Section A-Research paper
ISSN 2063-5346

SIMULATION OF COAL AND OLIVE CAKE COMBUSTION IN A CIRCULATING FLUIDIZED BED COMBUSTOR: A COMPARATIVE STUDY

Asim Aamir[1], Tony Suryo Utomo[1], Eflita Yohana[1], Abdulwahid A.A.S Al-Haddad[1], Zafran Ullah[2]

1- Department of Mechanical Engineering, Diponegoro University, Jl. Prof. Sudharto, SH, Semarang 50275, Indonesia
2- Department of Chemical Engineering, Diponegoro University, Jl. Prof. Sudharto, SH, Semarang 50275, Indonesia

Keywords: Circulating fluidized bed (CFB) reactor, Numerical modelling, Combustion efficiency, Pollutant emissions, Environmental sustainability.

Introduction: The utilization of circulating fluidized bed (CFB) combustors has garnered significant interest owing to their exceptional fuel adaptability, efficacy, and reduced emission levels. The present study offers a comparative evaluation of the combustion mechanisms of coal and olive cake within a circulating fluidized bed (CFB) framework.

Background: The study draws from an established body of research, notably the “Three-dimensional modelling of olive cake combustion in CFB,” extending the parameters to include coal as a fuel source. Previous research has primarily focused on individual fuels; this paper provides a comparative analysis, enriching our understanding of how different fuels perform under identical conditions.

Methodology: We simulated olive cake and coal combustion using a three-dimensional model, maintaining identical boundary conditions for both fuels. The simulation parameters included particle diameters, velocities, total mass flows, and temperatures at the inlet.

Findings: The simulations demonstrated unique combustion characteristics for each fuel. Olive cake combustion peaked at 1108.33°C and yielded reactant products such as CO, CO2, NO, HCN, and H2S. Conversely, coal combustion reached a higher maximum temperature of 1500.12°C, with the combustion process leading to a decrease in oxygen mass fraction at the fuel inlet and an increase in the mass fractions of CO2 and CO.

Conclusion: The study offers a comparative insight into an olive cake and coal combustion behaviours in a CFB combustor. Understanding these differences and their implications for efficiency, emissions, and possible optimizations can prove critical in designing and operating CFB systems for different fuel types. This paper establishes a foundation for further research into alternative and renewable fuel sources in CFB technology.

---

*Corresponding author Email:
asimaamir95@gmail.com

Diponegoro University, Jl. Prof. Sudharto, SH,
Semarang 50275, Indonesia

INTRODUCTION

Coal is a primary energy source in many countries, and its combustion in circulating fluidized bed (CFB) reactors has gained attention as an efficient and environmentally friendly way to produce electricity[1] . The combustion process in CFB reactors involves complex physical and chemical phenomena, which require accurate modelling and simulation to understand better and optimize the process. To this end, this research paper presents a comprehensive three-dimensional numerical model for coal combustion in a CFB reactor[2] . This study aims to gain insights into coal combustion in CFB reactors and to aid in designing more efficient and environmentally friendly combustion systems. CFB technology is widely used in the combustion of coal and other solid fuels due to its advantages over other combustion technologies, such as low emissions of nitrogen oxides (Nox) and sulfur dioxide (SO2), high fuel flexibility, and low maintenance costs[3]. However, the combustion process in CFB reactors is complex and involves many physical and chemical phenomena, such as heat transfer, gas-solid reactions, and particle dynamics[4] . Therefore, accurate modelling and simulation are necessary to gain insights into the process and optimize the system's combustion efficiency and environmental performance. Despite the many advantages of CFB technology, there are still some challenges and limitations in its combustion process. For example, forming carbon monoxide (CO) and unburned Carbon in fly ash can reduce combustion efficiency and increase the emissions of greenhouse gases and particulate matter[5].Therefore, developing a comprehensive numerical model that can simulate the combustion process in CFB reactors and provide insights into carbon burnout and emissions formation mechanisms is crucial. The objective of this study is to develop a comprehensive three-dimensional numerical model for the combustion of coal in a CFB reactor. The model will consider the fundamental physical and chemical phenomena, such as gas-solid reactions, heat transfer, and particle dynamics, and will be validated using experimental data from the literature. The model will investigate the effects of operating conditions, such as temperature, oxygen concentration, and fuel properties, on the combustion efficiency and emissions formation in CFB reactors. The research comprehensive three-dimensional numerical model for coal combustion in a CFB re- actor aims to gain insights into the combustion process and aid in designing more efficient and environmentally friendly combustion systems. The model will consider the critical physical and chemical phenomena and will be validated using experimental data. The study will investigate the effects of operating conditions on combustion efficiency and emissions formation in CFB reactors. This research will contribute to the understanding and optimization of the combustion process in CFB reactors and will have significant implications for the development of clean and sustainable energy systems.

The article is organized into distinct segments, which are as follows: The introductory section provides an overview of the research context and outlines the objective of constructing a comprehensive three-dimensional numerical model for coal combustion within a circulating fluidized bed (CFB) reactor. The present section offers a comprehensive review of the literature about CFB technology, its benefits, and the difficulties associated with comprehending the combustion mechanism in CFB reactors. The present section expounds on constructing the numerical model, encompassing the simulation methodologies employed to replicate gas-solid flow, chemical reactions, heat transfer, and mass transfer. The present study describes the CFB riser and its corresponding operating conditions in the simulations. The current section showcases the simulation outcomes, encompassing the flow patterns, voidage axial and radial distributions, gas and particle velocities, temperature profiles, and gas compositions. The segment further comprises an evaluation of gaseous emissions of pollutants. The present section provides an interpretation of the obtained results and deliberates on their implications for developing more efficient and eco-friendlier combustion systems. The section above elucidates the constraints of the study and the prospects for further investigation. The conclusion section provides a concise overview of the primary outcomes of the research and their implications for devising effective measures to mitigate emissions in CFB combustion systems. The study’s conclusion highlights its significant contribution towards comprehending the coal combustion process in CFB reactors.

LITERATURE REVIEW

CFB (circulating fluidized bed) boilers are an essential technology for generating power and have been widely used in coal combustion processes for almost a century [2]. Computational fluid dynamics (CFD) simulation has gained significant traction in contemporary times to investigate the intricate processes involved in coal combustion within circulating fluidized bed (CFB) boilers[6] . Various scholars have employed diverse methodologies and models to replicate the function of pulverized coal combustion in circulating fluidized bed boilers. As per a scholarly analysis of computational fluid dynamics (CFD) simulation of coal combustion in circulating fluidized bed (CFB) boilers, the eddy viscosity-based two-equation turbulent models, and the Eulerian-Lagrangian multiphase approach is predominantly favoured owing to their superior computational efficiency[7] . A comprehensive dynamic process simulation model has been developed for a 1 MWth circulating fluidized bed test facility, considering heat transfer, gas-solid interaction, and combustion[8] .

Aspen Plus has designed a new model to in- clude detailed information about coal/biomass co- firing in a fluidized bed reactor to optimize pollu- tant emissions[9]. A scholarly publication examined the combustion characteristics of pulverized coal within an axisymmetric two-dimensional combustion chamber model utilizing computational fluid dynamics. The findings were subsequently corroborated through experimental validation[10] . Using numerical simulation software, one study analyzed the influence factors and evolution law of spontaneous coal combustion (CSC) in a coal mine[11] . Last, but not least, it’s important to remember that professionals in the field of CFD modelling have years of expertise doing research in areas like heat transfer, inverse heat transfer, computational heat transfer, renewable energy, and internal combustion engines[12] . An increasing amount of scholarly inquiry has been directed towards the computational fluid dynamics (CFD) simulation of coal combustion in circulating fluidized bed (CFB) boilers. Several methodologies and techniques have been devised to enhance combustion efficiency and curtail the discharge of pollutants. These include the utilization of eddy viscosity-based two-equation turbulent models and the Eulerian-Lagrangian multiphase method, comprehensive dynamic process simulation models, and Aspen Plus simulations. Subsequent investigations have centered on examining the combustion properties of pulverized coal and the factors that impact the occurrence of spontaneous coal combustion.

