Modeling of Circulating Fluidized Bed Combustor (CFBC) for low grade coal using CFD

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Declaration

I certify that this research work titled “*Modeling of Circulating Fluidized Bed Combustor (CFBC) for low grade coal using CFD”* is my individual work. The work has not been presented elsewhere for assessment. The other sources material that has been used in this work has been properly acknowledged / referred.

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Copyright Statement

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First of all I would like to thank my almighty Allah Subhana-Watala who is the creator of whole universe and without the blessing of Allah I can't be able to complete this work.

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Abstract

Since last one decade, Pakistan is facing huge energy crises and because of that not even residentials but also the industries got suffered and majority of the industries withdraw their investments from Pakistan which was a big setback. Due to lack of local industries Pakistan is facing one side import burden and on the other side imported furnace oil for our power plants is a big challenge for our economy. Pakistan is coal enrich country and have a coal reserves of 185 billion tons and only 175 billion tons coal reserves are available in Thar coal field which are enough for a century to fulfill our energy requirements. After 2013, serious concentrations have bene paid by the Governments to resolve this Power crises in country and for Coal fired Power plants in the quickest option. Many Power Plants were installed all over the country with the assistance of china under the umbrella of CPEC projects. Among this, 1200 MW Thar Coal Power Project by Sindh Engro Coal Mining Co. at Block II of Thar coal field is under construction and will become operation by the end of 2019. This is the first mega project which started by private sector with the support of Govt. of Sindh and will used local Thar coal as a primary fuel. Although, Thar coal is ranges from Lignite to low bituminous coal which is low rank coal but still are capable enough to resolve our energy crises sufficiently. The objective of this research is to study the Thar coal performance under Circulating fluidized bed combustion (CFBC) technology through CFD. CFD simulations are the easiest way to analyze the performance and results of any process without investing huge time and money. In this study, two different designs CFBCs have been compared to analyze which design is better while keeping all the methodology is same for both designs because, previously and still now a day's research work is being carried out to improve the designs of CFBC furnace. Non-premixed combustion model is used to model the gas(air) phase while Discrete phase model is adopted to model the Coal properties. ANSYS FLUENT v16 is used for CFD working, geometries and meshing are generated through same software. Results shows that efficiency of CFBC is dependent on the design and improvement in CFBC furnace designs can gives better results.

Key Words: *Circulating Fluidized Bed Combustion (CFBC), Non-premixed Combustion, Discrete Phase model, China Pakistan Economic Corridor (CPEC), Thar Coal Field.*

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CHAPTER 1 INTRODUCTION

The introductory chapter includes a background, scope and motivation of this study. The objective of study and study plan has also been explained in this chapter.

1.1 Background, Scope and Motivation

The background of this study is that, for a last one-decade Pakistan has facing huge energy crises and because of that no industrial growth has witnessed. The development of industries in any country is important for its economy and for the job creation. In past few years tremendous work has been done at Govt. level to encourage private sectors to invest in the power sector in order to eliminate the power shortfall that became worst in our country. For this, primary focus has been given to resolve the power short fall issue in Pakistan in CPEC projects beside the other infrastructure related projects. Coal fired power plants were constructed with the assistance of China in many areas of Pakistan particularly in Sindh and Punjab.

As constructing Coal fired power plants are easy and quick to be install, to meet most of the power plants that are constructed in Pakistan in last 5 to 8 years are of coal fired power plants. Even few solar and wind power projects were also constructed in some area s of Pakistan.

There is a huge scope for constructing coal fired power plants in Pakistan because Pakistan has blessed with a huge amount of coal reserves of 185 billion tons, of this Thar coal which is a part of Thar coal field have a reserves 175 billion tons spread over a single geographically contained area of 9100 sq km in the south eastern part of the Sindh[9] [11]. The quality of pThar coal is not too good but eventually enough for using in power plants.

Recently, a very constructive development has been seen that one of the private sectors is investing in Thar Coal and constructing 1200MW power plant that will use totally a Thar coal as a fuel [12]. This project become operational in 2019 and the success of this project is beneficial for Pakistan as other investors will also come here and will invest in the energy sector and this progress will eventually reduce our decency in imported oil and will increase the utilization of local coal.

The motivation of this study is to understand the Thar coal performance with Circulating fluidized bed combustors (CFBCs) technique and to predict how much our locally available Thar coal is efficient to meet the energy crises that become going worst day by day.

This study also includes the complete simulation of Circulating fluidized bed combustor (CFBC) for two different designs CFBCs and tried to analyze which design geometry has better results. Non-premixed combustion model and discrete phase model (DMP) are used to model the Gas flow (Air) and discrete phase (Coal) to model the combustion.

1.2 Objectives of the study

The core objectives of this study are to provide a simple, easily managed, cheap, and ecologically friendly solution for getting better combustion simulation results that develop a system that maximizes combustion efficiency and minimizes operating and investment costs.

Bekow are the main objectives of this study.

- To development a model using computational fluid dynamics (CFD) in ANSYS FLUENT.
- The main objective of this study is to develop computational fluid dynamics model of two-phase flow for circulated fluidized bed by using Thar Coal properties (Low grade coal).
- Two different design geometries of circulating fluidized bed combustors have been studied by applying similar methodology and predict which one will produce more temperature.
- To give the overview of the indigenous Thar coal reserves and quality of Thar coal filed coal.

1.3 Thesis Layout

This study report contains **9** chapters.

Chapter 01: contains the introduction and objective of the study.

Chapter 02: contain the literature review of what kind of research work carried out in CFBC.

Chapter 03: contains the overview of Coal potential in Pakistan and Quality of Thar field coal.

Chapter 04: contains the overview circulating fluidized bed combustor (CFBC) technology.

Chapter 05: contains the Mathematical modelling and governing equation of CFBC.

Chapter 06: contains problem description of this study and pre-processing steps.

Chapter 07: contains Solver steps and Boundary conditions that are considered in this study.

Chapter 08: contains Results and Discussions and comparison of both design results.

Chapter 09: contains conclusions which made after this complete study and point out areas where future work can be carried out.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

This chapter deals with the progress of Circulating fluidized bed technology and its recent applications in different industrial processes. Additionally, discussion has also been made on the research work carried out by different researcher in the growth of CFB technology.

As the Circulating Fluidized Bed Combustors (CFBC) has a good mixing and thermal properties and because of that they are generally preferred over the Fixed bed combustor (FBC) technique [7]. Due to their higher adaptability more, concentration has been given to it and improvements are continuously being done in this field. Enhancement in designs to achieve the optimum outputs and reduction of emissions are the ultimate objectives for the researches nowadays.

Computational Fluid Dynamic (CFD) is a tool for the optimization of designs and operation of FB combustors can be analyzed in effective way. Recent achievements in numerical techniques and enhancement of solving and computing efficiencies has advanced CFD as a widely used practice to deliver effective design solutions in fluidized bed industry.

2.2 Background of CFB

Fluidization is an operation which involves the flow of solids in contact with gas. The fluidization technique was commercially used first in 1926 coal gasification, for various reasons the process did not find importance and no further developments were made till the start of the World War-II. In the earlies of 1940s, the first fluidized catalytic cracking technique was successfully used in the oil industry and remains today in petroleum refining process [21]. After the success of the FCC techniques, more concentration was being paid on this technique and several other processes using fluidized solids were being commercially used.

Interest in fluidized-bed combustion began to grow between 1970s and 1980s and at the same time, many research papers were published. These accomplishments in research area further inspired commercial applications.

CFB technique gained adaptability in processes because of their numerous features, such as good mixing, good gas-solid interaction at short residence times, excellent heat and mass transfer, and high output per unit cross sectional area made their application economically desirable [5] [21]. CFB systems have ability to operate with a wide variety of fuels. The high degree of fuel flexibility often allows CFBC to select desired fuel that is easily and economically available. Now fluidized beds are currently classified into three groups,

- Bubbling Fluidized Beds (BFBs)
- Circulating Fluidized beds (CFBs)
- Transport Reactors

2.3 Recent Research

As CFBC is widely used in processes for its numerous features and parallel to that huge research work is being carried out to achieve higher outputs by improving their designs and making it environment friendly by minimizing combustion emissions.

[1] In 2012, **Ravindra Kumar and K.M.Pandey** studied the CFD of circulating fluidized bed combustion using FLUENT. In this analyzed the impact of superficial velocities of primary air in fluidized bed, they used a low-grade coal i.e Lignite as a fuel with a particle size of 5 mm he concluded that increase of primary air velocity from 4m/s to 6m/s doesn’t put any impact of fluidized bed temperature.

[2] In 2012, **Anders Brink** elaborated the fundamentals which involved in developing a CFD model for fluidized bed combustion and gasification processes, fluid flow governed mathematical equations, heat and mass transfer and chemical reactions in fluidized bed combustion and gasification processes have been elaborated, he also identified area where work is required to improve the CFBC process.

[23] In 2009, **Ernst-Ulrich Hartge** used a two-fluid model(TFM) approach and develop a 3D reactor to explain the fluid mechanics involved in the fluid flow, he also presents the average distribution on different time scale of solid inside the riser.

[22] In 2011, **W. Zhou, C.S. Zhao** studied the formation of NOx & SOx with different rate of reactions in 2D CFBC by using CFD, his working is useful to understand the rate of reactions and formation of pollutant emissions in fluidized bed combustors.

[3] In 2015, **Amol S. Kinkar** studied the behavior & flow of flue gases inside the CFBC by using ICEM CFD (ANSYS) software. He also explained the failure of refractory of CFB combustors because of effect of flue gas flow during operation on refractory.

[4] **Jun Xie** in 2014, Studied the gaseous pollutant emissions produced during solid waste combustion in circulating fluidized-bed (CFB) by using CFD, the hydrodynamics, heat and mass transfer, and chemical reactions were also explained by him, he also illustrates the production of SO2, NO & N_2O releases with excess air and reduction of CO & CH4 with the increase of excess air.

[5] in 2010, **Benjapon Chalermsinsuwan** developed 2-D transient Eulerian model in combination with the kinetic theory of granular flow to acquire the hydrodynamic and chemical reaction behaviors in three different tapered shape geometries of circulating fluidized bed combustors, these risers have been compared for chemical reactions and its behaviors inside three different risers. According to his findings, the tapered inside riser was suitable for slow rate reactions and the tapered-out riser best for fast rate of reactions and medium rate reactions matched with the typical riser. His study is beneficial for selecting the appropriate type of geometry for CFBC.

[6] In 2015, **Eman Tora** analyzed a 3D CFBC by using CF (Fluent) to investigate the reasons of poor combustion and present his findings. According to his study, for proper and complete combustion temperature and velocities should be maintained in the corners and narrow areas when fuel is supplied to the port, particularly when the fuel contains higher moisture content and if the fuel is very wet it should be waged by mixing in dryer fuel.

[7] **Dr. Ahmad Hussain**, has performed experimental studies to burn the Palm Waste in circulating fluidized bed combustor, he also studied the impact of riser exist geometries. According to his study there is a significant influence of upper region of riser exit geometry.

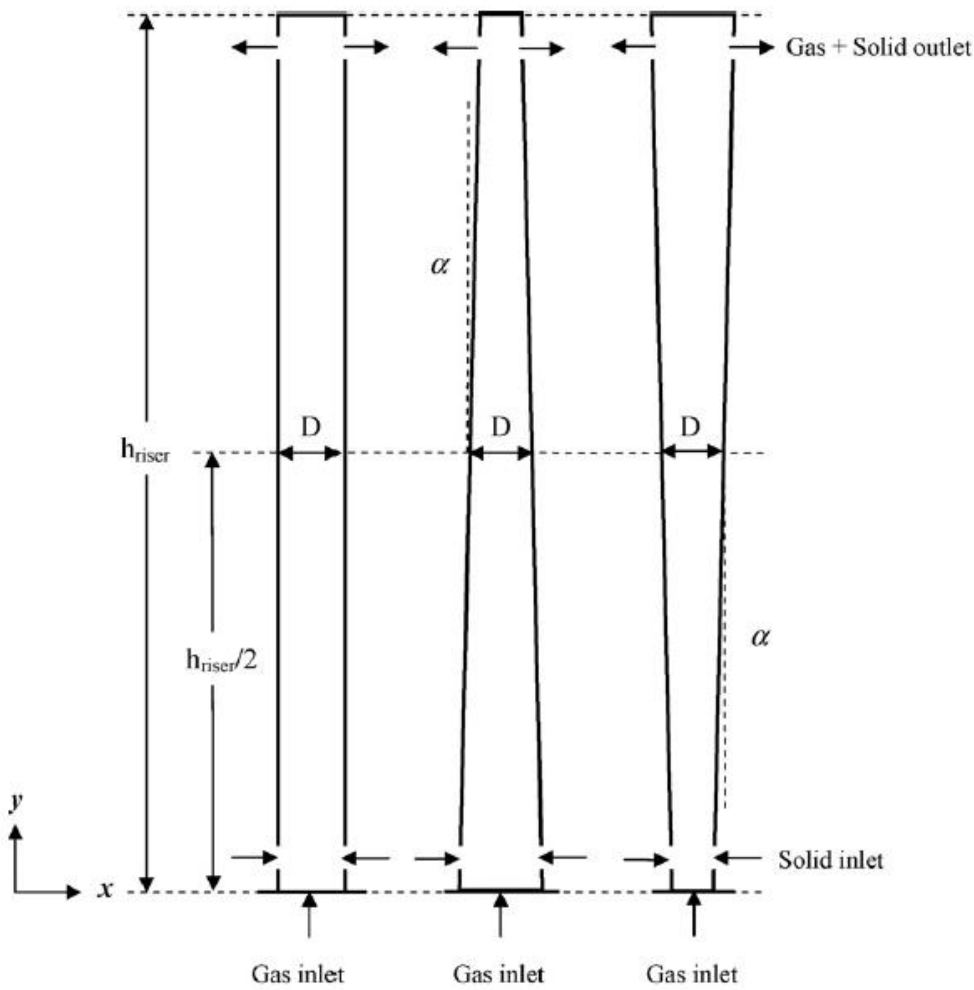


Figure 2. 1: Schematic drawing of (a) typical, (b) tapered-out & (c) tapered-in furnace designs [5]

2.4 Conclusion

As large amount of reach work is being carried out to improve the design of circulating fluidized bed combustor technology to get the maximum outputs with lower pollutant emissions different geometries behaviors and chemical reactions have been studied by many researchers and presented their findings. Selection of appropriate CFB combustor depends upon the desired rate of reactions, required temperature range, inside pressure, controlling of SOx & NOx and other desired results [23]. As it is the need of time to find out an alternate f fossil fuel so it is desirable to use fairly large quantities of biomass to produce power generation, majority of the reaches also been done to check the combustion behaviors of biomass, palm shell wastes, rice husks and other wastages, as coal is hazardous for our environment and its use is not appreciated to use the more economical fuels use of wastages as a fuel is important area to explore[7].

In addition to that, hydrodynamics of circulating fluidized bed combustors also studied by many researchers by using different model approaches like two-fluids models, eulerian-eulerian models and few other in ANSYS FLUENT [5].

CHAPTER 3 COAL POTENTIAL IN PAKISTAN

3.1 Introduction

Electricity is a vital player in the national growth and economic development of any country. Currently, in Pakistan, only about 60% of the population that can have availability to electricity and load shedding is the sever issue since 2009 and became a main obstacle in national growth. However, rapid increase in urbanization and industrialization in the country provide a great opportunity for investment in energy sector.

Pakistan has a high potential in coal, but, sadly, coal has not been gained attention for electricity generation for more than past thirty years due to not giving proper attentions by different governments. The demand/supply projection indicates that power shortages will appear from the year 2006 and will increase to 5,500 MW in the year 2010 [11]. The Government has now determined and aggressively focuses to facilitate private investments to investment in coal development and coal power generation to explore the local coal reserves to improve the sever power shortage situation of country.

Absence of sustainable and productive coal is the main reason to not achieve significant progress in coal power generation yet. The Federal and Provincial Governments, however, are continuously and aggressively trying to facilitate private investors in developing and promoting indigenous coal for power generation. After, China-Pak Economic Corridor (CPEC) china has made huge investment in power sector and main projects are of coal based. Coal is a cheap indigenous energy resource and, after the discovery of 175.5 billion tons of coal reserves in Thar area of Sindh [10]. Pakistan's coal power potential has increased significantly. According to studies, if Thar coal reserves are properly exploited, Pakistan's coal resources may able to generate more than 100,000 MW of electricity [10].

3.2 Coal & Its Types

There are four major types (ranks) of coal. The four ranks are:

- **Anthracite**: The highest rank of coal. It is a hard, brittle, and black shiny coal. Anthracite coal contain large share of fixed carbon and a low percentage of volatile matter and have high calorific value.

- **Bituminous:** Bituminous coal is a mid-rank coal between subbituminous and anthracite. Bituminous is most widely used coal for Power generation in US. It has slightly low percentage of fixed carbons and slightly high volatile matter thus have less calorific values.
- **Sub-bituminous:** Subbituminous is low rank coal. It is black in color and dull (not shiny) and has a higher heating value than lignite but lower than bituminous coal.
- **Lignite**: Lignite coal is the lowest rank coal and has low percentage of fixed carbon, higher ratio of moisture content, volatile matter and ash content as compare to all other three types of coal. Pakistan coal reserves largely consists of this lignite type coal.

3.3 Indigenous Coal reserves in Pakistan

Coal combustion studies have been done largely for bituminous coal. However, lignite and sub-bituminous coals reserves are largely existing globally and consist of approximately 48%. Pakistan is a coal rich country, and there are vast resources of low rank coal ranges from sub-bituminous to lignite, spread all over the country, including Azad Jammu & Kashmir. As indicated by the rough approximation, Pakistan has total coal reserves of more than 185 billion tons in which Thar coal field has significantly vast reserves and contain 175.5 billion tons coal reserves [9] [10].

Province	Resources in Million Tones	Heating Value (Btu/lb)
Sindh	184623	5,219 -13,555
Baluchistan	217	9,637 -15,499
Punjab	235	9,472 -15,801
KPK	91	9,386 -14,217
AJK	9	7,336 -12,338
TOTAL	**185175**	

Table 3. 1:Indigenous Coal reserves of Pakistan and their Heating Values [9]

3.4 Thar Coal Field

The Thar coal field has lignite rank coal and have heating value of 2.14 - 31.5 MJ/Kg. Thar coal field covers up to a range of 9100 sq. Km and contain 175 Billion tons of coal reserves which can able to generate 100000 MW electricity for more than two hundred years [12]. After the discovery of Thar coal Field, Pakistan is now the 6th richest nation of the world in respect of coal resources [29]. Due to unavailability of any reliable and workable energy resources in the country, Pakistan has to use fossil fuel to meet the energy requirements, Thar coal is a good substitution if exploited properly and able meet the energy deficit and to create the energy security in the country.

- Thar Desert Area: 22,000 km^2
- Coalfield Area: 9,100 km^2
- Total Drill Holes: 217
- Coal Resources: 175.506 billion tons

Coal resources of the Thar coal field (Block1,2,3 & 4) are estimated at 9,629 million tons, as shown below.

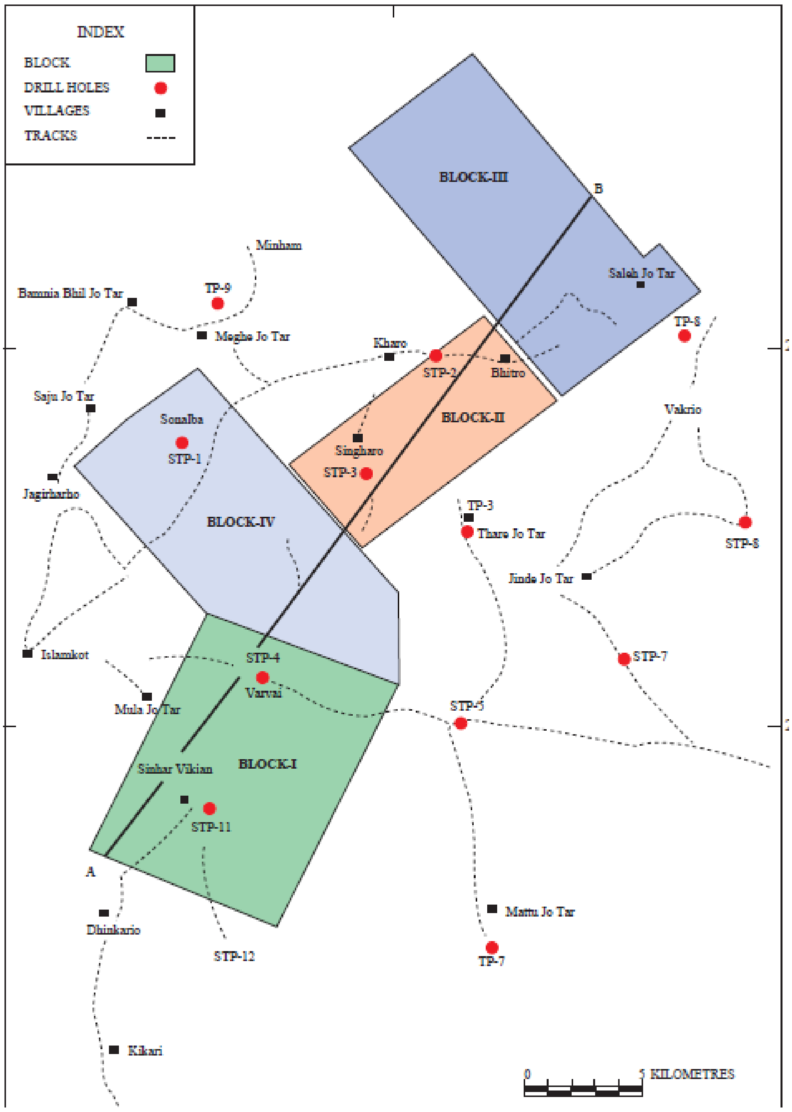


Figure 3. 1:Thar Coal field map (all four blocks) [11]

3.4.1 Quality of Thar Coal

Quality of Thar coal is mostly between lignite-B to sub-bituminous A-C. The Thar coal filed for Thar coal block-II resources were calculated based on the drill holes obtained date in accordance with JORC. The total coal resources in the area are estimated to be around 2 Billion tons, with proven resources of 414 million tons.

