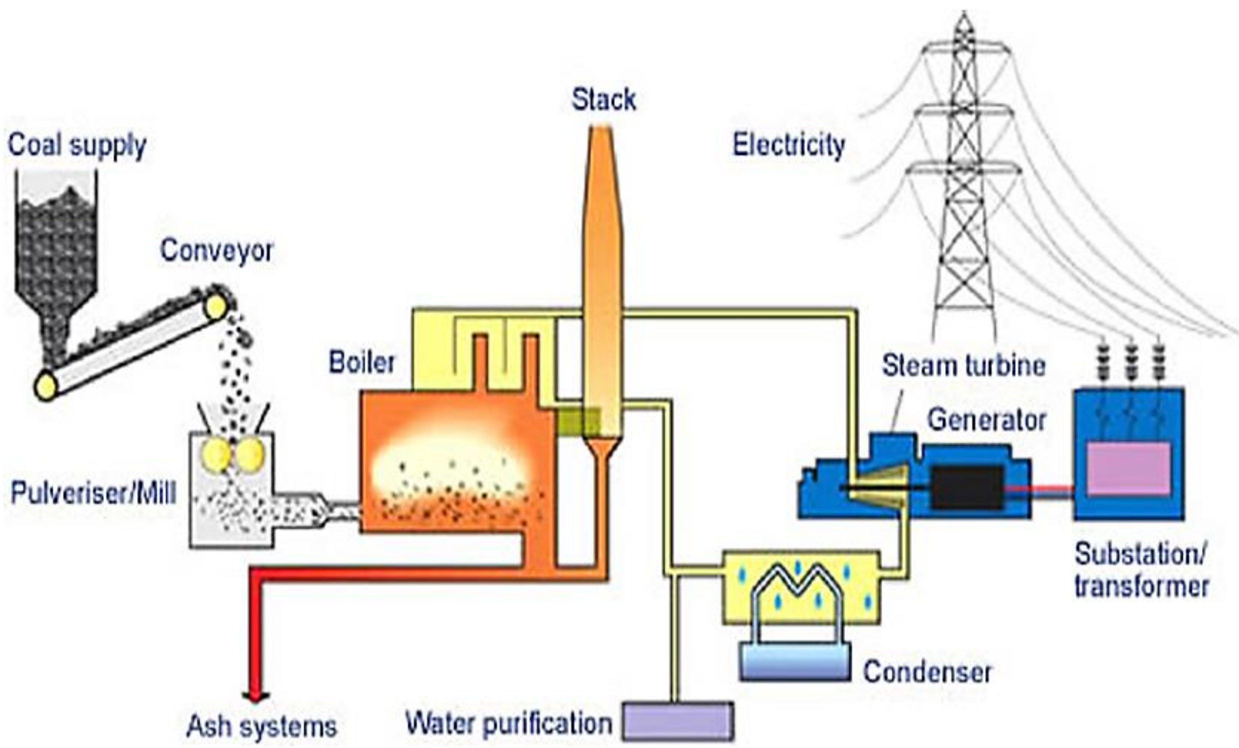


Figure 1.1: Power plant utilizing coal for production of electricity [1]

1.1 COAL COMBUSTION RESIDUALS

In coal-fired power plants, Combustion of coal produces materials called as Coal Combustion Residuals (CCR), which are otherwise called as Coal Combustion Products (CCP). The materials which come under this category are:

- Fly Ash
- Bottom Ash
- Boiler Slag
- Flue Gas Desulfurization Material (FGD)
- Material such as fluidized bed combustion ash and scrubber residues

There are a lot of differences in features and physical properties of CCRs. Beneficial reuse of building materials and replacement for other components like sand, gravel, or gypsum is determined by their size, shape, and chemical composition.

One of the excellent examples of implementation of CCR is EPA (Sustainable Materials Management Program Implementation). It also leads to generation of environmental, economic and performance benefits significantly. Coal combustion residuals can be substituted for another product using CCR's involvement based on performance criteria.

1.1.1 Fly Ash

The physical description of fly ash is that it is a very fine powdery material having the composition of silica (mostly) being spherically shaped. Presence of silt-sized and clay-sized glassy spheres give the fly ash a light tan colour thereby making it consistent with talcum powder. Fly ash is produced by burning finely ground coal in a boiler furnace to produce electricity. Primarily devices like electrostatic precipitators or bag houses remove exhaust gases from the plant and secondarily scrubber systems serve for the same.

Ordinary temperatures and presence of water makes fly ash a siliceous material react with calcium hydroxide producing cementatious compounds. Fly ash has an extensive role to play in cement and concrete usages mostly for its spherical shape and pozzolanic properties. These properties make it a good mineral filter which is used in hot mix asphalt usages thereby leading to the improvement in fluidity of flow able fill and grout in cases of use of these applications.

Uses of fly ash applications:

- Used as a raw component in concrete yields and grout
- Feed stock in manufacture of cement
- Fill material for structural uses and embankments
- Constituent in waste stabilization
- Element in soil alteration and stabilization
- Constituent of flow able fill
- Constituent in road bases and pavements
- Mineral putty in asphalt

1.1.2 Bottom Ash

The bottom ash is an agglomerated ash element, molded in milled coal furnaces. The bottom ash are comparatively too large and cannot be carried in the flue gases. They impose on the furnace walls or drop through open lattices where an ash hopper is there at the bottom of the furnace. Physically, bottom ash can be described as classically grey black in colour, being moderately angular in structures, and having a porous surface structure.

Bottom ash varies with fine sand grain sizes to fine gravel grain sizes. Bottom ash is well graded to meet gradation demands thereby avoiding the want of blending with other aggregates. Unlike conventional aggregates the bottom ash having structure of porous surface are different to wearing surface mixtures makes-

- The material less durable
- More suitable in base course,
- Suitable for use in shoulder mixtures,
- Suitable for many cold mix applications
- Lighter than conventional aggregate

Bottom ash applications are:

- Used as putty material in structural usages and embankments
- Constituent in road bases and pavements
- As a feed stock in the making cement
- Constituent of lightweight concrete goods
- Snow and ice traction regulator material

1.1.3 Boiler Slag.

The boiler slag is described as a composition of hard, black, angular particles giving a smooth, glassy outlook. The slag tap and cyclone type furnace produces the bottom ash at the base in molten form generally referred to as boiler slag.

Physically boiler slag, a black granular material can be described to be hard, uniformly sized and durable resisting to surface wear. Permanent black colour in boiler slag is highly required for asphalt applications thereby helping in snow melting. Removal from service of old power plants producing boiler slag has decreased its supply value.

Boiler slag applications include its use as a:

- Constituent of blasting grit and roofing granules
- Mineral putty in asphalt
- Seal material for structural uses and embankments
- Raw material in concrete goods
- Snow and ice traction control substance

1.1.4 Flue Gas Desulfurization Material

In coal fired boilers for avoiding SO_2 emissions from the exhaust gas systems refers to a process whose product is otherwise called as Flue Gas Desulfurization (FGD) material. A varying range from wet sludge to a dry powdered material decides the physical nature of FGD depending upon the process.

The dry material from dry scrubbers consists of a mixture of sulfites and sulfates that is captured in a bag house. This powdery substance is mostly called as dry FGD Material, lime spray dryer ash or dry FGD ash. FGD gypsum constitutes small, fine particles.

Calcium sulfate FGD material can be used as a substitute for gypsum in the production of cement. Once it has undergone dewatering, it can be utilized for wallboard manufacturing, which is the largest single market for FGD material. Calcium sulfite FGD material finds its use as an embankment and road base material

FGD material applications include its use as a:

- Raw good for wallboard
- Seal material for structural usages and embankments
- Feed stock in manufacturing of cement
- Raw material in concrete goods and grout
- Constituent in waste stabilization

1.2 COAL ASH DISPOSAL

1.2.1 Coal Ash Disposal Using Slurry Pumps

Choice of pumping arrangement for any slurry transportation is overseen more by the practical concerns rather than chastely on economic concerns of supreme efficiency. However, discharge pressure and abrasivity are the two significant factors for the selection of a pump. The main differences of slurry pumps from conventional pumps are:

- Presence of a stronger frame
- Having a heavier shaft
- Minimum impeller overhang
- More corrosion resistivity

1.2.2 Slurry Pump Selection Parameters

There are certain parameters which are to be taken into account for the correct and proper selection of a slurry pump in any slurry transport system, which are:

- Particle maximum size
- Particle size distribution
- Solids abrasivity
- Solids friability
- Particle shape
- Particle hardness
- Solids content
- Flow properties
- Slurry density
- Corrosivity
- Gas content
- Temperature
- Volume flow rate
- Reliability
- Cost

1.2.3 Working Principle of a Slurry Pump

Slurry pumps are those types of centrifugal pumps or peristaltic hose pumps which increase the pressure of solid and liquid particle mixture through centrifugal force and convert the electrical energy into slurry potential energy and kinetic energy. Many industries such as gold, silver, steel, iron ore, tin, coal, titanium, lead and zinc, copper, mineral sands, sand and gravel, agriculture uses slurry pumps for transporting corrosive or abrasive and high concentration slurry. The main components of a slurry pump are impeller, casing, shaft and bearing assembly, shaft sleeve, shaft seal and drive type.

The slurry pumps work on the principle of forced vortex flow that is when a specific mass of liquid is rotated by an external flow, an increase in the pressure head of the rotating liquid occurs. This rise of the pressure head at any point of the rotating liquid is directly proportional to the square of the tangential velocity of the liquid at that same point. This show at the outlet of the impeller where the radius is more, the increase in pressure head will be high and the liquid will be discharged at the outlet with high pressure head. So head liquid can be lifted to a high level due to this high pressure. Figure 1.2 shows the components of a slurry pump.

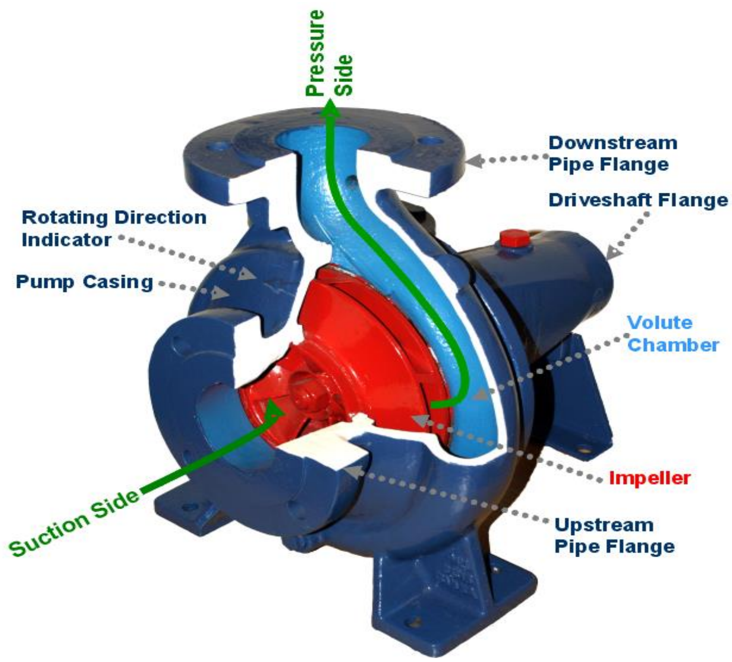


Figure 1.2: Components of slurry pump [2]

1.2.4 Pipeline Transportation of Coal Ash Slurry

Transportation of fly ash slurry via pipelines has been recognized as a potential economical and dependable mode of solid transportation. It also bids various other advantages over the conventional means of transportation. For improved understanding of the flow characteristics of these pipelines, investigators throughout the world have been analyzing the flow experimentally numerically and theoretically. The center of their investigation has been chiefly towards improvement in the elementary design of these pipelines, which includes a complex reliance on various geometrical and dynamical restraints.

Slurry pipelines are regularly used crosswise the world for the shipping of coal ash both fly ash and also the bottom ash from the power plant to the ash ponds. Majority of the pipelines functioning today in thermal power plants carries ash at low or intermediate concentrations over short as well as medium distances. These pipeline systems are very much energy intensive and also leads to excessive and inordinate wear of pipelines and wastage of water. Moreover, the current improved consciousness on the road to the inequity in the eco-system and connected stringent government policies are compelling the thermal power plants to implement environment friendly transportation systems. Here emerges the high concentration slurry disposal (HCSD) system has as a preferred choice to transport coal ash in thermal power plants as it is both economical and environment friendly. Figure 1.3 shows the projected energy usage in 2035 around the globe.