The process of coal combustion is multifaceted and encompasses a range of physical and chemical reactions. Coal ash is a residual substance that results from coal combustion in coal-fired power plants. It is predominantly composed of minute particulate matter, minerals, and various trace elements, including but not limited to mercury, arsenic, selenium, and lead[13] . Fly ash is a finely powdered material primarily composed of silica generated through the combustion of finely ground coal in a boiler. The coal combustion process involves the chemical reaction between the carbon present in coal and oxygen from the surrounding air, producing heat, water vapour, and carbon dioxide. The thermal energy generated through the process of combustion is utilized for various purposes, including the generation of electrical power and the synthesis of artificial compounds. The method of coal combustion results in the emission of a substantial quantity of carbon dioxide into the environment, thereby contributing to global warming and consequent climate change. The chemical processes during coal combustion are contingent upon various factors, including but not limited to the coal’s composition, temperature, and the quantity of oxygen accessible for combustion. Coal combustion can be categorized into three distinct stages, namely the drying stage, the devolatilization stage, and the char combustion stage. Throughout the drying phase, the moisture content within the coal undergoes evaporation, leading to a rise in the temperature of the coal. During the devolatilization phase, the volatile components present in coal are liberated, leading to a subsequent increase in the temperature of the coal. In the final stage of coal combustion, known as the char combustion stage, the residual solid substance in coal, referred to as char, undergoes a chemical reaction with oxygen resulting in the formation of carbon dioxide and other by-products of combustion[14] . The physical phenomena are also of paramount importance in coal combustion. The phenomena above encompass the fields of thermal conduction, convective heat transfer, diffusion, convection, and mass advection, as well as the study of fluid motion and its characteristics. The heat transfer process is facilitated by conduction, convection, and radiation, which are crucial for sustaining the requisite temperature for combustion. Mass transfer pertains to the transport of particles and gases within the combustion milieu, thereby influencing the kinetics of chemical reactions. Fluid dynamics relate to the orientation of gases and particles within the combustion milieu and are paramount in guaranteeing optimal combustion[15] . The coal combustion process is a multifaceted phenomenon that involves chemical and physical reactions. Chemical reactions are influenced by multiple factors, including the coal's composition, temperature, and the quantity of oxygen accessible for combustion. Efficient combustion necessitates the involvement of physical phenomena, including but not limited to heat transfer, mass transfer, and fluid dynamics.

Circulating Fluidized Bed (CFB) boilers have emerged as a compelling alternative for power generation owing to their superior efficiency and minimal emissions. The utilization of numerical models and simulation techniques is of paramount importance in the development, enhancement, and management of CFB boilers. Numerous investigations have been carried out to develop numerical models and simulation techniques for circulating fluidized bed (CFB) boilers. Researchers have conducted field tests and theoretical studies to examine the intrinsic reducing condition in the furnace of circulating fluidized bed (CFB) boilers[16] . Furthermore, a novel CFB combustion technology was devised based on fluidization state specification. The aim was to decrease the auxiliary power consumption and enhance the dependability of large-scale CFB boilers. This was achieved using an energy consumption calculation method and a modified one-dimensional CFB combustion model[17].

Numerical simulations have also investigated the lateral mass transfer and mechanism of bed-inventory overturn inside a pant-leg CFB[18] . Moreover, a circulating fluidized bed boiler case study was conducted to reduce NOx emissions by optimizing the boiler's structure. In this study, the simulation results were verified by experiments adopted. Furthermore, a review of different numerical models and simulation techniques used for CFB boilers has been conducted[16] . The present study focuses on diverse scenarios that could benefit from applying Computational Fluid Dynamics (CFD) and the essential components required for performing exemplary computations. The study delineates the benefits, drawbacks, and methodologies employed in machine learning algorithms that have been utilized to propose design parameters for various research-oriented algorithms. Numerous numerical models and simulation techniques have been devised to design, optimize, and operate circulating fluidized bed (CFB) boilers. Multiple models and procedures have been developed to address the issue of reducing emissions. These approaches encompass investigations into the underlying reducing conditions and optimization of the boiler structure. Furthermore, a comprehensive evaluation has been carried out on the diverse numerical models and simulation methodologies employed in the context of circulating fluidized bed (CFB) boilers.

METHODOLOGY

CFB Boiler Geometry and Operating Conditions

The efficient operation of Circulating Fluidized Bed (CFB) boilers, heralded for their adaptability, efficiency, and emission control capabilities, hinges significantly on two interrelated factors: their geometry and operating conditions. The geometry pertains to the meticulous design and dimensions of the boiler components, including the combustion chamber, cyclone separators, and loop seal, all of which influence fluidization, fuel distribution, and heat transfer processes. Concurrently, operating conditions encompass parameters such as temperature, pressure, fluidizing velocity, and fuel quality, directly impacting combustion efficiency, emissions, and overall boiler lifespan. This understanding is the foundation for comprehending CFB boilers' complexities and optimizing their design and operational conditions to ensure peak performance and sustainability.

Simulation Stage

Simulations were run to investigate the impact of the set variations on the performance of the Circulating fluidized bed, utilizing ANSYS 22R1 software. The simulation consists of three stages: preprocessing, processing, and post-processing. ANSYS Fluent, a highly versatile software application, was employed for conducting the computational fluid dynamics (CFD) simulations in this study. The software offers extensive capabilities for modelling complex physical phenomena, including multiphase flows, turbulence, heat transfer, and chemical reactions, which are crucial in understanding the co-firing of coal in a Circulating Fluidized Bed (CFB) boiler. ANSYS Fluent provides a range of turbulence models, such as Large Eddy Simulation (LES) and subgrid-scale models, which are integral for accurately capturing the intricate flow dynamics inside a CFB boiler. The meshing tools in ANSYS Fluent are specifically designed to handle complex geometries and allow for the creation of high-resolution grids, which are essential for wall-resolved LES and Wall-Modelled LES (WMLES) approaches. The software's user-friendly interface and comprehensive post-processing tools simplify the analysis and visualization of simulation results, facilitating a deeper understanding of the system's behaviour. However, it is essential to note that ANSYS Fluent simulations require significant computational resources, emphasizing efficient simulation strategies and adequate hardware capabilities.

A. **Solver Fluent**: The Fluent solver in ANSYS Fluent was employed for performing the simulations, carefully considering key parameters such as time behaviour, solver type, and gravitational force. These parameters play a critical role in ensuring the accuracy and efficiency of the simulations and serve as the foundation for effectively modelling the studied physical system.

B. **Energy Model:** The energy model within AN- SYS Fluent was activated to incorporate thermal coefficients, enabling a comprehensive analysis of heat transfer between the fluid and solid phases. This step was essential for accurately capturing the thermal dynamics of the system and gaining deeper insights into heat transfer processes and their impact on the overall system performance.

C. **Viscous Model:** The simulations of the circulating fluidized bed utilized the k-epsilon turbulence model, which is part of the Reynolds-averaged Navier-Stokes (RANS) approach. This model considers the effects of flow curvature, rotation, and turbulence on the flow dynamics within the circulating fluidized bed, allowing for an accurate representation of the fluid flow behaviour during combustion.

D. **Species Transport:** The combustion of fuels, namely olive cake and coal, in the circulating fluidized bed reactor was simulated using ANSYS Fluent by implementing a species transport model. The model was designed to integrate the principles of mass, momentum, and energy conservation equations in both the fluid and solid phases. The model considered a range of chemical reactions, such as devolatilization, char oxidation, and gas-phase combustion. The species transport model considered the migration of distinct species within the reactor and effectively depicted heat transfer between the fluid and solid phases. The accomplishment was attained by utilizing a two-phase heat transfer model and the discrete element method (DEM) to model the particle size distribution. This approach facilitated the simulation of the mobility and impact of solid particles within the circulating fluidized bed reactor.

Pre-Processing & Geometry Design

In this study proposal, the process of simulating the combustion of olive cake in a CFB riser is accomplished by utilizing the geometrical modelling approach. The diameter of the CFB riser is 125 millimetres, and its height is 1800 millimetres. At the very pinnacle of the riser is where you'll find the cyclone, and 370 millimetres above the distributor plate is where you'll find the recycling inlet pipe. A total of 116 holes, each measuring 1 millimetre in diameter, may be found in the distributor plate. It has been determined that the air partition coefficient between primary air and recirculated air is 0.2 Olive cake is the fuel used for this investigation, and it is burned using a bed material consisting of a combination of quartz sand and ash. This study comprehensively examines the fuel qualities of olive cake by conducting proximate analysis, ultimate analysis, and ash composition analysis. Moreover, the quantity of combustible recirculating ash, with an average weight percentage of 8.5, is considered.

