Numerical Modelling of Biomass Combustion in a Large-scale Industrial Furnace

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Candidate's Declaration

This is to certify that the work presented in this thesis, titled, "Numerical Modelling of Biomass Combustion in a Large-scale Industrial Furnace", is the outcome of the investigation and research carried out by me under the supervision of –

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It is also declared that neither this thesis nor any part of it has been submitted elsewhere for the award of any degree or diploma.

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Abstract

The world is making a major shift towards renewable energy. As the threat of climate change and global warming becomes more and more imminent, researchers are trying to find sustainable renewable energy sources. Biomass is a very cheap form of energy that does not require an intense capital investment in order to harness its power. As volatile matters are much more prominent in biomass than in coal and biomass combustion also emits toxic gases a strong case supporting the use of biomass instead of coal must be made. That is why the purpose of this thesis project is to understand if biomass energy is sustainable or not for Bangladesh which is a humid low-lying country with a natural abundance of biomass. An extensive 3-dimensional numerical analysis has been directed with a view of grasping the characteristics of biomass in a life-size boiler and observe the maximum temperature that can be obtained inside the boiler. Biomass particle has higher volatile materials than coal particles which ensures faster combustion in the boiler and the highest temperature was recorded at the throat of the boiler which is approximately (1900-2200K) at the BNR A-C. The CO_2 and O_2 mass fraction contour confirm the burning of oxygen which ensures the combustion in the boiler core. The effect of biomass diameter, burner inlet diameters and boundary conditions on the results of the simulation was obvious. The ultimate purpose of this research is to find evidence of sustainability for biomass combustion and replacing coal as a fuel source in every respect.

Keywords: DPM, transient solver, mass fraction, biomass combustion, active boiler, viscosity, energy.

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Chapter 1: Introduction

As we dive into 2023 climate change and global warming is one of the most pressing issues at hand that still needs a solution. On a per decade basis earth's temperature has been rising 0.08℃ since 1880. But since 1981 the rise of temperature per decade has become 0.18℃ [1] which is a real cause of concern for the earth dwellers. A climate change report of UN states that parts of the world will become unlivable in the next 30-50 years [2]. Climate change and global warming is not anymore, a phenomenon that might happen in the distant future. It has now become very much real and currently many countries are facing it. In 2022 we have seen many freakish weather events that shocked us all. From the Nile River drying to Heat waves in the UK. In 2022 for the first time ever in reported history the United Kingdom has recorded an average temperature of over 10 degrees centigrade in a year [3]. In 2023 during April, there was a Heat wave passed all over Bangladesh for 8-10 days. Temperature of almost every district was raised up to 44-45℃. Some of the areas had a huge humidity up to 85%. These are the results of global warning. Bangladesh is also a victim of it. As the threat of Global warming becomes imminent the Governments of the World have started to take combative measures to prepare for it and slow it down.

In order to slow down the advance of global warming Governments are turning to renewable sources of energy that will cause less emissions but also meet the growing energy demand. The energy producing industry can be held accountable for two-thirds of the total discharges and 81% of total energy is still created on fossil fuels [4]. Although it is changing for the better. The percentage of renewable energy sources is increasing every year. A study from Mckinsey & Company states that by 2026 the global renewable-electricity capacity will increase 80% from the 2020 levels [5]. Most countries are working to increase the total percentage of coming from the renewable sources. The countries which have successfully increased their renewable energy usage all had a positive impact on their economy [6].

Current per capita power generation for Bangladesh is 560kWh [7]. The fossil fuel energy consumption percentage of Bangladesh is 73.77% of the total energy [8]. In the year 2018 the total renewable energy capacity of Bangladesh was 439 MW. In 2018 Bangladesh's total Bioenergy capacity was 5MW [8]. Bangladesh can be considered a gold mine for bioenergy with all its greenery and cattle farms. But there is little to no work being done in order to progress the proper usage of the Biomass which is present in abundance all over the country. Bangladesh has a 400kWp biomass powerplant which is currently in operation [9] There are no other notable biomass powerplants in the country. One of the nations that is mostly susceptible to the effects of climate change is Bangladesh. With most of its land only a few meters above sea level, the nation is situated in a low-lying delta region. As a result, it is vulnerable to flooding and rising sea levels. Growing soil salinity can hinder the growth of crops as a result of rising sea levels. This may cause food insecurity and the eviction of residents of coastal areas. Infrastructure, homes, and crops can all be harmed by floods brought on by cyclones and heavy rains. These issues are probably going to get worse due to the increased frequency and severity of these weather events.

This is why more research into the renewable energy field is necessary from Bangladesh's point of view. It is evident in plain sight that Bangladesh as a country is gifted with plenty of Biomass. In recent times governments are considering biomass as a viable energy resource that can in the future replace coal completely. Of the world's total energy requirement, biomass provides around 50 exajoules. [10]. Biomass energy production produces organic fertilizers as a byproduct and the efficiency of energy production is far better compared to other fossil fuel sources [11].

The world is steadily moving towards Renewables but finding sustainable renewable energy sources is the main challenge. There are various forms of renewable energy sources available in nature like wind energy, oceanic energy, biomass energy, hydro energy, solar energy. But for a country with limited economic resources harvesting these renewable sources is no easy task. Energy sources like wind and solar is available in many countries around the world but only a few countries can harness this power for their benefit because harnessing power from these sources requires a gigantic amount of capital investment [12]. Even then the turnover might not fulfil the demand completely. That's why, renewable energy resources like solar and wind are not sustainable for most countries. But biomass energy is a different story. Biomass is abundantly available in most of the countries. Typically, more in Asian and African countries. It is the mostly available form of renewable energy which also produces energy efficiently. Although it produces less energy than coal but it also emits less amounts of harmful gases into the atmosphere [13].

Taking these factors into consideration the Biomass energy can be considered to be a sustainable form of energy.

Bangladesh is in an optimum geographical location for biomass growth and production. This optimum geographical location couples with plenty of rainfall to produce huge magnitudes of biomass every year. The mean yearly rainfall in Bangladesh varies from 1200 mm to 5800 mm. Rice straw, rice husks, and jute sticks provide for around 46% of Bangladesh's total biomass energy. Agricultural leftovers account for 66.64% of the total recoverable biomass, animal and poultry wastes (17.53%), municipal solid waste (7.64%), and forest residues (8.19%) [9].

As the availability of biomass is moderate in Bangladesh. Using biomass, as the alternative of coal in combustion, will be feasible for the combustion.

1.1: Objective of this Study:

1. To ensure sustainable development, using biomass in place of coal in boilers as well as using reducing the usage of coal as it’s decreasing day by day.
2. It instead of coal as the amount of coal is decreasing everyday
3. Reducing the emission of harmful gases from the power plants to the environment
4. To encourage researchers to pursue more work in this field to get best possible outcomes
5. Introducing first biomass based powerplant in Bangladesh.

1.2: Structure of Thesis:

In the following section the state of literatures on the topic of biomass combustion has been reviewed. This thesis report has six chapters.

The first chapter illustrates the project's overall scope and reasons to choose the model. An overview of the research field and its relevance is discussed in this chapter. The reason, why biomass is chosen over coal. About the environmental and other problems created by coal combustion. The availability of the biomass resources available in the world and in Bangladesh.

The second chapter is literature review in which all the relevant studies that have been analyzed to understand the numerical modeling and methodological approach to follow. A lot of papers have been reviewed to understand the chosen topic and modelling the topic. Relevant data was collected and to improve the modelling. The outcomings of the reviewed papers are also described in this chapter.

The third chapter is about the description of the physical structure of the thesis. The construction of the biomass boiler, the geometry of the boiler and the components (burners) of the boiler is discussed and illustrates providing necessary diagrams. The operating conditions and the fuel analysis is discussed in this chapter.

Computational modelling of the boiler is discussed in the fourth chapter. Methodology of designing the thesis is described here. Governing equations for the combustions, trajectories are also discussed. Meshing of the boiler geometry are described step by step. The edge sizing and the elements number for meshing, their importance and significance are discussed. Energy equations, viscous models, species flow model and discrete phase models are also written here.

The results and the discussion of the thesis is described at the fifth chapter. Main output of the thesis is found here. Using all boundary conditions and analysis, the result part has the data of the temperature rise at the boiler core and CO_2 and O_2 mass fraction distribution at the burner zone and all over the boiler domain.

At the sixth chapter, the conclusion of this thesis project is well written. The scopes and the possibilities of this project is discussed in the conclusion.