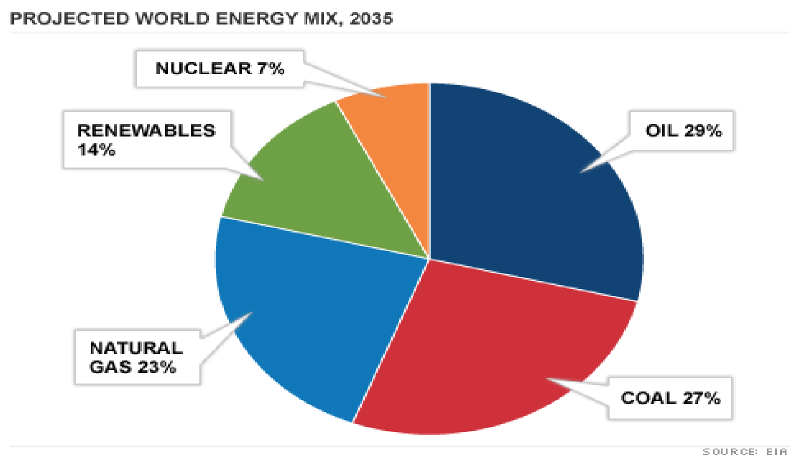


Figure 1.3: Projected energy usage in 2035 around the globe [3]

Investigators over the years have studied the dense phase conveying of liquid solid mixture in both horizontal and vertical pipelines and they have found that dense phase flow is possible at low velocities with overall pressure drop being small. Researchers detected that at a solid concentration above 40% by weight, fly ash slurries acquit like non-settling homogenous slurry and the pipe flow can be sustained in laminar regime at moderately lower velocities. So at low velocities, the pipeline will be exposed to minimal erosion wear. They also concluded that the safe limit of pumping for a centrifugal pump is a concentration of 50% by weight of coal ash and above this positive displacement pumps may become essential to pump coal ash slurries. Moreover a good awareness of slurry rheology is of very much importance principally in the

High concentration slurry transportation. So it is vital to launch the precise rheological nature of coal ash slurries at high concentration.

Objectives

The objective of the present work is to conduct a methodical and logical study of coal ash slurry transportation in a pipeline at higher concentrations by the use of computational fluid dynamics and study the flow characteristics and pressure drops.

1.3 COMPUTATIONAL FLUID DYNAMICS

CFD was established during the second half of the 20^{th} century and it became a well-known analysis tool for single-phase flow analysis during the 90ies with the arrival of commercial CFD software such as ANSYS CFX and ANSYS Fluent. The role of CFD in the area of multiphase flow is not as recognized. However, with the improvement of computer resources, making extra complex analyses probable, along with the assimilation of multiphase flow models in commercial programs such as those formerly mentioned, CFD is now attaining more importance also in this area.

Multiphase flow is now a phenomenon in many industrial procedures, amongst them the oil and gas industry and power plants are the main. Enormous amounts of oil and gas are consumed on a regular basis and even a small improvement in extraction efficiency will have a noteworthy impact on revenues for companies in the oil and gas industry. So, discovering reliable analysis tools for inferring and optimization of multiphase flows is a primacy for these companies.

Numerous error sources occur for numerical simulations and numerical approximation errors will constantly occur but added error source, which often is hard to detect, is usage error. This can happen due to accidental application of models, badly chosen constraints or wrongfully implemented boundary conditions can lead to unphysical and erroneous results. With the prolonged use of CFD simulations in engineering works it is of high relevance to investigate the accurateness of commercial codes as well as understanding the selection of models. As not much published works have been done on judging and studying commercial CFD codes and as the models and codes may be envisioned and established for a certain multiphase area, what is precise and appropriate for one business zone might be inappropriate to use for another field.

Therefore, there is a necessity to examine and associate the models available to develop an information base for multiphase flow simulations expending commercial software in the oil and gas business.

An effort is made in this study to develop comprehensive slurry flow model using Computational fluid dynamics and utilize it to predict pressure drop and validating the results with the calculated results. A broad CFD model was established in the current study to gain understanding into the solid-liquid slurry flow in pipelines. In contemporary years, CFD has become a powerful instrument which can be used in the area like fluid flow, heat and mass transfer, chemical reactions and associated phenomena by resolving mathematical equations that manage these processes by means of a numerical algorithm on a computer.

In the case of solid-liquid multiphase flows, the intricacy of modelling surges noticeably and this remains a zone for more research and improvement. Due to the characteristic complexity of multiphase flows, from a physical as well a numerical point of interpretation, “general” related CFD codes are non-surviving.

Taking into account the restrictions in the published works, the current work has been made effort to systematically make a CFD based model to analyze and predict the solid concentration profile in slurry pipeline. The purpose is to inquire into the capability of CFD to model such complex flow.

In this work, the solid suspension in a fully developed pipe flow was simulated and analyzed. The two-fluid model based on the Eulerian-Eulerian method beside with a standard k-ε turbulence model with mixture properties was taken.

CHAPTER 2

LITERATURE REVIEW

A comprehensive literature survey is carried out on the slurry transport and Computational fluid dynamics simulation and analysis of the flow properties. Research and studies on this field was started a long back and a few of those research works are presented in this chapter. The review is divided into some modules or sub-reviews such as theoretical studies, experimental studies and numerical studies. Based on this important review papers, scope and objective of the present study is established.

This chapter gives an insight into the present state of knowledge about the flow characteristics in these pipelines by exploring the obtainable literatures. This has also aided to decide the scope of the present study.

2.1 THEORETICAL STUDIES

W. Lee Daniels *et al.*[4] [2002] studied about coal fly ash and its beneficial reuse in Appalachian coal mining environments. They did not simply considered fly ash for the co-disposal of fly ash in mine fills, but environmentally safe use of it for purposes such as prevention of acid mine drainage or improvement of mine soil properties for re-vegetation. They concluded that fly ash can be beneficially used an agricultural amendment as it contains spherical amorphous alumino-silicate silt-sized particles. Alkaline fly ash acts as a liming material, and many ashes also provides micronutrients such as B, Mo, and Zn and many other trace elements are found in phytotoxic levels in fly ash. Fly ash can also be positively employed as a surficial soil modification to mine spoils or coal waste to enhance water holding capacity, soil pH, and certain macro- and micro-nutrient levels.

Nigel Heywood[5] [2003] has described three alternative methods to reduce pipe friction for highly viscous often non-Newtonian slurries. First method is by adding soluble ionic compounds to flocculated slurries which can result in significant pressure drop reductions in pipe flow in the laminar flow regime. Second is by injecting of water, aqueous polymer solution, heating oil or polyelectrolytes into the pump discharge pipe using a proper injection ring, thus creating a lubricating annulus in the pipe for the viscous slurry. Third is by injection of air or inert gas into the pump discharge pipe to lessen the proportion of the inner pipe wall wetted by viscous slurry. All these above methods have shown a pressure reduction from 50-90%.

Halima *et al.*[6] [2011] has explained the calculation of wall thickness for long distance slurry pipeline. Taken into account the relatively lesser velocity and around 20 years of expected life time of pipelines, it was implemented approximately double value for wall thickness. Supply and discharge pipelines, made of polyethylene of high density material, were installed in sticks about ten meters long with flange adapters. This technology completely used fly ash and bottom ash characteristics and all negative influences on production were eradicated.

Seshadri *et al.*[7] [2001] have mentioned that in India, slender phase fly ash slurry disposal system is by far the most extensively used method of ash transportation in the prevailing thermal power plants. The normal range of the ash concentration is around 10-15% (by weight). The design is extremely conservative and accordingly the system is very inefficient from the point of energy consumption. They have auxiliary shown that medium concentration slurry (Cw=40-50% by weight) can be easily transported by conventional centrifugal slurry pumps which are being used for ash disposal at the thermal power plants. For the dense phase fly ash dumping system, they have opined that, the concentration of ash should be above Cw > 60% by weight. At these higher concentrations distinct types of slurry pumps are essential to pump the slurry.

Bunn *et al.*[8] [1993] found that the ash slurries shows a non-Newtonian nature with rheological equation showing either Bingham or yield pseudo-plastic behavior. Different samples of fly ash collected from different power plants showed a difference in the rheological parameters like yield stress and Bingham plastic viscosity over a wide range. Thus, it is very vital to measure these factors before the ash disposal pipeline is planned. Once the rheological behavior of the slurry is established the head requirements for operating fly ash disposal pipelines at higher concentrations can be easily calculated. It is probable to reduce the head requirements by adding additives, which have dispersing/wetting as well as shear thinning properties.

Taimoor Asim *et al.*[9] [2012] worked on getting an optimal sizing of pipeline transporting solid-liquid mixture. Least cost principle was used in sizing such pipelines, which involves the determination of pipe diameter for given solid throughput corresponding to the minimum cost. Transportation of slurry having solids of homogeneously graded particles size has been included in the detailed analysis. This proposed procedure can be used for designing a pipeline for transporting any solid material for different solids. The flow parameters considered to the optimal size of the pipeline was taken in the normal range of operations.

Fethullah Canpolat1[10] [2011] described various coal combustion products and the current recycling use options of these materials. Materials, productions, properties, potential applications in production of evolving materials for supportable construction, as well as environmental impact were studied. He proposed that recycling not only helps disposal costs but also helps to conserve natural resources and it technical and economic benefits. Some of the uses of fly ash he mentioned in the study was using it as a constituent in blended cement, as an auxiliary of sand in making CLSM, in producing of light weight aggregates, in manufacturing high performance concrete, making super-plasticized structural grade concrete by substituting more than 50% of cement, as a filler in polymer matrix composite, as a replacement of 30 to 100% silica sand in manufacturing autoclaved cellular concrete.

Roy Betinol G *et al.*[11] [2009] worked on developing a design of a commercial long distance slurry pipeline, and the intent of this work was to present the design process and debate any novel methods and approach used today to guarantee a better, safer and cost-effective slurry pipeline. It is vital to consider the position of facilities, pipeline route, characteristics of slurry and quantity of solids to transport to determine the utmost economical pipeline system to use, while the blend of these parameters describes the economic feasibility of the pipeline transport system. For designing minimum slurry velocity calculation, friction loss calculation, steady state hydraulic calculation, and transient hydraulic calculation are to be done. Global Positioning System (GPS), Leak Detection System (LDS), Expert Control Systems, on line Viscometer, On-Line Corrosion-Erosion Monitoring System are some of the technologies which has helped in design and safe operation of the pipelines.

P.Slatter[12] [2006] explained that the key issue while designing a plant for slurry handling is the understanding of the slurry environment. There is always a pressure for using less amount of water and more amount of slurry concentration in a slurry transportation system, which directly affects slurry flow. By using Bingham plastic rheological model the impact that slurry rheology has on transitional pipe flow was studied, particle settling in laminar shear flow, losses in valves and fittings, centrifugal pump derating and launder flow were also investigated. He concludes that study of slurry rheology is the main aspect for sound design of a slurry transport system.

Heping Cui *et al.*[13] [2007] gave a review about the flow of biomass multiphase flow investigating aqueous pulp fiber suspension and slurries, by studying recent experimental techniques and modeling works. They tell that in every flow even at a concentration level of less than 1% inter-particle forces are to be taken into account. Nuclear magnetic resonance imaging pulsed ultrasonic Doppler velocimetry, particle image velocimetry, flash X-ray radiography, dynamic panoramic viewing and laser Doppler anemometry are some advanced experimental techniques and flow devices which give some solutions by taking into account the inter-particle forces, but all these techniques have some limitations. They say that industrial biomass processes are being limited and their potential is not being realized due to the limitations in experimental techniques. They proposed some advanced softwares and techniques for overcoming these problems which include capacitance tomography, X-ray tomography, MRI, PDA or PDPA, gas/particle/liquid tracking techniques, optical probes and imaging techniques.

2.2 EXPERIMENTAL STUDIES

Experimental studies have provided the database for further developments in the design aspects of hydraulic transportation system. Researchers study some critical factors like pressure drop, velocity, concentration, drag, turbulence, phase interaction which will affect the flow characteristics of fly ash slurry through pipelines. Number of models has been developed and validated based on the experimental studies reported from time to time.

H.K.Naik *et al*.[14] [2011] evaluated the rheological characteristics of fly ash slurry with and without additives at varying temperature environment to facilitate smooth flow of materials in the pipeline. Surfactant like cetyltrimethyl ammonium bromide (CTAB) and a counter-ion called sodium salicylate (NaSal) was used in the experiment. Surfactant reduces surface tension of the slurry, thereby increasing its spreading and wetting properties. The best surfactant dosage was found to be 0.3%, at a temperature ranging from 25°C to 30°C, as it gives the lowest shear stress. An improvement in the suspension stability of slurry was also observed. It was observed that fly ash has got greater potential to be transported in the pipelines with the addition of cationic surfactant and a counter-ion which will reduce specific energy consumption and water requirements.

Sunil Chandel *et al*.[15] [2010] from their experiments with coal ash and water resolved that with increase in concentration, yield stress and Bingham plastic velocity of slurry increases swiftly.

From experiment it was detected that for slurry at a flow velocity of 2.0m/s approximate increase in solid concentration from 60.2% to 65.3%, increases the pressure drop by 16%. Relative pressure drop represents additional head required to transport slurry as compared to water. Specific energy consumption decreases up to a concentration of 65% by weight and steeply increases beyond this value.