Moreover, the particle sizes of the olive cake and the silica sand play a significant role in the combustion process. Olive cake has an average particle diameter of 2.3 millimeters, while silica sand has an average particle diameter of 0.56 millimetres. The cumulative size distributions of the particles are given. The geometric modelling approach can provide realistic simulations of the combustion process in the CFB riser (as shown in Figure) because it considers all of these elements and can accurately simulate emissions and the efficiency of the combustion process.

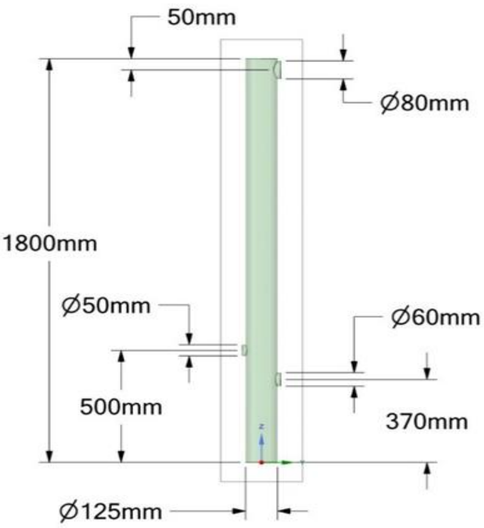

Figure 1. (A) Circulating fluidized

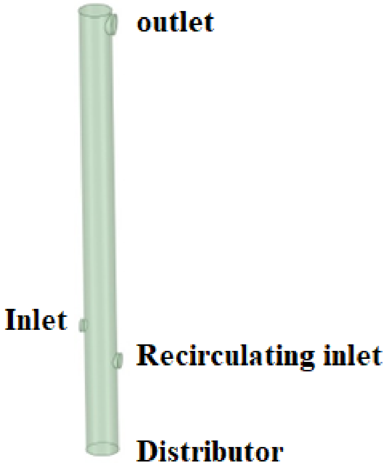

Figure 2. (B) Circulating fluidized

Grid Generation:

The meshing technique involves partitioning a given object for simulation into discrete and more minor elements. The equations for each case about the builder will be resolved in each of these components. The size of the mesh element utilized in the model is a crucial factor in the mesh. Reducing the mesh size in the model has been found to enhance the results' accuracy, albeit at the cost of increased computational power and time. It is imperative to ascertain the precise dimensions of the mesh elements. The process of generating meshes is accomplished through the utilization of ANSYS Mesh. We are employing the tetrahedron method to mesh the geometry of the Circulating Fluidized Bed. Figure 2 displays the quantity of mesh produced near the model.

Grid Quality (Skewness):

The number of elements generated around the surface is kept high so that the details of the combustion phenomenon can be observed along the length of the CFB chamber. The element size is kept equal to 1 mm while the total number of mesh generated is 262,448.

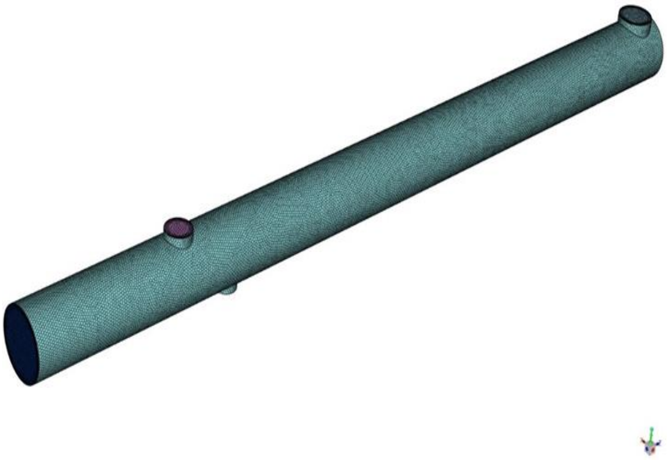

Figure 3. Mesh Generation around the Circulating fluidized bed

Boundary Conditions:

To simulate the process of olive cake combustion in a circulating fluidized bed (CFB) reactor, we used a three-dimensional model in the research paper published, "Three-dimensional modelling of olive cake combustion in CFB. As shown in Figure 4." For the model to faithfully depict the combustion process that occurs in the actual world, we incorporated a variety of boundary conditions. Secondly, we implemented an inlet boundary condition by in- fusing olive cake and bed materials into the CFB reactor at a predetermined flow rate. This was part of our inlet boundary condition. This guaranteed that the olive cake and bed components were dispersed evenly around the reactor's surface.

We used a distributor boundary condition, which fed primary air into the reactor via the distributor plate. This was part of our procedure. The direct air was dispersed uniformly through 116 holes, each with a diameter of 1 millimeter, and the air partition coefficient between the recirculation air and the primary air was adjusted to 0.2. In addition, we implemented a recycle boundary condition so that the recirculation of ash in the CFB reactor would be accurately represented. To ensure that the recirculated ash was distributed evenly throughout the reactor, the recycling inlet pipe was positioned 370 millimeters above the distribution plate.

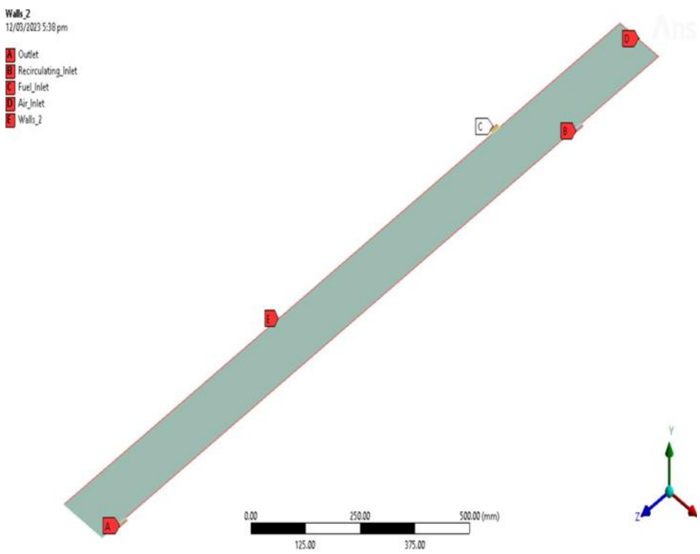

Figure 4. Boundary Conditions Applied

In addition to this, we utilized a wall boundary condition so that we could accurately simulate the CFB reactor's walls. We ensured the wall temperature was constant to imitate the reactor with isothermal walls. In addition, we implemented an out- let boundary condition to symbolize the cyclone at the top of the reactor. This cyclone was responsible for separating the solid particles from the flue gas. The boundary conditions we applied in the three-dimensional model were chosen carefully to precisely mimic the actual combustion process in a CFB reactor in the real world.

Numerical models used for unsteady simulations

firing of coal in Circulating Fluidized Bed (CFB) boilers involves complex, unsteady multiphase flows that can be modelled using Computational Fluid Dynamics (CFD) simulations. These simulations often employ mathematical and numerical models to capture intrinsic dynamics accurately. The equations are presented in the table in the left column, and their respective descriptions or models are provided in the right column.