Below mentioned is the proximate (as received basis) & Ultimate analysis of Thar coal which obtained based on bore-hole modelling.

Ultimate Analysis (dry basis)	
C (%)	74
H (%)	6.1
N (%)	1
S (%)	2.5
O (%)	18

Table 3. 2: Ultimate Analysis of Thar Coal (%)[12]

Proximate Analysis (As received basis)	
Lower Heating Value (LHV)	11.61 MJ/kg
Ash	7.8%
Sulphur	1.1%
Moisture	47.6%
Fixed Carbon	19.6%
Volatile Matter	25.10%

Table 3. 3:Proximate Analysis of Thar Coal (in %) [12]

The proximate analysis of all four blocks of Thar coal is shown in below histogram chart. According to this chart, block-II has high moisture content and approximately moderate fixed carbon content as compare to other three blocks. Similarly, block-I has high volatile matter and low Sulphur content as compare to others. The fixed carbon percentage in approximately equal in all four blocks [9].

As per histogram comparative chart of all four blocks heating values, block-I coal have high heating values about 6400 BTU/lb (14.88MJ/kg) as compare to other three blocks coal [9].

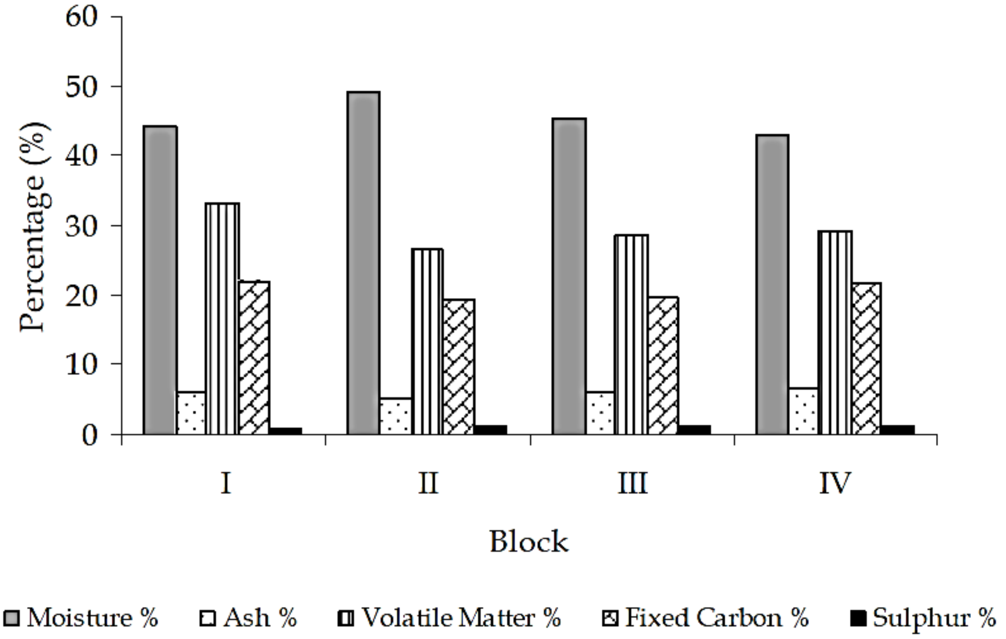


Figure 3. 2: Comparison of all four blocks Proximate Analysis of Thar coal field (as received) [9]

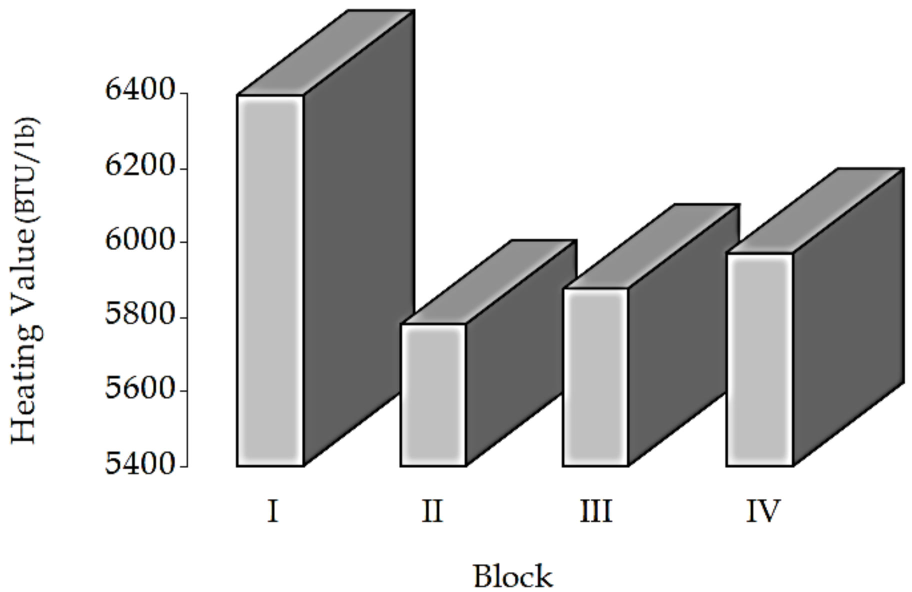


Figure 3. 3: Comparison of heating values of all four blocks of Thar coal field (as received basis) [9]

3.5 Thar Coal Power Project

Engro Corporation Limited is one of the leading corporations of Pakistan with their presences from fertilizers, food to power generation. Engro Powergen limited (EPL) is the fully owned subsidiary of Engro Corporation and established in 2008 with the main objective to develop power projects in Pakistan [12].

EPL and Government of Sindh (GoS) has made a long term and strategic relations by establishing **Sindh Engro Coal Mining Company (SECMC)** as joint venture to develop, construct and operate an open cast lignite mine and mine mouth power plant in Block-II of Thar coalfields. The SECMC had proposed a plan to develop an open cast mine of 6.5 million ton per annum capacity initially which would then be extend up to 22.5 million ton per annum further. EPL had a plan to build a power plant and generate electricity independently, 1200 MW in the first phase to be increased to 4000 MW with the extension of coal mine capacity [12].

RWE-Germany, Sino coal-China has completed the Bank Feasibility Study (BFS) for Engro Thar Coal Block-II power project.

BFS confirmed that total lignite reserve in Thar Block II are two Billion tons with available reserve of 1.57 Billion tons which can support 5000 MW for 70 years. GoS has issued 30 years Mining Lease (of 95.5 sq.km) to SECMC for Thar Block-II [9] [12] .

By March 19th, 2019, the first 330MW power plant successfully connected to the nation grid and started generating the electricity through local coal i.e Thar Coal which is a great achievement for our country. The next 330MW power plant will start its production very soon.

CHAPTER 4 CIRCULATING FLUIDIZED BED

4.1 Circulating Fluidized bed combustion (CFBC) Technology

Over the past few decades, CFB technology including CFB boiler operation and CFB boiler design has proven its ability due to its dwelling industrial applications such as combustion, gasification, pyrolysis, cracking, catalyst regeneration and to efficiently utilize a wide variety of fuels and controlling of highly pollutant emissions [7]. CFBC is getting wide research consideration in its potential as a financial and earth worthy engineering for smoldering or burning poor quality coal, biomass, natural waste, subsequently mixtures agricultural wastes like bagasse, paddy husks, sawdust and groundnut shells can be effectively used as fuels [21].

The advancement in Fluidized bed technology seen particularly in twentieth century. It has been utilized as a part of numerous branches of chemical engineering together physical methods (e-g. particle coating, drying) and synthetic methods (gas –solid non-catalytic reactions) [21]. The prominent fluidization innovation has been used for more than twenty years to many other processes including paralysis, catalytic processes, waste incineration, and coal combustion for power generation and calcining [21].

4.2 Typical components of CFB Boiler/Combustor

Following terminologies helps to understand the CFBC operation and their components.

4.2.1 Fluidization

Fluidization is a process similar to liquefaction like boiling of water whereby a granular material such as silica sand is converted from a static solid-like state to a dynamic fluid-like state. This process occurs when a fluid (Air) is passed up through the bottom of granular material (sand) [25].

In Fluidized bed combustor furnace the sand is present at the bottom of the furnace and it behaves like a bed when the high pressure and high velocity air introduced from the bottom of the bed through a specially designed nozzles then solid static bed of bed become start bubbling. The velocity of the air is higher than the average terminal velocity of particle and it lies between 4m/s to 8m/s and because of this high velocity bed material moves upward

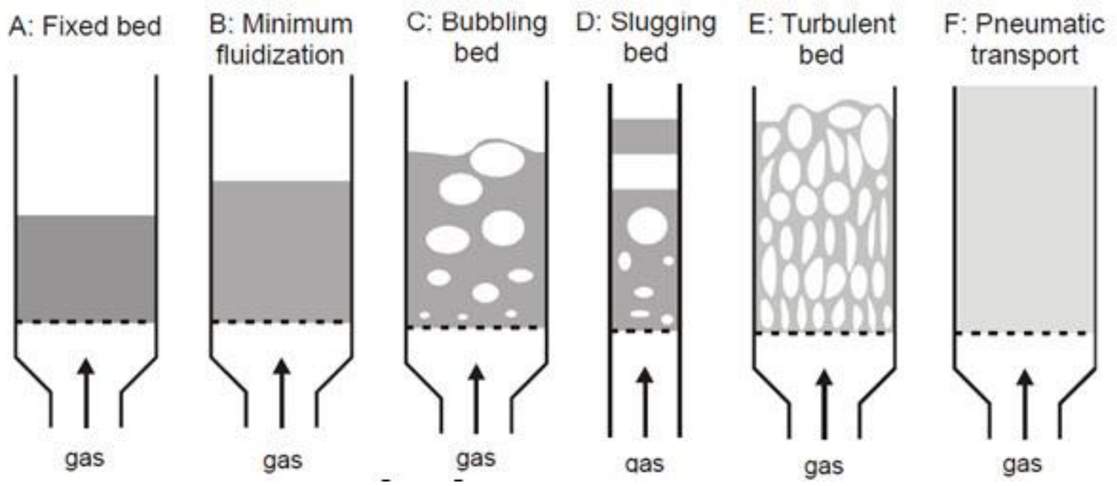


Figure 4. 1:Stages of fluidization (from steady state to fluidize state) [26]

direction in the furnace and will exhibit a fluidic behavior. Due to this fluidization the coal or burning fuel burnt with continuous interaction of hot sand particles.

4.2.2 Bed

Before start of the operation in furnace, sand is in stationary with zero velocity and maximum density at the lower level of furnace. A layer of burning fuel (coal or other material) also exists with same zero velocity. When high velocity air introduced from the bottom part of furnace or below the sand, the bed loses its solid state and become fluidized as mentioned in figure 4.1.

4.2.3 Circulation (Cyclone)

During burning inside the furnace fine particles of partly burned coal, ash and bed material(sand) are carried along with the flue gases to the upper areas of the furnace and then entered a cyclone. Cyclone is the important part of CFB combustor here, the heavier particles separates from the flue gases and again entered in to the furnace for participating again in reaction. Hence the name Circulating Fluidized Bed combustion. The hot gases from the cyclone go out of the combustor after passing from heat exchanger. Recycling maintains the bed height and increases the thermal efficiency.

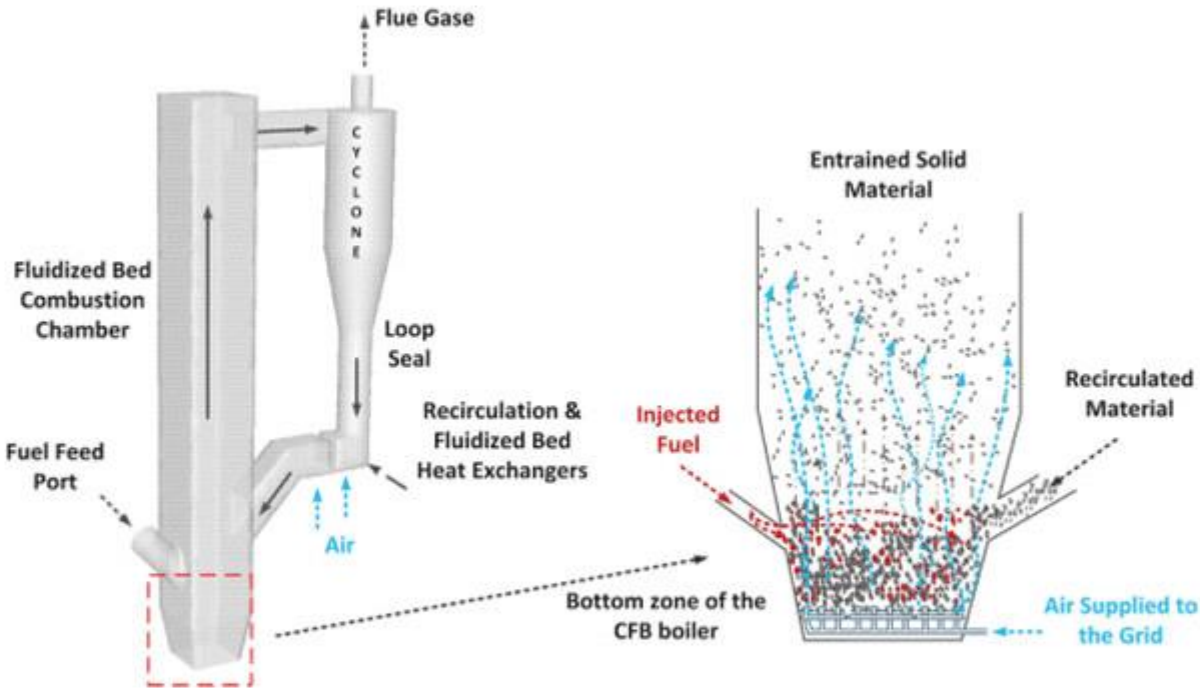


Figure 4. 2:Bed & Cyclone of CFB furnace [26]

4.2.4 Primary air

Primary air is fed into the furnace through nozzles which are available at the bottom area of furnace. This will help to the complete combustion of coal as the mixing of air and fuel. Primary air usually ranges from 4m/s to 8m/s and supplied through fans. Selection of appropriate primary air velocity is very important, and it depends on the size and design of furnace as well as on the coal particle sizes. The higher velocities usually reduce the combustion efficiency as the small size particles of coal directly gone to the cyclone without burning because of higher velocity.

4.2.5 Secondary air

Secondary air is and extra air that provide to the furnace for the complete combustion of fuel and to compensate the primary air. be an extra air that must be provided for complete combustion of fuel. It generally supplied to furnace through nozzle which connected through the side wall of the furnace which is above the bed level and usually ranges from 1 meter per second to 2 meter per second . The secondary air preheated through air preheater before supplying to the furnace for reducing moisture content of fuel and enhance the boiler efficiency.

4.2.6 Fuel induction

Solid fuel is fed into the furnace from the lower area and side wall of the furnace through a screw conveyor with different fed rates (mass flow rates) depending upon the size of furnace.

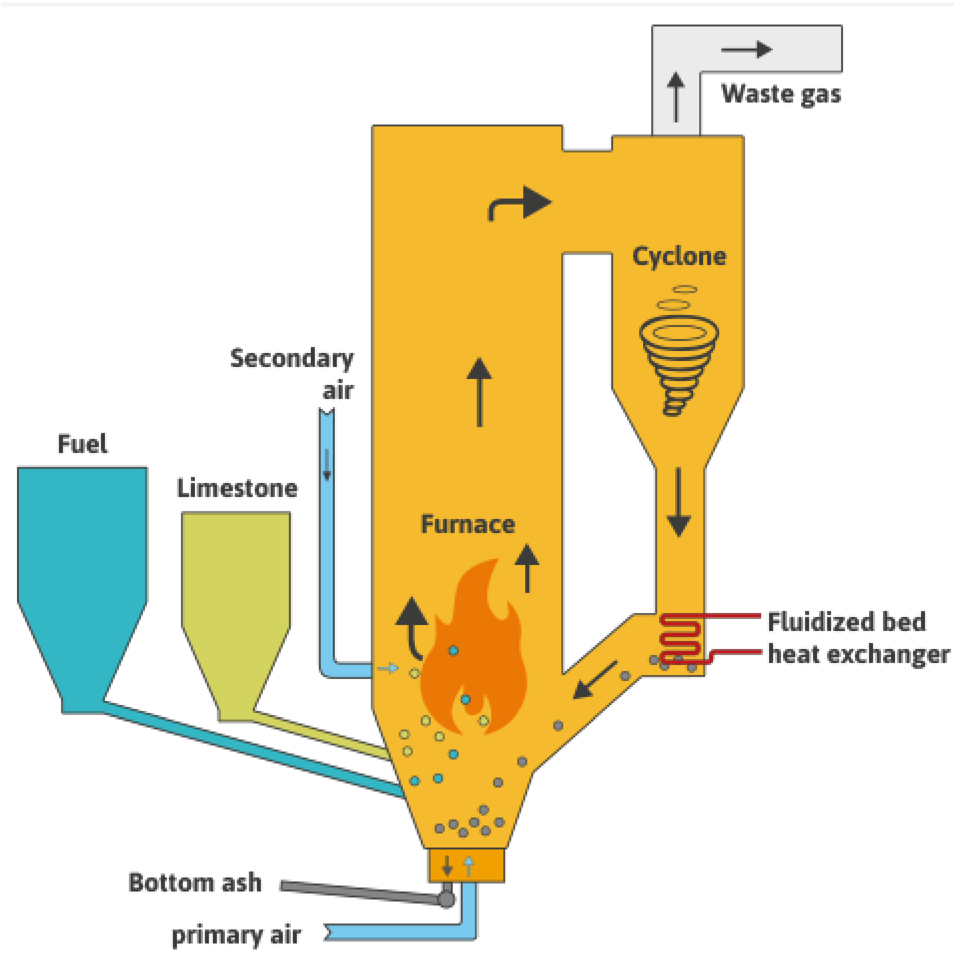


Figure 4. 3:Schematic diagram of CFBC with typical components [27]

4.2.7 Riser

A riser or boiler is the overall area of boiler or furnace where solid and gas mixing takes place. It usually made up of refectory material to maintain the furnace temperature and protect the furnace walls from erosion and other damages.

4.2.8 Ash collector

Ash collector is located at the extreme bottom side of the furnace and is used to take out the large ash which is not able to take out from furnace through fluidization. However, the large size ash takes away from furnace through high velocity fluidization.

4.2.9 Sand and lime stone

As coal contain higher contents of Sulphur then to reduce the SOx or desulfurization it is required to use a high amount of lime stone in furnace. Lime stone (CaCO3) contain the high amount of Calcium Oxides (CaO) and it will help to minimize higher Sulfur or Sulfur dioxides (SO_2). Lime stone is fed in to the furnace pneumatically or through gravitational fed from the side wall area slightly above the coal induction area.

4.3 Advantages of Circulating Fluidized Bed Combustor (CFBC)

Since 1985, CFBC technology was first used in the generation of electricity and now coal-fired power plants that are using CFBC technology are widely adopted and can be used in the US, Europe, Japan, China and other developed countries [13]. However, due to some limitation of unit sizes and sub-critical steam condition its use in power generation is limited. Research work has been carried out in CFBC field to improve the designs for the use of large unit sizes. The core advantages of CFBC technology are;

● Operation Performance

The circulating fluidized bed combustor is used to burn a low-grade fuels with aim to have a low pollutant emissions. CFBC boilers have high combustion efficiencies (up to >99%) because of large residence time and good mixing capabilities. Today, CFBC boilers on an average can achieve availability of 90% or more than it. It provides the uniform heat over the entire furnace [13].

