

# Review of Numerical Simulation of Biomass Combustion and Heat Transfer in Fixed-Bed Furnaces Using CFD

Arpit Suryavanshi<sup>1</sup>; Dr. Parag Mishra<sup>2</sup>; Bhagwat Dwivedi<sup>3</sup>

M. Tech Scholar<sup>1</sup>; Professor and Head<sup>2</sup>; Assistant Professor<sup>3</sup>

<sup>1,2,3</sup>Department of Mechanical Engineering, Radharaman Institute of Technology and Science, Bhopal India

Publication Date: 2026/06/15

**Abstract:** Biomass combustion in fixed-bed furnaces has emerged as a reliable and sustainable technology for thermal energy generation, particularly in small- to medium-scale applications. Due to the complex interaction of chemical reactions, fluid flow, and heat transfer, experimental investigation alone is often insufficient to fully understand furnace performance. Computational Fluid Dynamics (CFD) has therefore become an essential tool for analyzing biomass combustion behavior and optimizing furnace design and operating conditions. This review paper presents a comprehensive assessment of numerical studies related to biomass combustion and heat transfer in fixed-bed furnaces. Emphasis is placed on combustion modeling approaches, Porous media treatment of biomass beds, turbulence and radiation models, parametric investigations, and performance evaluation techniques. Key findings, modeling challenges, and future research directions are also discussed to provide a consolidated reference for researchers and postgraduate students working in the field of biomass energy systems.

**Keywords:** Biomass Combustion, Fixed-Bed Furnace, Computational Fluid Dynamics, Heat Transfer, Porous Media, Renewable Energy.

**How to Cite:** Arpit Suryavanshi; Dr. Parag Mishra; Bhagwat Dwivedi (2026) Review of Numerical Simulation of Biomass Combustion and Heat Transfer in Fixed-Bed Furnaces Using CFD. *International Journal of Innovative Science and Research Technology*, 11(4), 5092-5097. <https://doi.org/10.38124/ijisrt/26apr902>

## I. INTRODUCTION

The increasing global demand for energy, along with growing environmental concerns and the depletion of conventional fossil fuels, has accelerated the transition toward sustainable and renewable energy sources. Among these alternatives, biomass energy has emerged as a promising solution due to its carbon-neutral characteristics, wide availability, and suitability for decentralized energy generation, particularly in rural and semi-urban regions.

Biomass combustion is one of the most mature and widely implemented technologies for thermal energy production. It is extensively used in applications such as industrial process heating, power generation, and domestic energy systems. Among various combustion technologies, fixed-bed furnaces are widely preferred because of their simple construction, low operational cost, fuel flexibility, and ease of operation. These systems are particularly suitable for utilizing agricultural residues such as rice husk, wood chips, and other lignocellulosic biomass materials.

A fixed-bed furnace operates based on the controlled combustion of solid biomass arranged as a stationary bed over a grate. The combustion process occurs in a sequence of distinct thermochemical zones, including drying, devolatilization (pyrolysis), oxidation, and reduction. Initially, moisture present in the biomass is removed in the drying zone. This is followed by devolatilization, where volatile gases are released and combusted above the fuel bed. The remaining solid char undergoes oxidation, producing a significant portion of heat, while reduction reactions may occur in lower regions of the bed. These combustion stages and their interactions are illustrated in Fig. 1.

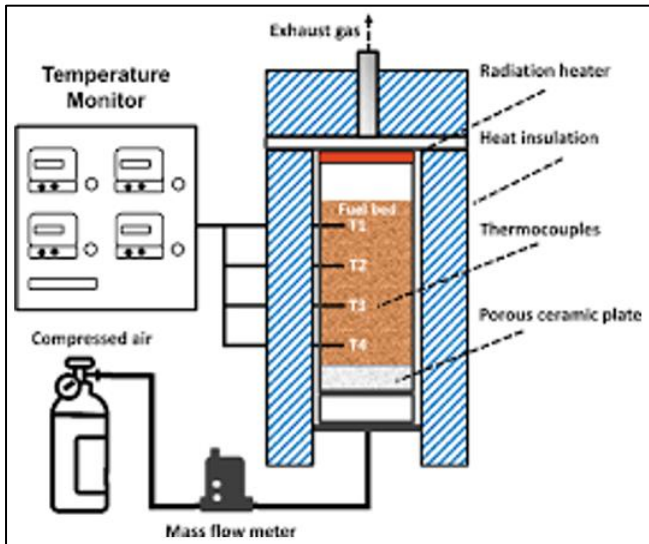


Fig 1 Process of Fixed-Bed Combustion [1]