Incompressible Navier-stokes equation in the LES turbulence model

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\overline{u_i u_j}\right) = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \nu \frac{\partial}{\partial x_j}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right) = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + 2\nu \frac{\partial}{\partial x_j}\bar{S}_{ij},$$

Sub-grid -Scale Model

$$\tau_{ij} - \frac{1}{3}\tau_{kk}\delta_{ij} = -2\mu_t \bar{S}_{ij}$$

Smagorinsky-Lilly model

$$\mu_t = \rho L_s^2 |\bar{S}|$$

Dynamic smagorinsky -lilly model

$$L_{ij} = T_{ij} - \dot{\tau}_{ij} = \overline{\rho \dot{\tilde{u}}_i \tilde{u}_j} - \frac{1}{\bar{\rho}}\left(\overline{\rho \dot{\tilde{u}}_i}\,\overline{\rho \dot{\tilde{u}}_j}\right)$$

Wall adapting local eddy viscosity (Wale) Model

$$S_{ij}^d = \frac{1}{2}\left(\bar{g}_{ij}^2 + \bar{g}_{ji}^2\right) - \frac{1}{3}\delta_{ij}\bar{g}_{kk}^2, \bar{g}_{ij} = \frac{\partial \bar{u}_i}{\partial x_j}$$

Dynamic kinetic energy sub grid -scale model

$$\rho\frac{\partial \bar{k}_{sgs}}{\partial t} + \rho\frac{\partial \bar{u}_j \bar{k}_{sgs}}{\partial x_j} = -\tau_{ij}\frac{\partial \bar{u}_i}{\partial x_j} - C_\varepsilon \rho \frac{k_{sgs}^{3/2}}{\Delta_f} + \frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\sigma_k}\frac{\partial k_{sgs}}{\partial x_j}\right)$$

Combustion Modelling:

The present study considered the validated simulation's parameters and outcomes to precisely simulate the combustion mechanisms of coal and olive cake in the Circulating Fluidized Bed (CFB) technology.

Olive Cake Combustion:

Based on the validated simulation using olive cake as fuel, the following combustion reactions were observed:

A. **Devolatilization:**

The devolatilization process of olive cake results in the release of volatile compounds. The de- volatilization procedure encompasses the thermal degradation of the fuel, leading to the production of gaseous by-products and the creation of char residue. The concept, as mentioned earlier, can be mathematically expressed as follows:

Olive cake (CmHnOx) → Gaseous products (CO, CO2, H2O, hydrocarbons, etc.) + Char residue

B. **Char Oxidation:**

The char residue left after devolatilization under- goes oxidation reactions with oxygen in the CFB system. The primary reaction involves the oxidation of Carbon (C) to form carbon dioxide (CO_2):

$$C + O_2 \rightarrow CO_2$$

A. Secondary Reactions:

During the combustion process, secondary reactions occur, resulting in the formation of various re- actant products such as carbon monoxide (CO), nitrogen oxides (NO_x), hydrogen cyanide (HCN), and hydrogen sulfide (H_2S). These reactions can be rep- resented as follows:

$N_2 + O_2 \rightarrow NO_x$ (various nitrogen oxides) $S + O_2 \rightarrow SO_2$ $2H_2S + 3O_2 \rightarrow 2SO_2 + 2H_2O$ $HCN + O_2 \rightarrow NO + CO + H_2O$

Coal Combustion:

In the subsequent simulation, the fuel source was changed to coal while keeping the boundary conditions consistent. The combustion reactions for coal combustion in the CFB system were as follows:

A. Devolatilization:

Like olive cake, coal undergoes devolatilization, which involves the thermal decomposition of the fuel, leading to the release of volatile compounds and the formation of char residue. The reaction can be represented as:

Coal ($C_xH_yO_z$) → Gaseous products (CO, CO_2, H_2O, hydrocarbons, etc.) + Char residue

B. Char Oxidation:

The char residue reacts with oxygen, resulting in the oxidation of Carbon (C) to form carbon dioxide (CO_2):

$$C + O_2 \rightarrow CO_2$$

C. Secondary Reactions:

Secondary reactions during coal combustion in- volve the formation of nitrogen oxides (NO_x) and sulfur dioxide (SO_2). These reactions can be represented as:

$$N_2 + O_2 \rightarrow NO_x$$

(Various nitrogen oxides) $S + O_2 \rightarrow SO_2$

The combustion model effectively represents the intricate combustion reactions of olive cake and coal within the CFB system. The process of devolatilization results in the liberation of volatile compounds, whereas char oxidation reactions facilitate carbon dioxide generation. Furthermore, secondary chemical processes lead to nitrogen oxides and sulfur dioxide generation. Comprehending the intricate combustion mechanisms is imperative to enhance the efficiency of CFB systems, evaluate the magnitude of emissions, and investigate alternative fuel options. The study's results offer significant contributions to understanding the combustion behaviors of various fuels in the CFB system, thereby promoting the progress of CFB technology and the adoption of renewable and alternative fuel sources. The modelling methods guaranteed that the complicated flow dynamics, heat transfer mechanisms, and chemical reactions associated with coal co-firing in a CFB boiler were accurately represented. The sophisticated features of ANSYS Fluent allowed for a thorough investigation of the system's behavior, shedding light on the interplay between the fluid and solid phases and giving crucial data for future studies for CFB system improvement.

RESULTS AND DISCUSSION

Olive Cake Combustion Validation Model

The validation of the numerical model was based on the paper "Three-dimensional modelling of olive cake combustion in a CFB." The study in the referenced article has been thoroughly reviewed, and it serves as the basis for validating our simulation results of coal combustion. The comparison between the results of our simulation and the referenced paper provides an evaluation of the accuracy and reliability of our simulation model.

Boundary Conditions

The boundary conditions were set as per the parameters mentioned in the previous paper:

1.) Air Inlet: The velocity at the air inlet was set at 1.75m/s, with a temperature of 700°C.

2.) Inlet for Coal Particles: The coal particles' diameter was 2.5 mm, with an inlet velocity of 0.01 m/s. The total mass flow at the inlet was 0.0042 kg/s, with a temperature of 700°C.

3) Inlet for Solid Particles: The diameter of solid particles were set at 0.56 mm, with an inlet velocity of 0.005 m/s. The total mass flow at the inlet was 0.03kg/s, with a temperature of 700°C.

Composition

the terms "Proximate Analysis" and "Ultimate Analysis" are standard forms of characterizing the properties of the fuel, in this case, coal.

Proximate Analysis

1.) Moisture (3.68%): This represents the coal's water content. High moisture content can lead to decreased combustion efficiency due to the energy evaporating the water.
2.) Volatile matter (74.03%): Volatile matter is the material driven off when coal is heated to 950°C without air. This generally includes a range of carbon-rich compounds which, when combusted, contribute significantly to the heat output of the coal.
3.) Fixed Carbon (21.17%): Fixed Carbon is the solid residue that remains after the volatile matter is driven off and after the complete oxidation of the coal. This provides a slow and continuous source of heat during combustion.
4.) Ash (1.12%): This non-combustible residue remains after complete combustion. Ash content can affect combustion efficiency and may cause issues in handling and disposal.

Ultimate Analysis

1. Carbon (C, 51.4%): Carbon is the primary combustible element in coal, contributing most to heat generation during combustion.
2. Hydrogen (H, 5.77%), Nitrogen (N, 0.16%), Sulfur (S, 0.01%): These elements also contribute to the combustion process and the resultant emissions. Nitrogen and sulfur, in particular, are associated with forming pollutants during combustion.
3. Oxygen (O, 37.86%): This represents the oxygen content in the coal itself. It is typically bound in various forms within the coal structure.

The proximate and ultimate analyses are crucial as they provide information on how the coal will be- have during combustion and the expected emissions types.

Turbulence Model

The turbulence model chosen for computational fluid dynamics (CFD) simulations of coal combustion in a circulating fluidized bed (CFB) can significantly impact the accuracy of the results. One of the most commonly used turbulence models in these types of simulations is large eddy simulation (LES), although many other models are also applicable depending on the specific requirements of the simulation. The model is widely used due to its relatively simple computation and reasonable accuracy under a wide range of turbulent flow conditions. However, in situations where there are significant swirls and recirculation, such as in a CFB, a Reynolds Stress Model (RSM) might be preferred. RSM can account for more complex flow patterns but requires more computational power.

Validation of Simulation

The simulation results were then compared with those presented in the referenced paper. This com- parison helps in validating our simulation model. Factors such as temperature distribution, particle concentration, and fluid flow rate were considered during this comparison. The agreement between the simulation results and the experimental data from the paper validated our model. We simulated the combustion process, wherein Olive Cake served as the fuel. The fuel, represented as particles, was injected from an inlet (depicted on the right in the accompanying diagram), initiating the combustion process that produced heat and, thus, elevated temperatures. Following injection, the Olive Cake was transported to a zone where it interacted with an air phase comprising oxygen ($O2$) and nitrogen ($N2$), introduced from an inlet at the bottom of the diagram. This interaction propagated the combustion, leading to further heat generation. During this process, the maximum observed temperature reached 1108.33°C, underlining the significant thermal potential of Olive Cake as a fuel source.