Chapter 2: Literature Review:

Biomass as a fuel compared to coal is different in a lot of aspects such as percentage of volatile contents, moisture content, particle diameter. But they are similar when considering emission characteristics. Biomass combustion much like fossil fuel combustion produces emissions such as NOx, CO2, CO. These emissions are exceedingly harmful for humans as well as for the environment and vegetations [14]. Although biomass combustion emits such harmful gases into the ambient air it is considered to be a renewable source of energy because from the production of biomass to harvesting and acquiring sufficient energy from it can be achieved with a smaller carbon footprint if done correctly. That is why there is steady flow of literature on reducing the emissions from biomass combustion and making it more efficient gradually.

Milic Mladenovic et al.,[15] in their paper discuss how NOx emission from biomass combustion can be controlled and reduced by the usage microbials during pre-combustion, combustion period and post-combustion. For the production of low-carbon energy, certain power stations in Europe still employ wood pellets and pulverized fire, particularly for the co-combustion of biomass and coal in big power systems. With a variety of biomass feedstock and boiler types, biomass co-firing has been successfully verified in over 230 installations around the world. NOx reduction systems, which employ staged air supply systems and/or SNCR, and DeNOx SCR systems, which are the most promising DeNOx alternative for biomass fueled medium and large-scale combustion units, are applicable control systems in pulverized fuel boilers.

Bijal Gudka et al. [16] in their paper discussed how cold water and hot water washing of biomass as pre-treatment for combustion reduces the usual emissions considerably. An examination of the literature revealed that washing biomass with water can lower the fuel's ash content, with higher temperatures improving the effectiveness of the removal process. Additionally, hot washing of waste wood can raise the melting point of the ash and lower the quantities of some elements, such chlorine and potassium. The production of acid gases and related environmental effects may be positively impacted by these decreases.

E.D. Vicente et al. [17], in their paper discussed how combustion of biomass in residential areas account for a surprising percentage of particulate emissions to the ambient air. There are noticeable differences between older-style residential appliances and advanced residential energy conversion systems, such as contemporary woodstoves, automatic pellet stoves, and boilers with higher combustion efficiency, according to the results of several studies and the breakdown of emissions factors by technology and fuel type. Although they can perform significantly better than conventional systems, new technologies for burning biomass are still in the early stages of development. These systems are easy to use, offering possible benefits including automatic control and facilitating a decrease in fuel usage and emissions. The collection of several measurements is crucial because better emission inventories call for the tying of emission components to activity information. Despite all efforts to estimate the PM emissions from burning biomass, a uniform standard measurement technique still needs to be put into place immediately. There are many inconsistencies in the literature about particle sampling and dilution techniques as well as reporting emissions. Bingtao Zhao et al. [18], in a paper found that SO2 and NOx emissions are highly dependent on the temperature at which the algae combustion takes place. It was also found that emission characteristics also depend of the species of algae/biomass that was combusting. Algal biomass can be directly burned to produce energy; however, this method may produce emissions of SO2 and NOx that could be harmful to the environment. While NOx emissions are not always correlated with nitrogen content, SO2 emissions and their conversion ratio are dependent on the sulfur concentration of the algal biomass. The peaks, quantities, and conversion efficiencies of SO2 and NOx emissions are strongly influenced by the temperature of burning and the species of algae.

Farooq Sher et al. [19], in the paper found that injection of secondary air from higher locations can minimize the NOx emission up to 30%. The findings of this research investigation investigating the effects of surplus air and air staging on the combustion of several types of biomass pellets in a bubbling fluidized bed combustion are presented in this scientific publication. The study discovered that air staging causes higher temperatures in the splash zone and freeboard, where the primary combustion reaction occurs, and that higher excess air causes larger NOx emissions due to the conversion of fuel-N to NOx. These findings have implications for improving biomass combustion systems' combustion efficiency and lowering emissions. A method for lowering NOx and CO emissions during the combustion of biomass is air staging. Injecting supplementary air into the combustor at certain points can raise gas temperatures and lengthen the time fuel particles spend in the primary combustion zone. This method can reduce NOx emissions by up to 30% and is particularly effective for non-woody biomass fuels with high fuel-N content.

Balal Yousaf et al. [20], in their paper found that biochar fuels co-combusted with coal can reduce the emission of potentially toxic elements into the air. It was also found that volatilization of potentially toxic elements reduced to 21% in comparison to coal. The study investigated the viability of co-firing crop residue biochars with coal as an energy source. The results demonstrated that pyrolysis of biomass materials increased the energy content and combustion performance of blended fuels while decreasing the environmental toxicity hazards of potentially toxic elements (PTEs). Additionally, the study highlighted the impact of pyrolysis temperature on the enhancement of biochar combustion quality and reduction of PTEs' potential negative consequences. Grzegorz Wielgosiński et al., [21], in the project investigated the emission characteristics of Biomass and Coal separately at different combusting temperatures ranging from 700-1100℃ and air flowrates. This study examined the combustion of various biomass varieties and compared their emissions to those of hard coal. The results demonstrated that the emissions of total organic compounds from biomass were unexpectedly greater than those from coal, suggesting that biomass may not be as environmentally benign as previously believed. Due to distinctions in chemical composition and emission properties, the study suggests that combustion of biomass necessitates different technological conditions than coal combustion.

I.Adánez-Rubio et al. [22], in their paper found that high carbon capture efficiency can be obtained using oxygen uncoupling as well as high combustion efficiency with no unburnt fuel. The article examines the efficacy of the CLOU process, which employs a Cu-based oxygen carrier to burn biomass fuel. The study determined that a fuel reactor temperature greater than 900°C is required for complete combustion and 100 percent CO2 capture efficacy. The authors also optimized the process to obtain a carbon capture efficiency of greater than 95% with a small amount of oxygen carrier inventories, indicating the possibility of using this technology with other types of biomass fuels. Anqi Zhou et al. [23], in their research found that increasing the air flowrate shortens burning period and increases the highest combustion temperature that can be reached. This paper presents a one-dimensional model that was created to simulate biomass combustion in a grate bed under varying boundary conditions. The study examines the effects of air supply on fuel combustion completion and overall efficiency, and suggests a primary air to secondary air ratio of 43:57 with an excess air ratio of 1.5 for optimal performance. In order to reduce particulate heat loss, the study also suggests increasing the ratio of primary air supply in the final zone from 10% to 15%.

Arafat A. Bhuiyan et al. [24], in their numerical study found that there is no change in CO2 concentrations with the increase of biomass percentage. This indicates that biomass is CO2 independent source of energy. A commercial CFD software was used with some user defined functions to carry out the inspections. Different amounts of co-firing ratios were investigated in order to find the most efficient one with least number of emissions. Mass fractions of various important species were identified inside the furnace after the combustion. Anqi Zhou et al. [25], in a numerical study it was found that a larger co-combustion fraction achieves a better NOx reduction. This reduction resulted because of less nitrogen input and other species. In order to better understand how NOX emissions are produced and reduced in grate boilers, this study built a model. The impact of co-combustion with methane on lowering NOX emissions and boosting efficiency was investigated using the model. The model examined fuel-N behaviour to forecast NH3 oxidation and HCNeNO reduction reactions in various zones of the boiler, and it combined local oxygen content and fuel bed models to produce more precise forecasts for N-species release during solid biomass burning.Viet Thieu Trinh et al., [26], in a numerical analysis found that the throat of the burner showed that highest temperature among all the surfaces. Also, the NOx emission characteristic was studied thoroughly. This study investigated combustion characteristics with respect to particle diameter size of the biomass, 100% bio-fuel combustion boilers. According to the numerical NOx modelling most of the NOx emission is accounted for in the thermal NOx formation. This study was also conducted with 4 sets of burners with 1 set being at stand by for efficient combustion. It was found that the position of biomass injectors greatly influenced the combustion characteristics of the biomass boiler.

Suyitno et al., [27] in an experimental study found that air-fuel ratio did not affect the overall efficiency of the furnace in a considerable manner. The study effectively designed and tested a 200 kW wood pellet-burning combustion furnace. The results indicated that increasing the AFR had no discernible effect on the furnace's efficacy, which ranged from 82% to 89% for AFRs between 5.4 and 9.0. However, alterations to the design of the furnace's air distribution could improve its performance, and future research could examine various methods for achieving this.