N.R.Steward *et al*.[16] **[2009]** tested fly ash and water mixtures in a closed loop pipe system at solids concentrations extending from 51% to 74% by mass, in three different pipe sizes, 40, 50 and 65 nominal bore. The occurred flow behavior was presented on pipe flow curves, and the laminar flow data was used to rheologically describe the material as viscoplastic, using the Herschel-Bulkley rheological model. The data for the flow rate versus pressure gradient shows that, as the pipe diameter increases the pressure gradient decrease, as the flow rate increases the pressure gradient increases, as the relative density of the fly ash, or solids concentration, increases the pressure gradient increases.

Aguilar *et al.*[17] **[2006]** proposed, use of polymer and surfactant is the most effective drag reducing technique for turbulent flows. Drag reduction phenomenon for the first time was observed in 1948. They used tris tallowalkyl ammonium acetate as surfactant. However use of polymer solutions are frequently too computationally concerning and cumbersome to use and also usage of polymer solutions for closed loops can cause permanent degradation of the solution. So, surfactant solutions are favored, since they suffer only temporal degradation when a certain wall shear stress is surpassed, but recover their drag reducing capacity when shear stress is decreased.

G.S.F.Shire *et al.*[18] **[2008]** experimented the pressure drop behavior occurring when ice slurries flows through constrictions. They suggested that ice slurries when flowing through constrictions incurs lower pressure drops when compared with water flowing at the same rate through the same topology. Ice crystals used for this experiment was of 20-50μm wide and 100-200μm long and was created using Ziegra ice machine. Ice slurry was circulated through the experimental test section by using a pump and measurements were taken for flow velocity and pressure drop and the test was repeated for different ice fractions. A small pressure drop reduction was detected for ice slurries of over 40% solids when equated with the pressure drop for water at the identical mean flow rate. The reasons they are telling for this phenomenon is due to complex heat transfer and phase change phenomenon those occurring at the ice-wall interface and also due to the ice particles obstructing the onset of turbulence in the ice slurries.

Wilson[19] [1982] observed that optimization studies done for a range of delivered solid concentration of 20-60% by volume, for a variety of applied interest flow rates, gives a simple technique for approximating the pipe diameter and operating velocity which will optimize pipeline design. He showed that both pipe diameter and operating velocity are less for dense phase flow than for other types of slurry transport. He also found that the specific energy consumption for dense phase flow was rather lower than that for coarse particle flow at lower concentration.

M. Barigou *et al*.[20] [2002] worked on food sterilization process which involves the flow of solid-liquid mixture in pipes. In food sterilization process it is important to know the minimum and maximum passage times in the heating and holding sections of the food sterilization system. The technique used in this experiment was Positron Emission Particle Tracking (PEPT) technique, which was used to determine the trajectories of almost neutrally-buoyant 5–10 mm alginate spheres in viscous non-Newtonian solutions. Hall Effect sensors or visual tracers were used to measure the particle passage times. Experimental conditions used in this study was wide and different, they used solid fractions from 16 to 55% volume and the mixture velocity taken was from 20 to 230 mm/s. Results showed that there is an existence of four different distribution of passage times (PTD) depending on the flow pattern present. A good agreement was seen between the predicted and experimentally measured PTDs.

Abhai Kumar *et al.*[21] [2006] studied the pressure drop taking place across a 90^0 horizontal bend, through which high concentration fly ash slurry was passed. Slurry concentrations taken for this study was between 50-65 % (by weight) and the result was used to find out the relative pressure drop bend loss coefficient and permanent pressure loss. From the experiment it was found out that the relative pressure drop across the bend in the pipe increases as the concentration increases at low velocity, and as the concentration increases the bend loss coefficient also increases at any velocity. A marginal increase in the permanent pressure loss was also noted with increase in concentration and velocity.

Lei Li *et al*.[22] [2002] investigated the pipeline transport of water-fly ash slurry to find out suitable stabilizing additives for the slurry which will prevent the sedimentation of fly ash during the pipeline transport. Additives S-194, S-130, CMC, and Vanzan were used in this experiment and the rheological characteristics and sedimentation stability of the slurry were measured. They tried to maintain the viscosity of the stable slurry is approximately equal to the viscosity of the slurry without additives, because the same pump was used, since the viscosity of the slurry increases with the concentration of the stabilizing additives used in the slurry. It was found out that s-194 additive gave a better stability to the slurry compared to the other additives used in the experiment since it had long molecular branches.

L.M.Stanley *et al*.[23] [1973] investigated the flow properties of dairy waste slurries, which is a non-Newtonian flow, for providing a design data for pumping and transporting dairy manures as slurry. Hay fibers and wood chips were removed from the collected manure samples by passing it through a standard sieves with 595 µmol openings and viscosity of the slurry was calculated. Pumping trials were done through pipes of different diameters (3 inch and 4 inch) for different solid concentrations and pressure drops and sump level readings were taken at 60-s intervals. These results were compared with the theoretical calculated values and a high level of correlation was found out between the two. They conclude that the pipe with diameter 3 inch can be economically used in designing the dairy waste slurry system since it showed less deviation between the field and calculated results.

2.3 NUMERICAL STUDIES

R.C.Chen[24] [1994] gave a numerical model for slurry flows with solid concentration up to 20% by volume. A system of differential equations to attain axial velocities of the solid and liquid, the solid concentration and the liquid turbulent kinetic energy and dissipation rate for solid-liquid slurry pipe flow in the homogeneous flow regime was established. In spite of the small changes for 5% slurry flow the turbulent kinetic energy of both 5% and 15% slurry flows was also detected to increase in the region towards the wall and decrease in the core region. Limitations of this model were assumptions of zero solid molecular viscosity and isotropic turbulence structure for dense slurry flows.

Gilles *et al.*[25] [2000] improved their own model to enhance its capabilities to predict pressure drop for high solid concentration, approximately up to 0.63 (by volume fraction) for intermediate sized particles, especially those with narrow grading. An evaluation with experimental results of narrowly sized coarse particles of one mm and specific gravity of 1.59 for 0.105 m diameter pipeline was conducted and a rational matching at low velocities, but a significant deviation occurred at higher velocities was detected.

Slatter *et al.*[26] [2002] introduced an exciting finding that the Bingham plastic model offers fundamental advantages over pseudo plastic model. The model is predominantly useful and robust for the calculation of laminar/turbulent- transition and the connection of rheological parameters. Bingham plastic model can also be used for head loss predictions of laminar and turbulent flow.

Dominik Kubicki *et al.*[27] [2012] took experimental data of solid distribution in horizontal pipelines and modeled using CFD and Discrete Element Method (DEM). Experimental data used was of pipe diameter in the range from 51 mm to 103 mm, the average sand particle size from 90 μm to 4400 μm and average solid volume fraction from 0.092 to 0.21. Standard k-ε model was used for modeling the turbulent flow. Drag force acting on the particles was modeled using the Gidaspow formula. The Eulerian Multiphase model implemented correctly predicted the distribution of solid particles in horizontal pipes for a wide range of particle sizes, pipe diameters and flow rates. The predictions are close to the experimental data for cases when solids are well distributed and also when the distribution of solids is poor. When the ratio of pipe diameter to particle diameter is small, close to 10, the accuracy of Eulerian simulations decreases.

Jouni Syrjänen *et al*.[28] [2009] studied the mixing of sand-water slurry at varying consistencies in a laboratory scale cylindrical tank equipped with a 45^0 pitched blade turbine. Solid phases with volume fractions of 5% and 10 % were investigated. Ultrasound Doppler velocimetry was used to measure three-dimensional velocity profiles along lines located circumferentially between two baffles of the tank. Standard k-ε model was used in turbulence modelling. Relatively good agreement between the simulated and the measured particle velocities was found in the central region of the vessel. Deviation of the results was observed with increasing solid concentration near the wall. Eulerian multiphase model was tested with parameters corresponding meticulously to those used with algebraic slip mixture model. There was a deviation in the results obtained from measurements more than mixture model predictions.

Tamer Nabil *et al.*[29] [2013] made an attempt to develop a generalized slurry flow model using the CFD simulation technique to have better insight about the slurry flow in pipelines and its complexity. Prediction of concentration profile, velocity profile and their effect on pressure drop taking the effect of particle size into consideration was done using the model. First simulation was done using a 2D model and the influence of the particle drag coefficient with the different conditions was studied. Then, 3D model was generated to complete understand and visualize the slurry flow behavior.

J. Ling *et al.*[30] [2003] introduced a simplified 3D algebraic slip mixture (ASM) model to obtain the numerical solution in sand–water slurry flow. The RNG k-ε turbulent model was used with the ASM model for the study to obtain the precise numerical solution in fully developed turbulent flow. A block-structured non-uniform grid was used to discretize the entire computational domain, and to solve the governing equations a control volume finite difference method was used. The numerical investigation displayed some important slurry flow characteristics in a fully developed section, such as volume fraction distributions, slurry density, slip velocity magnitude, slurry mean velocity distributions, and slurry mean skin friction coefficient distributions. The ASM model gave a good prediction for the liquid–solid slurry flow, if the critical deposition velocity is lower than the slurry mean velocity. The numerical predictions for the pressure gradients showed a decent equality with the experimental data.

Jesse Capecelatro et al.[31] [2013] did simulation of liquid-solid slurries in horizontal pipes to study the complex multiphase dynamics related with the functioning conditions above and below the critical deposition velocities. An entirely conventional immersed boundary method is employed to reason the pipe geometry on a uniform Cartesian mesh. Two cases were considered, in the first case a Reynolds number based on the bulk flow of the liquid of 85,000, resulting in a heterogeneous suspension of particles throughout the pipe cross-section was taken. Data on the concentration and velocity of the particle phase for this case showed exceptional agreement with experimental results. In the second case, they considered a lower Reynolds number of 42,660, leading to the formation of a stationary bed of particles. Three different regions were recognized in the flow operated beneath the critical deposition velocity, equivalent to a rigid bed, a highlycollisional shear flow, and a freely-suspended particle flow. The maximum variations in concentration, liquid and particle velocities, and particle diameter were positioned in the region just above the surface of the bed.

Mikhail *et al*.[32] **[2013]** compared the turbulence models with the experimental data for the jets flowing from two nozzles with Ma = 2 and 3, half-angles [theta] a = 8 and 15 degrees, diameter of the critical cross section d = 10.6 mm to coaxial cylindrical bore with diameter d=85 mm and 4.6, 6 and 13.8 calibers long. Pressure was set full to the upstream of the nozzle, then intermediate result was noted and then total pressure was increased by 5 atm, and the results acquired in the earlier step were used as initial conditions. Thus they obtained the reliance of bottom pressure from the total pressure upstream of the nozzle. Different grids convergence and the effect of local grid refinement at the walls were examined. But for the calculation of supersonic flows in the unsteady conditions these turbulence models cannot be directly used, as in their derivation uses the average flow parameters over time. However, there are low-frequency vibrations, which belong to quasi-stationary class, i.e. whose period is significantly longer than the characteristic time of the occurring gas-dynamic processes.

Charlie *et al.*[33] **[2013]** studied different turbulent models like k- ε model, k- ω model and zero equation model to describe the permeability of turbulent water in an artificial crack and the results were compared to a "universal" equation of flow in a porous media based on empirical fit or Barr's model of a simple general check. Here the k- ω model was considered to be the most suitable model for the problem, the main reason for it is the limitations of the other models. Between the k- ε model, k- ω model and zero equation models the discrepancies were small. The main reason of difference between the models may be due to the nature of the state of interest and interpretations that were applied to it. The results of this paper are very much important in the field of hydraulic fracturing and enhanced oil recovery.

CHAPTER 3

MATHEMATICAL MODELLING

The approach adopted by me in studying and solving the problems is mathematical modeling method. It consists of mainly two parts, they are analytical solution method and simulation and analysis solver preference. My way of approach is solving the problem through numerical simulations and validation against theoretical data. Water-fly ash slurry flow through pipelines will be investigated by both the methods mentioned above to make sure to the credibility of the results.