In addition to the combustion mechanism, the overall configuration of the biomass combustor plays a crucial role in determining performance characteristics such as airflow

distribution, mixing behavior, and heat transfer efficiency. A typical fixed-bed biomass combustor consists of a fuel bed, primary air supply system (introduced below the grate), secondary air injection (above the bed), combustion chamber, and exhaust outlet. The schematic representation of such a system, along with instrumentation and flow pathways, is shown in Fig. 2. This configuration governs the interaction between air and fuel, influencing combustion stability, temperature distribution, and heat transfer to furnace walls.

Despite their operational simplicity, the combustion process in fixed-bed furnaces is highly complex due to the coupling of multiple physical and chemical phenomena. These include moisture evaporation, thermal decomposition, heterogeneous and homogeneous chemical reactions, turbulent fluid flow, species transport, and combined modes of heat transfer such as conduction, convection, and radiation. The interaction of these processes results in highly non-uniform temperature, velocity, and concentration fields within the furnace, making accurate prediction and optimization challenging through experimental approaches alone.

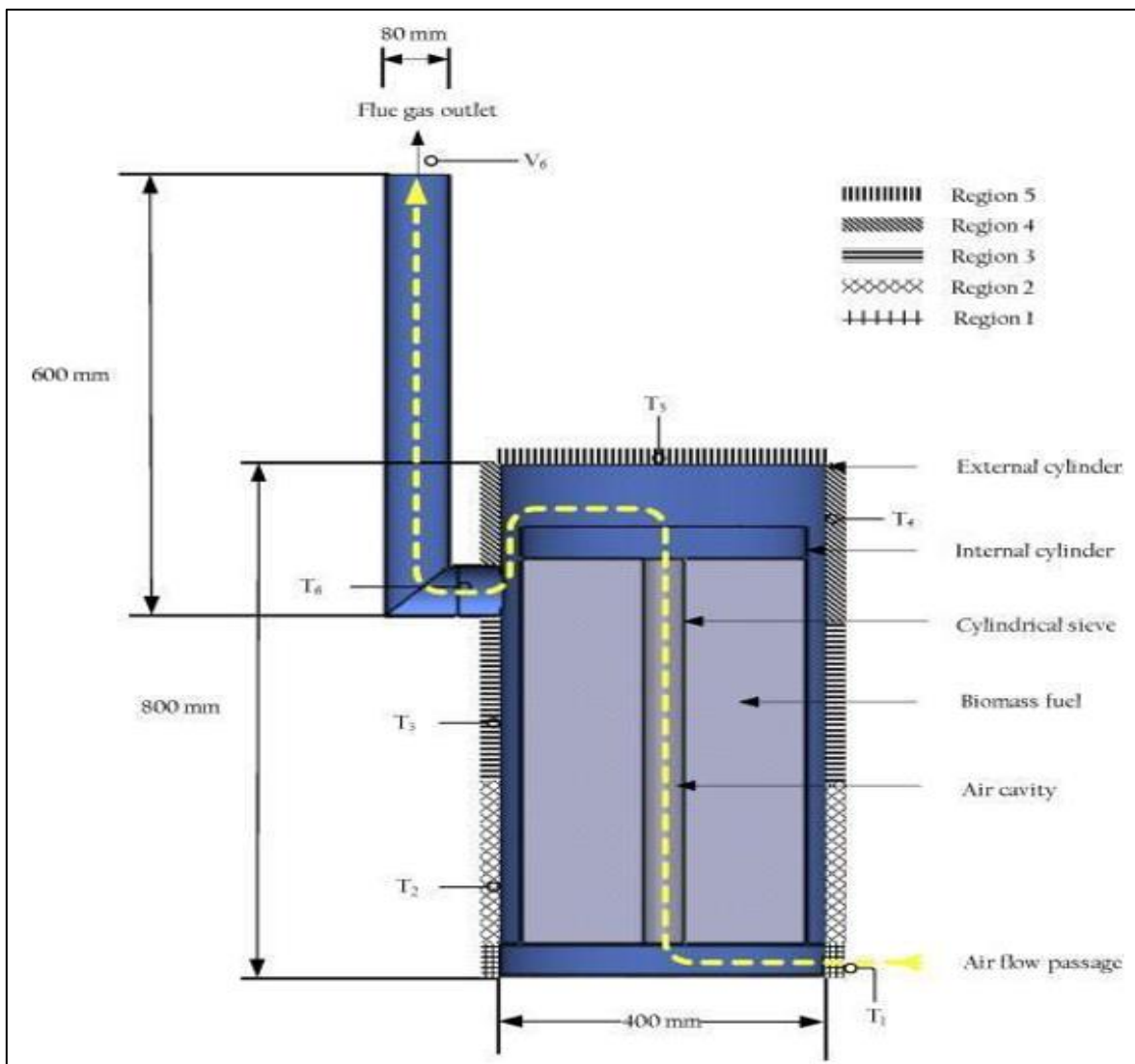


Fig 2 Schematic Representation of Biomass Combustor and Instrumentation Setup [2]

In this context, Computational Fluid Dynamics (CFD) has emerged as a powerful and cost-effective tool for analyzing biomass combustion systems. CFD enables detailed visualization and prediction of internal flow structures, temperature fields, species concentration, and heat transfer mechanisms. It allows researchers to perform parametric studies, evaluate design modifications, and optimize operating conditions without the need for extensive experimental setups.

Over the past decade, numerous CFD-based studies have been conducted to investigate biomass combustion in fixed-bed furnaces. These studies have focused on combustion modelling techniques, turbulence modelling, porous media representation of biomass beds, radiation heat transfer modelling, and the influence of operating parameters such as air velocity, equivalence ratio, and fuel properties.

The primary objective of this review paper is to systematically analyze and synthesize existing numerical studies on biomass combustion and heat transfer in fixed-bed furnaces. The paper aims to identify commonly used modelling approaches, evaluate their effectiveness, highlight key findings, and discuss current challenges and research gaps. Additionally, future research directions are proposed to support further advancements in the design and optimization of biomass-based thermal energy systems.