Niko P. Niemelä., [28], in their paper they provided the fundamental understanding on the chemical composition. Aerosol processes in a modern, pulverized wood-burning 100 MWth district heating facility were investigated in this study. Under 30% and 100% operating pressures, it was determined that wood combustion was highly efficient. The low CO, particulate, OC, and MA concentrations in the flue gas, as well as the low UBC concentration in the fly-ash, were indicators of efficient combustion. Flue-gas sampling, dilution, and measurements were conducted from two locations within the furnace using cutting-edge equipment. This allowed us to characterize the evolution of aerosol concentrations along the furnace's length. It was discovered that the majority of water-soluble fine particulates (PM 1) consist of inorganic compounds that nucleated/condensed from the gas phase. Potassium sulphate K_2SO_4 was the predominant aerosol species; however, lower concentrations of other sulphates including Na_2SO_4, $CaSO_4$ (or CaO), $MgSO_4$ (or MgO), and alkali chlorides (NaCl, KCl) were also measured. Yang Zhang. [30],– In this paper they investigated the progress in thermodynamic simulation and system optimization of pyrolysis and gasification of biomass. Simulation of thermodynamics and system optimization are essential to the efficient and sustainable conversion of biomass via pyrolysis and gasification processes. The thermal degradation of biomass without oxygen is known as pyrolysis., which yields biochar, bio-oil, and syngas. Gasification, on the other hand, uses a limited amount of oxygen to transform biomass into syngas, a gaseous propellant. Simulations of thermodynamics allow scientists and engineers to model and analyze the complex interactions and energy transformations that occur during these processes. Simulation models can precisely predict the behavior of biomass conversion systems by incorporating thermodynamic principles, including energy conservation and equilibrium considerations. These models aid in the optimization of process parameters by evaluating the performance of various reactor designs, feedstock compositions, and operating conditions.

Miguel-Angel Perea-Moreno[31], From this research we have known the biomass energy resources, their usage, scientific production growth on the usage of biomass as renewable energy resources and a very important growth due to energy policies to encourage the use of renewable energy due to the increase in the price of a barrel of oil. Based on a bibliometric evaluation, the United States has the most scientific production connected to biomass as a renewable energy source, followed by China, India, Germany, and Italy. Large populations in large countries are interested in using biomass as a new renewable energy source. The majority of research is focused on using biomass to generate thermal or electrical energy, and the primary language of publications on this topic is English.

[32] In their paper they investigated the inlet air entered by swirling which accelerates the air flow for the combustion, air about swirl has also affect on radiation heat flux and NOx mass fraction. The article describes a study that utilized computational fluid dynamics (CFD) to model the rapid pyrolysis of biomass in a fluidized bed reactor. The study examined the impact of various kinetic schemes, biomass particle type and diameter, and operating temperature on product yield. The results demonstrated that the advanced kinetic scheme enhanced the prediction of product yields, and further research can be conducted on the residence time distribution of gas and particle phases in the fast pyrolysis process.

Chapter 3: Description of the Physical System:

Boiler Specification and Operating Parameters: The Boiler used in the study can be considered to be an industrial size boiler. In the Figure 1, the domain was 34.76 m in height, and the furnace cross-sectional area was 14.63 m2; the entire Boiler geometry was simulated. [26].

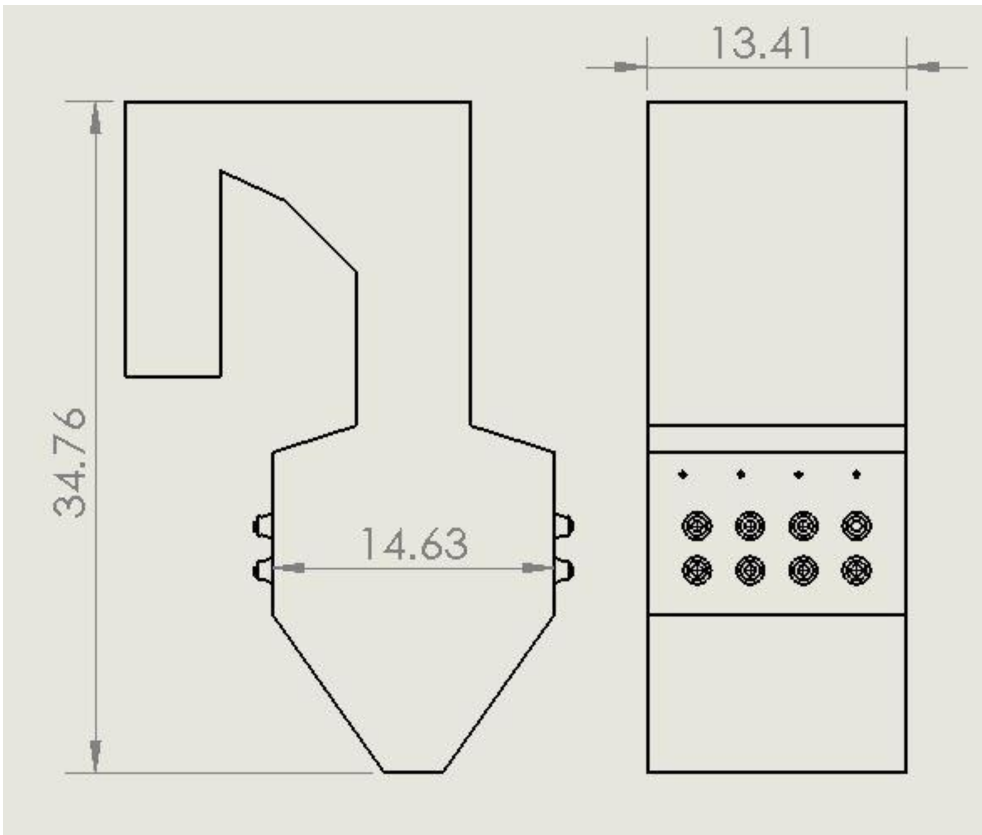

Figure 1: Boiler Geometry

There are total 8 OFA (Over fire air) inlet at two sides of the boiler. There are total 16 burners at the two side of the boiler. **Error! Reference source not found.Error! Reference source not found.**] shows that each burner has 3 air inlet ports. They are primary air inlet, secondary air inlet, tertiary air inlet. Biomass is injected to the boiler through the primary inlet. Air is injected from the OFAs and the three inlet ports of the burners.

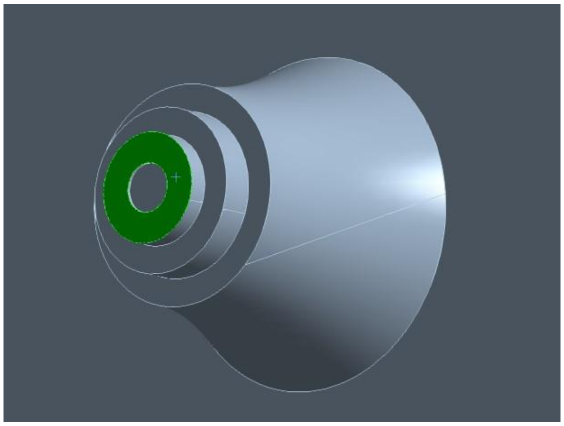

Figure 2: Primary Inlet

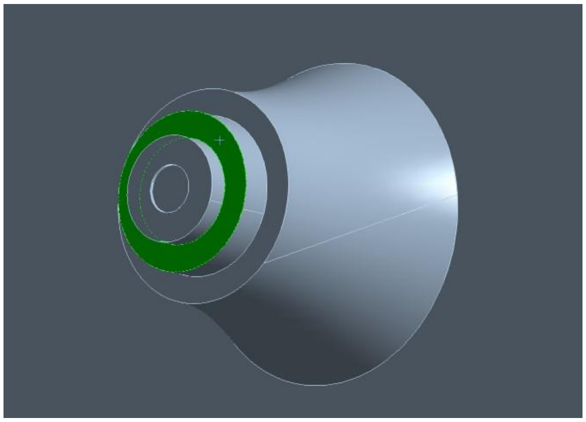

Figure 3:Secondary Inlet

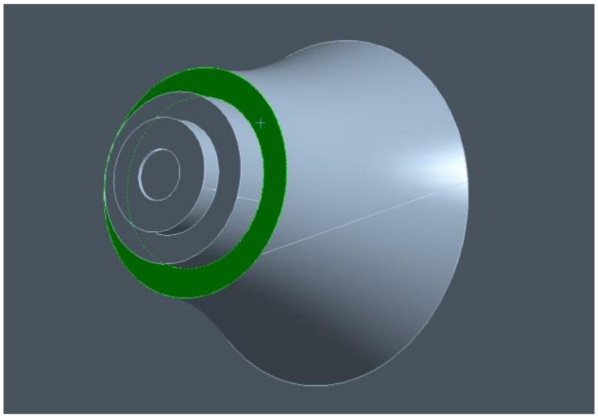

Figure 4:Tertiary Inlet

The typical components that biomass consists of are volatile materials, cellulose, hemicelluloses, lignin and ash. According to the elemental studies, biomass has a substantially greater oxygen content than coal, which causes coal's calorific value to be higher than that of biomass.

The biomass used in the experimental & numerical study has a gross energy value of 19713 J/kg. The amount of fresh-air needed in order for complete combustion to occur is 105905 g/s. The total air is distributed among the burners and OFA with 20 % at primary inlet. The remaining portion of fresh-air is distributed by secondary air (40 %), tertiary air (25 %), Over Fire Air (OFA) (15 %). 15% of excess air is necessary for complete combustion and emission reduction. This pumped into the furnace core in order to make complete combustion of the biomass occur.