The whole transportation system of fly ash slurry in power plants (Figure 3.1) consist of the following components like,

- Slurry mixer
- Stirrer
- Slurry pump
- Fly ash slurry pipe lines
- Pressure regulators
- Flow regulators
- Fly ash receiving ponds
- Return water pump
- Water pipeline back to the mixer

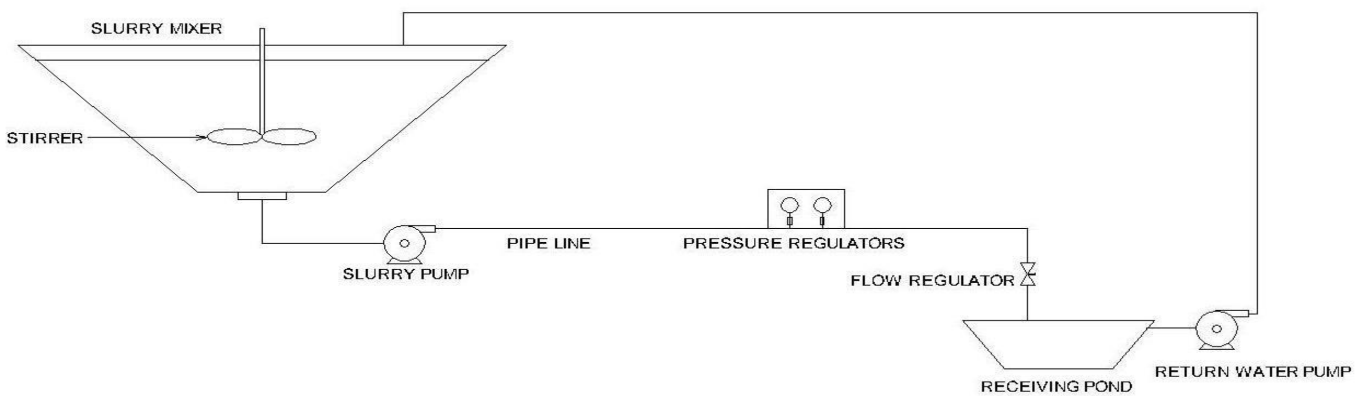


Figure 3.1: Fly ash slurry transportation system

3.1 ANALYTICAL SOLUTION METHOD

3.1.1 Multiphase Flow Theory

Physics of fluid flow are mathematically described using equations. Navier-Stokes equations also known as the continuity equation and the momentum equation are needed to describe the state of any type of fluid flow and are usually solved for all flows in CFD modeling, see equations 3.1 and 3.2 respectively. Additionally equations like energy equation and turbulence equation might also be needed to properly solve the flow problems satisfactorily depending on the nature of the flow.

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho u) = 0 \tag{3.1}$$

$$\frac{\partial \rho u}{\partial t} + \nabla.(\rho u u) = -\nabla p + \nabla.\tau + \rho g \tag{3.2}$$

Where ρ is density, u is instantaneous velocity, p is the pressure, τ is the viscous stress tensor and g is gravity vector.

Direct numerical simulations (DNS) are the process of solving the governing equations without any modeling. But running DNS-simulation is very much time consuming. In practice, all flows are turbulent and turbulent flow displays time scales of such pointedly different magnitudes that the mesh resolution needs to be so fine that the calculation times become impractical. Therefore, modelling is the method to which resort is taken. Turbulent effects and the topic of turbulence modelling has been the foremost focus of single-phase CFD research for the past couple of years.

Multiphase flow is flow with concurrent presence of diverse phases, where phase cites to solid, liquid or vapour state of matter. Further modelling is required for Multiphase flow due to complex behavior of interaction between the phases. So, when doing DNS-simulations for multiphase flow, modelling is needed.

There are four main categories of multiphase flows;

- Gas-Liquid,
- Gas-Solid,

- Liquid-Solid
- Three-Phase Flows.

Added characterization is commonly done conferring to the visual appearance of the flow as separated, mixed or dispersed flow. These are called the flow patterns or the flow regimes and the classification of multiphase flow in a particular flow regime is comparable to the importance of knowing if a flow is laminar or turbulent in single-phase flow analysis. Geometrical distribution of the phases is described using a flow pattern and the flow pattern significantly affects phase distribution, velocity distribution and etcetera for a certain flow condition. A number of flow regimes prevail and the likely flow patterns differ depending on the geometry of the flow domain. Figure 3.2 shows the flow patterns in solid-liquid flow.

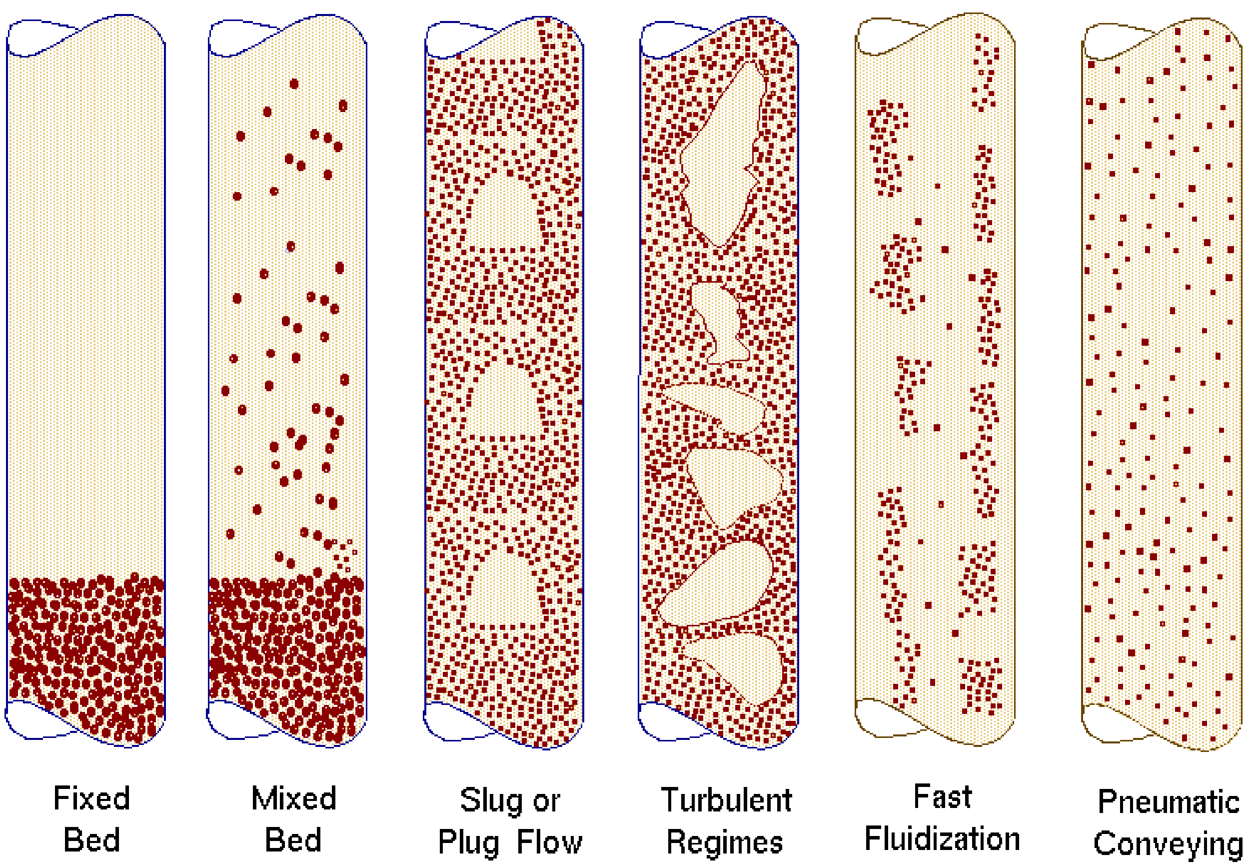


Figure 3.2: Flow patterns in solid-liquid flow [34]

3.1.2 Approaches to Multiphase Modeling

Models are used to be able to define and envisage the physics of multiphase flow. As formerly mentioned, modelling of multiphase flow is very intricate. In addition, there are also confines in time, computer ability etcetera when executing numerical studies. This has led to the implementation of models that can reason for different levels of information, implicating different levels of accuracy, and are appropriate for different multiphase flow applications. Some of these modelling approaches are introduced below.

3.1.2.1 The Euler-Lagrange Approach

In Euler-Lagrange approach, particles are traced on the level of a single particle where particle denotes either a solid particle or a gas/fluid bubble/droplet. Conservation equations are deciphered for the continuous phase and the particle phase is followed by solving the equations of motion for each particle as shown in equations 3.3, 3.4 and 3.5 below.

$$\frac{\partial \alpha_f \rho_f}{\partial t} + \nabla.(\alpha_f \rho_f u_f) = S_{mass} \tag{3.3}$$

$$\frac{\partial \alpha_f \rho_f}{\partial t} + \nabla.(\alpha_f \rho_f u_f u_f) = \alpha_f \nabla p - \alpha_f \nabla.\tau_f - Sp + \alpha_f \rho_f g = 0 \tag{3.4}$$

$$\frac{\partial u_p}{\partial t} = \sum F \tag{3.5}$$

Where α is the volume fraction, S_{mass} is a mass source term existing in the case of exchange of mass between the phases, S_p is the momentum source term existing in case of exchange of momentum between the phases and F is the force. Subscripts f and p denotes to the fluid and particle phases, respectively.

The forces acting on particles differ depending on the flow situations. The drag force is usually included and other forces that can be of prominence are for example the lift force, the virtual mass force and the history force. When executing numerical modelling it is up to the modeller to evaluate which forces that are of importance is to be included to the right hand side of the equation 3.5. Adding extra forces to model increases accuracy but also surges complexity.

Coupling between the continuous phase and the dispersed phase is attained through the source terms. These are included also in the equation for the dispersed phase but are not clearly shown here as they are a portion of the right hand side. Integration of equation 3.5 gives the position of the dispersed phase.

As this modelling approach resolves information on the level of a single particle it is quite computationally costly. To reduce the computational cost one can pick to track clusters of particles instead. But, this method is still computationally expensive and therefore Euler-Lagrange modelling is apt for dilute dispersed flow, means flows with a low volume fraction of the dispersed phase.

3.1.2.2 The Euler-Euler approach

In Euler-Euler method, different phases are dealt statistically as interpenetrating continua. Since the volume of a phase cannot be engaged by other phases, the concept of phasic volume fraction is presented. These volume fractions are supposed to be continuous functions of space and time and their sum is equivalent to one. Conservation equations for every phase are resolved to obtain a set of equations, which have comparable structure for all phases. These equations are secured by providing connections that are attained from empirical information or, in the case of granular flows, by implementing of kinetic theory. The governing equations for a two-fluid model with two continuous phases are shown below.

$$\frac{\partial \alpha_k \rho_k}{\partial t} + \nabla.(\alpha_k \rho_k U_k) = 0 \qquad (3.6)$$

$$\frac{\partial \alpha_k \rho_k Uk}{\partial t} + \nabla.(\alpha_k \rho_k U_k \text{ Uk}) = -\alpha_k \nabla P + \alpha_k \nabla.\tau_k + \alpha_k \rho_k g_k + S_k = 0 \qquad (3.7)$$

$$\frac{\partial \alpha_k}{\partial t} + \nabla.(\alpha_\text{k} \text{ U}_\text{k}) = 0 \qquad (3.8)$$

Where U is the mean velocity field and P is the mean pressure of the phases. The subscript k refers to the k:th continuous phase.

Figure 3.3 shows the different multiphase phase models. Three different Euler-Euler multiphase models are available:

- The Volume Of Fluid Model (VOF)
- The Mixture Model
- The Eulerian Model

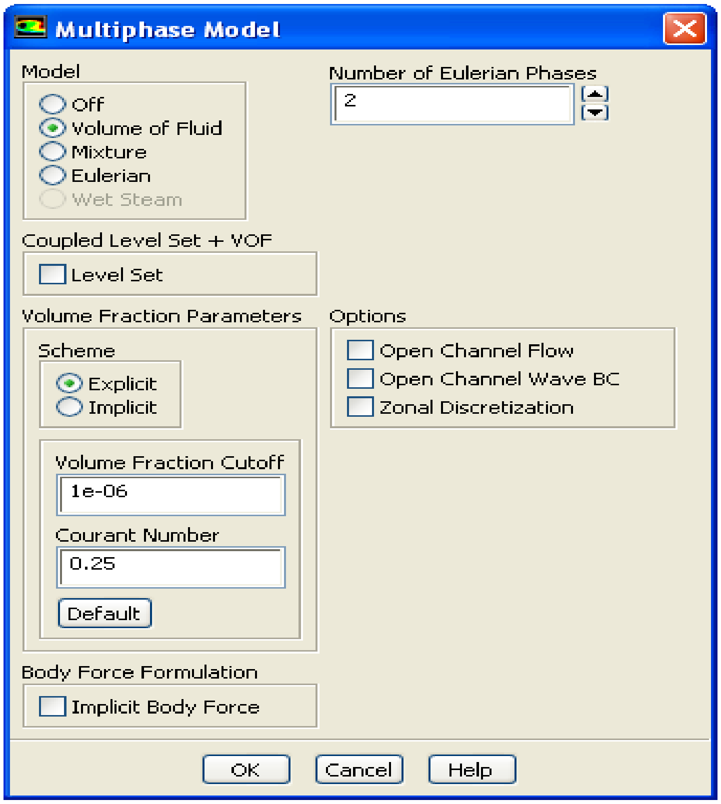


Figure 3.3: Different multiphase phase models [35]

3.1.2.2.1 The VOF Model

The VOF model is a surface-tracking procedure employed to a fixed Eulerian mesh. It is designed for two or more immiscible fluids where the situation of the interface amid the fluids is of interest. In this model, the fluids share a sole set of momentum equations, in each computational cell the volume fraction of each of the fluids is traced throughout the domain.

Applications of the VOF model comprises stratified flows, free-surface flows, filling, sloshing, the motion of large bubbles in a liquid, the motion of liquid after a dam breakdown, the calculation of jet breakup, and the steady or transient tracing of any liquid-gas interface.