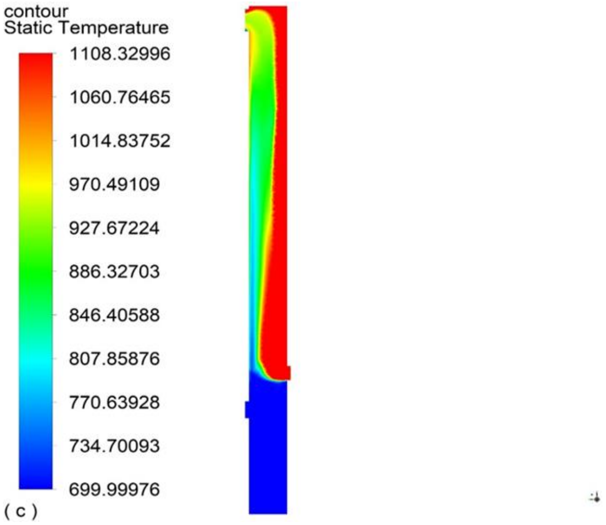

Figure 5. Temperature For Olive-Cake Combustion

Many reactant products are generated during combustion, underpinning the complexities of the chemical reactions involved. These products primarily include carbon monoxide (CO), carbon dioxide ($CO2$), nitric oxide (NO), hydrogen cyanide (HCN), and hydrogen sulfide ($H2S$). The diverse nature of these products highlights the multifaceted chemical dynamics at play during combustion. To further understand these dynamics, we quantitatively examined the mass fraction of each reactant product, providing an insightful representation of the relative contributions of these compounds to the overall combustion process. This analysis offers a nuanced perspective into combustion chemistry, elucidating the significant roles these reactant products play in influencing the energy output and environmental implications of the combustion process.

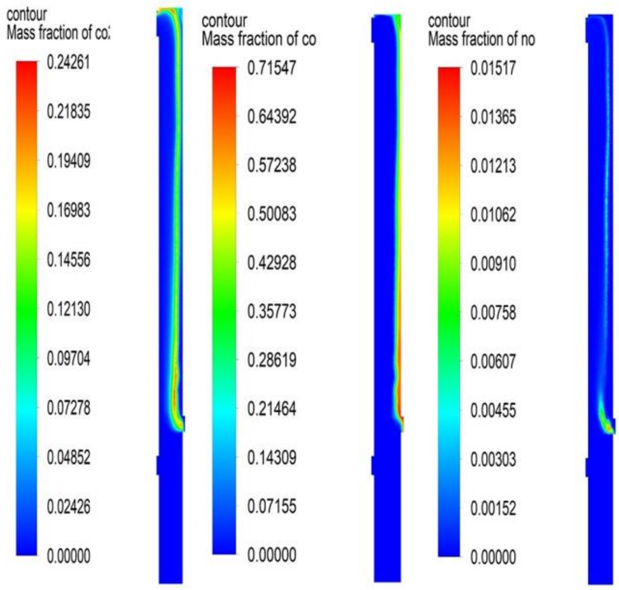

Figure 6. (A) Olive Cake Combustion Process Results

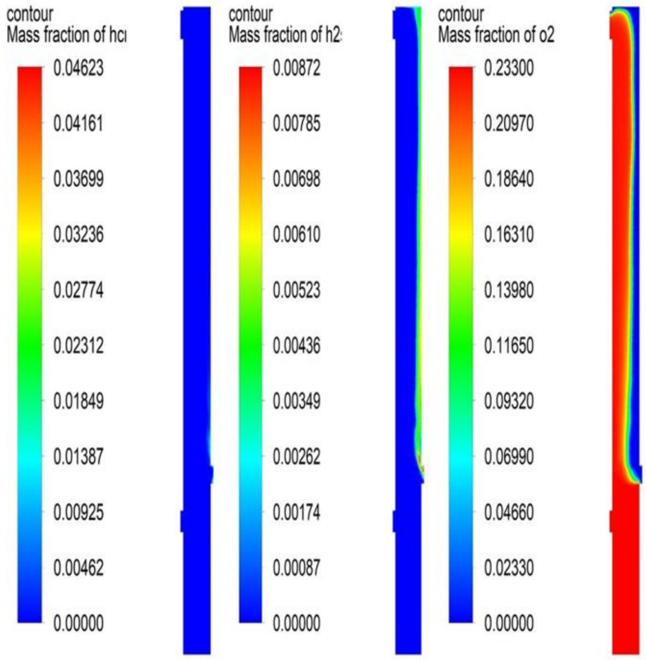

Figure 7. (B) Olive Cake Combustion Process Results

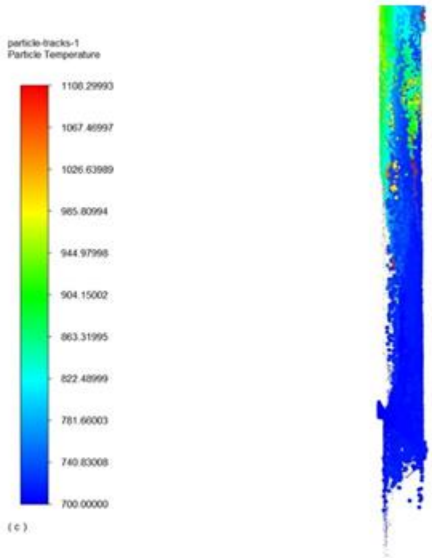

Figure 8. Particle Result

In the subsequent section, we present a graphical representation of temperature variation along the central axis of the combustor, a critical parameter influencing combustion dynamics. The trend indicates an initial increase in temperature at the location where fuel is introduced, reaching a peak indicative of combustion's peak heat release. Subsequently, a decrease in temperature is observed, attributed to the diminishing mole fraction of the fuel, signifying the progressive consumption of the fuel. Furthermore, at the fuel inlet, an observable decrease in the mass fraction of O2 is registered, stemming from the reaction with the injected coal. This reaction's occurrence signifies the conversion of fuel and oxygen into combustion products, a vital aspect of the combustion process. Significantly, the reactions between coal and oxygen produce carbon dioxide (CO2) and carbon monoxide (CO), leading to an uptick in their mass fractions. The observed increase in CO2 and CO underscores the chemical transformations during combustion, further emphasizing the intricate chemical interplay inherent to the process. These findings offer deeper insights into the combustion dynamics, shedding light on the transformative processes fundamental to fuel combustion.