The flow rate of the fuel is 20.05 kg/s which flows through the 12 primary inlets. In the geometry each 4 burners in a row are named Burner A, B, C, D accordingly. The operating condition of the operation is Burners A, C, B are active and burner D is standby.

Table 1: Operating Conditions [26]

Input conditions	**Values/Describes**
Fuel feed rate	20.05 kg/s through 12 primary inlets
Fresh-Air inlet-ports	105905 g/s with air percentages at primary 20%, at secondary 40%, at tertiary 25%, at OFA 15%.
Operating conditions	Burners which are labelled A, B, and C are active; Burner D is in standby condition.

Biomass Analysis:

Table 2: Proximate Analysis

Properties	**Biomass (%)**
Moist.	5.96
V.M.	70.35
Ash	4.17
F.C.	19.52

Table 3: Ultimate Analysis

Properties	**Biomass (%)**	**Char (%)**
C	44.60	76.32
H	5.62	0.67
N	2.79	3.07
O	46.07	27.93
S	0.92	0.51

Chapter 4: Computational Methodology

Solidworks 2018 software was used to model the geometry and Ansys Fluent 2020 R1 software was used to model the numerical simulation. In simulation procedure of raw biomass at first the moisture content gets evaporated from the biomass fuel. Following right after that pyrolysis of char, CO and volatile matter was modelled. Figure 5 illustrates the workflow of the methodology.

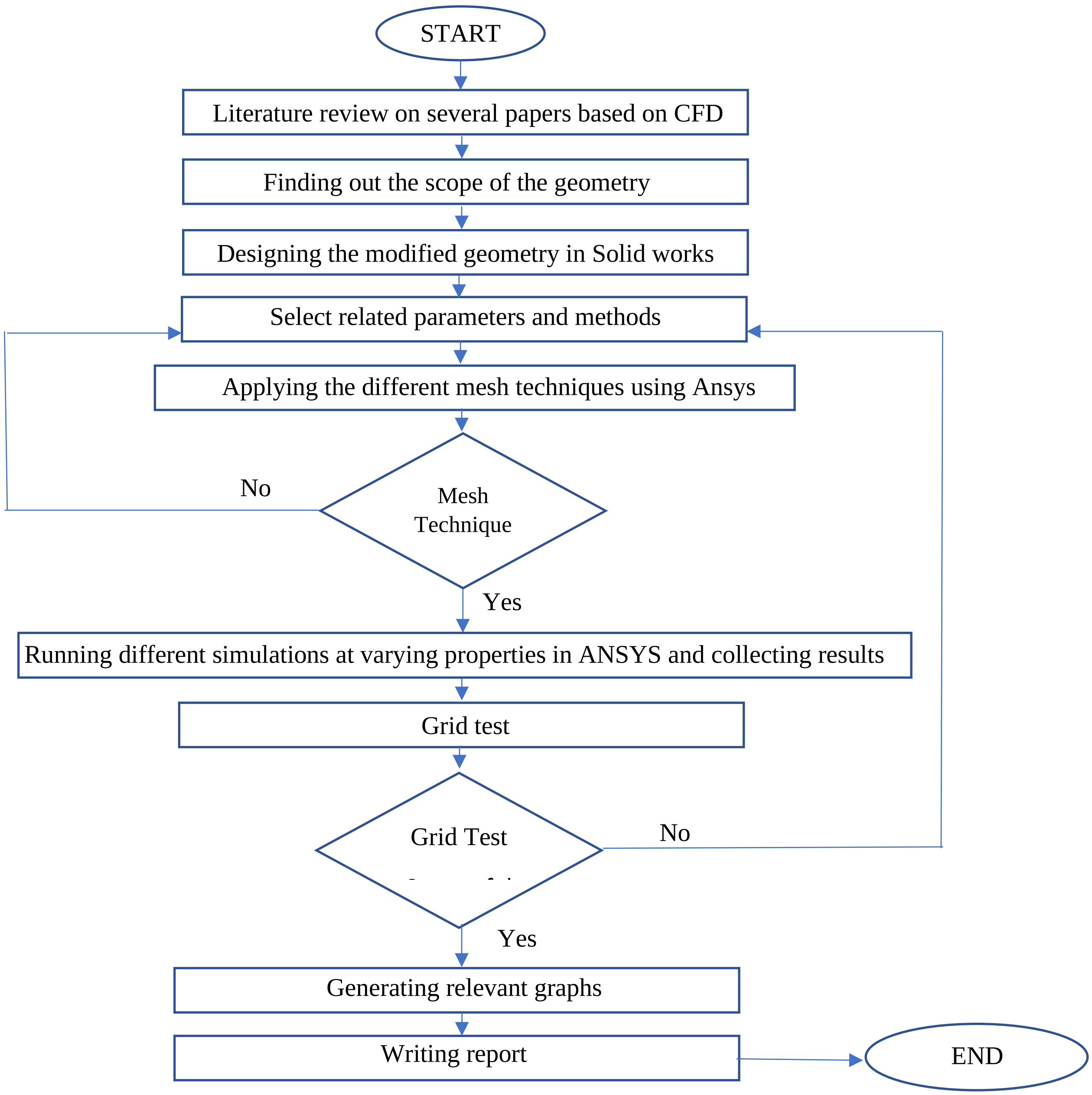

Figure 5: Flowchart of Methodology

Additionally, skewness quality is crucial for the robustness of the simulation. Skewed elements can lead to irregular mesh distortions, tangling, or folding, which can cause numerical instabilities and simulation failures. By minimizing skewness, the mesh remains more regular and distortion-free, enhancing the stability and robustness of the simulation.

In summary, maintaining high-quality skewness in computational simulations is of paramount importance for accurate results, convergence, and robustness. It ensures the accurate representation of physical phenomena, facilitates convergence of iterative solvers, and enhances the stability of the simulation. By prioritizing skewness quality, engineers and researchers can obtain reliable and precise results, enabling informed decision-making and optimization of various engineering applications.

In the Figure 6, The meshing was done using element size of 0.3m which produced element number of 13,37,114. Having a high number of elements in meshing is important for computational simulations for several reasons. Increasing the number of elements in the mesh offers several benefits that contribute to more accurate and reliable results.

Firstly, a high number of elements allows for better resolution of complex geometries and intricate flow or structural phenomena. Fine meshing can capture small-scale features, sharp gradients, and local variations in the solution domain. This level of detail is crucial for accurately capturing flow separation, boundary layer behavior, pressure gradients, or stress concentrations. By increasing the number of elements, the simulation can more precisely represent the physical reality, leading to more accurate predictions and analysis.

Furthermore, a high number of elements improves the accuracy of the numerical approximation. More elements provide a finer discretization of the solution domain, reducing the truncation error associated with the numerical scheme. This leads to improved accuracy and convergence of the simulation, resulting in more reliable and trustworthy results.

Additionally, a high number of elements can enhance the stability and robustness of the simulation. In cases where there are significant variations or discontinuities in the solution, such as shocks or complex boundary conditions, a fine mesh can better capture these features. This aids in mitigating numerical instabilities, oscillations, or non-physical artifacts that may arise due to insufficient mesh resolution.

4.1 Governing Equations:

The commonly employed kinetics and diffusion limited surface combustion model was used to determine the combustion response of char: [26]

$$\frac{dm_p}{dt} = -A_p p_{O_2} \frac{D_0 R}{D_o + R} \tag{1}$$

p_{O_2}(Pa)=Partial pressure of oxygen

$D_0(sm^{-1})$= Oxygen Diffusion rate

R(sm^{-1})=Char oxidation kinetic rate

Different forces, such as drag, buoyancy, and gravitational forces, have an impact on the trajectories of biomass particles. This balancing integral on the particle is as follows:[26]

$$\frac{du_p}{dt} = \frac{18\,\mu}{\rho_p d_p^2}\frac{C_D Re}{24}\left(u - u_p\right) + \frac{g\left(\rho_p - \rho\right)}{\rho_p} \tag{2}$$

Where, u is the velocity, μ is the viscosity and ρ is the density of the biomass particles, respectively

C_D=Drag Coefficient

Haider and Levenspiel developed the following correlation for non-spherical particles [33]:

$$C_D = \frac{24}{Re_{sph}}\left(\left(1 + b_1 Re_{sph}^{b2}\right) + \frac{b_3 Re_{sph}}{b_4 + Re_{sph}} \right) \tag{3}$$

Where,

$$b_1 = \exp(2.3288 - 6.4581\,\emptyset + 2.4486\emptyset^2) \tag{4}$$

$$b_2 = 0.0964 + 0.5565\emptyset \tag{5}$$

$$b_3 = \exp(4.905 - 13.8944\emptyset + 18.4222\emptyset^2 - 10.2599\emptyset^3) \tag{6}$$

$$b_4 = \exp(1.4681 + 12.2584\emptyset - 20.7322\emptyset^2 + 15.8855\emptyset^3) \tag{7}$$

$\emptyset$ =Shape Factor

For this research paper the drag was calculated for non-spherical particles [34] using shape factor of 0.54.

