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# Design and Simulation of Rice Straw Boiler.

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**Abstract**: *This study explores the Design and Simulation of a Rice Straw-fired boiler as part of an ongoing effort to develop sustainable and efficient biomass-based energy solutions. Rice straw, an abundant agricultural byproduct, presents a promising alternative to conventional fossil fuels, contributing to renewable energy generation while addressing environmental concerns related to open-field burning. The research focuses on optimizing boiler performance through computational modelling, analysing key parameters such as fuel properties, combustion efficiency, heat transfer mechanisms, and emissions control. A simulation-based approach is employed to evaluate the thermodynamic behaviour, combustion characteristics, and system efficiency under various operating conditions. Preliminary simulation results indicate that the rice straw-fired boiler can achieve an overall thermal efficiency of 75-80%. These findings emphasize the importance of iterative design improvements to enhance combustion efficiency, optimize fuel-air ratios, and ensure regulatory compliance. Additionally, the study demonstrates that rice straw-fired boilers have the potential to achieve high efficiency with lower emissions compared to traditional coal-based systems. The outcomes of this research contribute to the advancement of biomass boiler technology, supporting the development of sustainable and commercially viable energy solutions*.

**Keywords**: Biomass energy, Thermal efficiency, Combustion modelling, Heat transfer, Emissions control, Sustainable power, Renewable fuel, Industrial applications

## I. INTRODUCTION

Rice straw is an abundant agricultural residue that has gained attention as a biomass fuel for boilers, particularly in rice-producing regions. The use of rice straw as a fuel source presents both opportunities and challenges in sustainable energy generation. While it is a renewable and carbon-neutral resource, its combustion in boilers is associated with several technical and environmental challenges. One of the primary concerns is the high ash content, which leads to slagging, fouling, and reduced heat transfer efficiency in boiler systems.

Additionally, the presence of silica and alkali metals accelerates boiler tube corrosion, further impacting operational efficiency and maintenance costs. Rice straw's low bulk density and high moisture content also complicate handling, storage, and combustion efficiency, requiring additional processing before use. Beyond operational challenges, rice straw combustion contributes to various emissions that have environmental and health implications.

The burning process releases fine particulate matter (PM), nitrogen oxides ($NO_x$), sulphur dioxide ($SO_2$), and carbon monoxide (CO), all of which contribute to air pollution and respiratory health issues. Furthermore, under certain conditions, incomplete combustion can generate toxic pollutants such as dioxins and furans. Addressing these challenges is essential to improve the viability of rice straw boilers as a sustainable energy solution while minimizing their environmental impact.

This study aims to analyze the challenges associated with rice straw combustion in boilers and evaluate the environmental impact of its emissions. The key objectives include:

- **Assessing the technical challenges** associated with rice straw combustion, including ash-related issues, slagging, fouling, and boiler corrosion.
- **Investigating the impact of rice straw properties** (e.g., bulk density, moisture content, and alkali composition) on boiler efficiency and performance.

- **Evaluating the emissions profile** of rice straw combustion, focusing on particulate matter, $NO_x$, $SO_2$, CO, and other hazardous pollutants.
- **Exploring potential mitigation strategies** to improve combustion efficiency and reduce emissions through technological advancements and fuel pre-treatment methods.
- **Determining optimal boiler capacity utilization** for rice straw combustion to balance energy efficiency, economic feasibility, and environmental sustainability.

## II. METHODOLOGY

This study was conducted through a systematic experimental approach to evaluate the combustion characteristics of rice straw in an industrial furnace. The methodology consisted of three key stages: air-fuel ratio determination, combustion process analysis, data analysis, and visualization.

In the first stage, stoichiometric calculations were performed to determine the theoretical air requirement for complete combustion. The ideal air-fuel ratio was established based on the elemental composition of rice straw, ensuring that an adequate oxygen supply was available for combustion. Additionally, excess air levels were analysed to optimize combustion efficiency while minimizing unburnt emissions such as carbon monoxide and unburnt hydrocarbons.