- **Environmental performance**

Low pollutant emissions like NOx and SO2 production is another significant advantage of a CFBC boiler because of low combustion temperature inside the CFBC furnace and SOx can be desulphurization due to addition of lime stone [13].

- **Plant size and steam conditions**

Almost all the existing coal-fired CFBC power plants are based on the subcritical steam cycles and are relatively small in size. However, significant progress has been seen in CFBC technology to scale-up CFBC boilers and to adopt supercritical steam cycles. Today, SC CFBC boilers 800MW capacity and steam condition 25 MPa/600ºC/600ºC are available in market [13].

Chemical plants, steel work, utility and other industrial processes are widely using CFBC technology.

- **Fuel flexibility**

Through CFBC fuel from high quality coal like anthracite to very low grade fuels like biomass, agriculture wastes can easily be utilized. Simplified fuel feeding, pulverization is not required, crushing is enough [13].

CHAPTER 5 MATHEMATICAL MODELLING & GOVERNNG EQUATIONS OF CFBC

5.1 Mathematical Modelling

Below mentioned are the basic equations for mass, momentum, energy and species transport for gas phase. These are the fundamental equations of flow for gas phase when combustion and gasification takes place in fluidized bed. The mathematical equations and governing theory are described below,

5.1.1 Continuity Equation

This equation is derived from law of conservation of mass, which states that the mass of the system remains same. It is very simple, powerful and important equation in CFD. It is one of the main equations from five main equations of CFD. It can be written as

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \boldsymbol{u})[19]$$

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \boldsymbol{u})[19]$$

5.1.2 Momentum Equation

Navier Stokes(NSE) equation is derived from the law of conservation of momentum. It is a very vital equation in fluid dynamics, this equation is the extension of EULER equation [19]. Euler equation is for inviscid flow, but this equation is for viscous flow. In its simple form, NSE includes the sum of body forces and surface forces. When further simplified, it contains the velocity gradients with space and time, pressure gradients and viscosity changes with respect to time.

$$\rho \frac{Du}{Dt} = -\nabla \overline{p} + \mu \nabla^2 u + \frac{1}{3}\mu \nabla(\nabla. u) + \rho g \qquad [19]$$

5.1.3 Energy Equation

The energy equation depends on the law of conversation of energy. The energy equation can be written as,

$$\frac{\partial}{\partial t}\left[\rho\left(e+\frac{V^2}{2}\right)\right]+\nabla.\left[\rho\left(e+\frac{V^2}{2}\vec{V}\right)\right]=\rho\dot{q}+\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+$$
$$\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)-\frac{\partial up}{\partial x}-\frac{\partial vp}{\partial y}-\frac{\partial wp}{\partial z}+\frac{\partial u\tau xx}{\partial x}+\frac{\partial u\tau yx}{\partial y}+\frac{\partial u\tau zx}{\partial z}+$$
$$\frac{\partial v\tau xy}{\partial x}+\frac{\partial v\tau yy}{\partial y}+\frac{\partial v\tau zy}{\partial z}+\frac{\partial w\tau xz}{\partial x}+\frac{\partial w\tau yz}{\partial y}+\frac{\partial w\tau zz}{\partial z}+\rho\vec{f}.\vec{V} \qquad [2], [19]$$

These equations are the set of coupled, nonlinear partial differential equations. For majority of the engineering problems their analytical solution is not possible. However, approximate solution of these governing equation is possible to obtained through computer-based solution methods.

5.1.4 Species transport Equation

When choose to solve conservation equations for chemical species, **ANSYS FLUENT** predicts the local mass fraction of each species ***Yi,*** through the solution of a convection-diffusion equation for the ***ith*** species [28]. This conservation equation takes the following general form:

$$\frac{\partial}{\partial t}(\rho Yi)+\nabla.(\rho\vec{u}Yi) = -\nabla.Ji+Ri+Si[2]$$

where $\boldsymbol{Ri}$ is the net species production rate and $\boldsymbol{i}$ by chemical reaction and $\boldsymbol{Si}$ is the rate of creation by addition from the dispersed phase plus any user-defined sources.

5.2 Computational Fluid Dynamics (CFD)

Computational fluid dynamics (CFD) is a branch of Fluid Mechanics, through CFD problems of fluid flow, heat transfer and combustion can be solved numerically. As numerical methods are long and tedious and largely done by using computer software, so the speed of computer system is very important to solve the CFD problems. In modern period the speed of computers are increased significantly and because of that the use of high speed computers has been increased for solving practical engineering problems more accurately. While solving the combustion problems, CFD solves five main governing equations: Continuity equation, three equations of Naiver Stokes Equation and Energy equation. CFD solves problem by following three basic procedure,

5.2.1 Pre-Processing

In preprocessing step, the geometry of problem is defined. The geometry is then divided into small cells called a mesh or grid. The process of generating a grid or mesh is called Mesh/ grid generation. Grid generation is an difficult task and it takes a lot of time and effort to generate proper meshing to take desired results. Results are highly depending upon the generation of appropriate meshing. There are many soft wares commercially available through which Mesh/grids can be generated on any geometry such as Gridgen, Ansys ICEM, Ansys work bench, T grid, Gridpro etc. In this problem, ANSYS Workbench is used for meshing [19].

5.2.2 Solver:

Solver is the second step in CFD modelling here the Material properties, Combustion inputs, Flow type, Physics model and Boundary conditions have been defined. There are numerous commercial Solvers available such as Open foam, Ansys Fluent, CFD++, Star CCM, simscale [19].

Ansys Fluent v16 is chosen for this study because of its powerful and easy to use solver capacity for solving coal combustion problems.

5.2.3 Post processing:

After solver step the problem is solved and ready to draw the results. Results include the Contours (velocity contours, pressure contours etc.), Vectors, path lines, etc [19].

There are soft wares present which can perform these tasks easily few of them are EnSight, ParaView, FieldView, Ansys CFD Post, and Tecplot 360 etc.

5.3 CFD Models

Below described models have been used in this study to solve the combustion problem.

5.3.1 RANS based models

The Reynolds-averaged Naviere Stokes (RANS) equations represent transport equations for the mean flow quantities. In majority of works standard keε is used in combustion and gasification of fuels in fluidized beds [2].

- **Turbulent flow**

During combustion and gasification of fuels turbulence plays an important role in fluidized bed. Turbulent flow creates due to fluctuation of air velocity and particles inside the furnace. The turbulence plays an important role in combustion and gasification of fuels as it affects the heat and mass transfer in fluidized beds combustors.

5.3.2 Standard K Epsilon model

It is a most famous turbulent two equation models and is frequently used in practical engineering problems' K means turbulent kinetic energy and e stands for dissipation rate [19] [8]. Kinetic energy is about energy in turbulence whereas epsilon (dissipation rate) defines the scale of turbulence. It cannot give accurate results as it can only solve fully developed flow problems. It is used for low Reynolds numbers.

Following is equation of K (turbulent kinetic energy)

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial \rho k \mu_i}{\partial xi} = \frac{\partial}{\partial xj}\left[\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial xj}\right] + 2\mu_t EijEij - \rho\epsilon \qquad (1)$$

And another equation is for epsilon(dissipation rate), written as equation(1).

$$\frac{\partial(\rho\epsilon)}{\partial t} + \frac{\partial\rho\epsilon\mu_i}{\partial xi} = \frac{\partial}{\partial xj}\left[\frac{\mu_t}{\sigma_\epsilon}\frac{\partial\epsilon}{\partial xj}\right] + C_{1\epsilon}\frac{\epsilon}{k}2\mu_t EijEij - C_{2\epsilon}\rho\frac{\epsilon^2}{k} \quad (2)$$

5.3.3 Mixture fraction model

The mixture fraction/PDF modeling approach involves the solution of transport equations for one or two conserved scalars (the mixture fractions) quantities. In this approach, instead of solving the transport equations for individual species, certain species of interest are derived from the predicted mixture fraction.

5.3.4 Non-Premixed Combustion model

In non-premixed combustion, fuel and oxidizer enter in the furnace from different areas. The is opposite to premixed combustion systems where fuel first mixed with the oxidizer before entering the combustion chamber or furnace. Examples of non-premixed combustion include pulverized coal furnaces (FB), diesel internal-combustion engines and pool fires. Non-premixed combustion model does not solve individual species conservation equation during the combustor simulation of non-premixed combustion model [20].

5.3.5 Combustion and gasification sub-models

Devolatilization, combustion or gasification and draying of coal process begins when coal enters into the fluidized bed furnace. The fundamental equations of computational fluid dynamics incorporated with the sub-models to simulate the actual combustion and gasification processes in fluidized bed [20].

5.3.6 Devolatilization sub-model

The devolatilization of fuel begins when the solid fuel reaches a certain temperature. Many devolatilization models have been developed in previously. The most famous mechanisms are One-step global mechanisms and semi-global multi-step mechanisms [19].

5.3.7 Radiation Model

Heat transfer rate is influenced with the radiation process in the combustion and gasification process in fluidized bed systems, which in turn influences combustion and gasification process [19] [20].

The applicable models are.

(a) Discrete ordinates

(b) P-1

(c) Rosseland

(d) Discrete transfer radiation.

5.3.8 Discrete Phase Model

Discrete phase model is used to model the discrete partciles that are coal. In DPM modelling discrete particles are tracked (in a Lagrangian framework according to Newton's laws of motion) in the continuous phase flow field. For DPM it is to be preliminary consider that the coal particles or discrete particles entered the stream from a separate entry and their entry/injection conditions are to be specified in this modelling [20].

CHAPTER 6 PROBLEM DESCRIPTION AND PRE-PROCESSING

In this chapter the problem on which this study is based will be explained and the pre-processing steps of defining geomtery and meshing will be discussed.

The pupose of this study is to understand and predecit the perfomance of low grade coal partciluarly thar coal in circulating fluidized bed combustion technology. As Governmant sector is enagged with private sectors in exploration of thar coal and for this purpose a **Sindh Engro Coal Mining Company (SECMC)** has been established by (GoS) and private sector Engro Power Company is establishing 1200MW coal fired power project in Thar area. This study is done by inspiring with above development and decided to predict the performance of Thar coal in power generation [12].

6.1 Problem Description

A simulation of coal combustion involves a continuous gas phase flow field modelling and its interaction with coal particles which is a discrete phase. The coal partciles, travelling through the gas inside the furnace will devolatilize and under go char combustion, acting as a source of fuel in reaction. This reaction is modelled by using non-premixed combustion model.

Two different kind of CFBC geomteries have been selected one is duct from upper area while tapperd from bottom side and and second one is quite similar to 1st one but only tapper from one side from bottom bed area while the second end is straight. It has been decided to adopt a similar methodology to compare the results of both geomteries and predict which geomtery has better combustion efficiency. The required inputs related to quality of coal has been used here of Thar Coal.

6.2 Geomtery

2D geometries of CFB have been created on ANSYS Workbench v16. Both geometries have following design specifications.

Dimensions(meter)	Geometry 01	Geometry 02
Duct	15x6.7	15x6.7
Bed Cross section	4x3.2	4x4.95
Primary air inlet area	3.2	4.95
Secondary air inlet area	0.5	0.5
Secondary Air position	2.764	2.764
Coal inlet area	0.5	0.5
Coal inlet position	1.965	1.965
Out let area	6.7	6.7

Table 6. 1:Dimensional details of Geometry 01 & Geometry 02

6.2.1 Geometry 01

The 1st CFB furnace that is selected for this study has below geometry and dimensions. This kind of geometry has been studied by some reserches for different coals but, here Thar coal proeprties have been explored in this geometry.

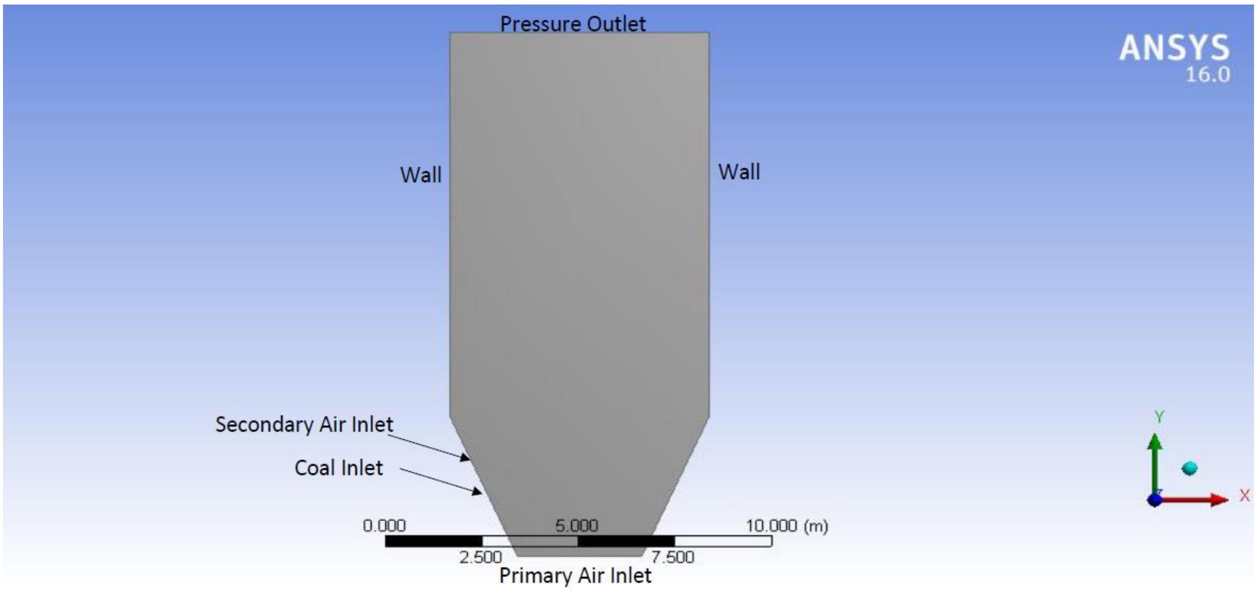
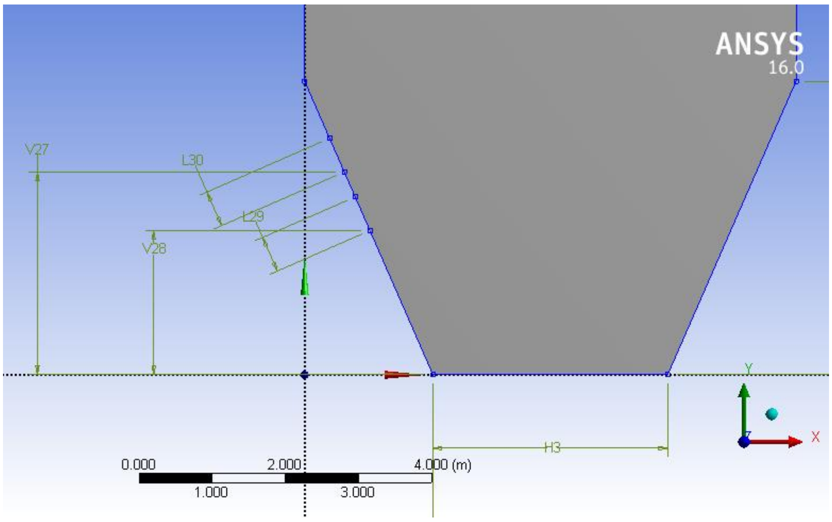


Figure 6. a: 2D model (labeled) of Geometry 01



etails View

H3	3.2 m
H8	6.7 m
L10	15 m
L11	11 m
L29	0.5 m
L30	0.5 m
V27	2.7643 m
V28	1.9657 m

Figure 6. b:Bed area of Geometry 01 (right) and their dimensions (right)

6.2.2 Geometry 2

The 2nd CFB furnace has following geometry and dimensions. Thar coal proeprties have been explored in this geometry and draw a comparisions of results between two geomteries.

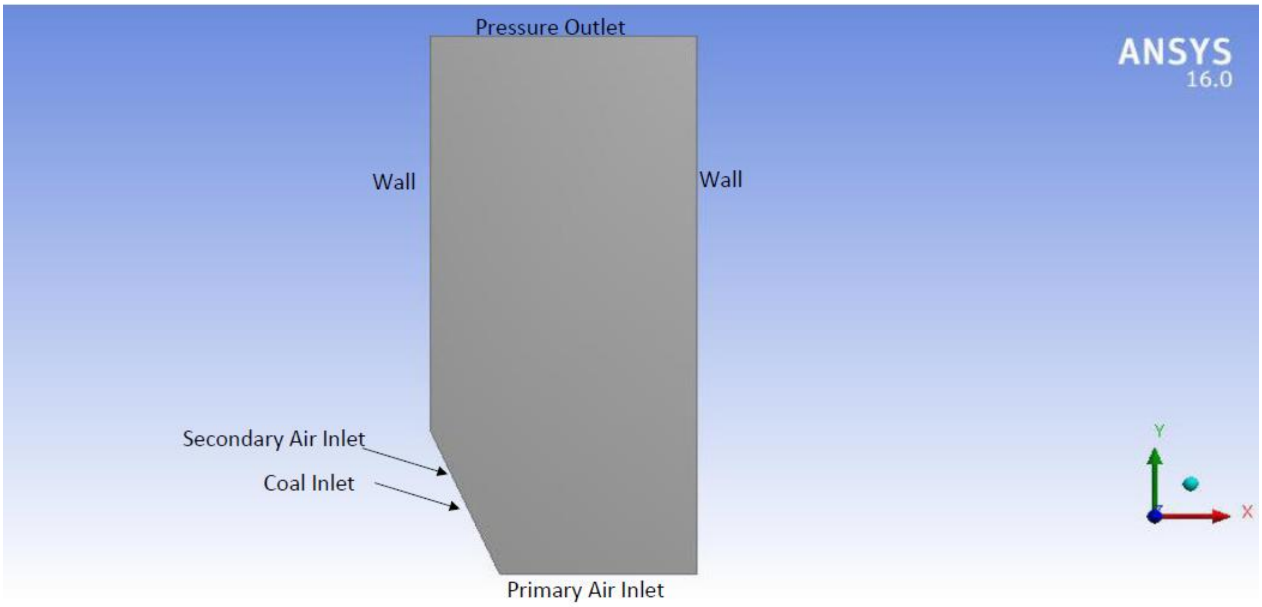


Figure 6. 3:2D model (labeled) of Geometry 02

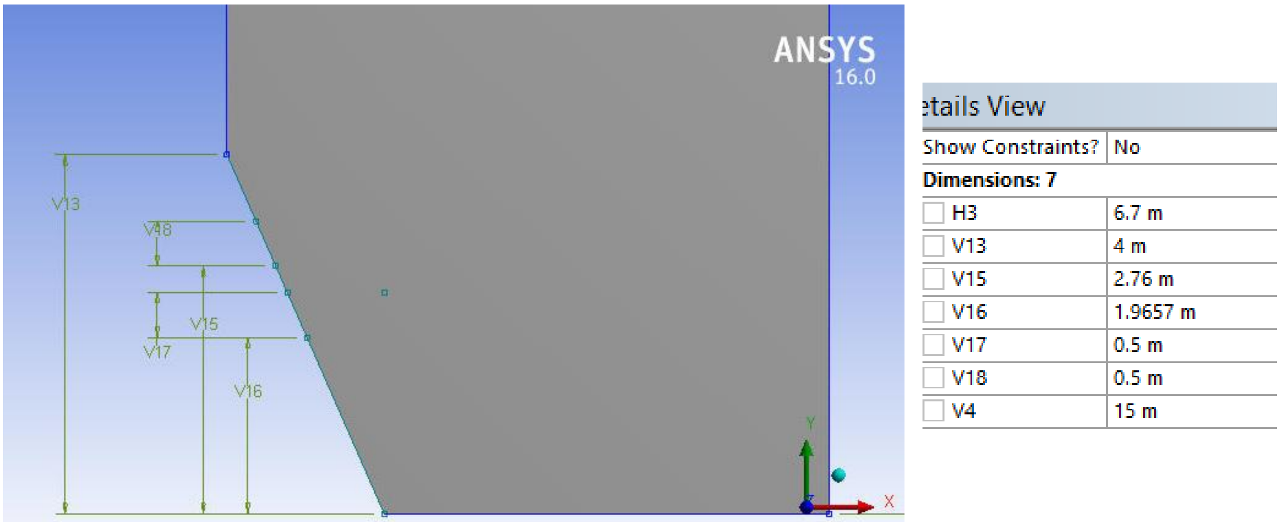


Figure 6. 4:Bed area of Geometry 02 (right) and their dimensions (right)

6.3 Mesh Generation

The mesh generation is the most important in solving any problem through CFD. In this study mesh have been generated in both geometries through ANSYS v16.0 because of its powerfull mesh generation capability. The stractured mesh of Quardiaterial type with element size 7cm (0.07m) have selected for both geometries. The generated meshes have following details,

	Geometry 01	Geometry 02
Nodes	14170	18144
Cell/Element	13888	17845
Cell Size	0.07	0.07
Faces	27495	35392
Type	Quardilateral	Quardilateral

Table 6. 2: Details of Mesh generation (Geometry 01 & Geometry 02)

6.3.1 Geometry 01

The mesh related details of geometry 01 is mentioned in table no 6.2. the minimum orthagonal quality of mesh is 0.91404. Here the mesh orthogonal quality is close to 1 hence, the mesh has good quality.