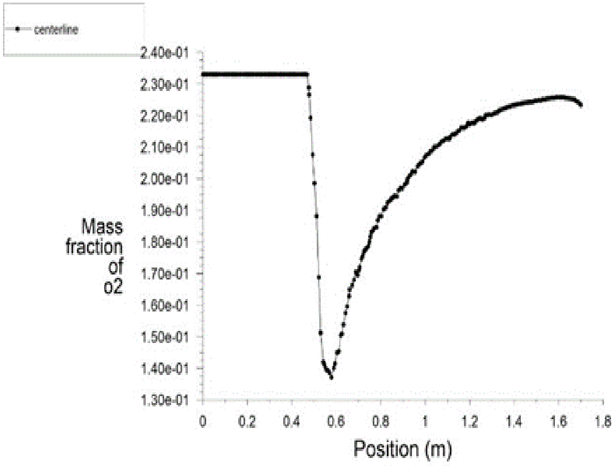

Figure 9. (A) Temperature versus Height of Combustor

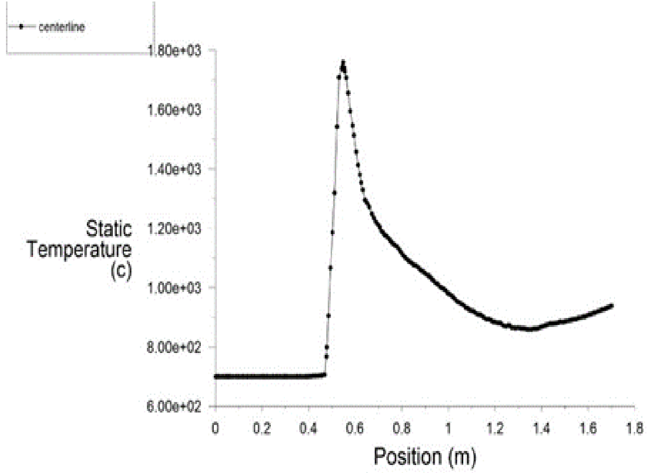

Figure 10. (B) Temperature versus Height of Combustor

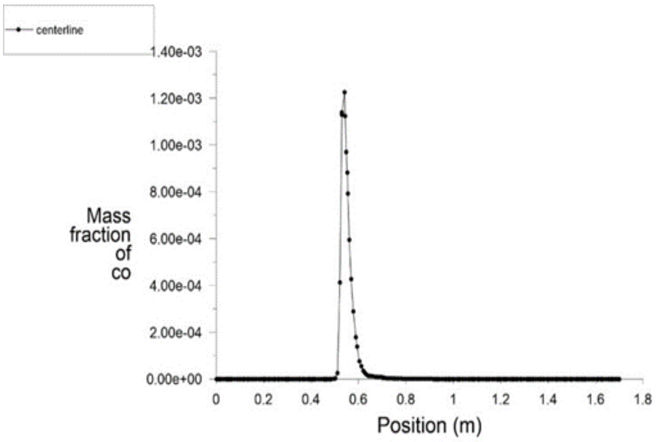

Figure 11. (C) Temperature versus Height of Combustor

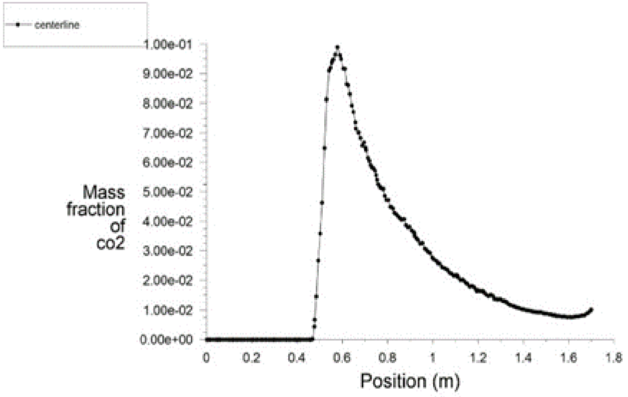

Figure 12. (D) Temperature versus Height of Combustor

Coal Combustion Analysis

Based on the foundation provided by the study "Three-dimensional modelling of olive cake combustion in CFB," the simulation results were subjected to the following boundary conditions. The air inlet was characterized by a velocity of 1.75 m/s and a temperature of 700 degrees Celsius. The coal particles, substituted for the olive cake particles, had a diameter of 2.5 mm, a velocity of 0.01 m/s, a total mass flow of 0.0042 kg/s, and the same inlet temperature of 700 degrees Celsius. Additionally, the model includes solid particles with a diameter of 0.56mm, a velocity of 0.005 m/s, a total mass flow of 0.003 kg/s, and the same inlet temperature. The boundary conditions remained constant throughout the simulations, while the coal's composition was adjusted according to the Proximate and Ultimate analysis data obtained from the study "Transient simulation of biomass combustion in a circulating fluidized bed riser". The Proximate analysis of the coal reveals a moisture content of 3.68%, volatile matter content of 74.03%, fixed carbon content of 21.17%, and ash content of 1.12%. The Ultimate analysis indicates that the coal contains Carbon (C) at 51.4%, Hydrogen (H) at 5.77%, Nitrogen (N) at 0.16%, Sulfur (S) at 0.01%, and Oxygen (O) at 37.86%. These simulations, considering coal as a replacement for olive cake, have been carried out to model the behavior of coal combustion under conditions that mimic real-world operating parameters. The insights from these results will improve our understanding of coal's performance in a circulating fluidized bed combustor and help optimize conditions for efficient and sustainable energy pro- duction. With all other boundary conditions held constant, the transition from olive cake to coal as fuel profoundly impacts the combustion process and the resultant temperature within the combustion chamber. Coal, due to its unique composition and physical characteristics, modify the combustion dynamics leading to a different thermal behavior compared to that of olive cake. The maximum temperature achieved during coal combustion as fuel was observed to be 1500.12 degrees Celsius. This elevated temperature, as compared to olive cake, signifies coal's higher calorific value and its more significant potential for energy generation in a combustion process within a circulating fluidized bed system. The observed temperature shift corroborates that the type of fuel used plays a crucial role in determining the combustion characteristics and the efficiency of energy conversion process.

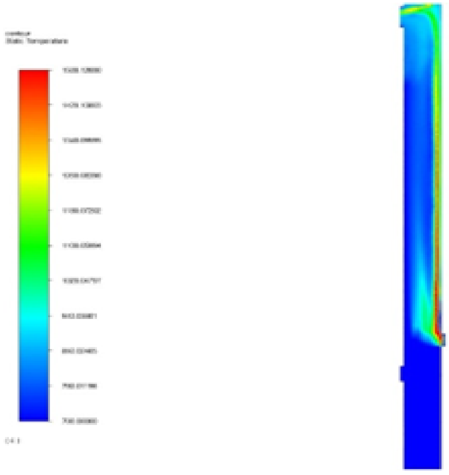

Figure 13. Temperature for Coal Combustion

The switch to coal as the primary fuel source significantly alters the resulting reactant products of the combustion process. The direct combustion products when coal is used as a fuel include carbon dioxide (CO_2), carbon monoxide (CO), hydrogen sulfide (H_2S), and oxygen (O_2). CO_2, the primary by-product of complete combustion, is prevalent due to the high carbon content of coal. Its presence indicates efficient combustion, as it suggests that the Carbon in the coal is being fully oxidized. CO is typically produced during incomplete combustion when insufficient oxygen prevents the complete oxidation of Carbon. Its presence could signify suboptimal combustion conditions or areas within the reactor with limited access to oxygen. H_2S, while a minor product, can be produced due to sulfur impurities in coal. Its generation is a critical consideration due to its toxicity and its contribution to the formation of acid rain. Lastly, O_2 presence in the products signifies extra oxygen after the combustion process, indicating that combustion may not be stoichiometric and suggesting opportunities for further optimization to improve combustion efficiency. The composition and concentrations of these reactant products provide essential insights into the combustion efficiency, environmental im- pact, and potential improvements for the combustion process when using coal as a fuel in a circulating fluidized bed system.

In the case of coal combustion, the temperature profiles across the height of the combustor would be comparable to those of olive cake combustion but will vary notably due to the different combustion characteristics of coal. Similar to the olive cake combustion process, upon introducing coal at the fuel inlet, there is a noticeable increase in temperature due to the onset of combustion. The temperature rises along the centerline of the combustor, reaching a maximum at the region where the coal particles are fully engaged in combustion reactions. However, this peak temperature for coal combustion is higher than that for olive cake. The maximum temperature reaches approximately 1500.12°C when using coal as a fuel, compared to 1108.33°C for olive cake.

This discrepancy is at attributable to coal's higher energy content or calorific value than olive cake. Following the peak, there is a decrease in temperature as the combustion process progresses upwards in the combustor.

This decrease is due to the gradual depletion of fuel as coal is consumed, similar to the trend observed with olive cake. At the coal fuel inlet, the mass fraction of O2 decreases due to the combustion reaction. Simultaneously, combustion products such as CO2 and CO are formed, causing an increase in their mass fractions. This trend mirrors the phenomena seen in olive cake combustion, although the specific quantities and ratios of the reactant products differ due to the differing compositions of coal and olive cake. This temperature profile is a vital characteristic of the combustion process and provides crucial information on combustion efficiency, heat transfer characteristics, and potential optimizations for coal combustion in a circulating fluidized bed system.