4.2 Mesh:

The geometry was created in Solid works 2022 in 1:1 scale of the physical geometry. After creating the geometry, it was imported to Ansys meshing. In ANSYS meshing the physics preference was set to CFD. CFD provides a comprehensive and accurate representation of the complex fluid flow and heat transfer phenomena involved in combustion processes. It allows for the simulation of turbulent flow, chemical reactions, and the interaction between combustion and fluid dynamics, which are crucial in understanding and optimizing combustion systems.

Furthermore, CFD enables the analysis of combustion in a wide range of geometries and conditions, making it applicable to various industrial applications. It allows engineers and researchers to study combustion in engines, furnaces, boilers, and other devices with different configurations and operating conditions. Because of its adaptability, CFD is a useful tool for increasing combustion efficiency, lowering emissions, and creating new combustion systems.

The availability of reliable and tested combustion models is another benefit of employing CFD for combustion simulation in ANSYS Fluent. Finite-rate chemistry, eddy-dissipation, and partially premixed combustion models are just a few of the many combustion models that Fluent provides. Since these models have undergone rigorous testing and validation against experimental data, their dependability and accuracy in forecasting combustion behavior are guaranteed.

It was decided to use linear element order. For combustion simulation in ANSYS Fluent, setting the element order to linear has a number of benefits that make it a wise decision. The term "linear element order" describes the application of linear shape functions to each finite element to approximate the solution. The following justifications explain why this decision is advantageous for combustion simulations.

First off, linear elements offer a fair compromise between computing efficiency and precision. Higher-order elements can produce answers that are more precise, but they also call for a lot more degrees of freedom, which raises the cost of computing. The computational load is lightened by using linear elements, without affecting the simulation's overall accuracy.

Second, compared to higher-order elements, linear elements have stronger robustness and stability characteristics. The possibility of numerical instabilities or convergence problems is reduced by the smoother approximation of the solution provided by the linear interpolation approach.

This stability is crucial for correct representation of complicated phenomena like species transport and flame propagation in combustion simulations. Additionally, the production of grids and meshes is made easier by linear elements. Since linear elements are straightforward, they are simpler to generate and manipulate, making it possible to produce high-quality meshes for combustion simulations. Because meshing is relatively simple, it is possible to tweak and adapt the grid effectively, which is essential for capturing localized combustion processes or resolving complex geometries. Due to a lack of processing capabilities, the adaptive sizing option was disabled in the sizing section. The mesh defeating option was enabled. It is impossible to emphasize the significance of mesh defeaturing when it comes to computer simulations and analysis. By eliminating extraneous elements or characteristics that have little or no bearing on the simulation's outcomes, a complex geometry is made simpler through defeaturing. This procedure is very important for producing high-quality meshes for a range of engineering applications. The reduction of processing resources needed for the simulation is one of the main benefits of mesh defeaturing. Large mesh sizes can emerge from complex geometries with fine details, which raises the memory and processing time requirements of computing. The mesh size can be greatly decreased without compromising the analysis's accuracy by deleting extraneous characteristics. This makes it possible to run simulations more effectively and permits the investigation of bigger, more intricate systems. Defeaturing also plays a vital role in ensuring mesh quality. Complex geometries with small features or sharp angles can lead to poor mesh quality, such as distorted or stretched elements, which can negatively impact the accuracy and convergence of the simulation. By simplifying the geometry through defeaturing, smoother and more regular meshes can be generated, leading to improved accuracy and stability of the simulation results. The capture curvature option was turned on due to the complexities in the boiler geometry. The importance of capturing curvature in computational simulations and analyses cannot be understated, particularly when dealing with complex geometries and intricate flow or structural phenomena. Curvature refers to the change in direction or shape of a surface, and accurately capturing it in the simulation is essential for obtaining reliable results.

One significant reason for capturing curvature is the accurate representation of fluid flow or structural behavior. In many engineering applications, such as aerodynamics or heat transfer, the flow or stress distribution is significantly influenced by the curvature of the surfaces involved. Neglecting curvature can lead to inaccurate predictions and flawed designs. By capturing curvature, the simulation can capture the flow separation, boundary layer behavior, pressure gradients, or stress concentrations accurately, resulting in more realistic and reliable results.

Furthermore, capturing curvature is crucial for mesh generation and refinement. Curved surfaces require appropriate mesh resolution to accurately capture the flow or structural behavior. Neglecting curvature may result in insufficient mesh resolution in these regions, leading to inaccurate results. By explicitly capturing the curvature, the mesh can be refined appropriately, ensuring that the solution is adequately resolved and capturing the essential features of the problem.

A high grade of mesh quality was achieved with max skewness being 0.91 which less than the threshold value of 0.95. The importance of skewness quality in computational simulations cannot be overlooked, as it directly impacts the accuracy, convergence, and reliability of the results. Skewness refers to the distortion or non-orthogonality of elements in a mesh, and maintaining high-quality skewness is crucial for ensuring the quality of the simulation.

One primary reason for emphasizing skewness quality is its effect on the accuracy of the solution. Skewed elements can introduce errors and inaccuracies in the simulation, especially in regions where the flow or stress gradients are high. Poorly skewed elements can lead to incorrect representation of flow patterns, boundary layer behavior, or stress concentrations, compromising the reliability of the results. By ensuring low skewness, a more accurate representation of the physical phenomena can be achieved, leading to more trustworthy simulation outcomes.

Moreover, skewness quality plays a significant role in achieving convergence in numerical simulations. Skewed elements can hinder the convergence of iterative solvers, especially when solving complex fluid flow or structural problems. High skewness might cause the solution to converge slowly, oscillate, or even not at all. By maintaining good skewness quality, the simulation can converge more reliably and efficiently, reducing computational costs and ensuring a stable and accurate solution.