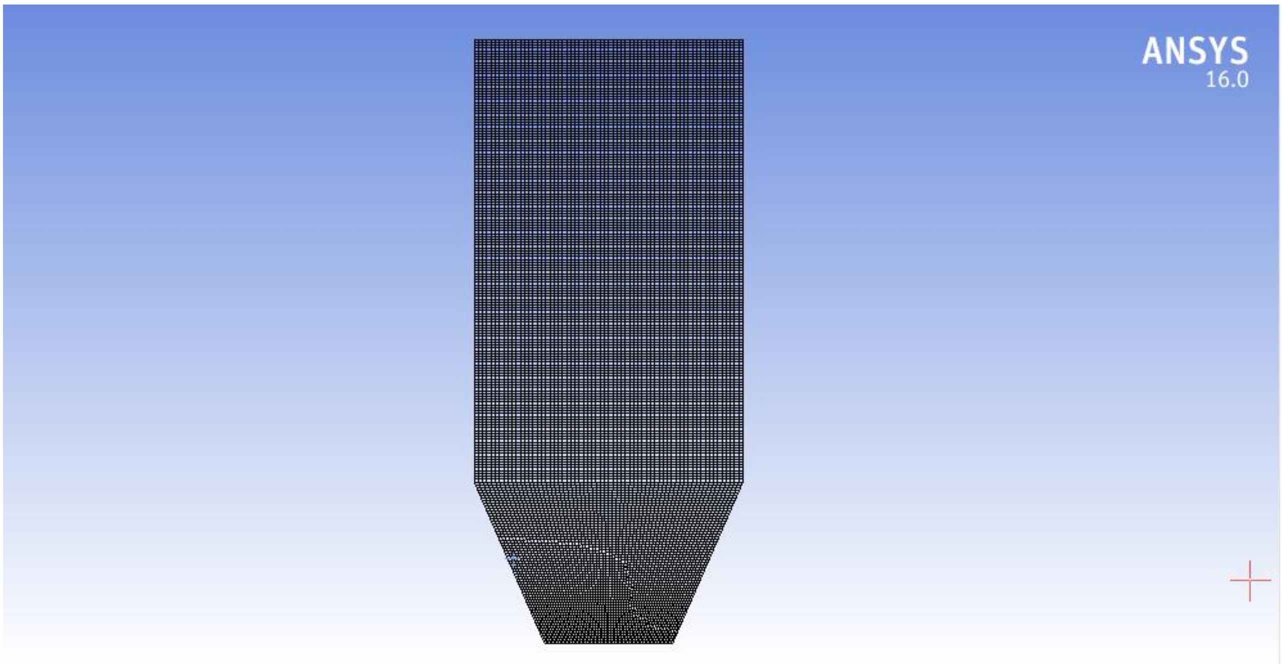


Figure 6. 5:Meshing in 2D model of geometry 01 through ANSYS v16

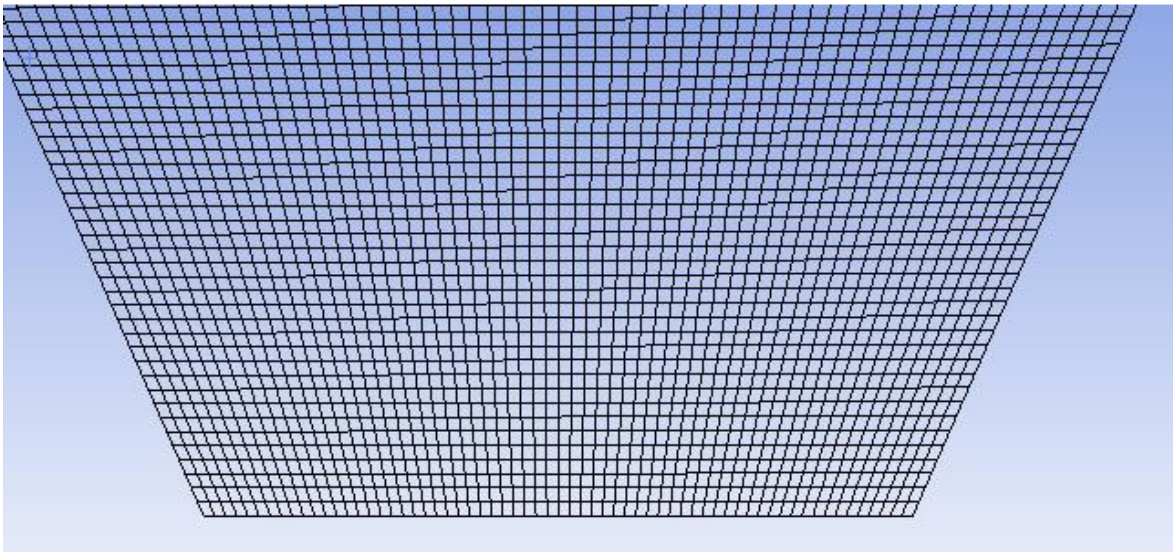


Figure 6. 6:Meshing in 2D model of geometry 01 (Bed area)

6.3.2 Geometry 02

The mesh related details of geometry 02 is mentioned in table no 6.2. the minimum orthagonal quality of mesh is 0.91677. Here the mesh orthogonal quality is close to 1 hence, the mesh has good quality.

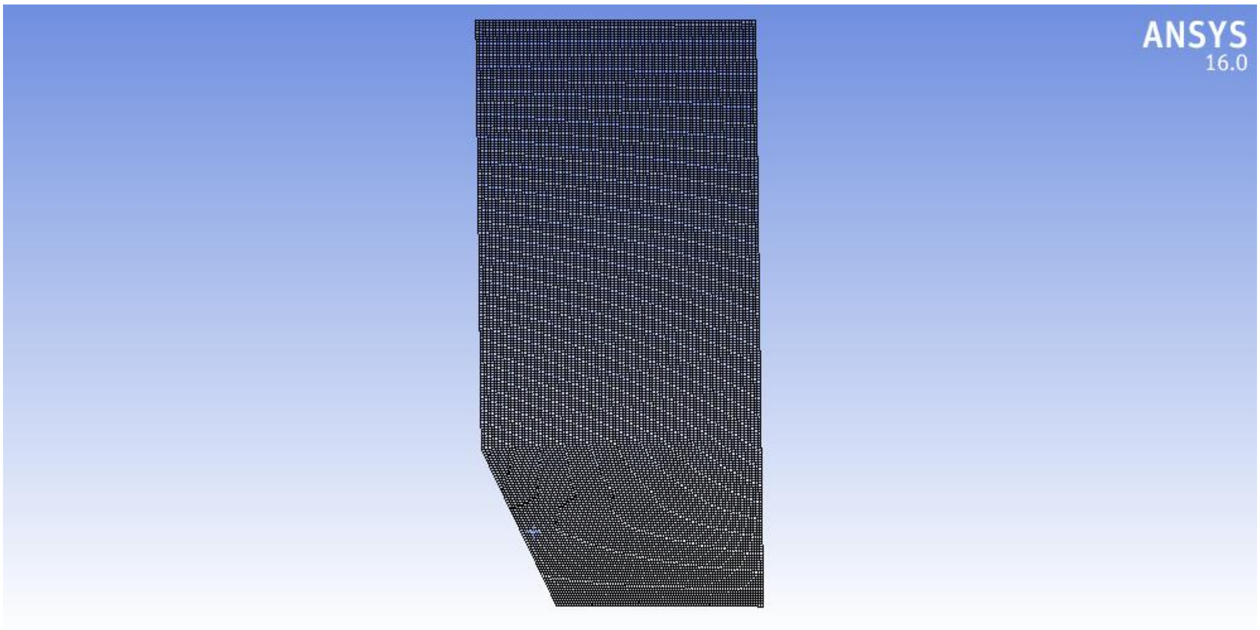


Figure 6. 7:Meshing in 2D model of geometry 02 through ANSYS v16

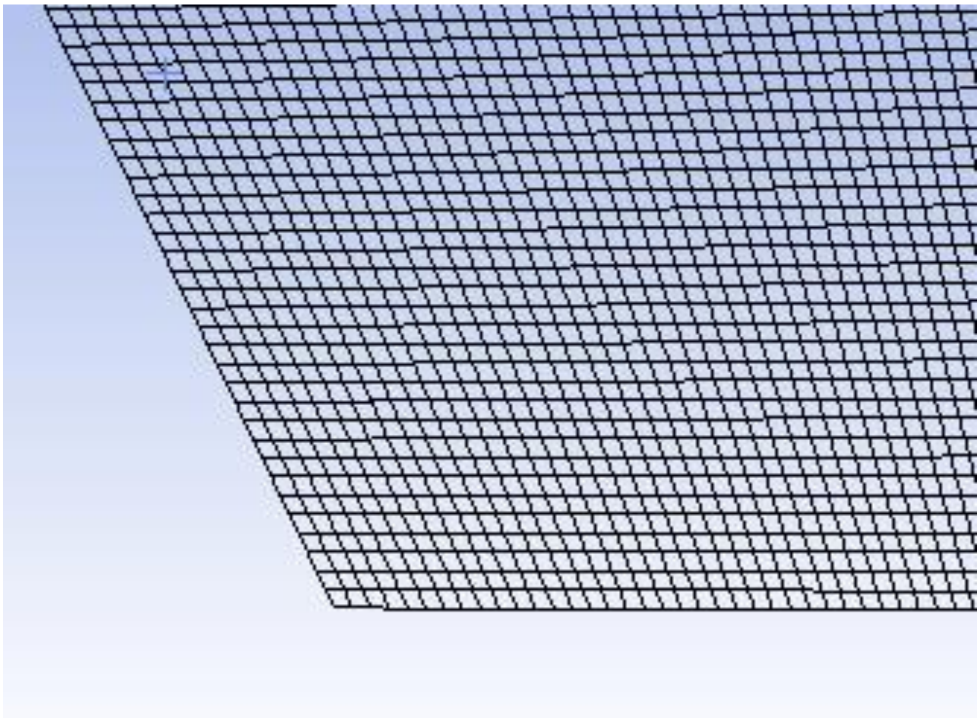


Figure 6. 8:Meshing in 2D model of geometry 02 (Bed area)

CHAPTER 7   SOLVER AND BOUNDARY CONDITIONS

In this chapter that the second phase of problem solving step the methodology which adopted here will explained in details. The boundary conditions which have been considered to solve this problem also explained in this chapter. Similar methodology and boundary conditions have been applied on both geometries to achive the results.

7.1 General Settings

2D ANSYS FLUENT v16.0 with double precission option is selected. Steady state, Pressure bsed and Planar solver is used. Gravity option is activated and provide the constant value -9.81m/s^2 in Y-axis.

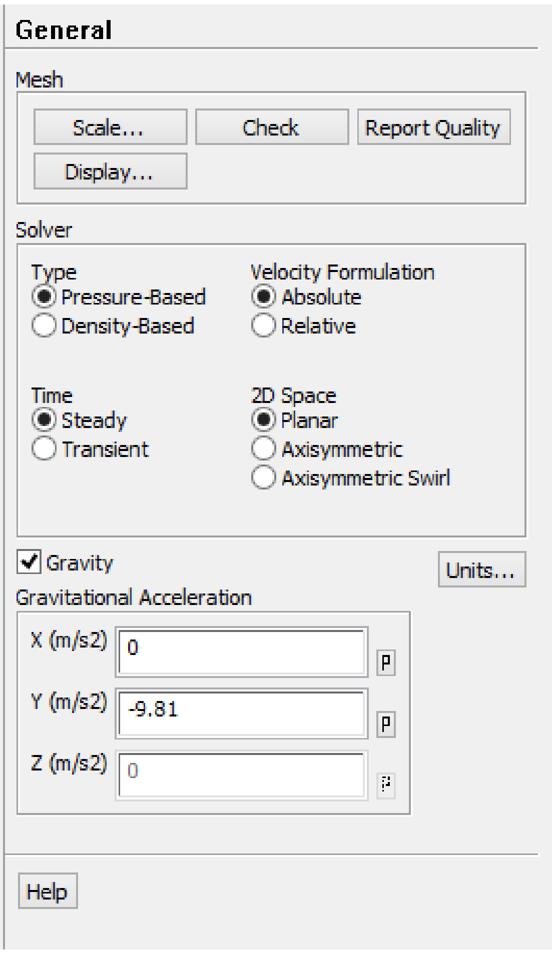


Figure 7. 1: Screenshot of ANSYS FLUENT v16 General settings

7.2 Models

In model Non-Premixed combustion model is largely adopted to model the coal reaction chemistry and discrete phase model is for model the discrete phase coal particles.

Before approaching to the non-premimxed combustion modelling first ON the energy equqtion and check the Radiation model P1 as during the coal burning heat produced and radiations released.

7.2.1 Viscus Model

In viscus model standard K-epsilon(2 equation) with standard wall fraction model is used. The model constants are listed below,

Cmu	0.09
C1-Epsilon	1.44
C2-Epsilon	1.92
TKE Pranddtle Number	1
TDR Pranddtle Number	1.3
Energy Prandtl Number	0.85

Table 7. 1:Viscus model input parameters (default value of ANSYS FLUENT)

7.2.2 Species Model(Non-Premixed Combustion)

In species model Non-Premixed combustion model is used because here Coal(fuel) and Air(oxidizer) enters in the CFB furnace in separate streams. Non-adiabatic, chemically equilibrium and emperical fuel stream options are selected under chemistry.

For non-premixed combustion model it is necessary to generated the probability density function (PDF) table by providing the coal properties(proximate analysis and ultimate analysis & high calorific value of coal).

Below listed coal properties (proximate and ultimate analysis and heating values) of selected Thar coal have been used here in coal calculator.

Proximate Anlysis		**Ultimate Analysis**	
Moisture(%)	46.125	C(%)	51.186
Ash Content (%)	5.87	H(%)	5
Volatile Matter(%)	28.45	N(%)	0.31
Fixed Carbon(%)	20.67	S(%)	2.45
		O(%)	15

HHV (As Received)	14.16 MJ/Kg

Table 7. 2:Proximate & Ultimate Analysis, Heating Value used to solve this problem [9]

- **Coal Calculator Table**

The difference which exists here between the ultimate analysis values mentioned in table and in coal calculator is because software itself adjusted the values to reach the sum of 1. However, proximate analysis has not such cosiderable difference.

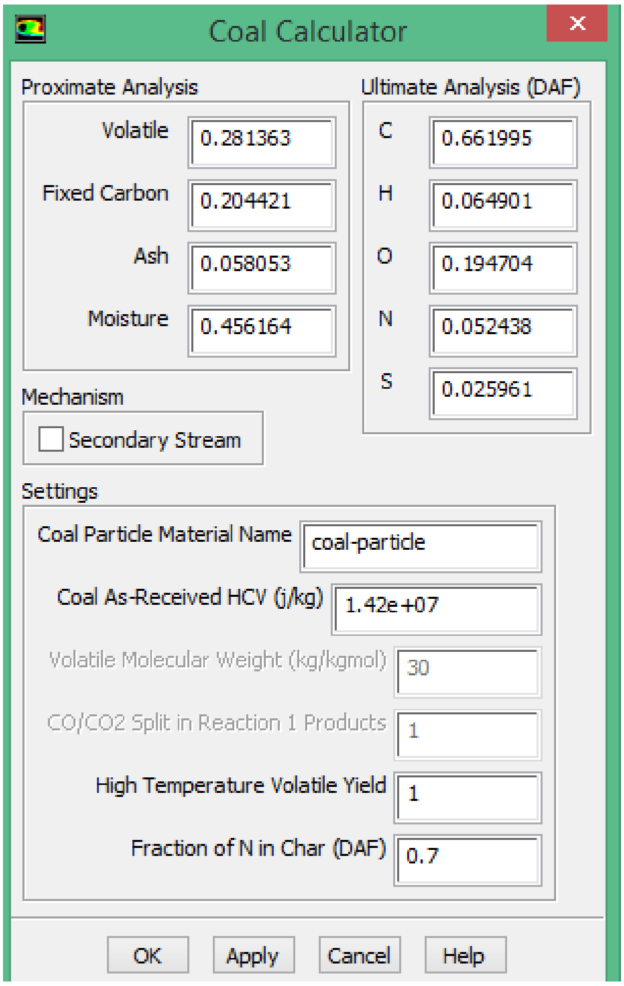


Figure 7. 2:Screen shot of Coal Calculator (Non-premixed Combustion model)

- **Calculating PDF Table**

In same step, after inseting coal proeprties in coal calcualtor and defining number of species calculating the PDF table under Table option.

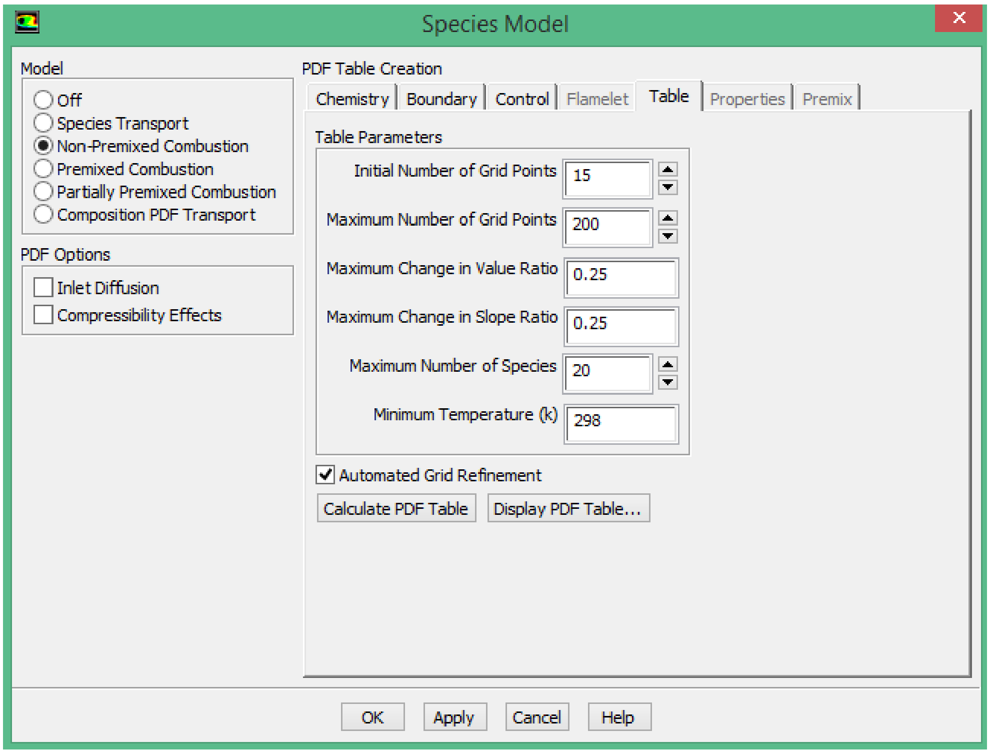


Figure 7. 3:Screen shot of PDF table calculation

7.2.3 Discrete Phase Model(DPM)

Discrete phase model is used to model the discrete partciles that are coal that are tracked (in a Lagrangian frame of reference) in the continuous phase flow field like oxidizer (Air).

In discrete phase model, surface type injection system is used and interaction of discrete phase particles with continuous phase flow is allowed to burn the fuel or complete the reaction. In particle type combusting option is selected.

Uniform diameter of coal particle is considered that is 5mm that is entered to the furnace with a mass flow rate of 0.5Kg/Sec.