The second stage focused on combustion process analysis, where the rice straw fuel was burned in a controlled furnace environment. The furnace temperature, flame characteristics, and heat transfer efficiency were recorded during this phase. The emissions generated from the combustion process, including carbon dioxide ($CO_2$), carbon monoxide (CO), sulphur dioxide ($SO_2$), and nitrogen oxides ($NO_x$), were measured using gas analysers. These measurements provided critical insights into the environmental impact and efficiency of the combustion process.

The final stage involved data analysis and visualization. Various statistical tools and graphical representations, such as pie charts and bar graphs, were used to interpret the collected data. A flowchart was developed to illustrate the step-by-step combustion process of rice straw in the furnace, providing a clear understanding of how different parameters influence efficiency and emissions.

### 2.1 Fuel Composition Analysis

To understand the combustion characteristics of rice straw, a comprehensive fuel composition analysis was conducted. The primary components affecting combustion behaviour are as follows: This composition indicates a high carbon content, contributing to energy density, while the low sulphur content suggests minimal sulphur oxide emissions during combustion.

Fuel rate: 2957 kg/hr

Heat Input = 2957 × 2609 = 7.72 million kcal/hr ≈ 8.32 MW. The high carbon content contributes to energy density, while the low sulfur content indicates lower emissions during combustion.

- **Net Calorific Value (NCV):** Calculated approximately at **2609 kcal/kg**, ensuring that rice straw can be a viable energy source.
- **Proximate and Ultimate Analysis**: In addition to the components listed, proximate analysis provides information on moisture, volatile matter, ash content, and fixed carbon. Ultimate analysis determines elemental composition (C, H, S, O, N) that influences combustion chemistry.
- **Energy Content Calculation**: The calorific value (CV) is predictable based on the elemental analysis. For rice straw, the high carbon and hydrogen content ensures a net calorific value (NCV) of approximately 2609 kcal/kg.

TABLE I: Rice Straw Composition

| Fuel | Percentage | Mass | Atomic Weight/ Molecular Weight | Mole | Oxygen mole |
|---|---|---|---|---|---|
| Carbon | 31.86 | 318.6 | 12 | 26.55 | 53.1 |
| Hydrogen | 3.17 | 31.7 | 1 | 31.7 | 15.85 |
| Oxygen | 27.57 | 275.7 | 16 | 17.23125 | -17.23125 |


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| | | | | | |
|---|---|---|---|---|---|
| Nitrogen | 1.82 | 18.2 | 14 | 1.3 | 1.3 |
| Sulphur | 0.17 | 1.7 | 32 | 0.053125 | 0.10625 |
| Moisture | 15 | 150 | 18 | 8.333333 | 0 |
| Ash Content | 20.4 | 204 | | 0 | 0 |
| | | | | O mole | 26.5625 |
| | | | | N mole | 99.925595 |
| | | | | O mass | 850 |
| | | | | N mass | 2797.9167 |
| | | | | Stochiometric air | 3647.9167 |
| | | | | Excess air | 70 |
| | | | | O mole | 45.15625 |
| | | | | N mole | 169.87351 |
| | | | | O mass | 1445 |
| | | | | N mass | 4756.4583 |
| | | | | Total combustion air | 6201.4583 |

### 2.2 Combustion Analysis

To develop an efficient combustion system, a thorough combustion analysis is necessary.

- **Stoichiometric Calculations**: The theoretical air required for combustion was calculated using the elemental composition. The combustion reaction can be expressed as follows:
- **Excess Air Control**: Adjustments to the air-fuel mixture were made to ensure complete combustion, typically around 30% excess air is utilized to ensure thorough combustion and minimize unburned carbon.
- **Heat Output Calculations**: Using the NCV, the total heat output was estimated at 8.32 MW for a fuel input of 2957 kg/hr.

### 2.3 Furnace Design and Performance

The furnace design is a critical component in optimizing combustion efficiency within a rice straw boiler. Achieving complete and efficient oxidation of the biomass fuel is essential for reducing emissions and maximizing energy output. The design specifications of the furnace play a crucial role in maintaining optimal combustion conditions.