3.1.2.2.2 The Mixture Model

The mixture model is intended for two or more phases, either fluid or particulate. Likewise in the Eulerian model, this model considers the phases as interpenetrating continua. The mixture model resolves the mixture momentum equation and recommends relative velocities to describe the dispersed phases. Usages of the mixture model comprise particle-laden flows with low loading, bubbly flows, sedimentation, and cyclone separators. The mixture model can also solve problems of dispersed phases without relative velocities to model homogeneous multiphase flow.

3.1.2.2.3 The Eulerian Model

Among all the multiphase models, Eulerian model is the most complex. It resolves a set of ’n’ momentum and continuity equations for each phase. The pressure and interphase exchange coefficients are used to achieve coupling in this model and the way in which this coupling is dealt depends upon the type of phases involved. Granular or fluid-solid flows are handled differently than non-granular or fluid-fluid flows. For granular flows, the properties are attained from application of kinetic theory. Momentum exchange among the phases is also dependent upon the type of mixture being modeled. Usages of the Eulerian multiphase model include bubble columns, risers, particle suspension, and fluidized beds.

3.1.2.3 Guidelines for Choosing Appropriate Model

The first and foremost step in resolving any multiphase problem is to determine which of the regimes best exemplifies our flow. Some guidelines for choosing the most appropriate model for a given problem are:

- For St<<1.0, the particle will trail the flow strictly and any of the three models (discrete phase, mixture, or Eulerian) is appropriate. One can therefore go for the least expensive (the mixture model, in most cases), or the most appropriate taking other factors too.

- For St > 1.0, the particles will traffic independently of the flow, either the discrete phase model or the Eulerian model is appropriate.
- For St ≈1.0, again any of the three models can be used. One can select the least expensive or the most appropriate taking other factors.
- If a wide distribution of the dispersed phases is involved, the mixture model may be desirable. But if the dispersed phases are concentrated just in quotas of the domain, one should follow the Eulerian model instead.
- If interphase drag laws that are applicable to system accessible (either within FLUENT or through a user-defined function), the Eulerian model can generally provide more precise results than the mixture model.
- If the interphase drag laws are not known or their pertinence to system is problematic, the mixture model may be a superior choice.
- If the problem to be solved is simple and needs less computational effort, the mixture model may be a healthier option, since it solves a fewer number of equations than the Eulerian model.
- If accuracy is more significant than computational exertion, the Eulerian model is a superior choice. But one thing to be remembered is that, the complexity of the Eulerian model can make it less computationally stable than the mixture model.

3.1.3 Turbulence Modelling

Fluctuations occurring in the velocity field blend transported amounts such as momentum and energy and cause the transported quantities to vary as well. These fluctuations can be of a very minor scale and consequently can create tremendously huge computational expenditures for applied engineering calculations. An improved set of equations that involve much less computational expenditure are used. This is achieved by time-averaging the instantaneous governing equations which then include added unknown variables. Turbulence models are required to solve these unknown variables.

No lone turbulence model can be universally applied to all conditions. Always remember that some consideration has to be taken when selecting a turbulence model which includes; physics involved in the flow; level of accuracy; and computation resources accessible. Mainly two turbulence models will be discussed in here they are k-ε and k-ω turbulence models.

3.1.3.1 The k-ε Turbulence Model

The k-ε model is one of the most extensively used turbulence models as it delivers robustness, economy and judicious accuracy for an extensive variety of turbulent flows. The two transport equations k and ε independently solves for turbulent velocity and length scales. Figure 3.4 shows the different k-ε models.

Again the k-ε model is classified into three categories, they are:

- The Standard k-ε Model
- Realizable k-ε Model
- Renormalization Group (RNG) k-ε Model

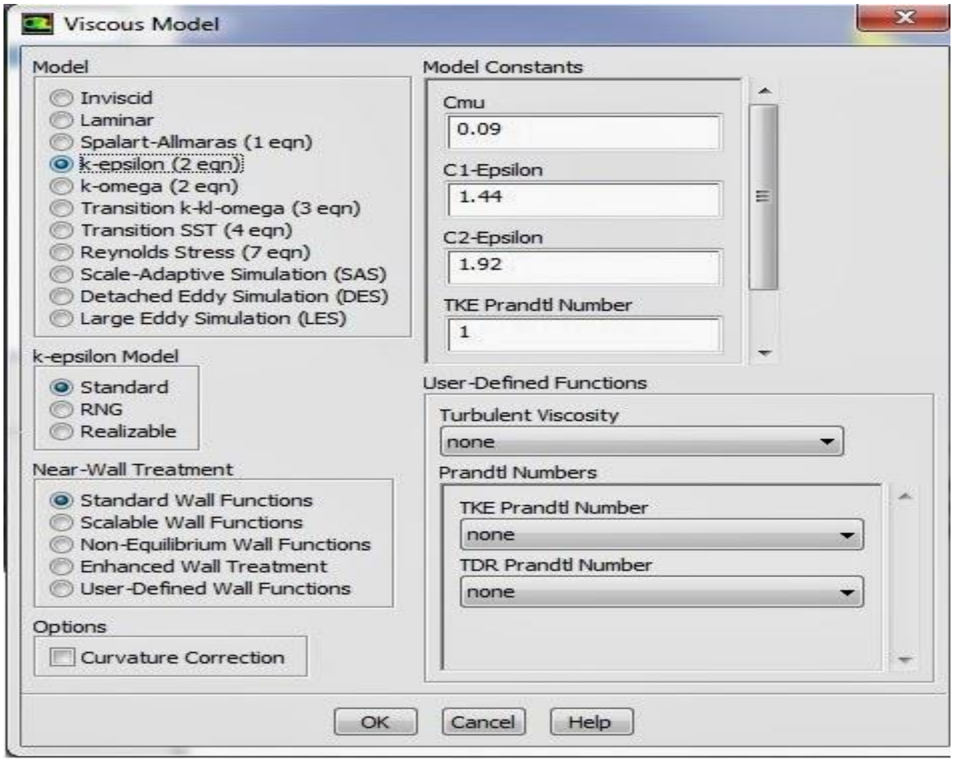


Figure 3.4: Different k-ε models [36]

Main differences between the three models are;

- Turbulent prandial numbers which governs the turbulent diffusion of k and ε.
- Generation and destruction terms which are present in the equation of ε.
- The way in which turbulent viscosity is calculated.

3.1.3.2 The k- ω Turbulence Model

The k-ω model has the advantage that is that it does the near wall treatment. The model is comparatively more robust and accurate. The model assume that the turbulent viscosity is linked to the turbulent kinetic energy and the turbulent frequency. It solves two equations, one for turbulent kinectic energy and other for turbulent frequency. The k-ω model is numerically more stable than other models. One of its disadvantge is that it is very sensitive to inlet free stream turbulences. Figure 3.5 shows the different k-ω models. The k-ω model is also categorized into two, they are:

- The Standard k-ω Model
- Shear Stress Transport (SST) k-ω Model

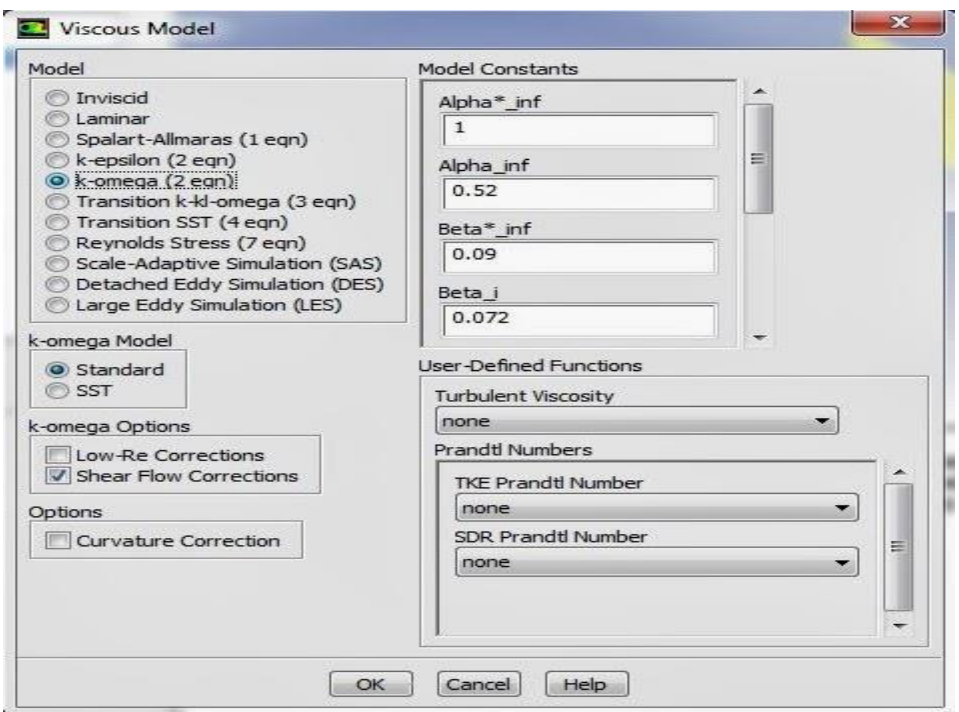


Figure 3.5: Different k-ω models [36]

Both of the two variations of the k- ω model uses similar transport equations for the k and ω, but the shear stress transport (SST) model differs from standard model by using a modified turbulent viscosity equation for the transportation of the principal turbulent shear stresses.

3.1.4 Pressure Drop of Slurry Flow in Pipeline

Pressure drop is the most important parameter for solid liquid transport in mineral and other solids handling industry. Power consumption and successively the whole economics of the hydro-transport hinge on it. For this cause, pipeline design is primarily based on optimization in pressure drop and preliminary investment. There are fat number of empirical and semi empirical correlations accessible in literatures to predict pressure drop. Most of these equations have been established based on limited data embracing of even or narrow size-range particles with very low to moderate concentrations. As the relationships are empirical in nature, their pertinence is inadequate e.g. the correlations developed for sand-water slurry flow do not crop promising results when they were implemented on coal-water slurry flows. These correlations are susceptible to great ambiguity as one departs from the limited database that backs them.

Transportation of slurries via pipeline is very much common in mineral and petrochemical industries and its enormous power consumption are getting consideration in recent years. Need and advantage of precisely calculating the vertical solid concentration profiles and the pressure drop of slurry pipelines in the course of design phase is enormous as it helps in superior selection of slurry pumps, optimization of power consumption and also helps to make best use of economic possibilities. Even though the large area of application, the accessible published models telling the slurry pressure drop and concentration profile do fully satisfy engineering requirements. Efforts are still on to cultivate more rational model for estimation of pressure drop and concentration profile in pipes and in this area.

Pressure drops in pipelines are mainly caused due to the following reasons, they are:

- Friction
- Vertical Pipe Difference or Elevation
- Changes of Kinetic Energy

For determining pressure drop along a pipeline when a fluid flows through it is done by adopting the following steps in the given order.

The steps are:

a) Determine Reynolds Number (Re),

$$\mathrm{Re} = \frac{\rho u d}{\mu} \tag{3.9}$$

Where, ρ is density of the fluid (kg/m³)

u is velocity of the fluid (m/s)

d is diameter of the pipe (m)

μ is dynamic viscosity of the fluid (Pa.s)

From equation 3.9 if it gives Reynolds Number < 2320, then it is a laminar flow

And if it gives Reynolds Number > 2320, then it is turbulent flow.

b) Determine Pipe Friction Coefficient (λ)

For laminar flow, $$\lambda = \frac{64}{\mathrm{Re}} \tag{3.10}$$

For turbulent flow, $$\frac{1}{\sqrt{\lambda}} = -2\log\left[\frac{2.51}{\mathrm{Re}\times\sqrt{\lambda}} + \frac{k}{d}\times 0.269\right] \tag{3.11}$$

Where, k is absolute roughness (m) [37]

d is diameter of the pipe (m)

c) Determine pressure drop (Δp)

$$\Delta p = \lambda \times \frac{l}{d} \times \frac{\rho}{2} \times u^2 \tag{3.12}$$

Where, l is length of pipe (m)

ρ is the density of the fluid (kg/m^3)

3.2 SIMULATION AND ANALYSIS SOLVER PREFERENCE

Present work is to conduct a methodical and logical study of fly ash slurry transportation in a pipeline at higher concentrations by the use of computational fluid dynamics and also to study the rheological properties and pressure drops. ANSYS Fluent software has been used to model and simulate the flow through pipeline and its analysis is done and then it is validated against theoretical data.