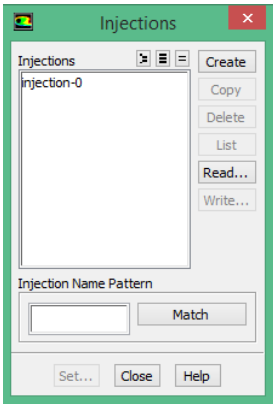


Figure 7. 4:Screenshot of Coal injector (DPM)

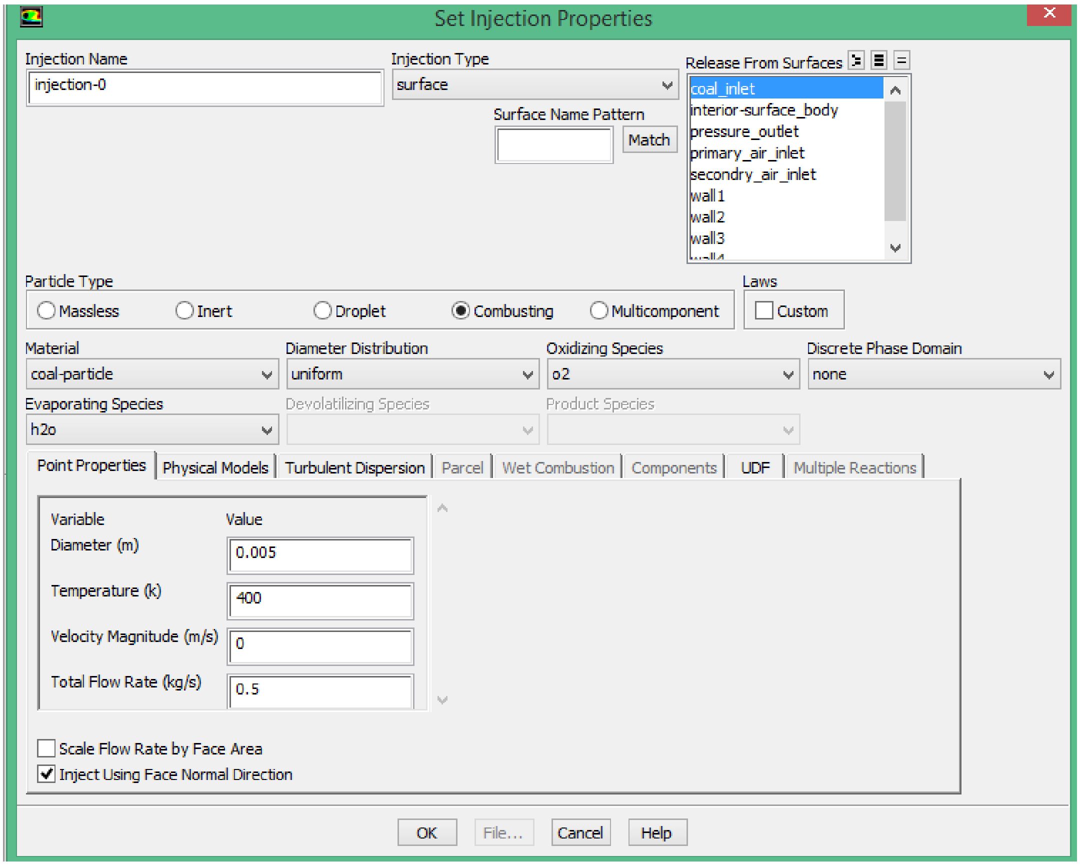


Figure 7. 5:Screen shot of Coal Injection properties setting (DPM)

7.3 Defining Material

Two types of material defines here.

1. Material:Continuous Phase

2. Material:Discrete Phase

7.3.1 Material:Continuous Phase

For non-premxed combustion model, all necessary data like density, specific heat and ethalpies have been extracted from PDF table which was calculated during species modeling. These extracted properties are tranformed as pdf-mixture material. In this step all properties are kept constant except absorption coffocient for which wsggm-domain-based is selected.

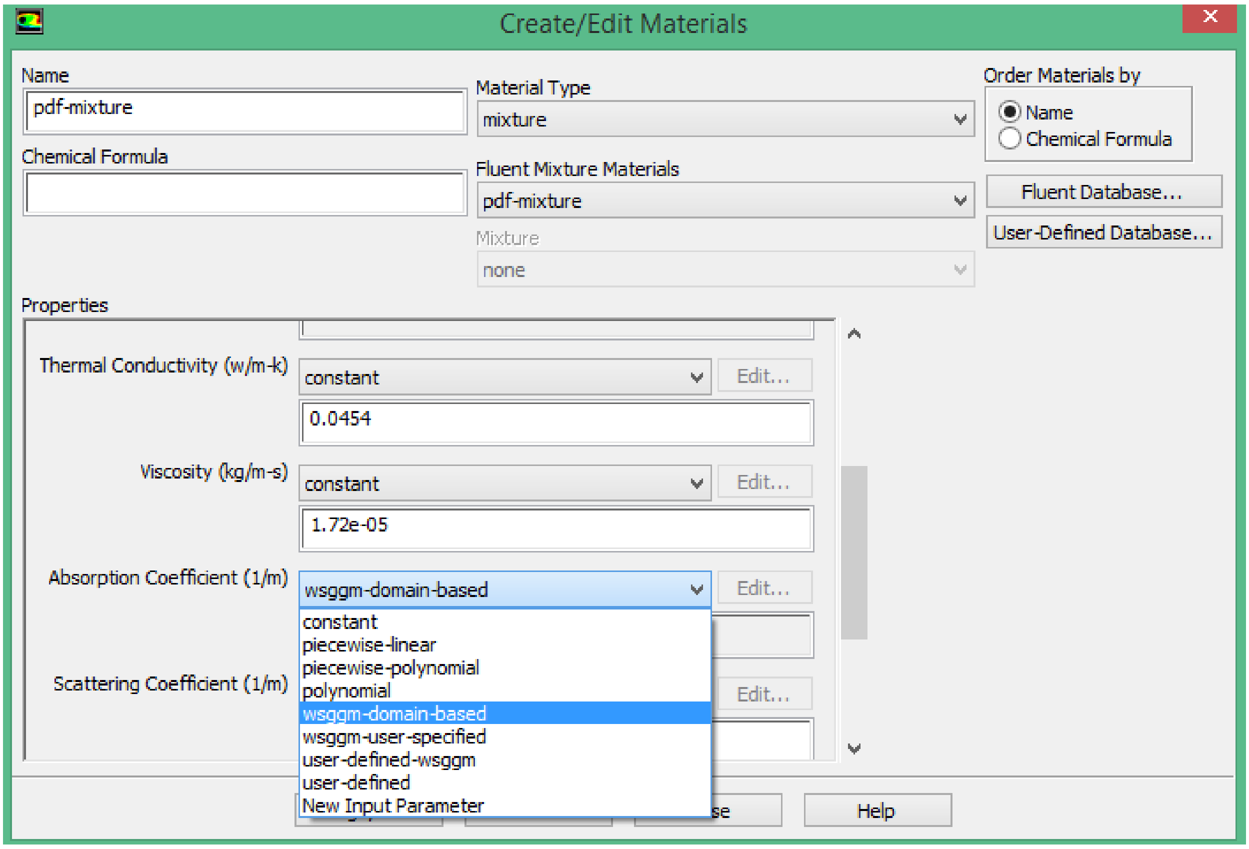


Figure 7. 6:Screen shot of Material: Continuous phase (Air)

7.3.2 Material:Discrete Phase

In discete phase material type use a Combusting particles and coal-particle in fluent combusting particle material. Other than that below listed proeprties have been input here.

Density	1350 Kg/m3
Cp	1000 j/Kg-k
Latent Heat	0
Vaporization Tempeature	400 K
Volatile Component Fraction(%)	28.45
Binary diffusivity	4e-05 (m2/Sec)
Particle Emissivity	0.9

Partcile Scattering Factor	0.9
Swelling Coefficient	1.4
Burnout Stoichiometric Ratio	2.67
Combustible Fraction (%)	20.67

Table 7. 3:Material properties for Discrete Phase (Coal)[20]

7.4 Boundary Conditions

Defining boundary conditions to solve any problem is important and necessary in CFD. The Navier Stock equation requires boundary conditions to be defined to solve the problem. The turbulent intensity of 10% is selected for combustion air flow. The hydraulic diameters has been set to twice the size of 2D inlet system [20]. Here, boundary conditions for each parameter have been provided.

7.4.1 Primary Air inlet

The primary air velocity is selected 4m/s based upon the research work [1]. The hydraulic diameter is 6.4m which twice the 2D inlet of primary air (3.2m). The temperature of primary air at inlet is 503K.

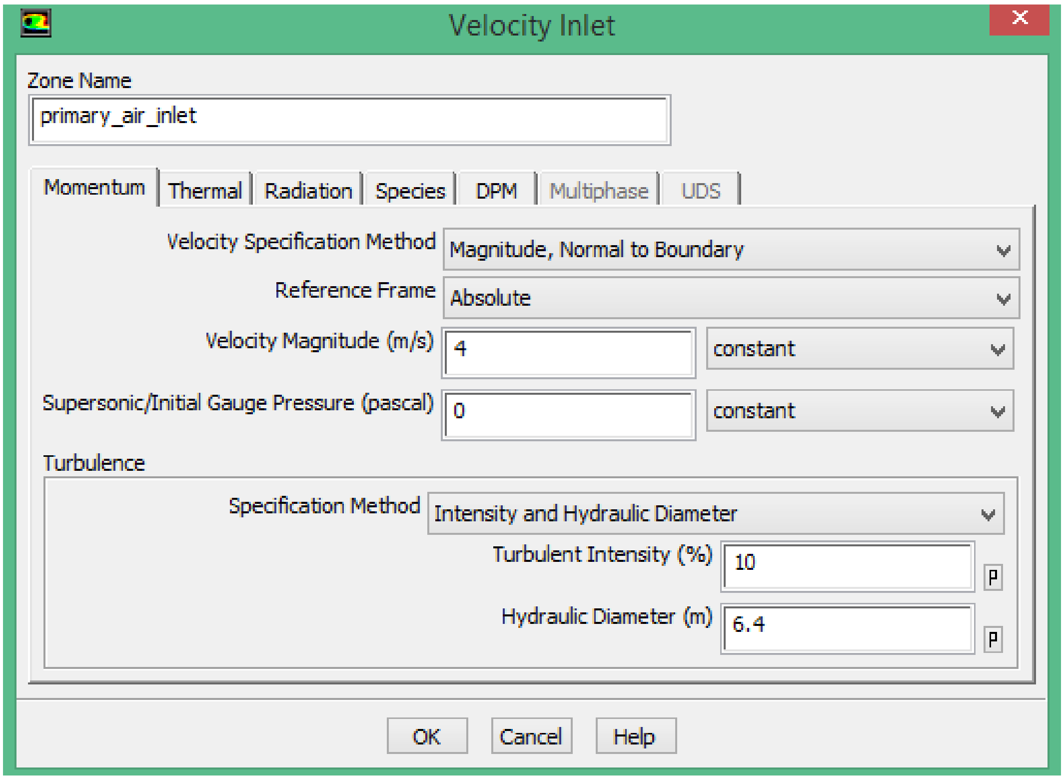


Figure 7. 7:Screenshot of Primary Air boundary conditions

7.4.2 Secondary Air inlet

Secondary air is preheated as of primary air and has a temperature of 473K that enter into the furnace with velocity magnitude of 2m/s [1]. The hydraulic diameter is selected as 1 which double the 2D inlet of secondary air (0.5m).

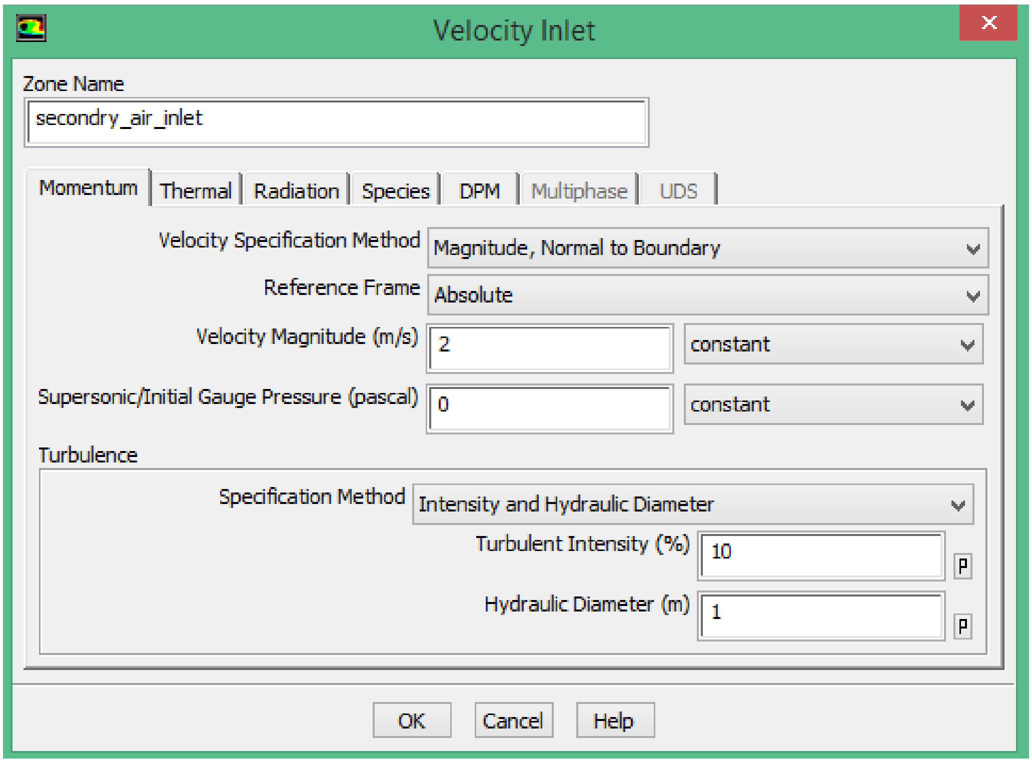


Figure 7. 8:Screenshot of Secondary Air boundary conditions

7.4.3 Outlet

The back flow total temperature is set 1800K. Shown in figure 7.9.

7.4.4 Coal Inlet

Coal entered the furnace with a mass flow rate of 0.5 kg/sec and preheated to 400K. The hydraulic dimeter is selected 1m (2x0.5m=1m). Shown in figure 7.10.

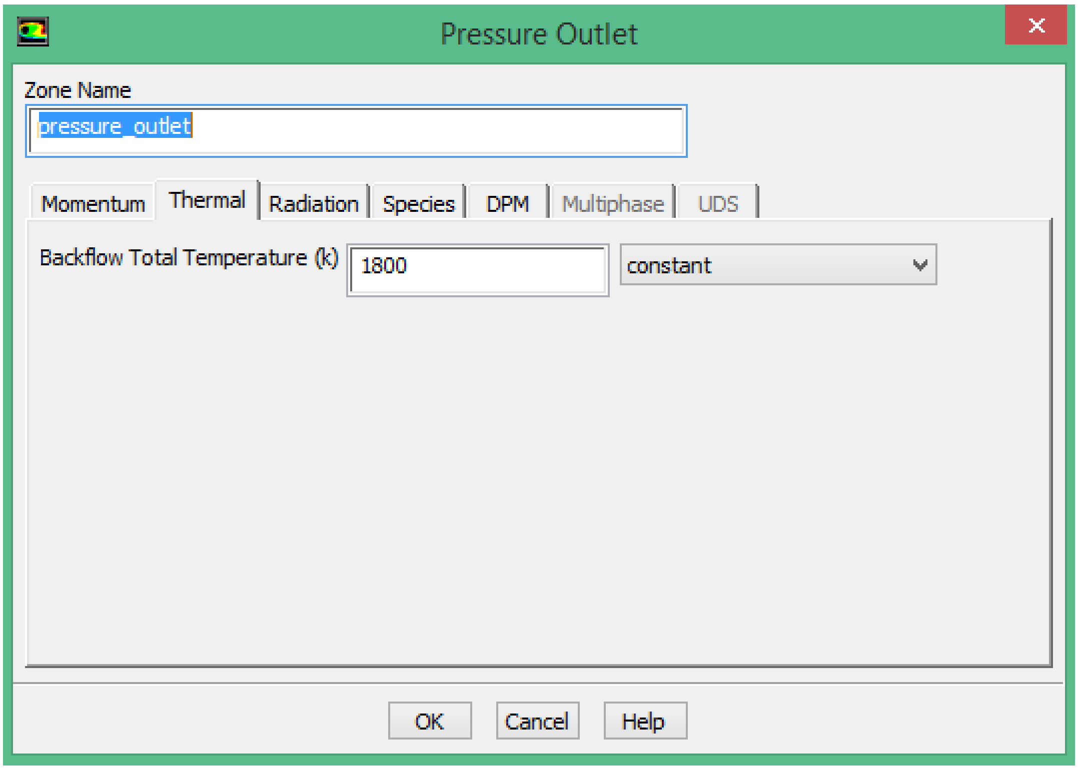


Figure 7. 9:Screen shot of Pressure Outlet boundary conditions

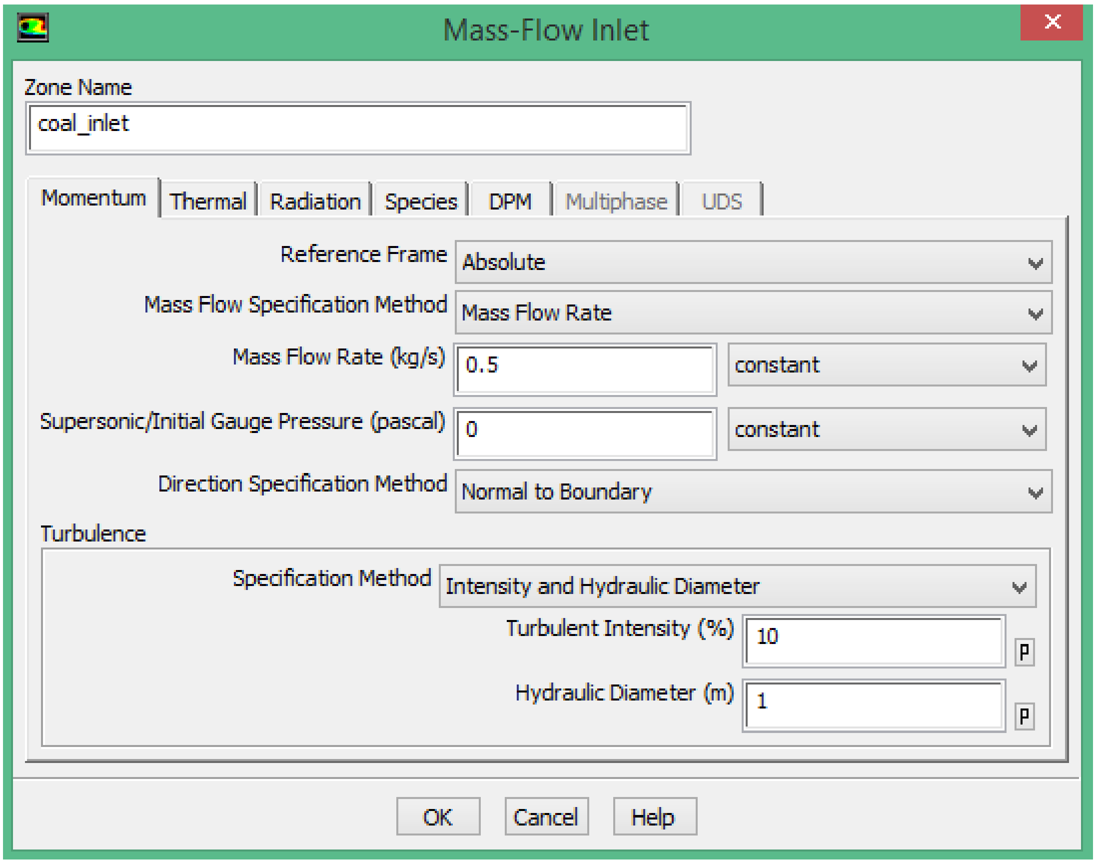


Figure 7. 10:Screenshot of Coal inlet boundary conditions

7.4.5 Wall (Wall no 1, 2, 3 & 4)

Wall temperature is set to be 2000K for all walls.

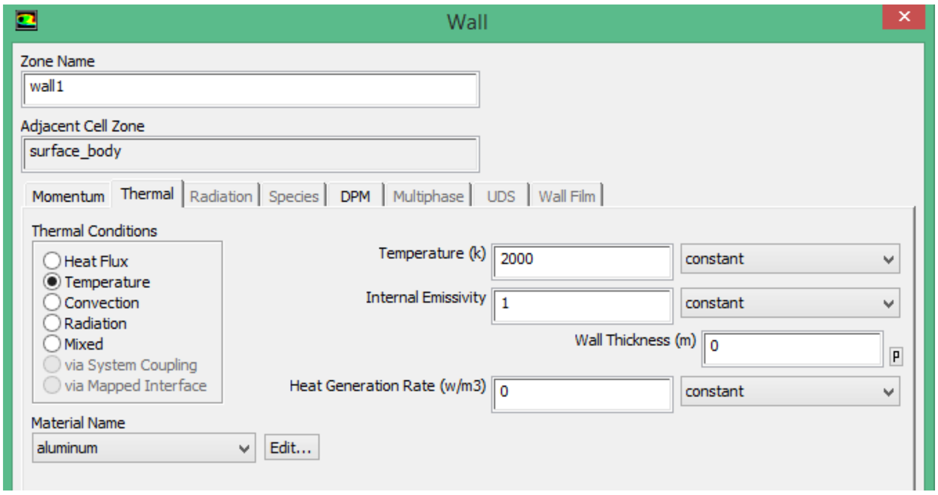


Figure 7. 11:Screenshot of Wall boundary conditions (same for all 4 walls

7.4.6 Summary of Boundary Conditions

PARAMETERS	SET VALUES
Primary air inlet velocity	4 m/s
Primary air inlet temperature	503K
Oxygen concentration at inlet	21%
Secondary air inlet velocity	2 m/s
Secondary air temperature	473K
Coal particle size	5 mm
Coal density	1350 kg/m^3
HCV (As received)	14.16 MJ/kg
Mass flow rate of coal	0.5 kg/s
Coal initial temperature	400K
Back flow temperature	1800K
Operating pressure	$1.0x10^5$ Pa
Wall temperature	2000K

Table 7. 4:Summary of all considered boundary conditions

7.5 Solver

The finite volume method (FVM) is used to discretize the governing equation on generated grids. In solution method, SIMPLE scheme is selected foe pressure-velocity coupling scheme and other schemes kept default for spatial discretization parameters.