## II. LITERATURE REVIEW

Over the past decade, significant research has been carried out to understand biomass combustion and heat transfer in fixed-bed furnaces using Computational Fluid Dynamics (CFD). These studies focus on modeling combustion behavior, analyzing heat transfer mechanisms, and evaluating the influence of key operating parameters such as air supply, fuel properties, and furnace configuration. Researchers have employed various numerical approaches, including simplified reaction mechanisms, porous media modeling, and different turbulence and radiation models, to improve prediction accuracy while maintaining computational efficiency. The following section presents a systematic review of relevant studies, arranged chronologically to highlight the evolution of research and key advancements in the field.

Khan et al. [3], 2023, evaluated thermal efficiency based on energy balance analysis. The study showed that efficiency increases with optimized air–fuel ratio and proper operating conditions. The authors emphasized that performance evaluation using efficiency metrics is essential for assessing furnace design and operation.

Patel et al. [4], 2022 numerically investigated the combustion behavior of agricultural biomass residues, particularly rice husk, in a fixed-bed furnace. The study evaluated the influence of moisture content and airflow rate on temperature distribution and heat release rate. Results showed that higher moisture content significantly reduces combustion efficiency by lowering peak temperature and delaying ignition. The authors recommended pre-drying of

biomass to enhance combustion performance and highlighted the importance of fuel properties in numerical modeling.

Brown et al. [5], 2022 compared different turbulence models, including standard  $k-\epsilon$  and realizable  $k-\epsilon$  models, for predicting combustion behavior. Both models showed similar trends; however, the realizable  $k-\epsilon$  model provided better accuracy in regions with strong recirculation and mixing. The study concluded that relatively simple turbulence models are sufficient for steady-state simulations.

Verma et al. [6], 2022 investigated the effect of secondary air injection on combustion performance. The introduction of secondary air enhanced volatile oxidation, improved temperature uniformity, and reduced unburned fuel regions. The study demonstrated that secondary air injection is an effective technique for improving combustion efficiency without significant design changes.

Park et al. [7], 2022 compared P-1 and DO radiation models under identical conditions. The DO model provided more accurate prediction of radiative heat transfer, particularly at high temperatures, while the P-1 model required less computational effort. The authors recommended selecting the radiation model based on the trade-off between accuracy and computational cost.

Das et al. [8], 2022 analyzed the effect of biomass bed height on combustion efficiency. The results showed that increasing bed height enhances heat release up to an optimal value, beyond which oxygen limitation leads to incomplete combustion. The study reinforces the importance of optimizing fuel bed geometry.

Müller et al. [9], 2022 examined gas flow patterns and recirculation zones within the furnace. The presence of recirculation improved mixing between air and fuel gases, leading to enhanced combustion efficiency. The study highlights the importance of flow field optimization in furnace design.