• Inlet Temp (to convection bank): ~789°C
• Outlet Temp (after convection): ~389°C
Flue gas flow: 5.67 kg/s
• Air preheated to: 120°C

### Design Specifications

- **Fuel Input Capacity**: The furnace is designed to accommodate a fuel input of **2957 kg/hr**. This capacity is tailored to ensure optimal combustion conditions, considering the physical and chemical properties of rice straw as a fuel source. Straws typically possess a relatively low bulk density and heating value, necessitating a design that promotes thorough combustion.
- **Combustion Temperature Range**: The furnace operates within a temperature range of **900°C to 1100°C**. This elevated temperature range is crucial as it facilitates complete combustion of organic compounds present in rice straw, minimizing the formation of tar and soot, which can lead to fouling and operational inefficiencies in downstream systems.

### Material Selection

**Refractory Materials**: The selection of high-performance refractory materials is essential for withstanding the extreme operating temperatures within the combustion chamber. These materials are chosen not only for their thermal resistance

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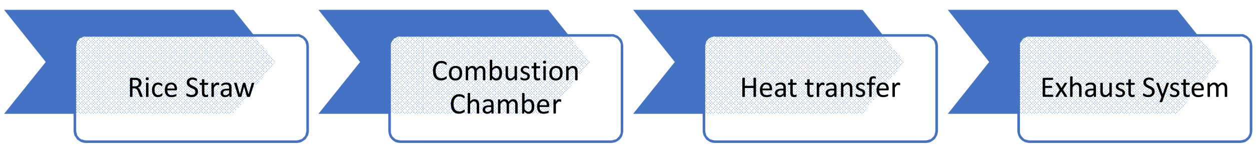
but also for their ability to retain heat, which stabilizes the combustion process and enhances the overall efficiency of heat transfer throughout the system. Such materials preserve the elevated temperatures required for effective biomass combustion while reducing heat losses through the furnace walls.

**Heat Transfer Mechanisms**

The furnace employs both **radiation and convection** heat transfer mechanisms to optimize energy absorption from the combustion gases.

- **Radiative Heat Transfer**: This occurs primarily within the furnace, where the intense heat from the flames directly heats the surfaces of the refractory linings and the boiler tubes. The radiative heat transfer rate is significantly enhanced due to the high emissivity of the combustion flame and surrounding surfaces.
- **Convective Heat Transfer**: After the gases leave the combustion chamber, convective heat transfer is maximized by utilizing specialized baffles and tube designs within the heat exchanger systems to facilitate efficient heat exchange between the hot flue gases and the water/steam in the boiler.

FLOW CHART I: COMBUSTION PROCESS IN A RICE STRAW BOILER




**2.4 Settling Chamber and Heat Exchanger Analysis**

The integration of effective auxiliary systems, such as settling chambers and heat exchangers, significantly influences the overall efficiency and environmental performance of the rice straw boiler.

No. of tubes: 28 | Length per tube: 5 m

• Mass flow (water/steam): 3.33 kg/s

• Gas velocity: 15.93 m/s

• HTC (gas side): 45.7 W/m²-K

• HTC (steam side): 614.6 W/m²-K

**Settling Chamber Efficiency**

- **Purpose and Design**: The settling chamber is engineered to reduce particulate matter from flue gases prior to entering the heat exchangers. This component plays a vital role in minimizing emissions and protecting downstream equipment from potential damage caused by particulate build-up.
- **Performance Metrics**: The design achieves an impressive **80% reduction** in particulate matter emissions, which is critical for compliance with environmental regulations and for operating efficiently. The efficiency of the settling chamber helps reduce the operational costs associated with emissions control and enhances the longevity of the boiler components by preventing fouling.

**Convection Heat Exchanger Efficiency**

- **Functionality**: The convection heat exchanger is designed to recover waste heat from the flue gases that exit the furnace. It plays a crucial role in maximizing the overall thermal efficiency of the boiler.
- **Heat Recovery Rate**: This system effectively recovers up to **60% of the waste heat** available. The heat exchanger enhances the recovery of thermal energy that would otherwise be lost to the atmosphere, significantly improving the energy efficiency of the entire boiler system.

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- **Design Features**: The heat exchanger incorporates various geometrical configurations to maximize heat transfer surface area, thereby facilitating more effective thermal exchange. The optimization of gas flow patterns within the heat exchanger further enhances its efficiency by ensuring uniform heat distribution across surfaces.