3.2.1 By Using ANSYS Simulation

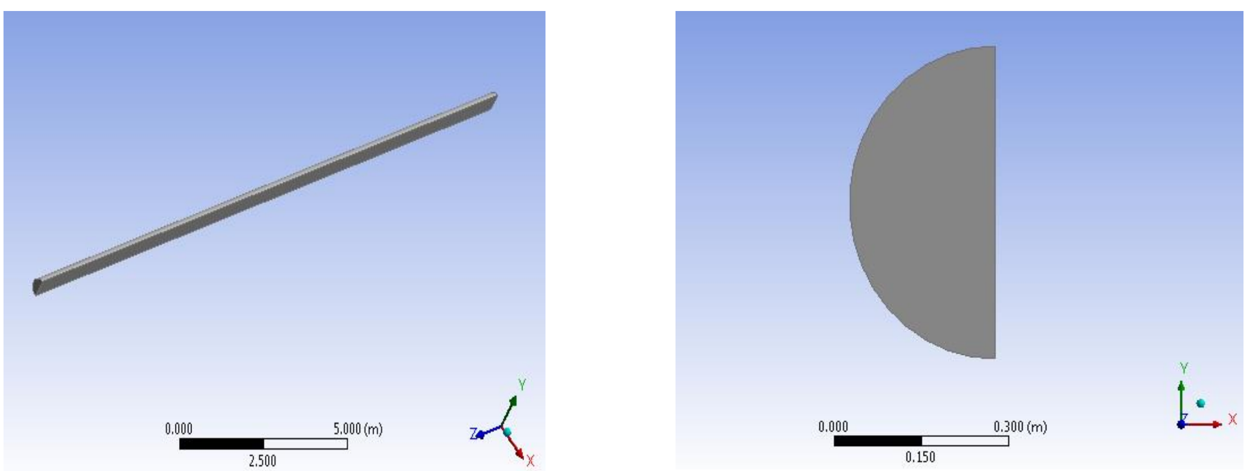
3.2.1.1 Geometry Creation

A three dimensional planar geometry is created due to the symmetry of the model and to save the simulation and calculation time. The geometry cell is used to create, edit, or import geometry that is used for analysis. For creating geometry for analysis, double-click on the Geometry cell; the Design Modeler window will be displayed (Figure 3.6).

Planar symmetry created uses the following parameters:

Diameter of pipe = 0.5 m

Length of pipe = 20 m



(a) (b)

Figure 3.6: (a) Pipe geometry along the length, (b) Pipe geometry a planar view

Extrusion method is used for the geometry creation. The geometry created has a volume of 1.9635 m^3, a surface area of 25.904 m^2, 4 faces, 6 edges and 4 vertices.

3.2.1.2 Meshing Process

A hexa sweep mesh is used here for meshing the model created. We can use the mesh component system to create and/or open geometry or mesh files. A grid independence test was conducted to find the apt number of grids which can be effectively used in meshing and found out to be 600 number of sweep divisions (Figure 3.7).

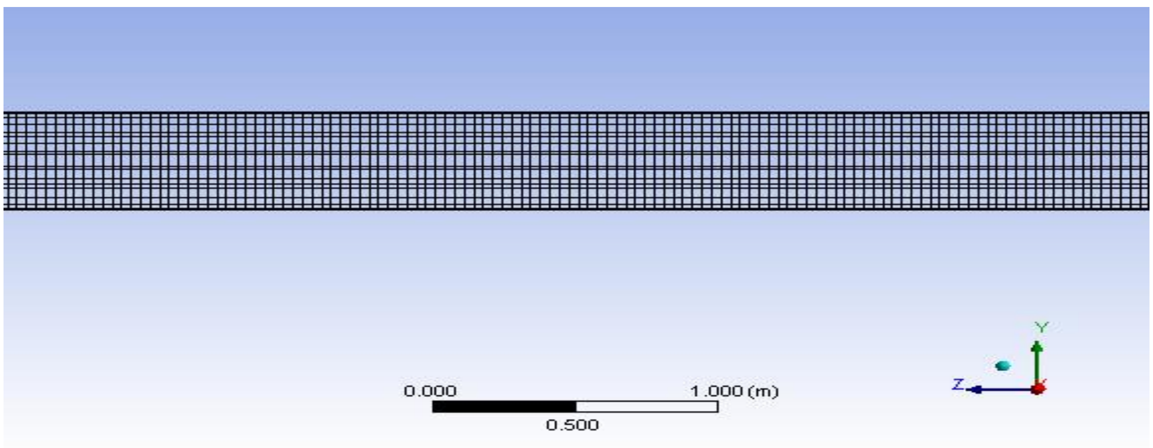


Figure 3.7: Hexahedron sweep mesh

Number of nodes created in meshing is 24040 and number of elements created is 17400.

3.2.1.3 Setup and Solution

A pressure based solver is used for simulation process. Since the concentration of slurry flow which is to be simulated is very high, Eulerian multiphase model with implicit volume fraction parameter is employed. The k-ε turbulence model is selected over the k-ω turbulence model after trial simulations where carried out and observing that the results did not show any variations, but the simulation time for k-ω model was more compared to k-ε model, which encouraged the selection of k-ε model over k-ω model.

Fly ash and water properties are entered in the phase area of the problem setup. Intend is to measure pressure drop at various flow velocities at various concentrations in the range of 50-70% by weight. Specific gravity of fly ash taken is 2.01. Granular diameter of the fly ash is taken as 75 μm. Different velocities considered for simulation process are 3 m/s, 3.5 m/s, 4 m/s, 4.5 m/s and 5 m/s. Rheological properties of fly ash slurry are given in Table 3.1.

Table 3.1: Rheological properties of fly ash slurry [15]

% Con (C_w) (by weight)	Temp (^{0}C)	Yield Stress τ_y (Pa)	Slurry Viscosity η_p ($\times 10^{-3}$) (Pa-s)	Water Viscosity η_w ($\times 10^{-3}$) (Pa-s)	Relative slurry Viscosity η_r	Remarks
0	25	--	--	0.891	1.0	Newtonian
50	25	0.043	3.20	0.891	3.60	non-Newtonian
60	25	0.254	11.30	0.891	12.70	non-Newtonian
65	25	1.10	44.90	0.891	50.40	non-Newtonian
68	25	1.28	136.50	0.891	153.20	non-Newtonian
70	25	1.45	201.0	0.891	225.60	non-Newtonian

Boundary Conditions

- Inlet is ‘velocity-inlet’ with phases inputted as water and fly ash
- Both the phases are given velocities for each concentrations
- In the inlet zone fly ash is each also given volume fractions according to the concentration flowing through the pipe

In the pressure velocity coupling coupled scheme is taken and spatial discretization uses first order upwind for momentum, volume fraction, the turbulent kinetic energy and the turbulent dissipation rate. In monitors $1e\text{-}^{06}$ is the residual used for equations with an absolute convergence criterion. Solution initialization is done by using standard initialization with computing from the inlet. Number of iteration given for the solution is 4000 and calculation part is started.

3.2.2 By Using Theoretical Procedures

Theoretical equations and parameters are used for validating the results got in computational fluid dynamics method. For this, equation for getting Reynolds number (3.9), equation for calculating pipe friction coefficients (3.10) and (3.11), pressure drop equations (3.12) are used.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 When the Slurry Concentration by Weight is 50%

Here the viscosity of fly ash slurry is 3.2×10^{-3} Pa.s. The graph plotted for pressure drop between simulated values and calculated values are given in the figure 4.1 and the figure 4.2 shows the pressure contour obtained for transportation of 50% concentration by weight of fly ash slurry.

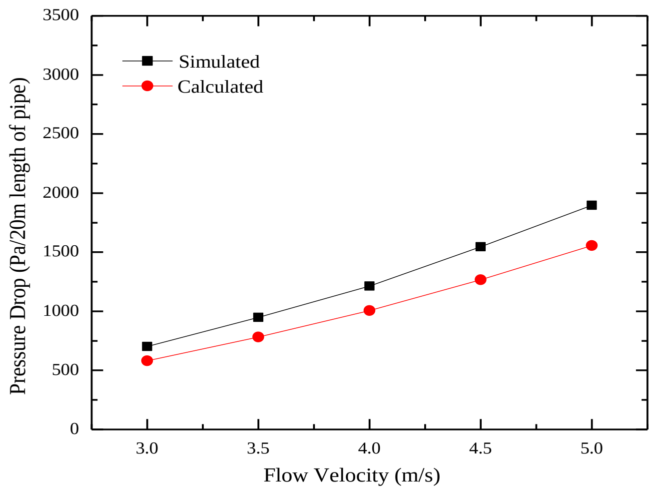


Figure 4.1: Comparison between calculated and simulated pressure drop at 50% concentration

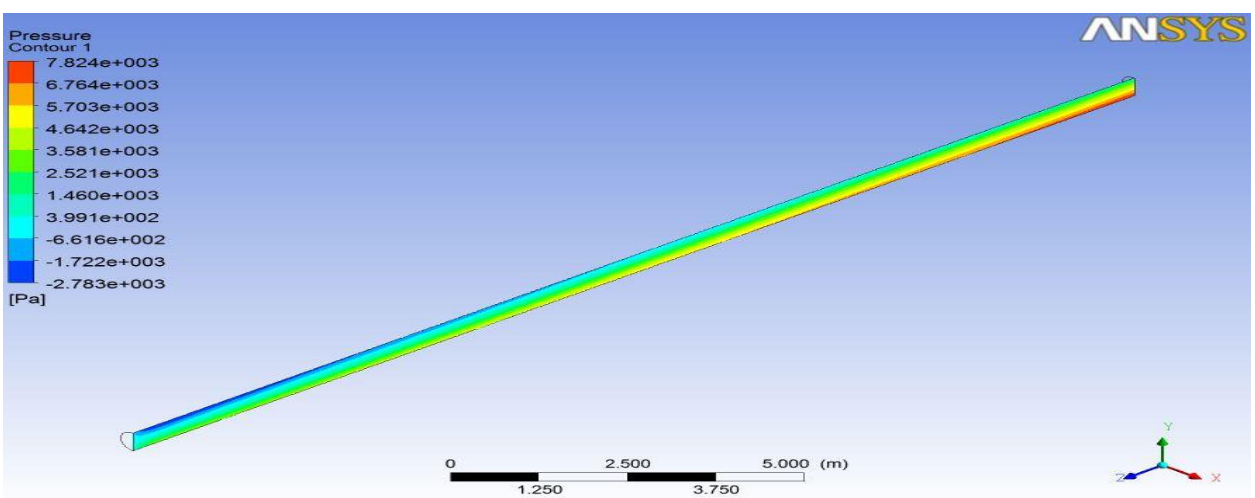


Figure 4.2: Pressure contour for 50% concentration

4.2 When the Slurry Concentration by Weight is 60%

Here the viscosity of fly ash slurry is 11.3 $\times 10^{-3}$ Pa.s. The graph plotted for pressure drop between simulated values and calculated values are given in the figure 4.3 and figure 4.4 shows the pressure contour obtained for transportation of 60% concentration by weight of fly ash slurry.

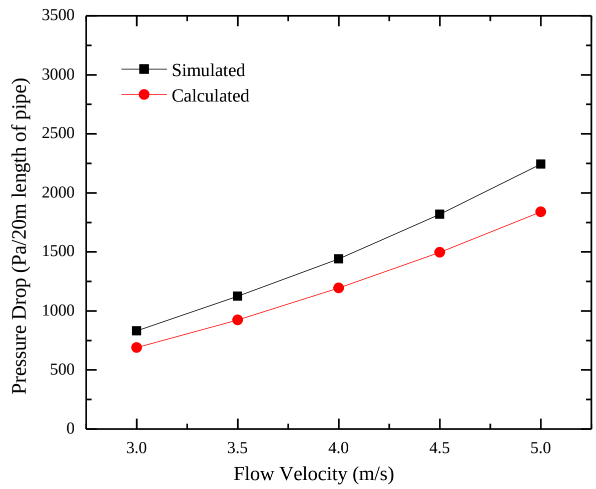


Figure 4.3: Comparison between calculated and simulated pressure drop at 60% concentration

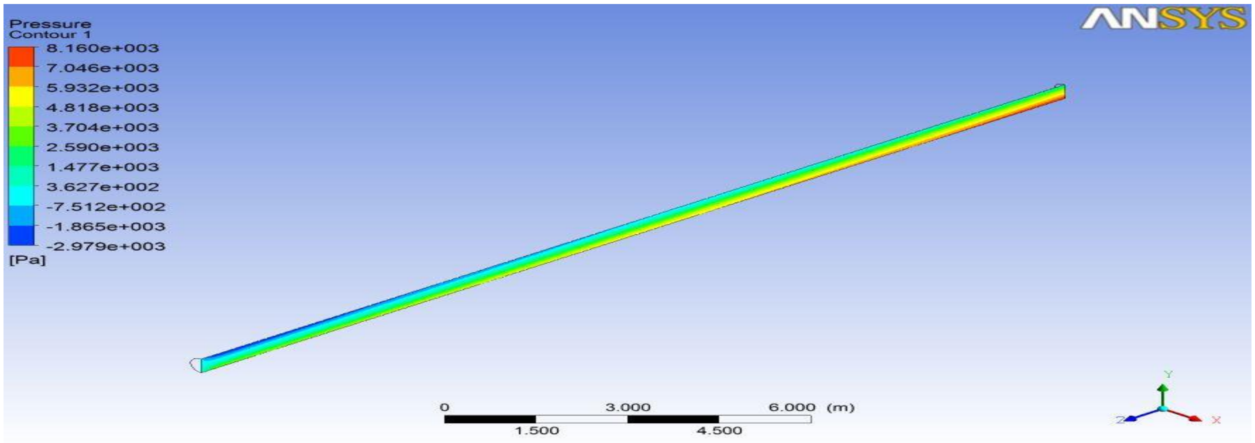


Figure 4.4: Pressure contour for 60% concentration

4.3 When the Slurry Concentration by Weight is 65%

Here the viscosity of fly ash slurry is 44.9 $\times 10^{-3}$ Pa.s The graph plotted for pressure drop between simulated values and calculated values are given in the figure 4.5 and the figure 4.6 shows the pressure contour obtained for transportation of 65% concentration by weight of fly ash slurry.