Accuracy and convergence are important during solution to obtain the accurate results. For converging the solutions relaxation factor for variables to be changed. Low value of relaxation factor leads to long computational time. There is proper rule for selecting the relaxation factor.

The relaxation factor on which this solution has been performed are mentioned in table no 7.5 and these factors are lower than the default factors.

This same solution was run under default, high and low relaxation factors, no such variation observed in results however, only the difference which observed is the variation in computational time.

Under below listed relaxation factors solution is converged after running 825 iteration for geometry 01 and 888 for geometry 02.

Pressure	0.35
Density	1
Body Force	1
Momentum	0.7
Turbulent KE	0.8
TDR	0.8
Turbulent Viscosity	1
Energy	0.5
Temperature	0.9
P1	1
Mean Mixture Fraction	0.8
Mean Fraction Variance	0.8
Discrete Phase solution	0.5

Table 7. 5:Relaxation factors used for convergence of solution

7.5.1 Iterations

5000 iterations have been set but solution gets converged after 825 iteration for geometry 01 and 888 for geometry 02. The residual plot for both geometries given here.

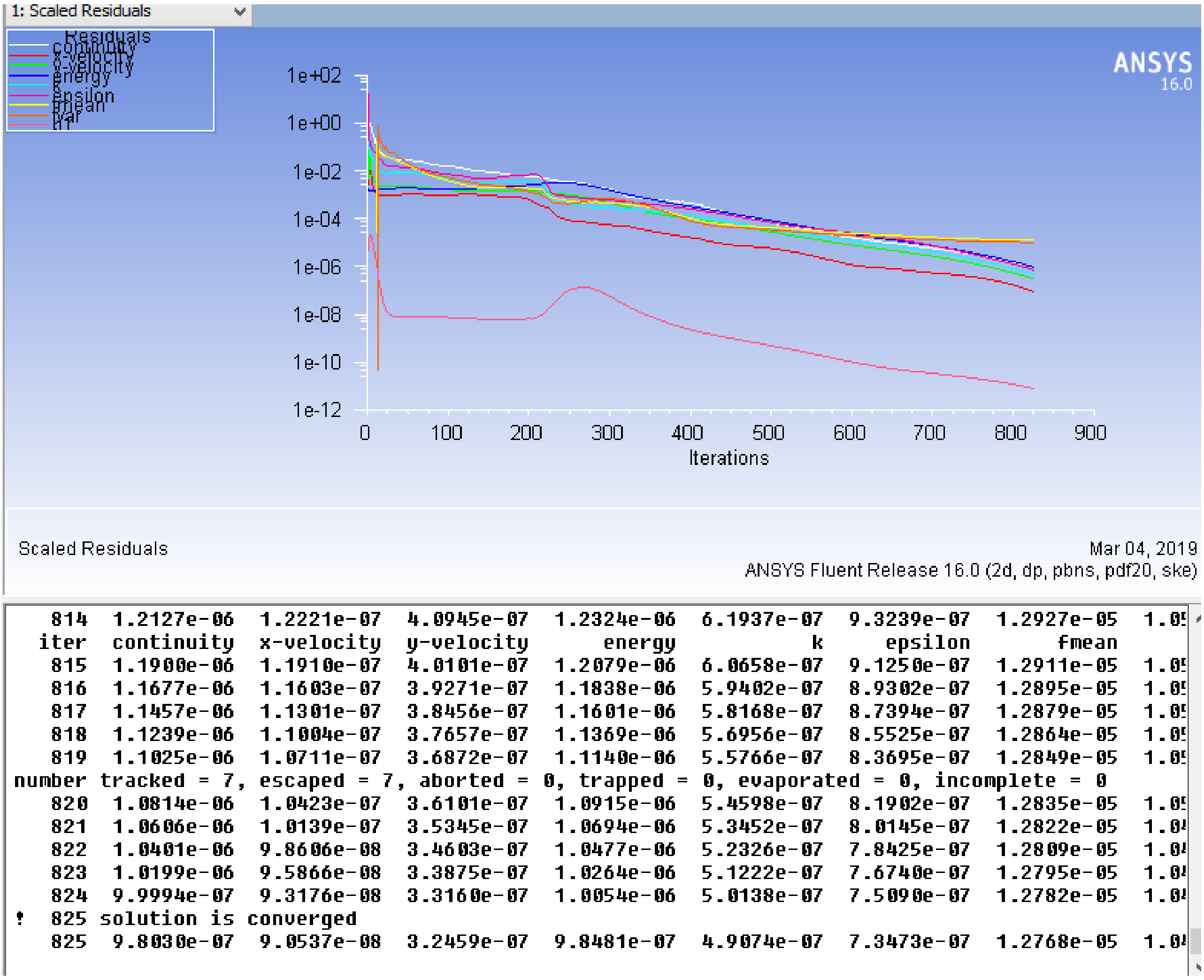


Figure 7. 12:Screenshot of residual plot for geometry 01 (solution converged at 825 iterations)

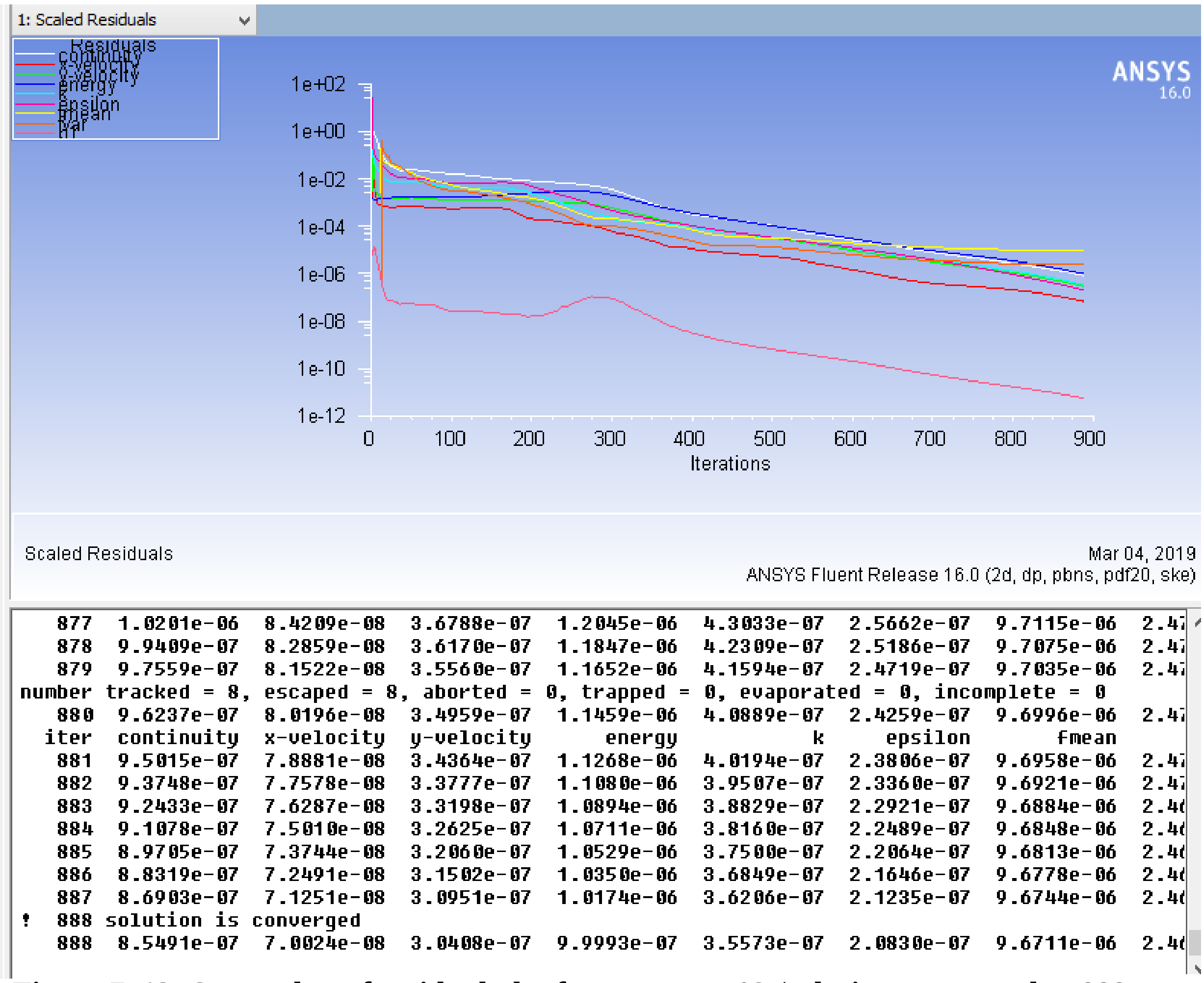


Figure 7. 13: Screenshot of residual plot for geometry 02 (solution converged at 888 iterations)

7.6 Grid Independence Test

Grid independence test is used to verify that the solution is grid sensitive or not. This is the other way to validate the results.

For this, two different sizes mesh (one is medium and second one is fine) have been generated other than the mesh size which is selected in this whole solution and apply the same methodology for all. Any basic flow variable can be used for comparison either temperature velocity, pressure. Therefore, temperature variable is selected for comparison in different grid results. The simulation has been run for geometry 01 only.

Following tables showing the comparative results for different grid sizes

Element Size	Node	Cells	Temperature(K)	Variation (%)
0.07	14170	13888	1013	1.3
0.04	43505	43008	1027	

Element Size	Node	Cells	Temperature(K)	Variation (%)
0.04	43505	43008	1027	0.2
0.02	173025	173215	1029	

As per above results, the percentage difference between element size 0.02 and 0.04 is less than the difference between element size 0.04 & 0.03 which is 0.2%. Hence it can say that this solution is insensitive to grids. Below bar graph showing the percentage difference between different no of cell or element sizes grids.

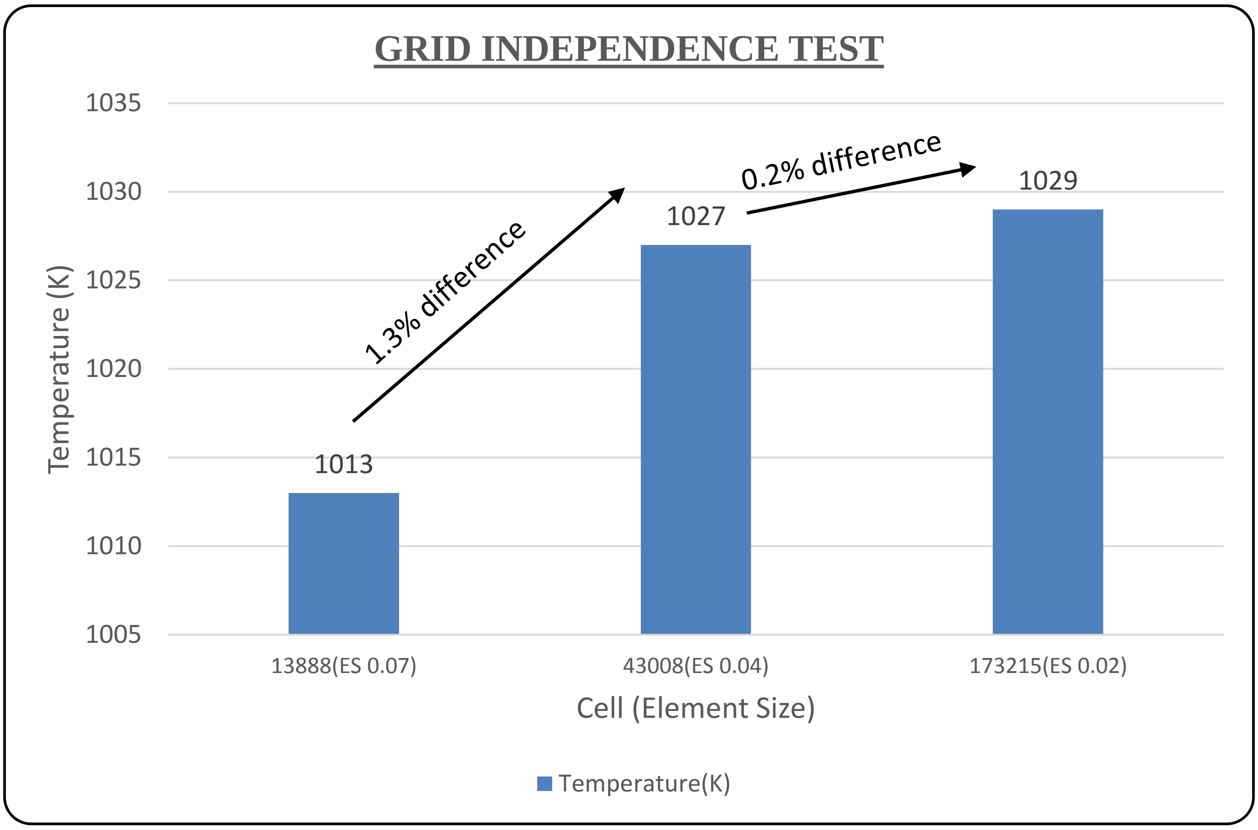


Table 7. 6:Bar Graph showing comparative results of Temperature at different grid sizes

CHAPTER 8 RESULTS AND DISCUSSION

In this chapter, the results of different variables for both geometries will show here and will discuss their results.

8.1 Contour Plots

Contour plots are the way to represent three-dimensional surface on two-dimensional way [19]. Contour plots for Temperature, Total pressure, Turbulent Kinetic energy, Mixture fraction distribution and Mass fraction for CO2, H2O and O2 will show here for both geometry no1 and geometry no 02.

8.1.1 Total Temperature

The total temperature profile of geometry 01 shows that the peak temperature reaches during combustion is 1013K. It happens when coal burns due to highly velocity preheated air(at 503K) enter the furnace and combustion takes place and temperature of the furnace increases rapidly.

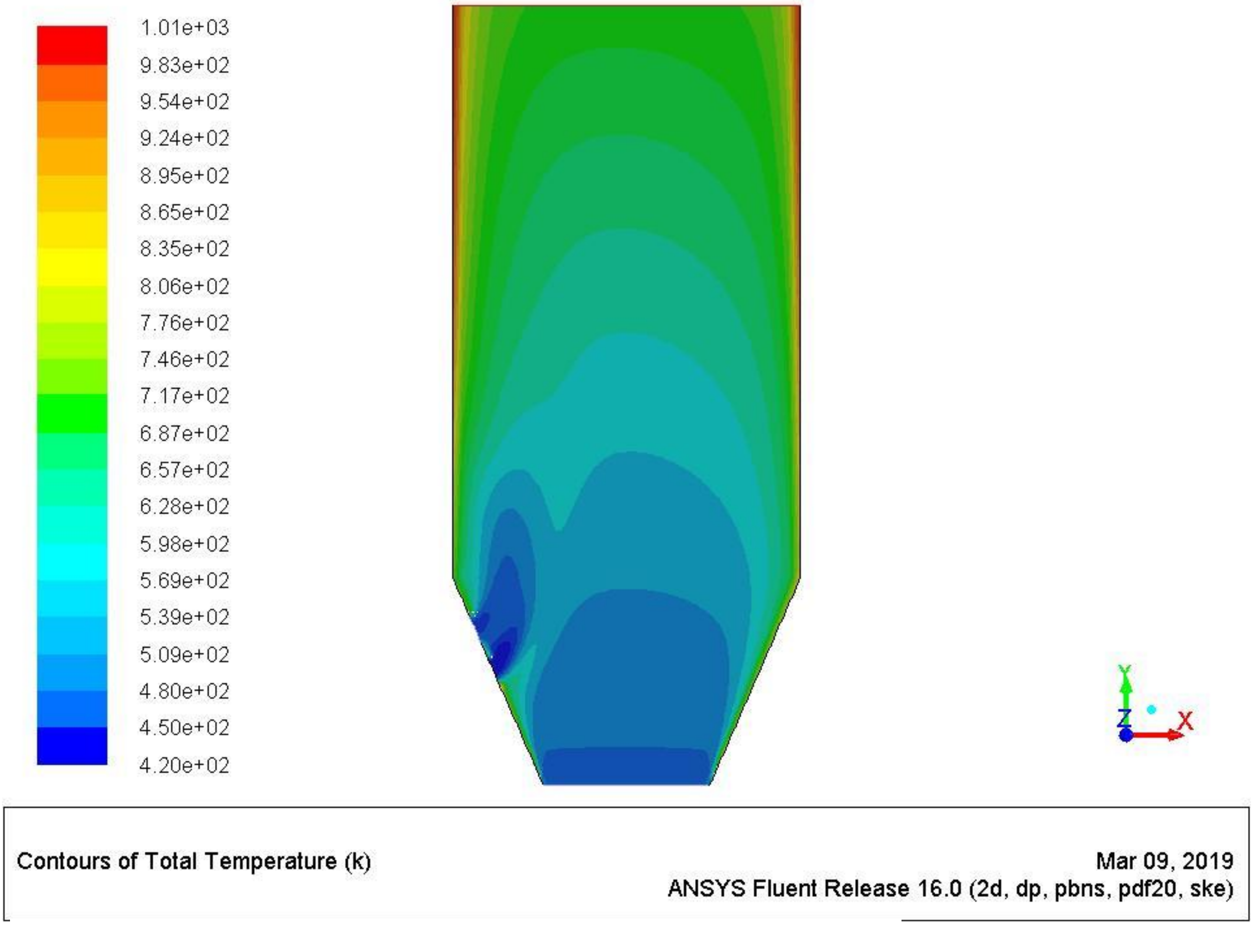


Figure 8. 1:Contours of Total Temperature (Geometry 01)

For geometry 02 the peak temperature found to be 1073K. The geometry 02 have higher temperature then the geometry 01 and geometry 02 has 60K higher temperature then geometry 01.