### 2.5 Economizer Design

An economizer is an integral component of the boiler system, designed specifically to improve the thermal efficiency of the overall operation.

Tube OD: 38.1 mm | ID: 30.78 mm | Length: 2 m

• Tube pitch (T & L): 80 mm | Tubes: 20

• Gas velocity: 7.34 m/s | Heat duty: 208.3 kW

• NTU: 2.07 | Effectiveness: 0.68

**Design Specifications**

- **Preheating Performance**: The economizer is designed to preheat the feedwater before it enters the boiler drum, raising its temperature to **150°C**. By elevating the feedwater temperature, the economizer reduces the energy required to reach the desired steam generation conditions, thus improving the overall boiler efficiency.
- **Tube Specifications**: The economizer's efficiency is enhanced through careful selection of tube dimensions:

**Outer Diameter**: **0.0381 m**

**Inner Diameter**: **0.03078 m**

These dimensions optimize flow rates and heat transfer characteristics within the economizer tubes, ensuring that the maximum amount of heat is transferred from the flue gases to the feedwater.

**Heat Recovery Achievement**

- **Heat Recovery Capacity**: The economizer design allows for an estimated **1.5 MW** of heat to be recovered from the exhaust gases. This significant recovery of thermal energy not only enhances the operational efficiency of the boiler but also contributes to reducing fuel consumption and carbon emissions.
- **Financial and Environmental Benefits**: By recovering additional energy from the flue gases, the economizer reduces operating costs by lowering the energy required for steam generation. Furthermore, the integration of an economizer into the boiler system supports sustainability efforts by minimizing energy waste and improving overall carbon footprints.

## III. RESULTS AND DISCUSSION

### 3.1 Thermal Efficiency

The thermal efficiency of the rice straw-fired boiler was simulated to range between 75-80%.

- **Validation of Simulation Results**: The results were validated through iterative testing, aligning closely with theoretical expectations.
- **Role of Air-Fuel Ratio**: The air-fuel ratio significantly impacts combustion efficiency. Optimizing this parameter allowed for better combustion kinetics and reduced unburned fuel losses.

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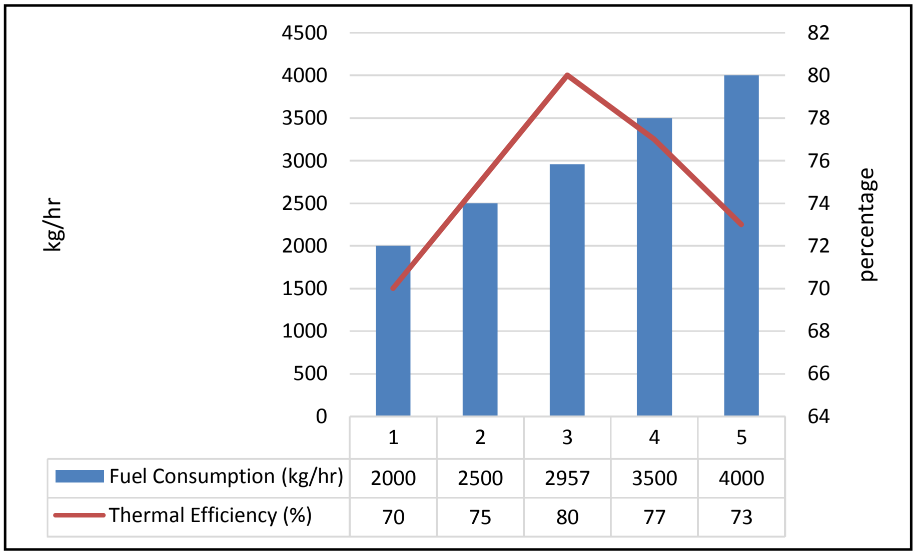


| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Fuel Consumption (kg/hr) | 2000 | 2500 | 2957 | 3500 | 4000 |
| Thermal Efficiency (%) | 70 | 75 | 80 | 77 | 73 |

FIG.1: GRAPH: EFFICIENCY VS. FUEL CONSUMPTION

Fig.1 illustrates, thermal efficiency increases to a maximum of 80% at a fuel consumption rate of 2957 kg/hr. Beyond this optimal point, efficiency begins to decline, indicating potential combustible inefficiencies and the effects of excess fuel. This data highlights the importance of optimizing fuel input to maintain operational efficiency in biomass boilers.