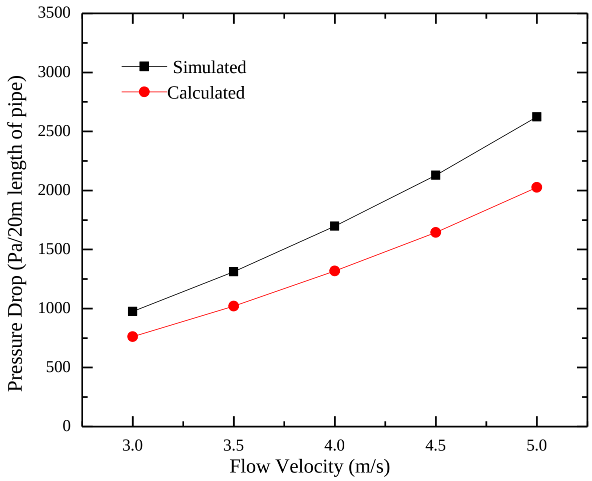


Figure 4.5: Comparison between calculated and simulated pressure drop at 65% concentration

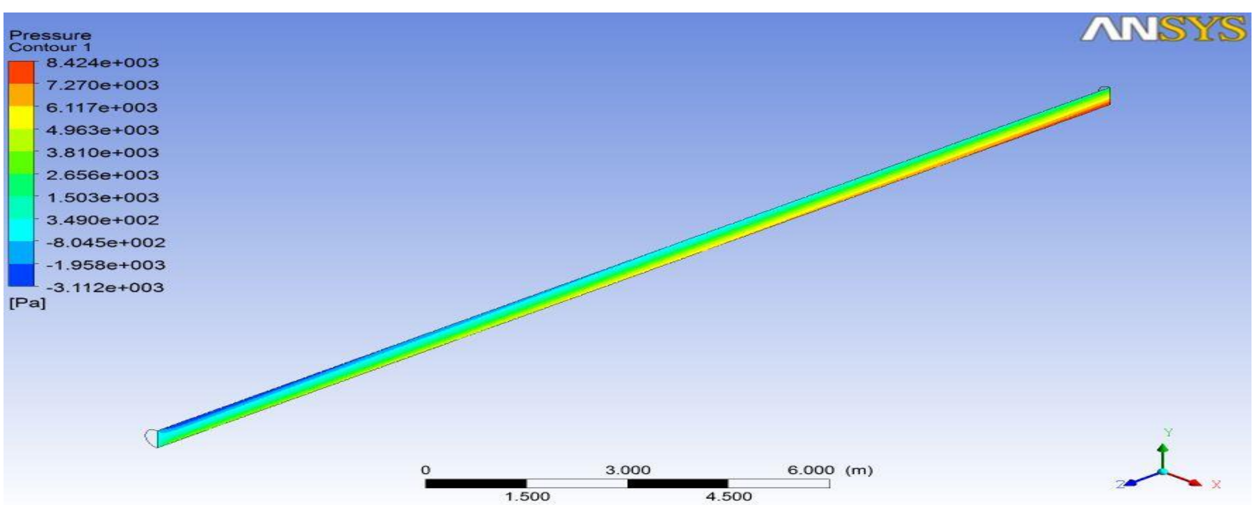


Figure 4.6: Pressure contour for 65% concentration

4.4 When the Slurry Concentration by Weight is 68%

Here the viscosity of fly ash slurry is 136.5 $\times 10^{-3}$ Pa.s. The graph plotted for pressure drop between simulated values and calculated values are given in the figure 4.7 and the figure 4.8 shows the pressure contour obtained for transportation of 68% concentration by weight of fly ash slurry.

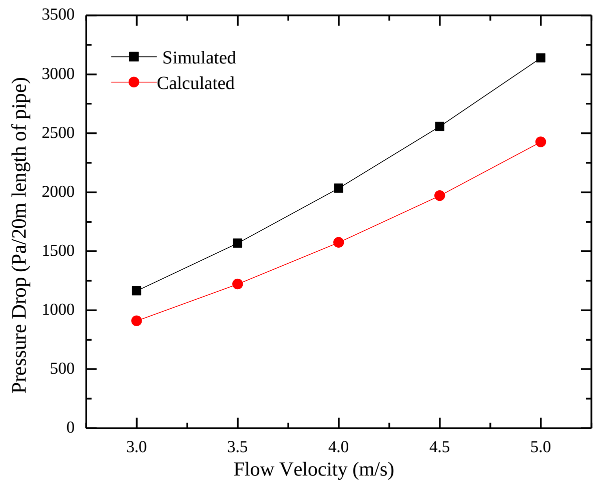


Figure 4.7: Comparison between calculated and simulated pressure drop at 68% concentration

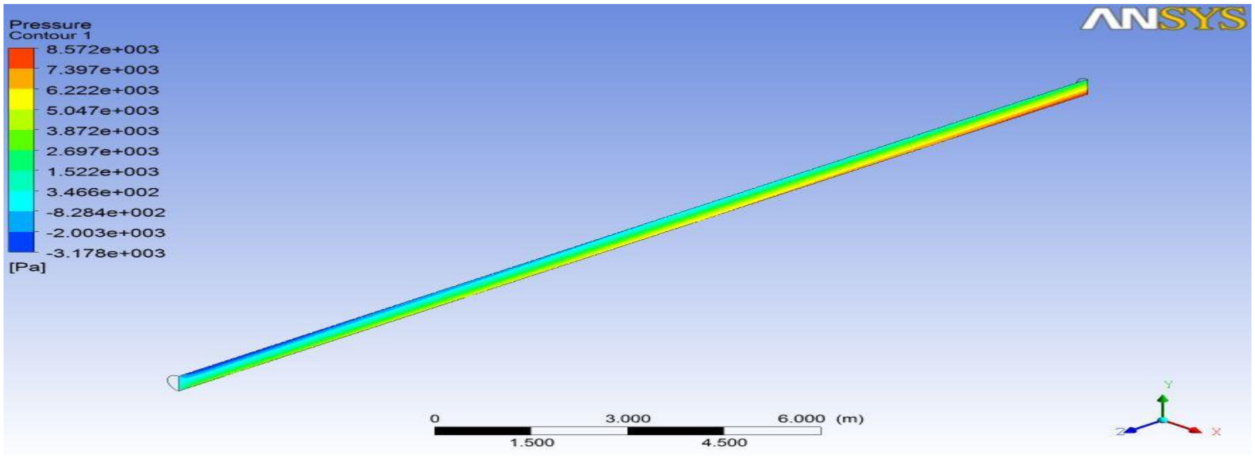


Figure 4.8: Pressure contour for 68% concentration

4.5 When the Slurry Concentration by Weight is 70%

Here the viscosity of fly ash slurry is 201.0 $\times 10^{-3}$ Pa.s. The graph plotted for pressure drop between simulated values and calculated values are given in the figure 4.9 and the figure 4.10 shows the pressure contour obtained for transportation of 70% concentration by weight of fly ash slurry.

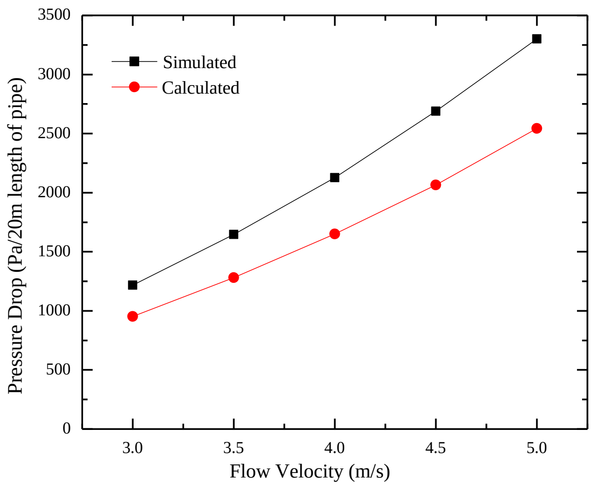


Figure 4.9: Comparison between calculated and simulated pressure drop at 70% concentration

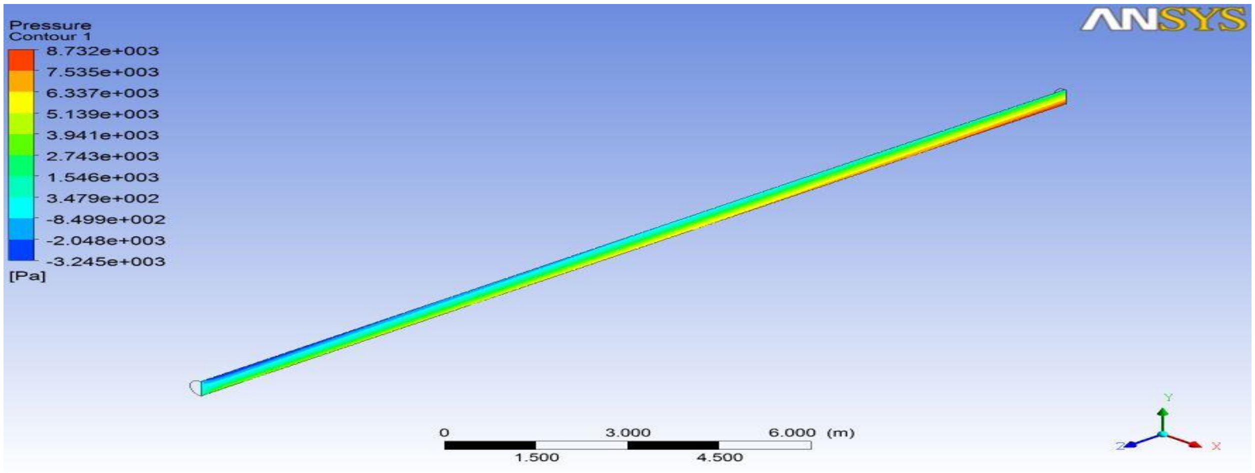


Figure 4.10: Pressure contour for 70% concentration

4.6 Comparison between Simulated and Theoretical Pressure Drop Values

The pressure drop measurements both by simulation and theoretical procedures for fly ash slurry in a 0.5 meter pipe for solid concentrations 50%, 60%, 65%, 68% and 68% by weight are graphically shown in for velocities 3, 3.5, 4, 4.5 and 5 m/s are shown in figure 4.11 and 4.12 respectively.

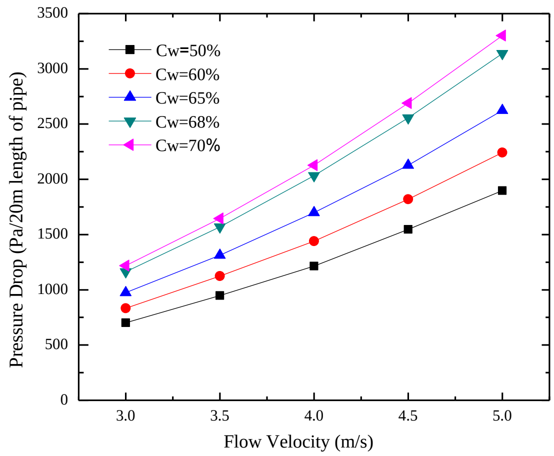


Figure 4.11: Simulated values of pressure drop variation for fly ash slurry at different concentrations

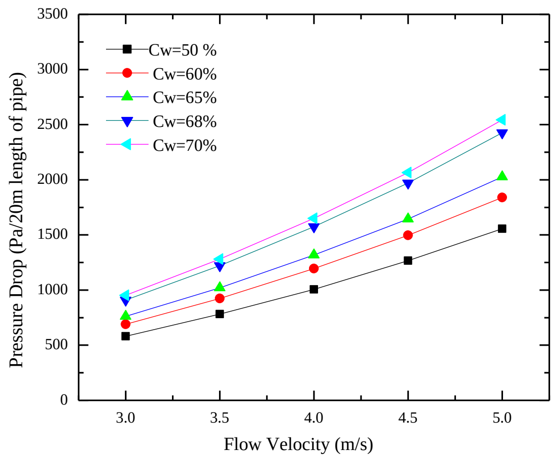


Figure 4.12: Calculated values of pressure drop variation for fly ash slurry at different concentrations

From the graphs and values obtained from both theoretical method and computational method gives a lot of resolutions. When the concentration is increased from 50 to 60% by weight of fly ash the pressure drop got increased by 15%, and when the concentration is increased from 60 to 65% by weight of fly ash the pressure drop got increased by 14%. An increase of 17% in pressure drop is observed when the concentration is increased from 65 to 68% by weight of fly ash. The reason behind the increase in pressure drop with concentration is, with the increase in concentration of the fly ash slurry the viscosity gets increased and the effects of fluid friction, pipe friction and eddies formation. Even for a small change in slurry concentration the increase in viscosity is enormous. When the viscosity is increased it leads to the increase in friction between the fluid layers and also increases the friction between the pipe and fluid flowing. This is the main reason behind the drastic increase in pressure drop even for a small increase in slurry concentration.