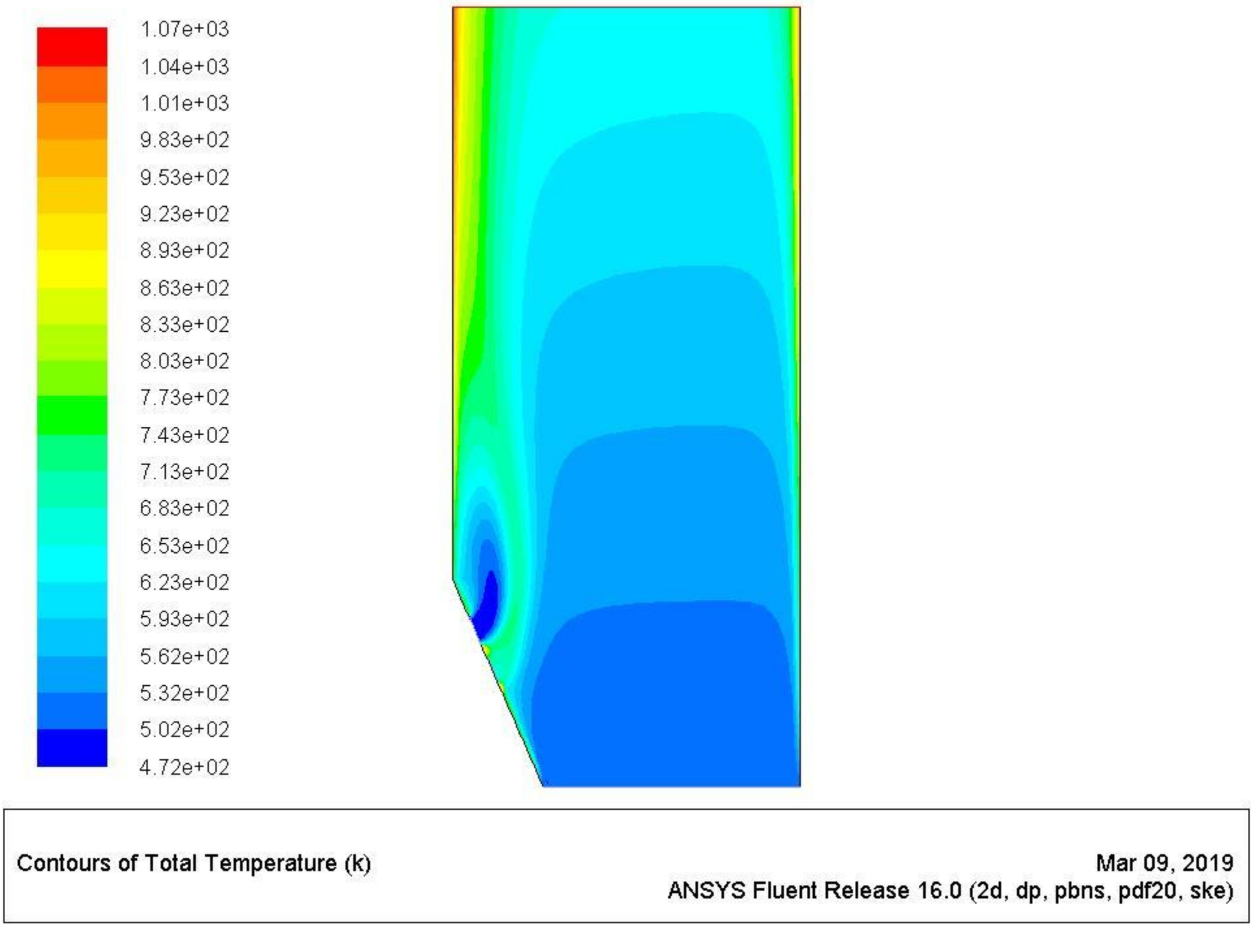


Figure 8. 2: Contours of Total Temperature (Geometry 02)

Hence, the total temperature shows that the temperature inside the furnace depends upon the shape and design of the furnace. Here, in this case both geometries are much like each other particularly the coal inlet and secondary air inlet area but the difference of 60K is significant. Geometry 02 CFB furnace produced higher temperature because large amount of air enters the furnace due to its large primary air inlet are that is 4.9n and helps coal to burns completely while, geometry 01 has 3.2m.

8.1.2 Total Pressure

The maximum total pressure value for geometry 01 found to be 9.29 Pascals after combustion process. The pressure at the primary air inlet area is approximately 6.30 Pa to 6.9 Pa. While, for geometry 02 the maximum total pressure found to be 12.0 Pascals and total pressure at the primary air inlet area is between 7.70 Pa to 8.42 Pa. The primary air inlet velocity for both CFB furnace geometries is same that is 4m/s.

Hence, for total pressure comparisons geometry 02 CFB furnace produces more pressure as of geometry 01 CFB furnace.

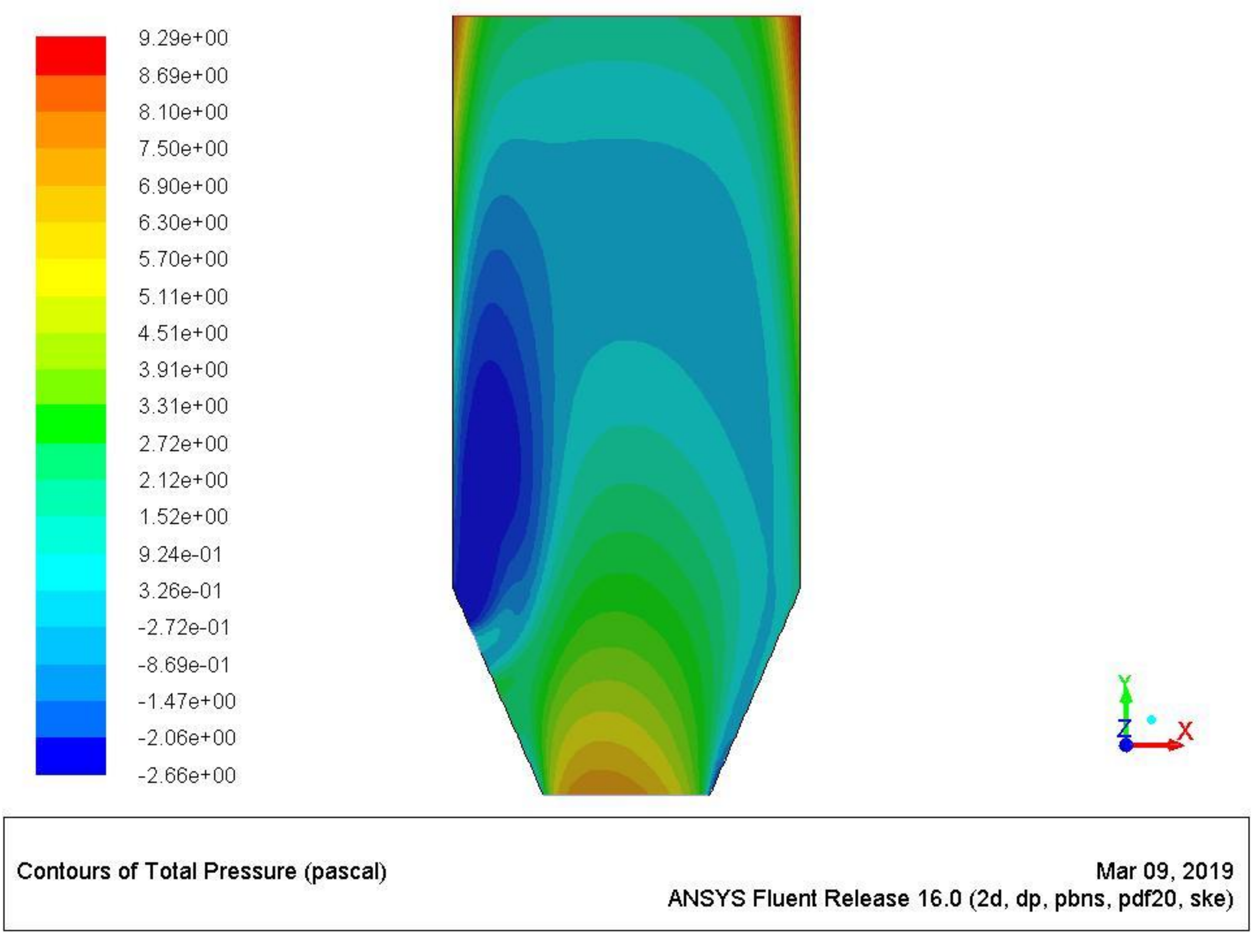


Figure 8. 3: Contours of Total Pressure (Geometry 01)

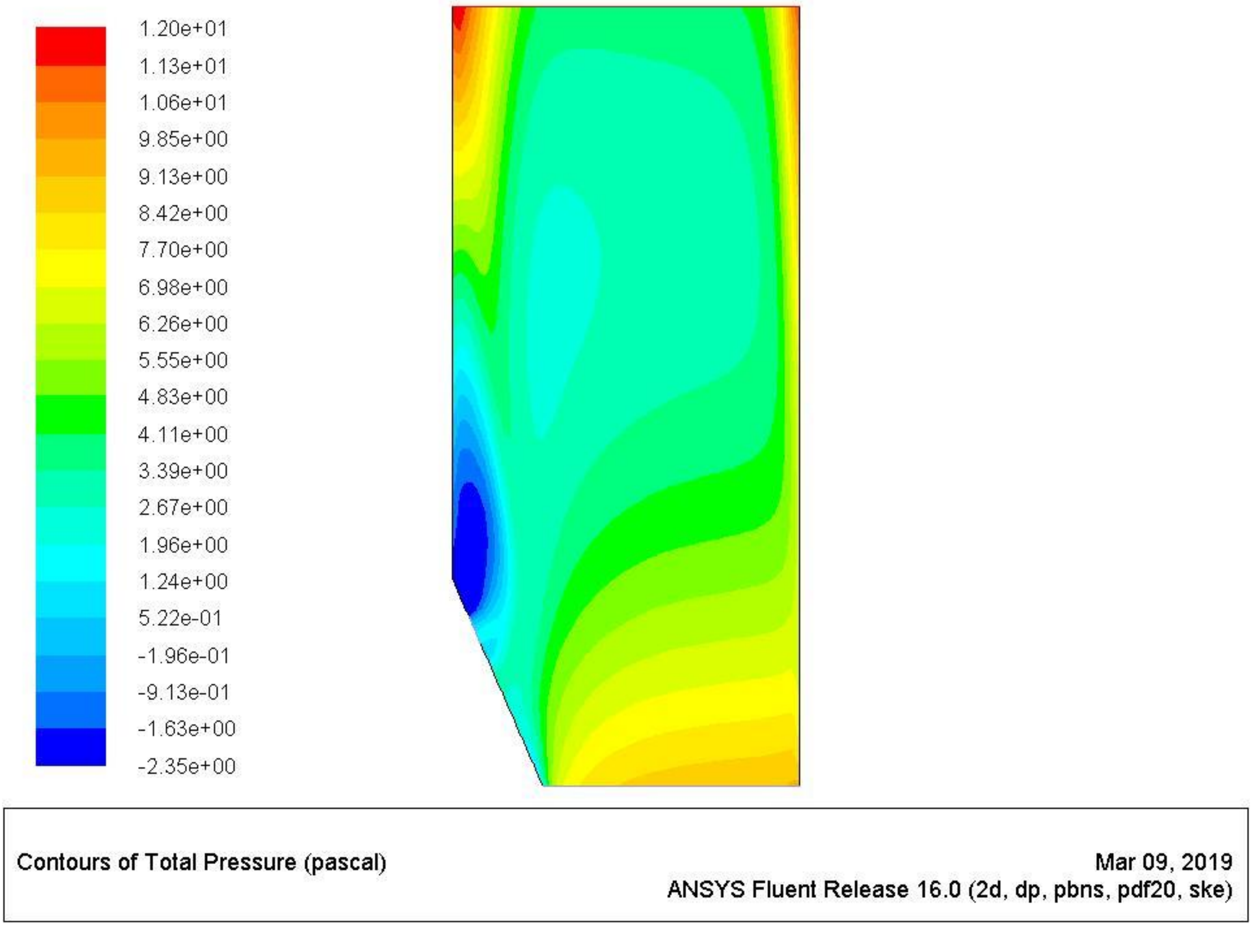


Figure 8. 4: Contours of Total Pressure (Geometry 02)

8.1.3 Turbulent Kinetic Energy (TKE)

The maximum turbulent kinetic energy after combustion found to be 9.16e-01 for geometry 01 and 7.37e-01 for geometry 02. In circulating fluidized bed combustor, the height velocity primary air enters the furnace from the bottom of bed the bed loses it stationary state and start bubbling and due to continuous supply of high velocity air the bed start bubbling and behaves like a bubbling fluid.

The results showing that geometry 01 design CFB has higher turbulent KE then design 02 CFB furnace this is because the symmetric design of the geometry 01 from the bottom area.

Below are the contours of TKE for geometry 01 and geometry 02.

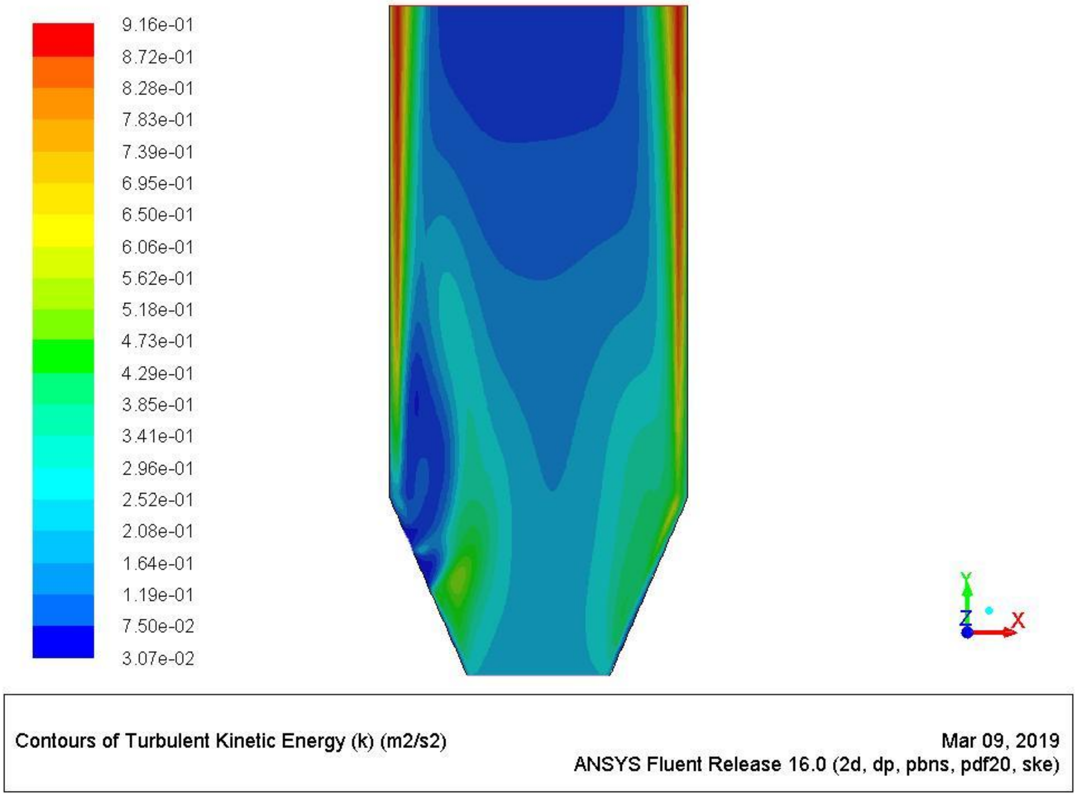


Figure 8. 5: Contours of Turbulent KE (Geometry 01)

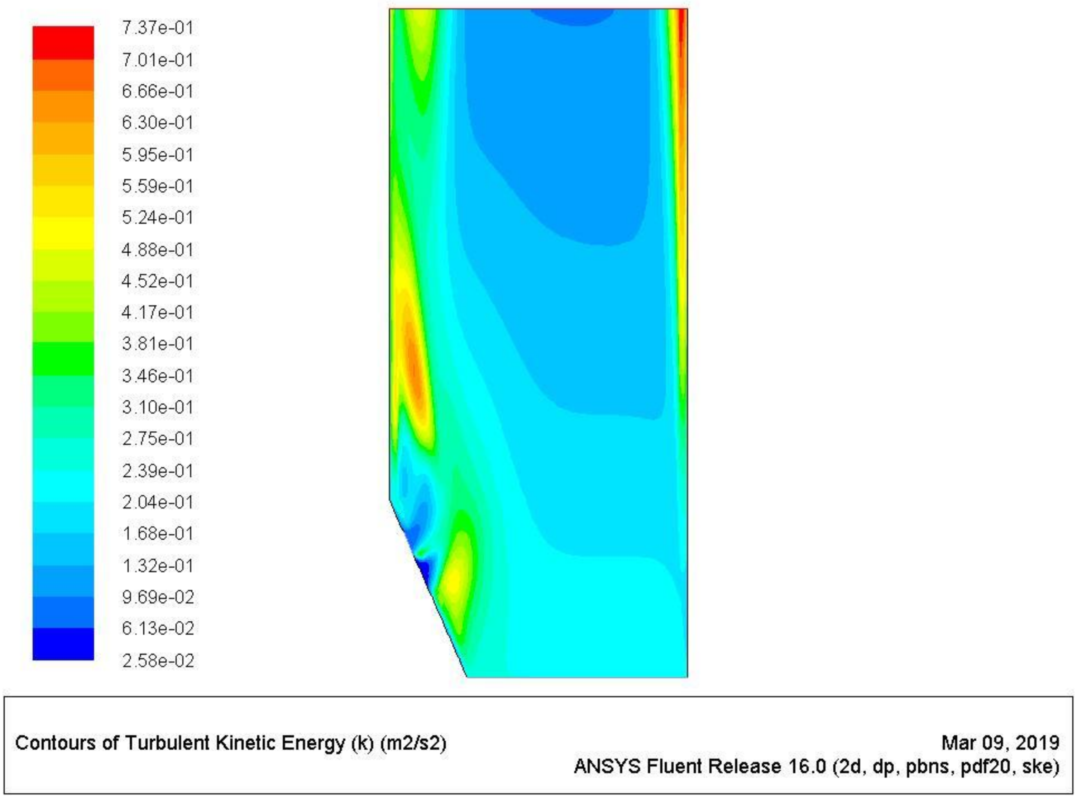


Figure 8. 6: Contours of Turbulent KE (Geometry 02)

8.1.4 Contours of Mean Mixture Fraction

The geometry 02 has high mean fraction (1.15e-02) as compare to geometry 01(1.01e-04). The mean fraction is maximum at the coal inlet area where combustion takes place.

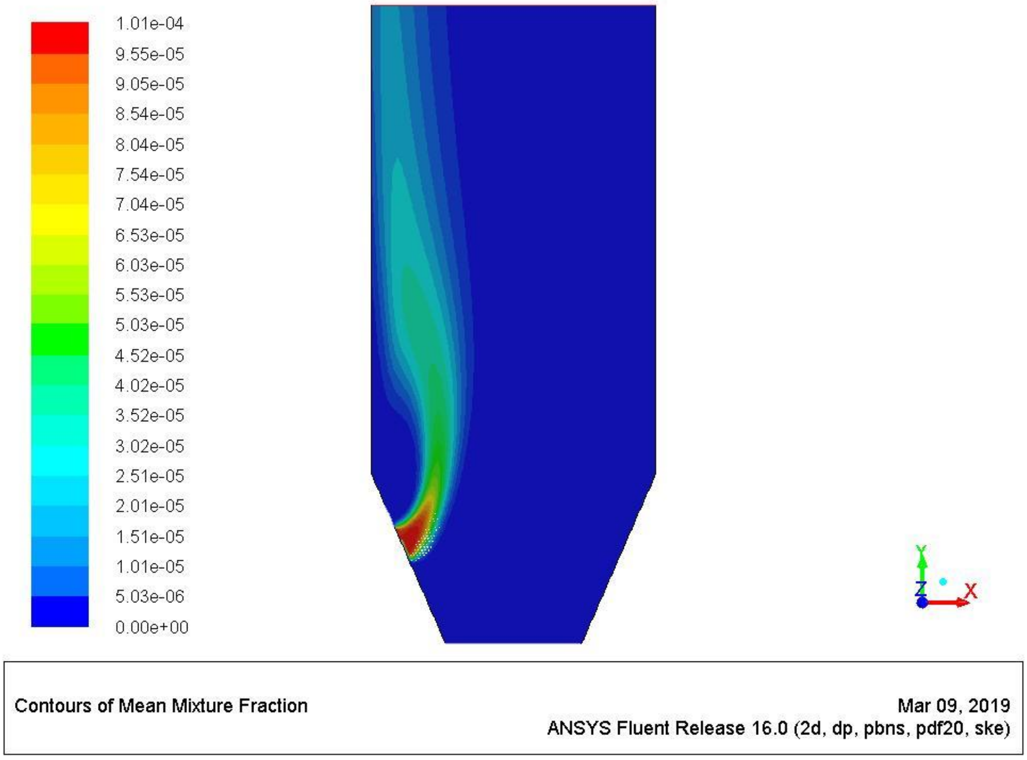


Figure 8. 7:Contours of Mean Mixture Fraction (Geometry 01)

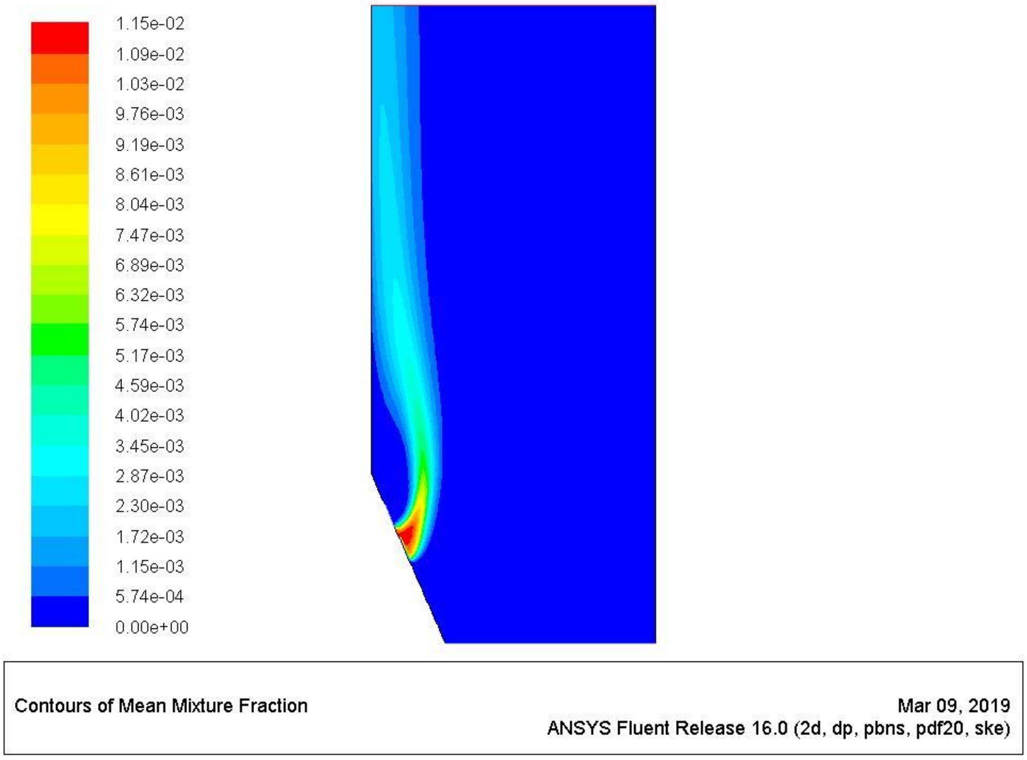


Figure 8. 8:Contours of Mean Mixture Fraction (Geometry 02)

8.1.5 Contours of Mass Fraction of CO_2

The geometry 02 produced more CO2 (2.80e-02) as compare to geometry 01(2.44e-04).