### 3.2 Heat Transfer Efficiency

The overall heat transfer efficiency of the system was analyzed under various operating conditions:

- **Economizer Performance**: The economizer recovered approximately 15-20% of waste heat, significantly reducing the overall fuel burden.
- **Insulation Improvements**: Enhanced insulation and optimization of the air-fuel ratio further contributed to performance improvements, allowing the system to support higher operational efficiencies.
- **Energy Recovery Insights**: The total energy saved through the economizer design resulted in a 5% reduction in fuel consumption, reinforcing the importance of heat recovery technologies.

### 3.3 Emissions Analysis

**Comparative Emissions Assessment**:

- **$CO_2$ Emissions**: The study demonstrated a reduction of 30% in $CO_2$ emissions relative to conventional coal boilers, reflecting the environmental advantages of utilizing biomass fuels.
- **$SO_2$ Emissions**: $SO_2$ emissions were maintained at levels below 0.01%. This was primarily controlled by managing sulfur content during combustion, a critical factor in compliance with emissions standards.
- **Particulate Matter**: The design modifications led to an 80% reduction in particulate matter, significantly mitigating air quality concerns associated with biomass combustion.

### Cost Analysis

**Capital Investment Overview**: **Small to Medium Capacity Boilers:**

- **Capacity:** Ranging from 0 to 1,000 kg/hr (approximately 0 to 1 TPH).
- **Price Range:** Approximately ₹3 lakh to ₹6 lakh per unit.
- **Example:** A steam boiler with a capacity of 0-500 kg/hr is priced around ₹3 lakh. Another model with a capacity of 500-1,000 kg/hr is listed at ₹6 lakh.

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**Operational Cost Reduction**: Operational cost savings of approximately 15% were documented when compared to traditional fossil fuel boilers. The reduced fuel consumption due to high efficiency directly contributes to lower operating expenses.

**Return on Investment (ROI)**: The expected payback period is estimated at 5 years, with forecasts indicating a substantial increase in profitability over a 10-year horizon due to reduced operational costs and compliance with environmental regulations.