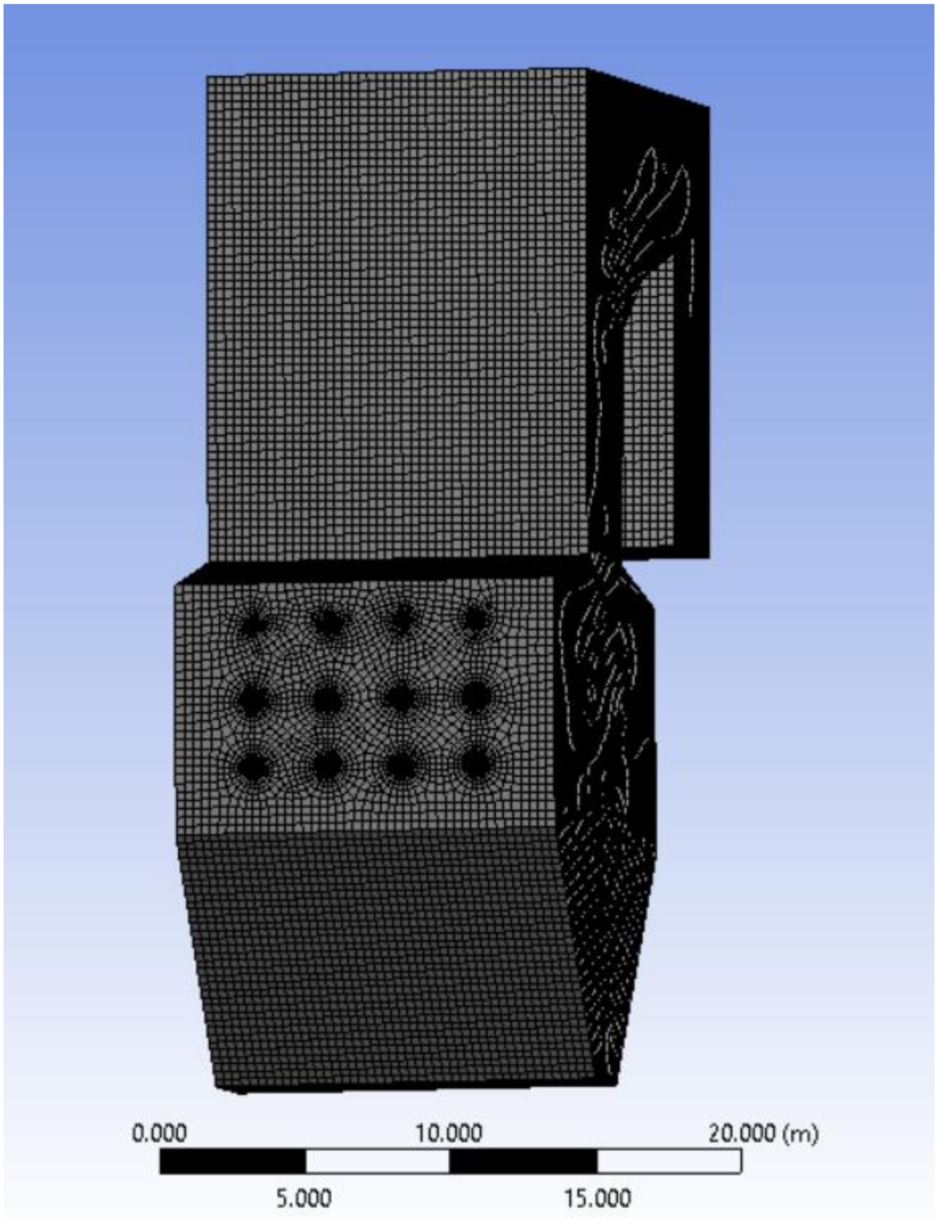

Figure 6: Meshed Geometry

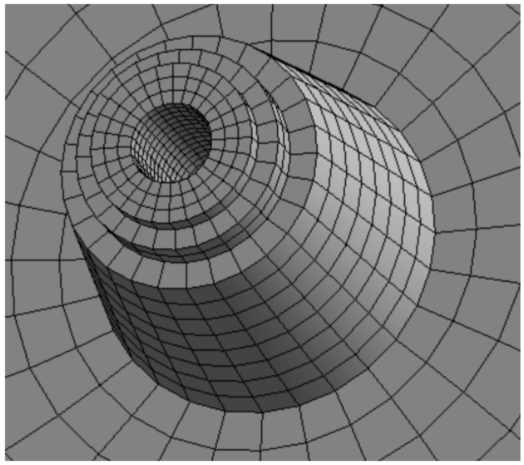

Figure 7: Meshed Inlet

Cylindrical co-ordinate system was set at each burner entry points which was used for giving swirl at the inlet boundary conditions. Named selection of each boundary was made manually so that velocity can be inputted individually at all of the boundary conditions.

Edge sizing was used in all of the relevant edges and the meshing method was selected to be Multizone Method. The multizone meshing method is of great importance for structured mesh generation in computational simulations due to its ability to efficiently handle complex geometries and optimize mesh quality. This method divides the computational domain into multiple zones or subdomains, allowing for better control over mesh resolution and topology in each region.

One significant advantage of multizone meshing is its ability to accommodate varying levels of mesh refinement. Different zones can have different mesh densities, with finer meshes in regions of interest or high gradients, and coarser meshes in less critical areas. This adaptability ensures that computational resources are allocated effectively, focusing on capturing the important flow or structural features while reducing unnecessary resolution in other regions. It enables efficient utilization of computational resources without compromising the accuracy or convergence of the simulation.

Furthermore, multizone meshing helps in achieving high-quality structured meshes. By defining specific zones, it allows for greater control over mesh topology, ensuring that structured grids are maintained. Structured meshes offer numerous advantages, such as better numerical stability, accurate representation of flow or structural behavior, and improved convergence rates. With multizone meshing, the structured nature of the mesh can be preserved and optimized in each zone, resulting in a more reliable and efficient simulation.

4.3 Models:
The solver model used for this simulation is transient solver. As the transient solver is more robust it can handle higher order complexities of a biomass combustion simulation smoothly compared to steady state solver.

4.4 Energy Equation:

$$\nabla \cdot \left(\vec{v}(\rho E + p)\right) = \nabla \cdot \left(k_{eff}\nabla T - \sum_j h_j \vec{J}_j + \left(\overline{\overline{\tau}}_{eff} \cdot \vec{v}\right)\right) + S_h \tag{8}$$

The energy equations option in Ansys Fluent is turned on. The inclusion of energy equations is essential when simulating biomass combustion due to the significant heat transfer and thermal behavior involved in the process. Biomass combustion simulations aim to understand and optimize the energy conversion and thermal performance of biomass-based systems such as boilers, furnaces, or biomass power plants.

By turning on the energy equations in the simulation, ANSYS Fluent considers the transfer of thermal energy through convection, conduction, and radiation. This enables the accurate representation of heat transfer within the system, including heat release from biomass combustion, heat transfer to surrounding surfaces, and heat absorption by fluid or solid components. Including energy equations allows for a comprehensive analysis of important parameters such as temperature distribution, heat fluxes, and thermal efficiency. It provides insights into the performance of the combustion system, such as the location of peak temperatures, areas of heat losses, or thermal gradients.

The energy equations also make it possible to assess the system's thermal stresses and deformation. High temperatures and thermal gradients produced by biomass combustion may affect the system's structural integrity. The assessment of thermal expansion, stress distribution, and potential structural failure zones is made possible by the inclusion of energy equations. Energy equations must also be taken into account when researching pollutant generation and emissions. The temperature field affects chemical processes and the production of particulate matter and nitrogen oxides (NOx), two pollutants. The simulation can shed light on how temperature affects the production of pollutants by incorporating energy equations, making it easier to optimize biomass combustion processes to reduce emissions.

In summary, adequate representation of heat transmission, thermal behavior, thermal stresses, pollutant generation, and thermal efficiency requires activating the energy equations in models of biomass burning. It offers thorough thermal performance study of the system and aids in streamlining biomass-based energy conversion procedures for increased effectiveness and diminished environmental impact.

4.5 Viscous Model:

$$\frac{du_p}{dt} = \frac{18\mu}{\rho_p\, d_p^2}\; \frac{C_D Re}{24}\left(u - u_p\right) + \frac{g(\rho_p - \rho)}{\rho_p} \qquad (9)$$

A popular turbulence model with several benefits for modelling combustion processes is the k-viscous model. This model, which is offered in ANSYS Fluent, offers a dependable and effective method for encapsulating the intricate turbulence phenomena connected to combustion. The capacity of the k-viscous model to precisely anticipate the properties of turbulent flow is one of its main benefits. Due to the mixing of the fuel and oxidizer, combustion processes frequently entail high degrees of turbulence, which have a substantial impact on pollutant production, flame spread, and heat transfer. The quality of combustion simulations is improved by the realistic flow field predictions made by the k-model, which accurately represents the turbulence eddies and their interactions.

In addition, the computational efficiency of the k-model is superior than that of more intricate turbulence models like the Reynolds Stress Model (RSM) or Large Eddy Simulation (LES). Two transport equations for turbulent kinetic energy (k) and its dissipation rate serve as the foundation for this formulation. The k-model is well suited for industrial-scale combustion simulations where broad domains and transient phenomena need to be taken into account because of its simplicity and computing efficiency. Premixed and non-premixed combustion are just a few of the instances for which the k-model is ideal. For flame properties like flame front placement, flame thickness, and flame stability, it offers trustworthy predictions. The examination of combustion efficiency, pollutant production, and emissions is made possible by the k-model, which also takes into account the interaction between turbulence and chemical reactions.

In conclusion, the k-viscous model is a good option for combustion modelling because of its accuracy in predicting turbulent flow, efficiency in computation, and application to a range of combustion scenarios. With the use of this model, engineers and researchers may analyze pollutant emissions, optimize burner designs, and enhance the general performance of combustion systems.

4.6 Species Flow Model:

$$\nabla \cdot (\vec{v}\rho Y_i) = -\nabla \cdot \vec{J_\iota} + R_i + S_i \tag{9}$$

where,

$$\vec{J_\iota} = -\left(\rho D_{im} + \frac{\mu_t}{Sc_t}\right)\nabla Y_i - D_{T,}\frac{\nabla T}{T} \tag{10}$$

This numerical simulation utilized the Species Transport Model as the species flow model. A key element that enables the simulation and analysis of species concentration and distribution within a fluid flow is the species transport model in ANSYS Fluent. It is essential for comprehending a variety of processes, including combustion, chemical reactions, and the creation of pollutants. The conservation equations for each species present in the system form the basis of ANSYS Fluent's species transport model. These equations take into account the rates of chemical reaction, advection, and diffusion as well as species transfer. The paradigm views species as distinct entities with unique characteristics, such as diffusivity, molecular weight, and reaction kinetics. Convective transport resulting from fluid flow, diffusive transport resulting from concentration gradients, and any additional source or sink terms resulting from chemical processes are all taken into consideration when ANSYS Fluent solves the continuity equation for each species to simulate species transport. The governing equations for fluid flow and energy transport are coupled with the equations for species transport, allowing for the interaction of the two with other physical phenomena. Finite-rate chemistry, the eddy-dissipation concept, partially premixed combustion, and other techniques are available in ANSYS Fluent to simulate the movement of species. These modelling methodologies include assumptions and simplifications that are customized to the unique conditions of the combustion or chemical reaction under investigation. The ANSYS Fluent species transport model is a useful tool for analyzing concentration profiles, reaction rates, and pollutant formation within a system. Researchers may use this tool to look into combustion processes, enhance combustion, and evaluate how the concentrations of various species effect the outcomes. A species transport model and the turbulence chemistry interaction known as Finite Rate/Eddy-Dissipation were utilized to represent the two-step reaction process employed by the coal calculator.