Rao et al. [10], 2021 studied the influence of air inlet configuration on combustion efficiency and flow behavior. Different inlet angles and positions were analyzed to evaluate their impact on mixing and temperature distribution. The results showed that optimized inlet configurations significantly improved airflow uniformity, enhanced mixing, and reduced temperature gradients. The study demonstrated that even minor design modifications in air supply systems can lead to substantial improvements in furnace performance.

Chen et al. [11], 2021 performed a transient CFD analysis to investigate the dynamic behavior of biomass combustion during ignition and shutdown phases. The study revealed rapid temperature rise during ignition and significant thermal gradients within the furnace. Although steady-state simulations are commonly used, the authors emphasized that transient analysis provides deeper insight into operational behavior and is essential for understanding startup and shutdown processes.

Gomez et al. [12], 2021 conducted a numerical study focusing on temperature uniformity and heat transfer efficiency using a porous media approach combined with the Discrete Ordinates (DO) radiation model. The study analyzed airflow rates, temperature fields, and wall heat flux. Results showed that optimized airflow improved temperature uniformity and minimized localized hot spots, which are critical for enhancing efficiency and prolonging furnace lifespan.

Ahmed et al. [13], 2021 examined the effect of inlet air temperature on combustion characteristics. The results indicated that preheated air enhances ignition, increases peak temperature, and improves overall heat transfer. However, excessively high inlet temperatures resulted in increased exhaust heat losses. The study emphasized the need for optimizing inlet air temperature to balance efficiency and energy losses.

Liu et al. [14], 2021 investigated the effect of biomass particle size by modifying porosity and permeability parameters in the porous media model. Smaller particle sizes increased surface area, leading to higher combustion rates and heat release. However, very fine particles caused higher pressure drop and flow resistance. The study highlighted the importance of selecting an optimal particle size for stable combustion and efficient heat transfer.

Sharma et al. [15], 2021 analyzed heat loss mechanisms in biomass furnaces, including wall losses, exhaust losses, and radiative losses. The results indicated that wall heat losses constitute a significant portion of total energy loss, particularly at high operating temperatures. The authors suggested improved insulation and optimized operating conditions to enhance overall system efficiency.

Fernandez et al. [16], 2020 developed a simplified CFD model for small-scale biomass furnaces with a focus on computational efficiency and model robustness. A global reaction mechanism was used to represent biomass combustion processes. The results showed good agreement with experimental trends for temperature distribution and heat output, demonstrating that simplified models can provide reliable predictions for preliminary design and academic research. The study supports the use of reduced-order models in situations where computational resources are limited.

Singh et al. [17], 2020 examined the effect of equivalence ratio on combustion performance by varying conditions from fuel-lean to fuel-rich regimes. The study found that near-stoichiometric conditions produced maximum temperature and highest thermal efficiency due to optimal air-fuel mixing. In contrast, fuel-rich conditions resulted in incomplete combustion, while fuel-lean conditions caused excessive heat loss. The authors identified equivalence ratio as a critical parameter for controlling combustion efficiency in fixed-bed systems.

Wang et al. [18], 2020 investigated wall heat flux distribution along the height of a biomass-fired furnace using

CFD simulations. The study revealed a non-uniform heat flux profile, with peak values occurring near the volatile combustion zone. This variation was attributed to changes in combustion intensity and gas temperature along the furnace height. The findings highlight the importance of accurate heat flux prediction for thermal design, material selection, and structural safety of furnace components.

Zhang et al. [19], 2019 investigated heat transfer characteristics in a biomass-fired fixed-bed furnace using a porous media approach to represent the fuel bed. The study incorporated the P-1 radiation model to account for high-temperature radiative heat transfer. The influence of biomass bed height on temperature distribution and wall heat flux was examined. Results showed that increasing bed height enhanced peak temperature and radiative heat transfer; however, excessive bed thickness resulted in oxygen deficiency and incomplete combustion. The study highlighted the trade-off between fuel loading and air supply in achieving efficient furnace performance.

Kumar et al. [20], 2019 analyzed the effect of air staging on combustion performance using a steady-state CFD model incorporating mass, momentum, energy, and species transport equations. The study demonstrated that proper distribution of primary and secondary air significantly improves volatile combustion and enhances mixing within the furnace. This leads to reduced temperature gradients and increased heat transfer rates at furnace walls. The authors concluded that air staging is an effective operational strategy for improving combustion efficiency without requiring major design modifications.