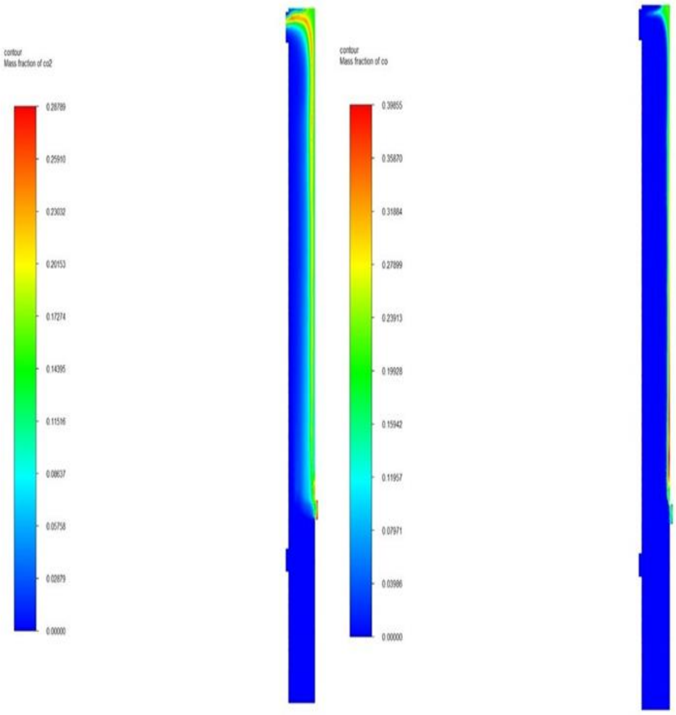

Figure 14. (A) Coal Reactor Results

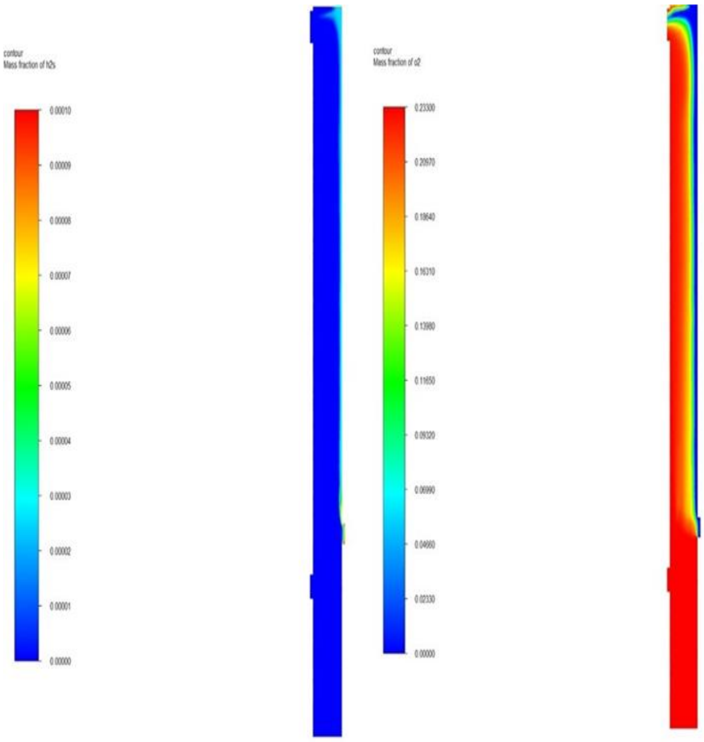

Figure 15. (B) Coal Reactor Results

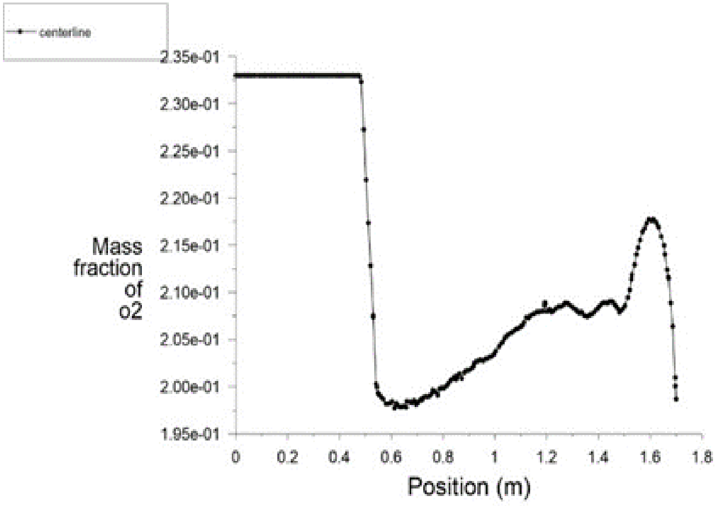

Figure 16. (A) Temperature versus Height of Combustor

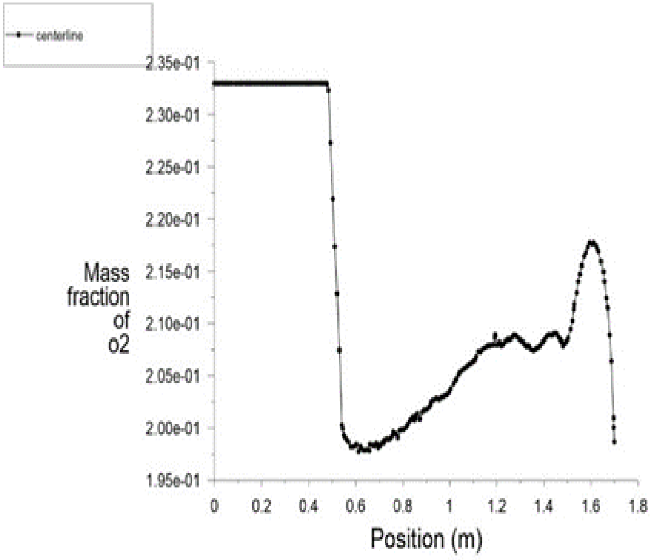

Figure 17. (B) Temperature versus Height of Combustor

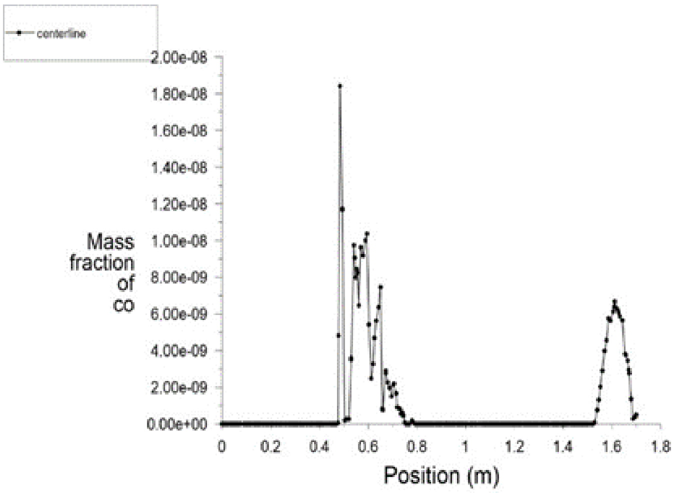

Figure 18. (C) Temperature versus Height of Combustor

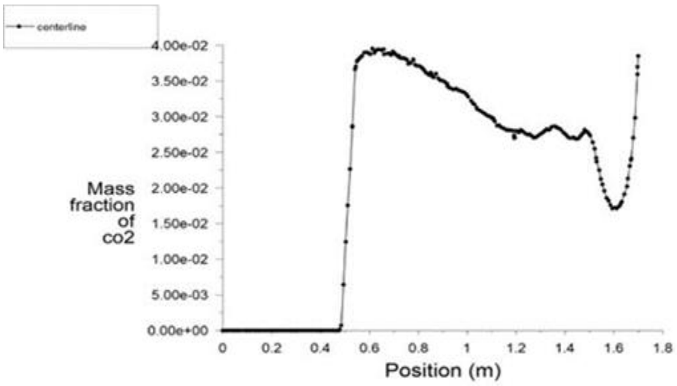

Figure 19. (D) Temperature versus Height of Combustor

The temperature-height graph in the research paper reveals essential insights into the reactor's behaviour during the combustion process. Initially, from 0 to 0.5 m in height, the temperature remains constant at 700◦C, which is the inlet air temperature. No reaction occurs at this stage, resulting in unchanged reactants and products, including 23% oxygen, 0% CO2, and 0% CO. Between 0.5 and 0.7 m height, a sudden increase in temperature occurs, peaking around 1000◦C. This temperature surge is attributed to the combustion reaction facilitated by the injection of coal fuel. As the fuel reacts with air, a combustion reaction occurs, leading to significant changes in reactants and products.