Another issue noticed from the investigation is that for every concentration studied the velocity when changed from 4.5 to 5 m/s a drastic increase in pressure drop is observed and the pressure drop values given by the computational method is greater than the values given by theoretical methods.

So it is concluded that slurry with concentration of 65% by weight of fly ash is the desired concentration to be transported in slurry pipelines with lowest rate of pressure drop. Taking the specific energy into account 65% is the concentration which can be economically transferred through a pipeline in industries. The specific energy consumption is defined as the amount of energy required for transporting one ton of slurry over a distance of one kilometer. Also the desired velocity which can be used for transporting slurry is 4.5 m/s because further increase in velocity gave a tremendous increase in the pressure drop. So it shows that we can’t increase the velocity as per our wish for fast transport of the slurry, which may lead to negative impact on transportation of slurry.

4.7 Fly Ash Volume Fraction Distribution

Volume fraction of a component in a mixture or fluid is the ratio between the components volume in the mixture to the total volume of the mixture. It is dimensionless and has unit 1 and is expressed as a number and is sharing the same concept of volume percentage. Sometimes volume fraction is also called as volume concentration.

It was seen that the volume fraction of fly ash remained uniform in the beginning of the flow and towards the end more volume fraction distribution is found at the bottom portion of the pipe and comparatively low at the top part of the end portion of pipe. The main reasons for this difference in volume fraction distribution along the length of the pipe are sedimentation of fly ash in the slurry, high viscosity of slurry flowing and high density of the fly ash slurry. The contour plot of volume fraction distribution is shown in figure 4.13.

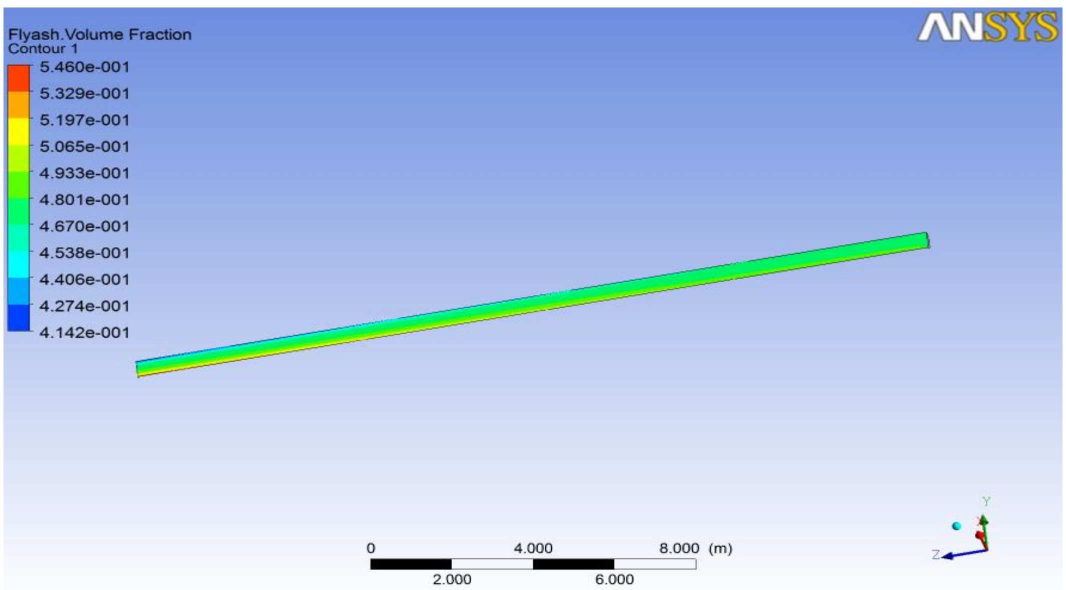


Figure 4.13: Contour for fly ash volume fraction

4.8 Eddy Viscosity

Eddy viscosity is caused due to the turbulent transfer of momentum by eddies which gives rise to an internal fluid friction, which can be compared to molecular viscosity in laminar flow, but taking place on a much bigger scale. Eddy viscosity is always a function of the flow and is more for fluids with high turbulence.

It is observed that many variations are taking place in eddy viscosity along the length of the pipe throughout the flow. In the beginning the rate of eddy viscosity is maximum, which in the later part decreases and towards the end of the pipe it becomes minimum.

Pressure drop is the main reason behind these variations in eddy viscosity. Other main reasons for this variation in eddy viscosity are turbulence formation and boundary layer effect. The contour plot of eddy viscosity is shown in figure 4.14.

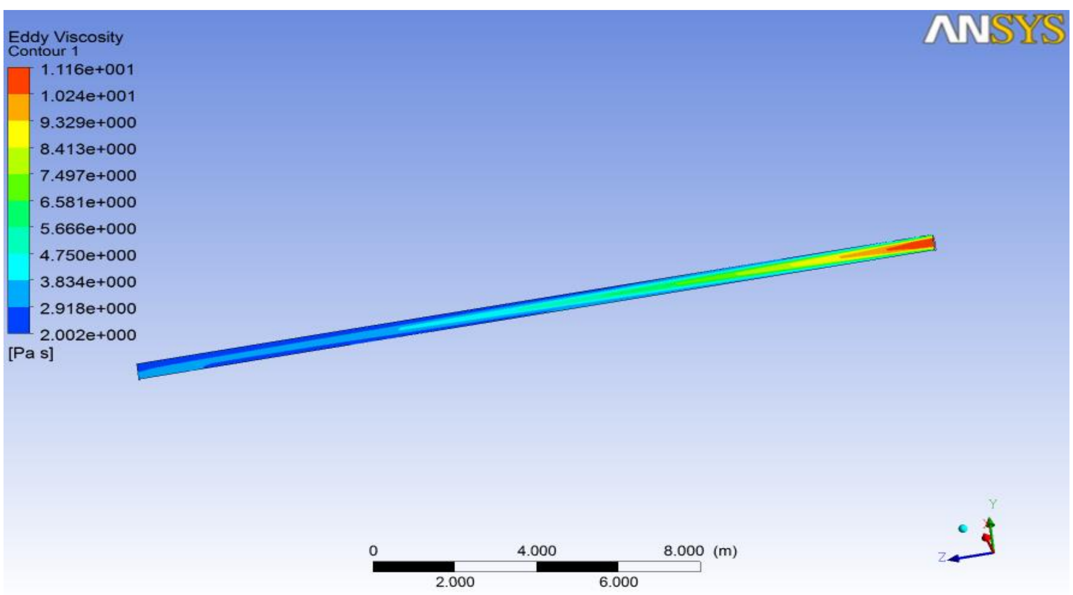


Figure 4.14: Contour for eddy viscosity in slurry flow

4.9 Turbulence Kinetic Energy

Turbulence kinetic energy is mean kinetic energy per unit mass. Turbulence and turbulent kinetic energy are very strongly related to each other as the intensity of turbulence decides the intensity of the turbulent kinetic energy. Idea of turbulent kinetic energy is very much similar to that of kinetic energy, since in a flow the energy can be divided into two they are mean kinetic energy of the flow and turbulent kinetic energy of the flow.

It is observed that in the fly ash slurry flow, turbulence kinetic energy is minimum towards the end of the pipe and maximum at the beginning. As the main reasons behind creation of turbulence kinetic energy (TKE) are fluid shear, eddy formation and fluid friction it gives a clear explanation for the maximum turbulence at the beginning of the pipe. In the beginning the velocity of flow is more so the mean kinetic energy will also be more, so turbulence kinetic energy is more in the beginning. The contour plot of turbulence kinetic energy is shown in figure 4.15.

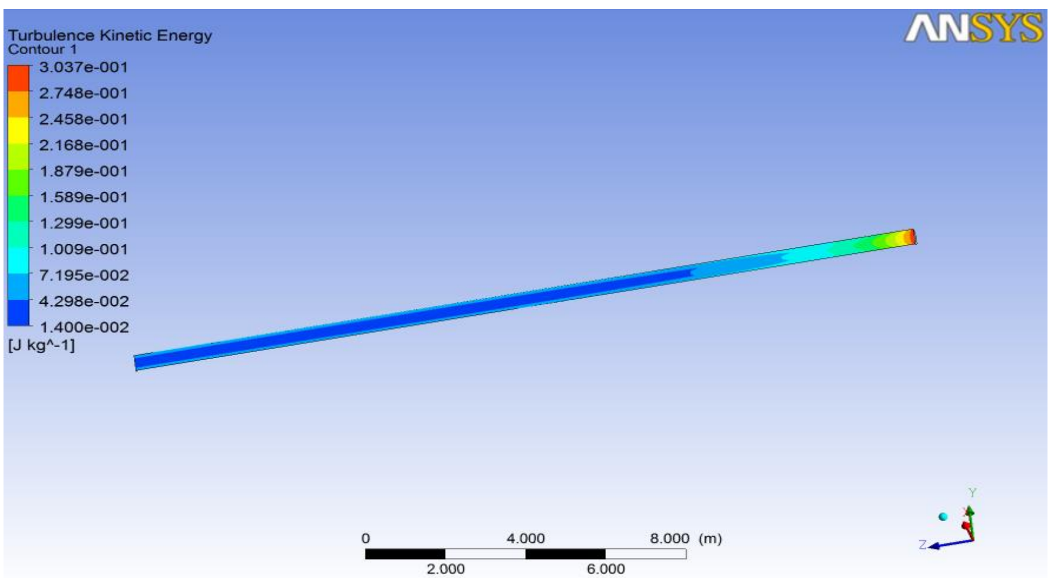


Figure 4.15: Contour for turbulence kinetic energy in slurry flow

CHAPTER 5

CONCLUDING REMARKS

5.1 CONCLUSION

From this project work the following conclusions are made

- Fly ash slurry with concentration of 65% by weight of fly ash is the desirable concentration to be transported in slurry pipelines with lowest rate of pressure drop.
- The most desirable velocity for slurry transport in pipeline is found out to be 4.5 m/s since beyond this velocity a great increase in pressure drop was detected.
- For a certain slurry concentration it is observed that as the velocity increases the pressure drop also gets increased consequently.
- For a certain velocity the pressure drop increases with increase in concentration of the slurry.
- Specific energy consumption increases with increase in concentration and velocity of flow, so a concentration of 65% weight of fly ash and 4.5 m/s velocity is the desirable concentration and velocity for economical transport with least specific energy consumption.
- Even for small increase in concentration of fly ash slurry the increase in viscosity is enormous.
- When the viscosity is increased it leads to the increase in friction between the fluid layers and also increases the friction between the pipe and fluid flowing. This is the main reason behind the drastic increase in pressure drop even for a small increase in slurry concentration.
- The pressure drop values given by the computational method is greater than the values given by theoretical methods, because in computational process a lot of flow factors are taken into account compared to theoretical procedures undertaken.
- The volume fraction of fly ash remained uniform in the beginning of the flow and towards the end more volume fraction distribution is found at the bottom portion of the pipe and comparatively low at the top part of the end portion of pipe.
- Many variations are taking place in eddy viscosity along the length of the pipe throughout the flow. In the beginning the rate of eddy viscosity is maximum, which in the later part decreases and towards the end of the pipe it becomes minimum.

- In the beginning the velocity of flow is more so the mean kinetic energy will also be more, so turbulence kinetic energy is more in the beginning.
- A lot of time can be saved by using CFD method for calculation of pressure drop compared to manual calculations.
- Eulerian model is the apt multiphase model that is to be used in simulation of slurry flow because flows with high concentration needs Eulerian model for getting accurate results.
- Usage of sweep mesh method in meshing process gives high solver accuracy and also reduces mesh cell counts which leads to a serious speedup in calculation time.
- Simulation time for k-ω model was more compared to k-ε model, which encouraged the selection of k-ε model over k-ω model.

5.2 SCOPE OF FUTURE WORK

- The work can be expanded for other slurries also, like minerals, ores, gold, silver, copper etcetera.
- The study can to be extended to fly ash slurries in which additives for reducing viscosity are added.
- Experimental validation.
- CFD modeling capability is to be extended to model slurry flow in vertical pipeline, pipe bends and through pipe fittings and pressure drop for each case can be found out and optimized.

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