Li et al. [21], 2019 performed a comprehensive analysis of heat transfer mechanisms in biomass combustion systems, focusing on the relative contributions of conduction, convection, and radiation. The study revealed that radiation is the dominant mode of heat transfer at high temperatures, contributing more than 60% of total heat transfer to furnace walls. Convective heat transfer was found to be significant near air inlet regions due to higher gas velocities. The authors emphasized that neglecting radiation effects in CFD models can result in significant underprediction of wall heat flux and temperature distribution.

Smith et al. [22], 2018 conducted a detailed CFD-based numerical investigation of biomass combustion in a fixed-bed furnace, focusing on the interaction between airflow, combustion reactions, and heat transfer. A simplified single-step reaction mechanism was employed to reduce computational cost while maintaining reasonable accuracy. The study analyzed temperature contours, velocity fields, and heat flux distributions under varying air inlet velocities. Results indicated that increasing airflow enhanced combustion intensity and mixing; however, excessive air velocity led to increased heat loss through exhaust gases. The authors emphasized the importance of optimizing airflow conditions to achieve uniform temperature distribution and improved thermal efficiency.

The reviewed literature clearly demonstrates that Computational Fluid Dynamics (CFD) has become an indispensable tool for analyzing biomass combustion and heat transfer in fixed-bed furnaces. Most studies adopt simplified combustion models and porous media approaches to balance computational efficiency with predictive accuracy. Key parameters such as air–fuel ratio, biomass bed height, airflow configuration, and fuel properties have been consistently identified as critical factors influencing combustion efficiency, temperature distribution, and heat transfer characteristics. Furthermore, radiation has been recognized as the dominant mode of heat transfer at high temperatures, emphasizing the need for accurate radiation modeling.

Despite significant advancements, several limitations remain, including simplified reaction mechanisms, limited consideration of transient behavior, and challenges in accurately representing biomass heterogeneity and ash formation. These gaps highlight the need for more advanced and integrated modeling approaches. Overall, the literature indicates a clear trend toward improving model accuracy while maintaining computational feasibility, providing a strong foundation for further research and optimization of biomass-based thermal systems.

### III. PROPOSED METHODOLOGY

To investigate biomass combustion and heat transfer characteristics in a fixed-bed furnace, a Computational Fluid Dynamics (CFD)-based numerical framework is adopted. The methodology is designed to capture the essential physical and chemical processes involved in combustion while maintaining computational efficiency through appropriate modeling assumptions. The approach integrates simplified reaction mechanisms, porous media representation of the biomass bed, and standard turbulence and radiation models to simulate the furnace behavior under varying operating conditions.

#### ➤ Objective

The main objectives of the present study are:

- To analyze biomass combustion and heat transfer characteristics in a fixed-bed furnace using a CFD-based approach
- To evaluate the effect of key operating parameters such as air inlet velocity, biomass bed height, and equivalence ratio on furnace performance
- To investigate temperature distribution, flow behavior, and wall heat flux within the combustion chamber
- To assess the influence of porous media representation of the biomass bed on airflow and heat transfer characteristics
- To examine the effectiveness of simplified combustion modeling techniques, including single-step global reaction mechanisms
- To achieve a balance between computational efficiency and prediction accuracy in CFD simulations.

#### ➤ Modelling Approach

A two-dimensional axisymmetric model of the fixed-bed furnace is developed to reduce computational cost while retaining the essential physics of the system. The biomass fuel bed is represented as a porous medium, allowing airflow through the bed while accounting for resistance and internal heat generation using Darcy–Forchheimer relations.

The governing equations of mass, momentum, energy, and species transport are solved using the finite volume method under steady-state conditions. A single-step global reaction mechanism is employed to simplify the complex chemical kinetics of biomass combustion. Turbulence effects are modeled using the standard  $k$ – $\epsilon$  model due to its robustness and reliability for industrial flow simulations. Radiative heat transfer, which dominates at high temperatures, is incorporated using the P-1 radiation model.

Appropriate boundary conditions are applied at the air inlet, outlet, furnace walls, and porous bed region. Numerical discretization schemes and convergence criteria are selected to ensure solution stability and accuracy.

#### ➤ Parametric Study

A parametric analysis is carried out to evaluate the influence of key operating conditions on furnace performance. Parameters such as air inlet velocity, biomass bed height, and equivalence ratio are systematically varied. The simulation results are analyzed in terms of temperature distribution, velocity fields, wall heat flux, and overall thermal efficiency.