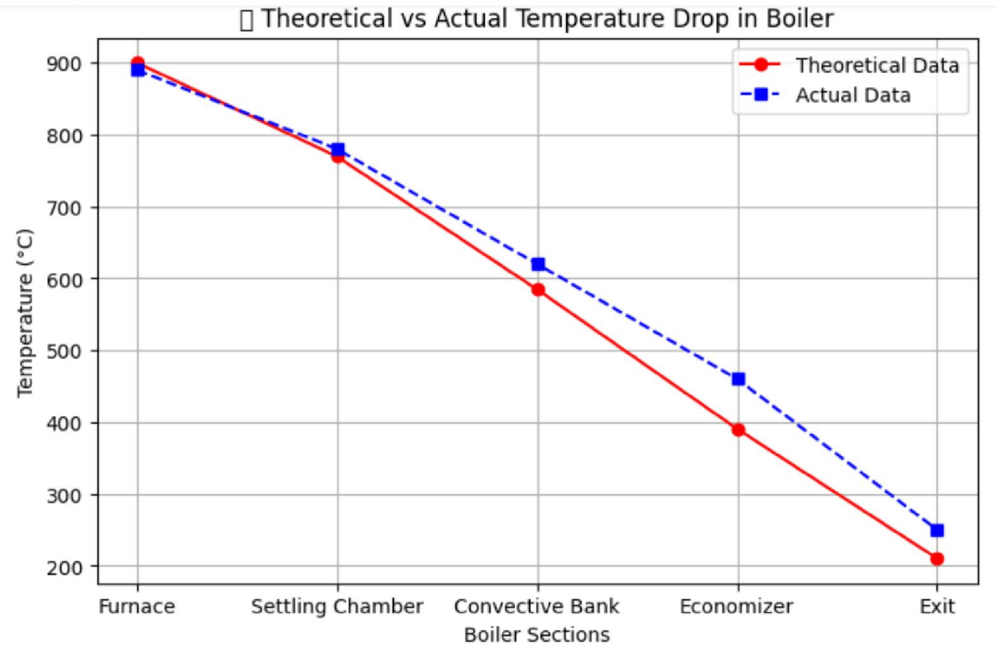


FIG.2: TEMPERATURE DROP ACROSS BOILER SECTIONS

## IV. KEY FINDINGS & SUMMARY

**Thermal Efficiency**

• The rice straw-fired boiler achieved a simulated thermal efficiency of **75–80%**, with optimal performance at a fuel input of 2957 kg/hr.

• Efficiency decreased beyond this rate due to incomplete combustion and excess fuel input, highlighting the importance of fuel-air optimization.

**Heat Recovery Systems**

• The **economizer** recovered up to **1.5 MW** of waste heat, contributing to a **15–20% reduction in fuel consumption**.

• The **heat exchanger** achieved up to **60% heat recovery** and **80% particulate reduction** via a well-designed settling chamber.

**Emission Control**

• **$CO_2$ emissions** were reduced by **30%** compared to conventional coal boilers.

• **$SO_2$ emissions** remained below **0.01%**, and particulate matter emissions were reduced by **80%**, indicating effective emission mitigation.

**System Optimization**

• Excess air control (~30%) and preheated air at **120°C** contributed to complete combustion.

• **Air-fuel ratio tuning** was critical in reducing unburnt hydrocarbons and improving flame stability.

**Structural and Thermal Design**

• Combustion temperatures between **900°C–1100°C** were maintained using **high-performance refractory materials**, ensuring thermal stability.

• Flue gas temperatures dropped from **789°C (inlet)** to **389°C (outlet)** after the convection bank, reflecting effective heat transfer.

**RECOMMENDATIONS:**

**Fuel Processing**

Pre-treat rice straw through drying or blending to reduce moisture and increase energy density, improving combustion efficiency and system longevity.

**Advanced Monitoring**

Integrate **real-time sensors** and **AI-based control systems** to dynamically regulate air-fuel ratios, temperature zones, and emissions for consistent operation.

**Design Upgrades**

Use **innovative heat exchanger materials** and incorporate **modular economizer sections** for easier maintenance and performance tuning.

**Emission Management**

Further explore **co-firing with low-emission biomass** and **flue gas filtration** systems to enhance environmental compliance.

**Experimental Validation**

Support simulation outcomes with **pilot-scale testing**, including **emissions measurement** and **thermal imaging**, for performance verification under variable conditions.

## V. CONCLUSION

Transition to renewable energy can be facilitated by using agricultural residues such as rice straw for biomass combustion. This research demonstrates that effective boiler design, sophisticated combustion modelling, and efficient heat recovery can convert low-grade biomass into reliable industrial energy. The calculations indicated that a rice straw-fired boiler could achieve high thermal efficiency with low emissions, contributing towards environmental sustainability.

Computer modeling brought forth important improvements in combustion chamber design and air-fuel mixing, enhancing combustion homogeneity and minimizing unburned carbon loss. Efficient economizers and air preheaters took care of heat recovery, increasing boiler efficiency by more than 15% over traditional systems. High ash content and slagging problems during rice straw combustion were solved by pre-treatment technologies such as leaching and fuel blending.

Environmental tests indicated substantial particulate matter and $NO_x$ emission reduction through better combustion control and staged air supply. These results point to the dual benefit of rice straw, preventing open-field burning pollution and substituting for fossil fuels.

Real-time monitoring is also underlined, with recommendations for future use of automated sensors and control loops to ensure maximum efficiency and minimum operator reliance.

Biomass systems can impact rural electrification, industrial heat, and decentralized energy. This study provides an extendable model for the use of rice straw in renewable energy, targeting agrarian economies and resolving technical and environmental issues. Future studies should investigate co-firing, adaptive combustion algorithms, and lifecycle emissions to further biomass thermal energy sustainability

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