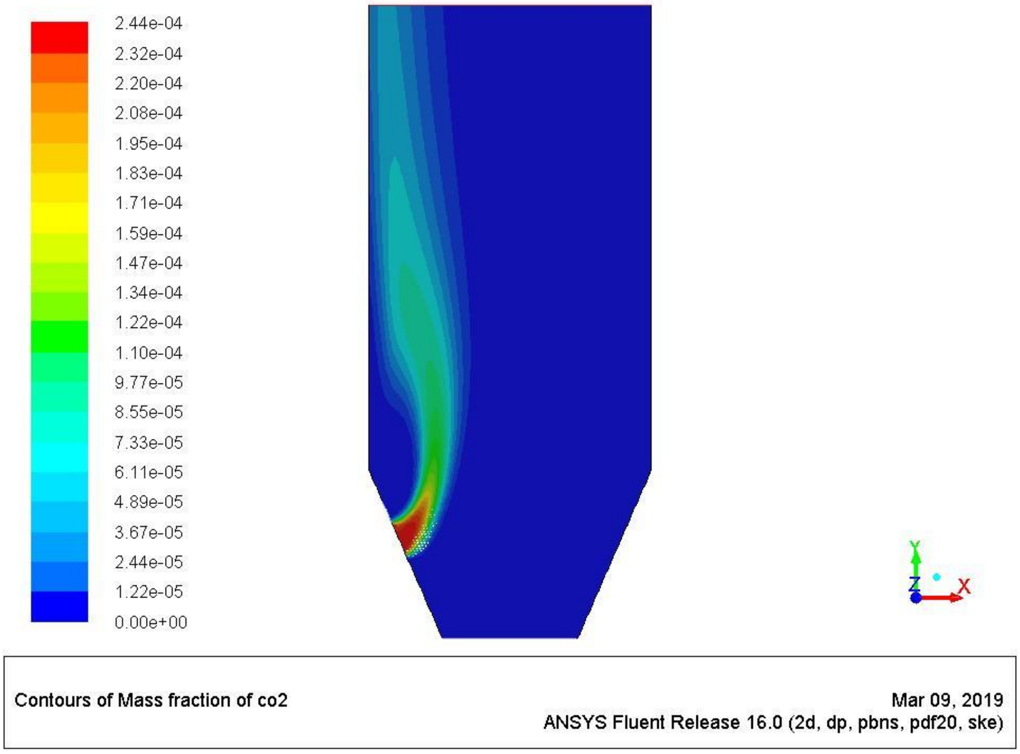


Figure 8. 10:Contours of Mass Fraction of CO2 (Geometry 01)

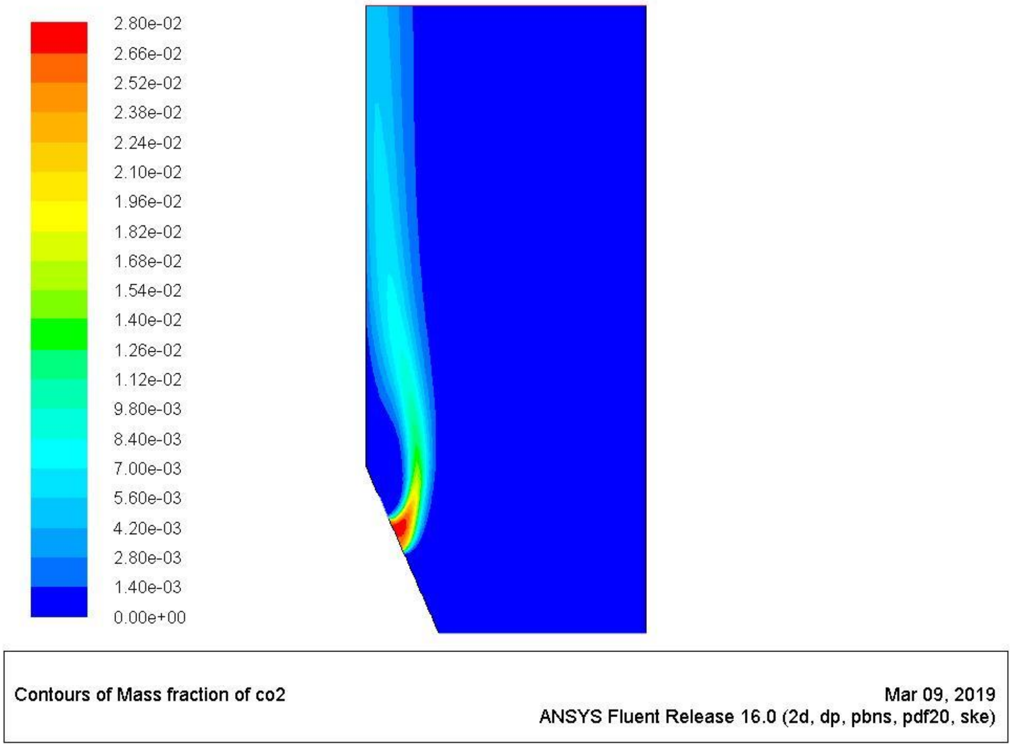


Figure 8. 9:Contours of Mass Fraction of CO2 (Geometry 02)

8.1.6 Contours of Mass Fraction of H_2O

The geometry 02 produced more H2O (6.7e-03) as compare to geometry 01(5.84e-05).

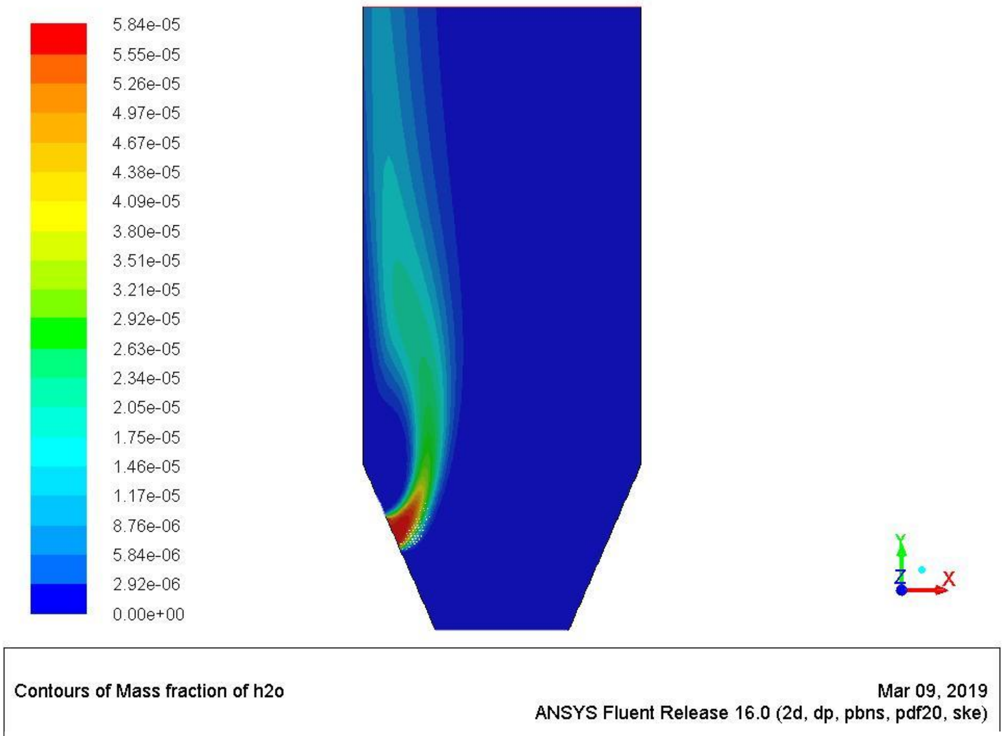


Figure 8. 11:Contours of Mass Fraction of H2O (Geometry 01)

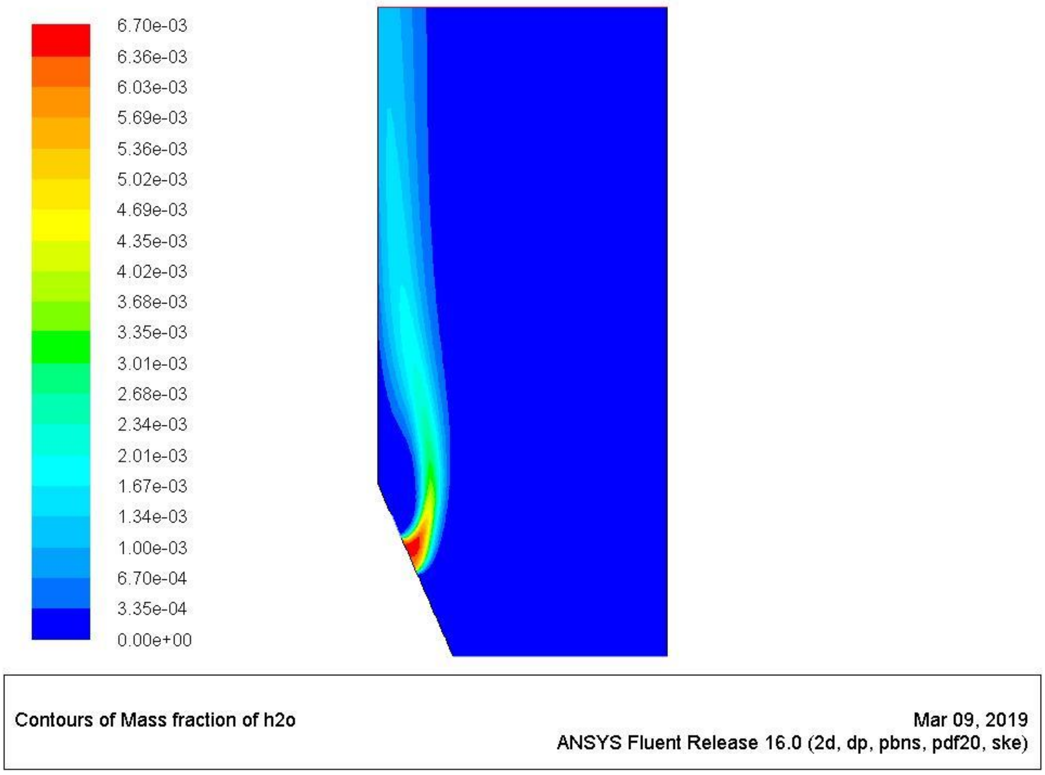


Figure 8. 12:Contours of Mass Fraction of H2O (Geometry 02)

CHAPTER 9 CONCLUSION AND FUTURE WORK SUGGESTIONS

9.1 Conclusion

After this study it has been concluded that large amount of coal reserves available in Pakistan, but they are of low quality and have low calorific value and high moisture contents. Thar coal is ranges between lignite to low bituminous coal [9]. However, they are good enough to use as a primary fuel source for producing electricity.

A major burden on our economy is in the form of importing furnace oil for our power plants despite o the increase in oil demands electricity shortfall is still exists and majority of the rural and urban parts of Pakistan still facing electricity shortfall. This supply demand difference become increases in the summer.

In between 2007 to 2012 the electricity short fall condition is Pakistan became worst and even no significant consideration was given to tackle this problem. However, during the 2013 to 2018 and after the start of Shina Pakistan Economic Corridor (CPEC) projects major focus was given to develop the new power projects in Pakistan to meet the power shortfall and majority of power plants were completed in Pakistan in the assistance of CHINA. Majority of the power plants are of coal based (imported coal), few are of LNG based and few are based on wind energy power plants.

In the same period, Govt. of Sindh and Engro Power company has started exploring the Thar coal mines and decided to develop a 1200MW coal fired power plant by using local coal (Thar Coal) and will become operational in 2019. This is the only project right now which uses local coal as a fuel for power generation.

This study has been carried out by inspiring the development that is going on for Thar coal to be utilized in power generation and tried to analyze how much Thar coal is feasible to produce the electricity. Hence, it can be said that Thar coal with CFBC technology are good enough to be used for power generation and based on the success of the Thar coal power project, more other power plants will hopefully be developed with local coals to meet the country`s power demand and Govt. should encourage public or private sectors to build more local coal based power projects in Pakistan.

As the value of US dollar against Pak rupee is increasing day by day and because of that importing oil is a big burden on our economy. This is a high time that Pakistan should focus on the local available natural reserves to meet the national demands.

Secondly, by analyzing the results that obtained after this study shows that, selection of proper CFBC furnace design is important for achieving desired variable results. In this study, focus given on the Temperature profile. Hence, the geometry 02 CFB design produced more temperature than design 01 CFB geometry with Thar coal properties given in table no 7.2.

9.2 Future Work Suggestions

Below mentioned are the areas where more research work can be carried out.

1. Performance of other blocks of Thar coal field can be studied with CFBC technology through CFD.
2. As Thar coal has high moisture content, performance can be studied by preheating the coal on high temperature before inserting into the furnace through CFD.
3. By varying the boundary conditions or input parameters of CFBC furnace in CFD, impact of these parameters on the temperature, pressure, coal combustion properties can be studied.
4. By using the Thar coal properties, some other CFB designs can be studied through CFD
5. Formation of chemical species in CFBC furnace can be studied for Thar coal via CFD.
6. With Thar Coal, the refractory condition of CFBC furnace can be studied.
7. Emission behavior of CFBC furnace with Thar coal can be studied.

REFERENCES

[1] R. Kumar and K. Pandey, "CFD ANALYSIS OF CIRCULATING FLUIDIZED BED COMBUSTION," *IRACST – Engineering Science and Technology: An International Journal (ESTIJ),* vol. 2, pp. 163-173, 2012.

[2] R. Inder Singh, A. Brink and M. Hupa, "CFD modeling to study fluidized bed combustion and gasification," *Applied Thermal Engineering,* vol. 52, pp. 585-614, 2013.

[3] A. S. Kinkar, G. M. Dhote and R. Chokkar, "CFD Simulation On CFBC Boiler," *INTERNATIONAL JOURNAL OF SCIENTIFIC & TECHNOLOGY,* Vols. VOLUME 4,, no. ISSUE 02,, pp. 34-38, 2015.

[4] J. Xie, W. Z. Zhong, B. Jin and Y. Shao, "Three-Dimensional Eulerian−Eulerian Modeling of Gaseous Pollutant," *Energy Fuels,* vol. 28, p. 5523−5533, 2014.

[5] B. Chalermsinsuwana, P. Kuchonthara and P. Piumsomboon, "CFD modeling of tapered circulating fluidized bed reactor risers: Hydrodynamic descriptions and chemical reaction responses," *Chemical Engineering and Processing,* vol. 49, p. 1144–1160, 2010.

[6] E. Tora and E. Dahlquist, "CFD Ansys - Fluent simulation of prevention of dioxins formation via controlling homogeneous mass and heat transfer within circulated fluidized bed combustor," *Energy Procedia,* vol. 75, pp. 130-136, 2015.

[7] A. Hussain, I. Ahmed and H. H. Sait, "Experimental and Simulation Study of Fluidization Behavior of Palm Biomass in a Circulating Fluidized Bed Riser," *Industrial & Engineering Chemistry Research,* vol. 52, p. 17529−17537, 2013.

[8] K. Pandey and R. Kumar, "Numerical Analysis of Coal Combustion in Circulating Fluidized Bed," *International Journal of Chemical Engineering and Applications,* vol. Vol. 2, no. No. 6, pp. 390-394, December 2011.

[9] M. A. F. Choudry, Y. Nurgis, M. Sharif, A. A. Mahmood and H. N. Abbasi, "Composition, Trace Element Contents and Major Ash Constituents of Thar Coal, Pakistan," *American Journal of Scientific Research,* no. 11, pp. 92-102, 2010.

[10] JAPAN INTERNATIONAL COOPERATION AGENCY (JICA), "Data Collection Survey on Thar Coal Field In Pakistan," Nippon Koei Co., Ltd. & Coal Resources & Mining Engineering Co., Ltd., February 2013.

[11] "Pakistan Coal Power Generation Potential," Private Power & Infstracture Board, Islamabad, June 2004.

[12] Sindh Engro Coal Mining Company , "Thar Mining & Power Project," Sindh Engro Coal Mining Company Ltd, n.d.

[13] Q. Zhu, "Developments in circulating fluidised bed combustion," *IEA Clean Coal Centre,* April 2013.

[14] "CFD Fluent tutorial - Species transport, combustion and NOx production," www.youtube.com, [Online]. Available: https://www.youtube.com/watch?v=yb6-ETWFzxI. [Accessed 01 February 2019].

[15] "Coal Combustion/Gasification Using CFD: Part 3 (Simulation & Post Processing)," [Online]. Available: https://www.youtube.com/watch?v=hMISfd5xP9E. [Accessed 16 January 2019].

[16] "Coal Combustion/Gasification Using CFD: Part 1 (Geometry)," [Online]. [Accessed 21 December 2018].

[17] "Coal Combustion/Gasification Using CFD: Part 1 (Geometry)," [Online]. Available: https://www.youtube.com/watch?v=B6QhyUlk2F4. [Accessed 21 December 2018].

[18] "Coal Combustion/Gasification Using CFD: Part 2 (Mesh)," www.youtube.com, [Online]. Available: https://www.youtube.com/watch?v=12FZNb95DIw. [Accessed 02 January 2019].

[19] K. Ahmed, "CFD analyses of enhanced heat transfer through textured Surfaces in plate heat exchanger," PNEC-NUST, 2018.

[20] FLUENT (User Guide), *Tutorial 13: Using the Non-Premixed (User Guide),* FLUENT, 2003.

[21] C. B and K. P, "Effect of circulating fluidized bed reactor riser geometries on chemical reaction rates by using CFD," *Chemical Engineering and Processing:Process Intensification*, vol. 48, pp. 165-177, 2009.

[22] W. Zhou, C. Zhao, L. Duan, X. Chen and C. Liang, "Two-dimensional computational fluid dynamics simulation of nitrogen and sulfur oxides emissions in a circulating fluidized bed combustor," *Chemical Engineering Journal,* p. 564– 573, 2011.

[23] E.-U. Hartge, L. Ratschow, R. Wischnewski and J. Joachim, "CFD-simulation of a circulating fluidized bed riser sulfur oxides emissions in a circulating fluidized bed combustor," *Particuology 7,* p. 283–296, 2009.

[24] C. Liu, M. Zhao, W. Wang and J. Li, "3D CFDsimulationofacirculating fluidized bedwith on-line adjustment ofmechanicalvalve," *Chemical Engineering Science,* vol. 137, p. 646–655, 2015.

[25] Wikipedia, "Fluidization," www.wikipedia.org. [Online]. [Accessed 03 March 2019].

[26] "Fluidization," umich.edu, [Online]. Available: http://umich.edu/~elements/12chap/html/12prof2a.htm. [Accessed 25 February 2019].

[27] www.researchgate.net, "Application of the Numerical Techniques for Modelling Fluidization Process Within Industrial Scale Boilers," [Online]. Available: https://www.researchgate.net/figure/Scheme-of-a-circulating-fluidized-bed-boiler-used-in-the-power-generation-sector_fig13_307617704. [Accessed 27 February 2019].

[28] ANSYS FLUENT 12 USER GUIDE, "Species Transport Equation," ANSYS FLUENT, [Online]. Available: http://www.afs.enea.it/project/neptunius/docs/fluent/html/th/node128.htm] . [Accessed 28 February 2019].

[29] NEPRA, "Coal Reserves in Pakistan," NEPRA (Govt. Regulatory Authority), [Online]. Available: www.nepra.org.pk.