The validity of the numerical model is assessed through comparison with published literature data, ensuring the reliability of the adopted methodology.

### IV. CONCLUDING REMARKS

#### ➤ The Key Conclusions Drawn from this Review are as Follows:

- Computational Fluid Dynamics (CFD) is an effective and reliable tool for analyzing biomass combustion and heat transfer in fixed-bed furnaces
- Combustion performance is strongly influenced by operating parameters such as air–fuel ratio, airflow distribution, biomass bed height, and fuel properties
- Radiation is the dominant heat transfer mechanism at high temperatures and must be accurately modeled for realistic prediction of furnace behavior
- Simplified modeling approaches, including porous media representation of the biomass bed and single-step global reaction mechanisms, provide a good balance between computational efficiency and prediction accuracy
- Turbulence models such as the standard and realizable  $k$ – $\epsilon$  models are widely used and offer satisfactory performance for steady-state simulations
- Parametric studies play a crucial role in identifying optimal operating conditions and improving furnace efficiency

- Despite significant advancements, challenges remain in accurately representing biomass heterogeneity, ash formation, and detailed chemical kinetics
- Most existing studies rely on steady-state assumptions, limiting the ability to capture transient combustion behavior

### REFERENCES

- [1]. Moodley, S., Naidoo, N., Mohammadi, A. (2019). An Overview of Coal Combustion. DOI: 10.13140/RG.2.2.12590.87365.
- [2]. T.T. Al-Shemmeri, R. Yedla, D. Wardle, Thermal characteristics of various biomass fuels in a small-scale biomass combustor, *Applied Thermal Engineering*, Volume 85, 2015, Pages 243–251, ISSN 1359-4311.
- [3]. Khan, A., et al. (2023). Thermal efficiency evaluation of biomass furnaces. *Fuel*, 330.
- [4]. Patel, R., et al. (2022). Numerical study of agricultural biomass combustion. *Renewable Energy*, 146, 1235–1246.
- [5]. Brown, D., et al. (2022). Turbulence model comparison for biomass combustion. *Processes*, 10.
- [6]. Verma, V., et al. (2022). Secondary air injection effects in biomass furnaces. *Biomass and Bioenergy*, 156.
- [7]. Park, J., et al. (2022). Radiation model comparison in biomass combustion. *Applied Thermal Engineering*, 201.
- [8]. Das, S., et al. (2022). Effect of bed height on biomass combustion. *Renewable Energy*, 186, 121–132.
- [9]. Müller, T., et al. (2022). Flow field analysis in fixed-bed biomass furnaces. *Energy Reports*, 8, 556–568.
- [10]. Rao, K., et al. (2021). CFD optimization of air inlet configuration in biomass furnaces. *Thermal Science*, 25, 789–800.
- [11]. Chen, L., et al. (2021). Transient CFD analysis of biomass combustion. *Energy Reports*, 7, 312–324.
- [12]. Gomez, M., et al. (2021). Numerical optimization of biomass combustion furnaces. *Sustainable Energy Technologies*.
- [13]. Ahmed, S., et al. (2021). Effect of inlet air temperature on biomass combustion. *Journal of Energy Resources Technology*, 143.
- [14]. Liu, Y., et al. (2021). Influence of particle size on biomass combustion. *Powder Technology*, 384, 52–63.
- [15]. Sharma, R., et al. (2021). Heat loss analysis in biomass furnaces using CFD. *Case Studies in Thermal Engineering*, 28.
- [16]. Fernandez, J., et al. (2020). Simplified CFD modeling of small-scale biomass furnaces. *Applied Energy*, 261.
- [17]. Singh, P., et al. (2020). Effect of equivalence ratio on biomass combustion. *Fuel Processing Technology*, 198.
- [18]. Wang, H., et al. (2020). Wall heat flux analysis in biomass-fired furnaces. *International Journal of Heat and Mass Transfer*, 154.
- [19]. Zhang, Y., et al. (2019). Numerical investigation of heat transfer in biomass-fired fixed-bed furnaces. *Applied Thermal Engineering*, 148, 108–119.
- [20]. Kumar, A., et al. (2019). Effect of air staging on biomass combustion using CFD. *Fuel*, 245, 45–56.
- [21]. Li, X., et al. (2019). Heat transfer mechanisms in biomass combustion systems. *Energy*, 179, 1034–1045.
- [22]. Smith, J., et al. (2018). CFD modeling of biomass combustion in a fixed-bed furnace. *Energy Conversion and Management*, 165, 285–296.