4.7 Discrete Phase Model (DPM):

In computational fluid dynamics (CFD) simulations, the discrete phase model (DPM) is a frequently used method that enables us to accurately simulate the complex behavior of dispersed particles or droplets in a continuous fluid environment. This method is very useful for understanding multiphase flows incorporating particles or droplets, such as those seen in spray atomization, particle-laden flows, or particle deposition, and for performing research on these flows. The discrete phase model's noteworthy strength is its capacity to precisely track and evaluate the individual trajectories taken by particles or droplets, giving us precise trajectory data for in-depth research. The DPM computes each particle's velocity individually while taking drag, gravity, and inter-particle interactions into consideration since it views particles as Lagrangian entities. This enables the simulation of complex particle behaviors including coalescence or disintegration of particles as well as particle dispersion, interactions with barriers, and coalescence.

Analysis of major particle attributes, including particle size distribution, concentration profiles, and deposition patterns, is also made feasible by the DPM. By tracking individual particle trajectories, the model may provide exact information on particle behavior and its impact on the flow field. The efficiency of combustion in furnaces, spray atomization in fuel injectors, and particle deposition in filters may all be improved with this understanding. The Discrete Phase Model was employed in this numerical model to include point attributes such as fuel particle sizes, velocities, temperatures, and flowrates. A 0.54 form factor non-spherical particle physical model was chosen.

4.8 Solution Methods:

Due to its reliability, stability, and convergence characteristics, the SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) pressure-velocity coupling scheme is a preferred option in computational fluid dynamics (CFD) simulations. It offers several advantages that make it a suitable option for a wide range of flow problems.

One key reason for selecting the SIMPLE pressure-velocity coupling scheme is its ability to handle incompressible flow accurately. The scheme effectively enforces the continuity equation by iteratively updating the pressure and velocity fields in a segregated manner. This ensures the preservation of mass conservation and allows for the simulation of incompressible flows with high accuracy.

As the simulation was conducted in transient state, after initialization, the solution converged with number of time steps set to 1000 and time step size was set to 0.25 seconds. We set for 10 iterations per time step.

Chapter 5: Results and Discussion

In the results it is observed that the maximum temperature within the furnace reaches 2300K. Figure 8,Figure 9,Figure 10] illustrates the overall temperature distribution of the boiler. From longitudinal plane cut we can see the total temperature distribution in the whole furnace. The exit temperature shows close to 600K which is very close to the measured value. The exit hopper temperature shows 1200K temperature which is also very close to the measured value. From the contour it is evident that maximum temperature of 2200K occurs in the furnace core and heat is lost as the mixture flows towards the outlet.