The mass fraction of oxygen reduces to 19.8%, indicating its consumption in the combustion process. Meanwhile, the mass fractions of CO2 and CO increase to approximately 4% and insignificantly, respectively. From 0.7 to 1.2 m height, the reac- tor temperature decreases to 800◦C, primarily due to residual fuel combustion. This temperature de- cline impacts the composition of reactants and prod- ucts, with the mass fraction of oxygen increasing to around 21%, as less oxygen is required for combustion. The mass fraction of CO2 decreases to about 3% due to reduced combustion, while the mass fraction of CO remains at 0%. Between 1.2 and 1.8 m in height, the reactor temperature rises to 900℃, at- tributed to the compressed airflow near the top of the reactor before reaching the outlet gate. This temperature increase influences the composition of reactants and products, which varies based on the concentration of substances at the upper end of the reactor. The research simulations' olive cake and coal combustion results provide a comparative analysis of their combustion characteristics in a circulating fluidized bed (CFB) setup.

For the olive cake combustion, temperature profiles within the combustor showcased increased temperature where the fuel was introduced, peaking at 1108.33◦C. This was followed by a gradual decrease due to the reduction in fuel mass fraction. The composition of the reactant products included CO, CO2, NO, HCN, and H2S. The energy content of the olive cake determined the maximum temperature reached during the combustion process.

In contrast, the combustion characteristics of coal showed different dynamics. Maintaining the same boundary conditions as with the olive cake, the switch to coal as a fuel resulted in a higher peak temperature of 1500.12◦C due to coal's higher calorific value. The combustion process also led to a decrease in oxygen mass fraction at the fuel inlet and an increase in the mass fractions of CO2 and CO. Both simulations indicated an initial rise in temperature due to combustion onset, reaching a peak and then declining due to fuel depletion. However, the different coal and olive cake compositions led to variations in the maximum temperatures and the composition of the produced gases. In summary, the simulations highlight the characteristic combustion behaviors of olive cake and coal in a CFB context. These insights are invaluable in understanding the efficiency, emissions, and potential optimizations for different fuel types in circulating fluidized bed combustion systems.

CONCLUSIONS AND RECOMMENDATIONS

The research on olive cake and coal combustion in CFB boilers may draw several significant conclusions. The preliminary results showed that olive cake combustion (1108.33˚C) and coal combustion (1500.12˚C) significantly increased temperature. Combustion reactant products such as carbon dioxide (CO2), carbon monoxide (CO), hydrogen sulfide (H2S), and oxygen (O2) displayed various behaviours and changes depending on the fuel type. The composition analysis provided vital information about the coal's moisture, volatile matter, fixed Carbon, and ash content, revealing both its proximal and final analyses.

The results of this work have significant consequences for advancing computational fluid dynamics (CFD) models of CFB boilers and hence for the future of this field of study. To improve CFB systems' combustion efficiency and emissions control, researchers may use the measured temperature profiles and reactant product patterns as a starting point. Turbulence models, such as the Reynolds Stress Model (RSM), should be improved in future research to better describe the complicated flow dynamics inside CFB boilers. To further improve simulation accuracy, considering the turbulence-chemistry interaction during combustion using more extensive chemistry models, such as the Eddy Dissipation Model (EDM) or Eddy Dissipation Concept (EDC), is recommended.

Recommendations for better combustion: The research provides various suggestions for bettering the combustion process in CFB boilers. The input's air velocity, temperature, and fuel particle characteristics must be precisely controlled to produce the required temperature profiles and distributions of the reactant products. The results show that playing with these variables may affect how well a combustion system works. This research also emphasizes the significance of fuel composition analyses, as differences in fuel moisture, volatile matter, fixed Carbon, and ash concentration may all affect how the fuel burns. This data may direct fuel selection and preparation to maximize combustion efficiency and reduce emissions. To boost CFB boiler performance, further study is needed to uncover cutting- edge control systems and optimization methodology gives that use the data provided by CFD modelling.

As a result of this research, we now know more about how coal and olive cake burn in CFB boilers. The results provide light on the implications of fuel mix, temperature profiles and distributions of reac- tant products. These results may serve as a foun- dation for further study to improve turbulence models, including more sophisticated chemistry models, and design more effective techniques for enhancing CFB boilers' combustion efficiency.

References

[1] Circulating Fluidized Bed Combustion: A Re- view of Technology and Applications, *Energy & Fuels*, **2011**, 25, 11, 5541–5558.

[2] The Potential of Circulating Fluidized Bed Combustion for Power Generation, *Journal of the Air & Waste Management Association*,**2008**, 58, 11, 1325–1335.

[3] Krzywanski, J., et al., Modelling of SO2 and NOx Emissions from Coal and Biomass Com- bustion in Air-Firing, Oxyfuel, iG-CLC, and CLOU Conditions by Fuzzy Logic Approach, Energies, 2022, 15, 21, 8095–8095.

[4] Abdelmotalib, H. M., Youssef, M. A., Hassan, A. A., Youn, S. B., and Im, I. T., Heat transfer process in gas-solid fluidized bed combustors: A review, International Journal of Heat and Mass Transfer, 2015, 89, 567–575.

[5] Nussbaumer, T., Combustion and co-combustion of biomass: fundamentals, technologies, and primary measures for emission reduction, Energy & fuels, 2003, 17, 6, 1510–1521.

[6] Mohsenian, H. and Ghiasi, N., Modeling and simulation of an industrial combustion reactor using computational fluid dynamics, Int. J. En- viron. Sci. Technol, 2023, 20, 1247–1258.

[7] Ghose, P., Sahoo, T. K., and Sahu, A. K., Pul- verized coal combustion computational mod- eling approach: A review, Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 2023, 237, 4, 797–818.

[8] Alobaid, F., Kuhn, A., Nguyen, N. M., Johnen, B., Peters, J., and Epple, B., Numerical and experimental study of co-combustion of refuse-derived fuels in a circulating fluidized bed during load change, Frontiers in Energy Research, 1188.

[9] Zhakupov, D., Kulmukanova, L., and Sar- bassov, Y., Flue gas analysis for biomass and coal co-firing in fluidized bed: process simu- lation and validation, Int J Coal Sci Technol, 2022, 9, 59–59.

[10] Sakolaree, P., Rattanaphaibun, K., Sukhanon- sawas, W., and Sukjai, Y., Numerical simu- lation and experimental validation of pulver- ized coal combustion by using CFD, AIP Con- ference Proceedings, 2022, 2610, 70009– 70009.

[11] Pan, R., Wang, X., Chao, J., Jia, H., and

Shen, H., Analysis of the Coal Spontaneous Combustion Risk Space Evolution in the Goaf Un- der Ventilation and Extraction Coupling, Com- bustion Science and Technology, 2022, 1–19.

[12] Kumar, P., Parwani, A. K., and Vitankar, V., Multiphase Computational Fluid Dynam- ics Simulation of Air and Fuel Reactors of Chemical Looping Combustion, Heat Trans- fer Engineering, 2022, 1–13.

[13] Deonarine, A., Schwartz, G. E., and Ruhl, L. S., Environmental Impacts of Coal Combustion Residuals: Current Understanding and Future Perspectives, Environmental Science & Technology, 2023, 57, 5, 1855–1869.

[14] Zhao, D., et al., Tendencies of research and development in resources chemicals and materials-Summarization of a Youth’s topic forum, Resources Chemicals and Materials, 2023.

[15] Xu, S., Yu, D., Yao, F., and Wang, K., Numerical simulation and optimisation of CFB boiler furnace with air staged low NOx com- bustion. Progress in Computational Fluid Dy- namics, an International Journal, 2022, 22, 6, 392–410.

[16] Panchigar, D., Kar, K., and Shukla, S., Machine learning-based CFD simulations: a re- view, models, open threats, and future tactics, Neural Comput & Applic, 2022, 34, 21677– 21700.

[17] Deng, B., Zhang, Y., and Yang, H., Operation Optimization of Circulating Fluidized Bed Boilers Integration of Variable Renew- ables, Energies, 2022, 15, 16, 6007–6007.

[18] Çam, M. M., Soyhan, H. S., Qubeissi, M., and Çelik, C., Designing a new bell-type pri- mary air nozzle for large-scale circulating flu- idized bed boilers, Fuel, 2023, 335, 127065– 127065.