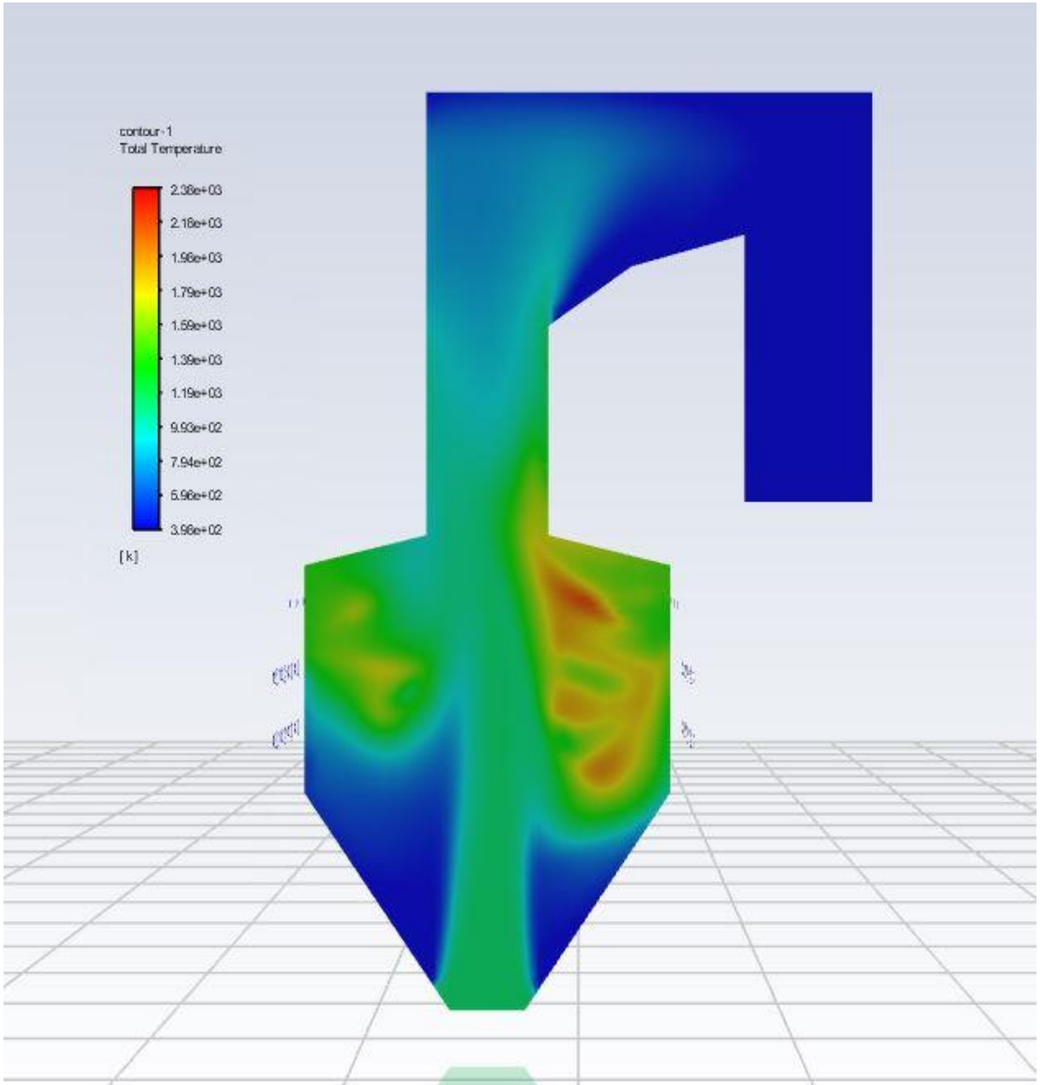

Figure 8: Temperature Contour of the tangential furnace in the vertical position

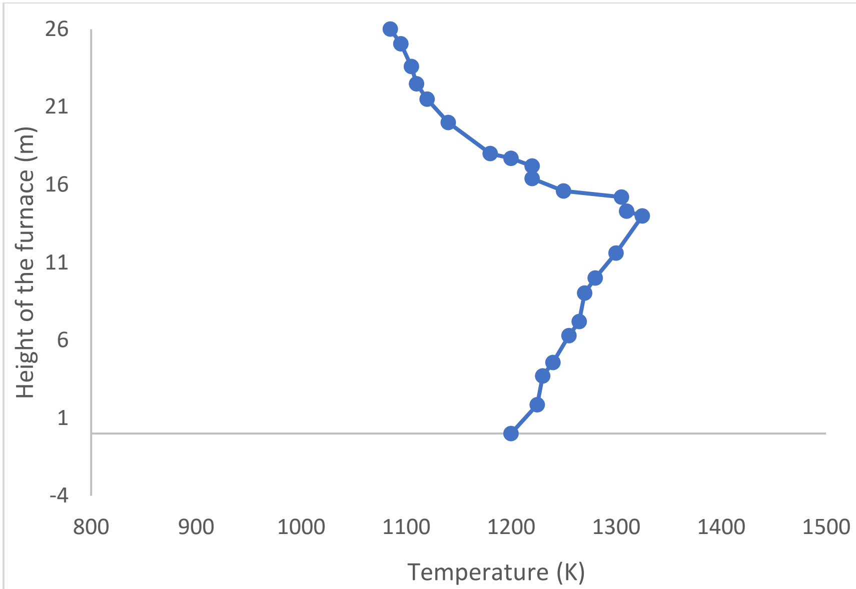

Figure 9: Average Temperature Distribution Graph

Lower Burner B-D

Upper Burner A-C

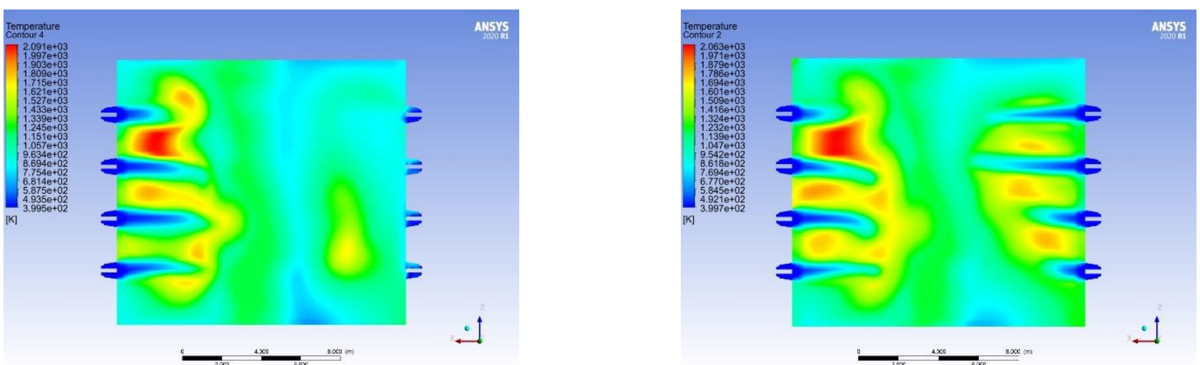

Figure 10: Temperature Distribution Contour of Burners

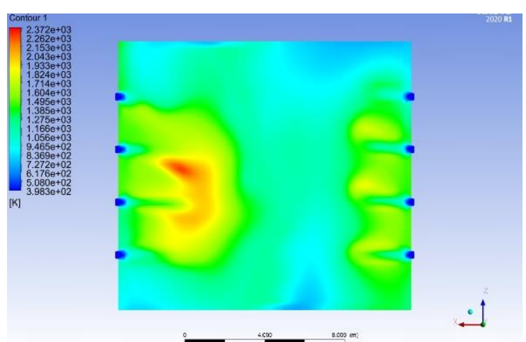

Figure 11: Temperature Distribution Contour of OFA

5.1 Temperature rise in boiler core:

From Figure 8, the temperature at the core of the boiler the highest temperature is recorded 1300K. The highest temperature is recorded 2300K. Figure 9, shows the temperature raise in the boiler core. From Figure 10, Highest temperature is raised at the upper BNR A-C level. The highest temperature is not recorded at the middle of the boiler because one set of lower burners (Burner D) was at standby. So, temperature rise in the boiler is not well distributed. As BNR A-C burners were active so air and fuel was injected from both sets while at lower boilers, only BNR C was active. Biomass with a high percentage of volatile materials than coal particle, ignites easily and burns out quickly.

5.2 O_2 mass fraction and CO_2 mass fraction

From the mass fraction contour of O_2 and CO_2, it is seen that the amount of fractioned oxygen and carbon di-oxide at the XZ plane. At first, there were oxygen inside the boiler. After the combustion happened, the oxygen started to burn out and converted to CO_2. O_2 is burnt and CO_2 is being created which ensures combustion in the boiler core. From Figure 13: O2 Mass Fraction distribution at the burner location for the contour shows the burned and unburned O_2 due to combustion. The changes in CO_2 mass fraction contour, Figure 12, proves the combustion of biomass.

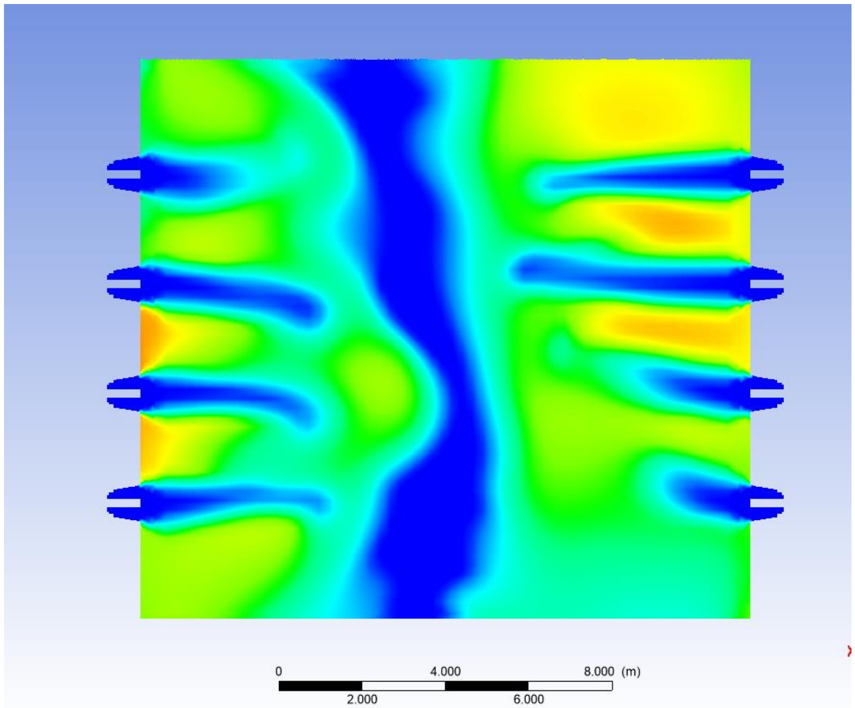

Figure 12: CO_2 Mass Fraction Distribution at the burner location for BNR A-C

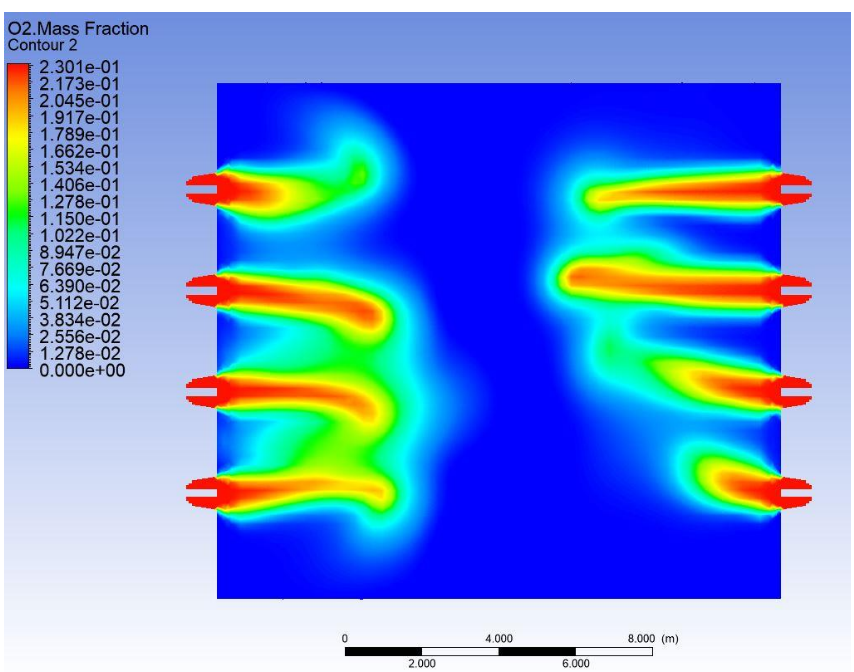

Figure 13: O_2 Mass Fraction distribution at the burner location for BRNR A-C

Chapter 6: Conclusion

In conclusion it can be said that biomass might very well be the fuel of the future. That is why it is necessary to conduct more research in the efficient use of biomass that available in abundance in the environment. In this thesis, we made a working numerical model furnace for biomass combustion. This model can be further used to conduct more in-depth numerical research. It can be used to model NOx emission characteristics and amount of char at boiler outlets. Better computational resources can be used to achieve results which are more accurate.

Biomass combustion research holds significant importance in the quest for sustainable energy solutions and mitigating environmental impacts. Understanding the combustion behavior of biomass fuels is essential for optimizing energy conversion processes, improving combustion efficiency, and reducing emissions. Biomass combustion research helps identify efficient and clean combustion technologies, enabling the utilization of biomass resources as renewable energy sources. It also aids in the development of emission control strategies and pollutant reduction techniques. Furthermore, biomass combustion research contributes to the advancement of biomass-based industries, such as biomass power plants and bioenergy production, fostering economic growth and promoting a transition to a more sustainable and carbon-neutral energy sector.

In Bangladesh, coal resource is limited. Availability of biomass in rural areas are very high. Biomass as the raw materials of combustion is the best alternative to reduce the limited coal resources.

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