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Failure Mode and Effect Analysis (FMEA) for Improving the Efficiency of a Two Combustion Chamber Downdraft Gasification Stove

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Abstract

The growing energy demand in areas lacking access to modern infrastructure drives the development of biomass-based thermal technologies, such as the dual-chamber downdraft gasification stove. This stove offers higher efficiency and lower emissions compared to direct combustion but still poses failure risks in various system components. This study aims to identify critical failure modes affecting the thermal efficiency of the stove through the Failure Mode and Effect Analysis (FMEA) approach. The analysis involved mapping the system's structure and functions, followed by evaluating failure modes using three parameters: Severity (S), Occurrence (O), and Detection (D) to obtain the Risk Priority Number (RPN). Results indicate the highest risk occurs in the combustion system (RPN 180), followed by the air control system (RPN 160). Key causes include suboptimal secondary air distribution and valve blockage. Other systems such as insulation, maintenance access, safety, and fabrication had lower RPNs but still require design and quality control improvements. Recommendations focus on improving airflow design, using high-temperature-resistant materials, and adopting precision fabrication procedures. Using the FMEA approach, the gasification stove can be enhanced in terms of reliability, efficiency, and user safety, making it more feasible as a small-scale renewable energy solution for communities.

Keywords: biomass stove, failure mode, FMEA, gasification, thermal efficiency,

1. Introduction

The growing global demand for energy, particularly in rural areas that remain underserved by modern energy infrastructure, has driven the development of renewable and efficient energy technologies. Biomass has emerged as a promising renewable energy source, especially for small-scale applications such as household stoves, due to its abundant availability and carbon-neutral properties (Tayari et al., 2021).

The downdraft gasification stove is one innovation in the conversion of biomass into cleaner and more efficient thermal energy compared to direct combustion. By directing air downward through a column of biomass fuel, the gasification process generates producer gas that is subsequently burned in a secondary combustion chamber. This dual-chamber configuration enhances thermal efficiency and reduces harmful emissions such as carbon monoxide (CO) and particulate matter (Zhou et al., 2020).

Nevertheless, several potential failure modes in this system such as uneven air distribution, suboptimal combustion chamber design, and the use of materials that are not resistant to high temperatures remain significant challenges that can reduce combustion efficiency and overall system performance (Singh et al., 2018). Therefore, a systematic analysis of potential failures is essential to improve the reliability and effectiveness of the system.

One effective method for analyzing failure risks in engineering systems is Failure Mode and Effect Analysis (FMEA). FMEA is a proactive approach used to identify possible failure modes, evaluate their severity and likelihood, and provide corrective recommendations based on risk prioritization (Wang et al., 2019). This method has been widely applied in energy systems to enhance operational efficiency and reliability, including in biomass-based thermal systems (Gupta & Kumar, 2021).

This study aims to apply the FMEA method to a dual-chamber downdraft gasification stove to identify the most critical failure modes affecting thermal efficiency. The findings are expected to serve as a foundation for improving the stove's design and operation, thereby enhancing the performance and sustainability of biomass-based energy technologies.

2. Methodology

2.1. Description of the Dual-Chamber Downdraft Gasification Stove

The stove analyzed in this study is a dual-chamber downdraft gasification stove, designed to utilize biomass as fuel. It features two stages of combustion: a pyrolysis (gasification) chamber and a secondary combustion chamber. The purpose of the analysis is to identify potential failures in key components and determine risk priorities using the FMEA method.

The technical specifications of the stove are presented in Table 1, while the general design is illustrated in Figure 1.

Table 1. Technical Specifications of the Dual-Chamber Gasification Stove

Component	Specification
Overall dimensions	350 mm × 350 mm × 600 mm
Combustion chamber material	Heat-resistant steel AISI 310
Fuel	Dry wood (≤15% moisture content)
Air system	Controlled primary & secondary air
Fuel capacity	2.5 kg

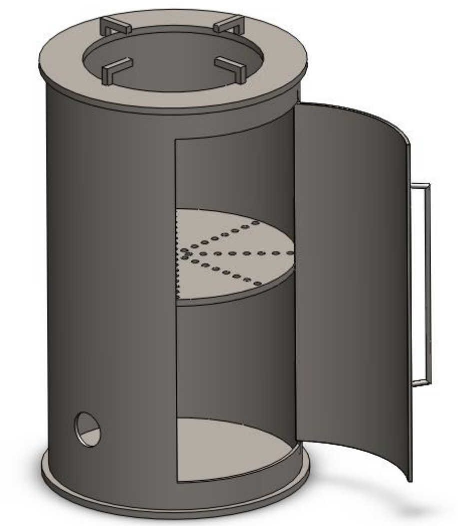

Figure 1: Design of the Dual-Chamber Downdraft Gasification Stove

The dual-chamber design aims to ensure complete combustion of the producer gas, reduce CO emissions, and improve thermal efficiency. This configuration has proven to provide more stable heat distribution compared to single-chamber designs (Zhou et al., 2020).

2.2. Identification of Subsystems and Main Components

The initial step in the FMEA method is identifying the system, subsystems, and key components. To support this process, a functional and structural mapping approach is used through the following diagrams:

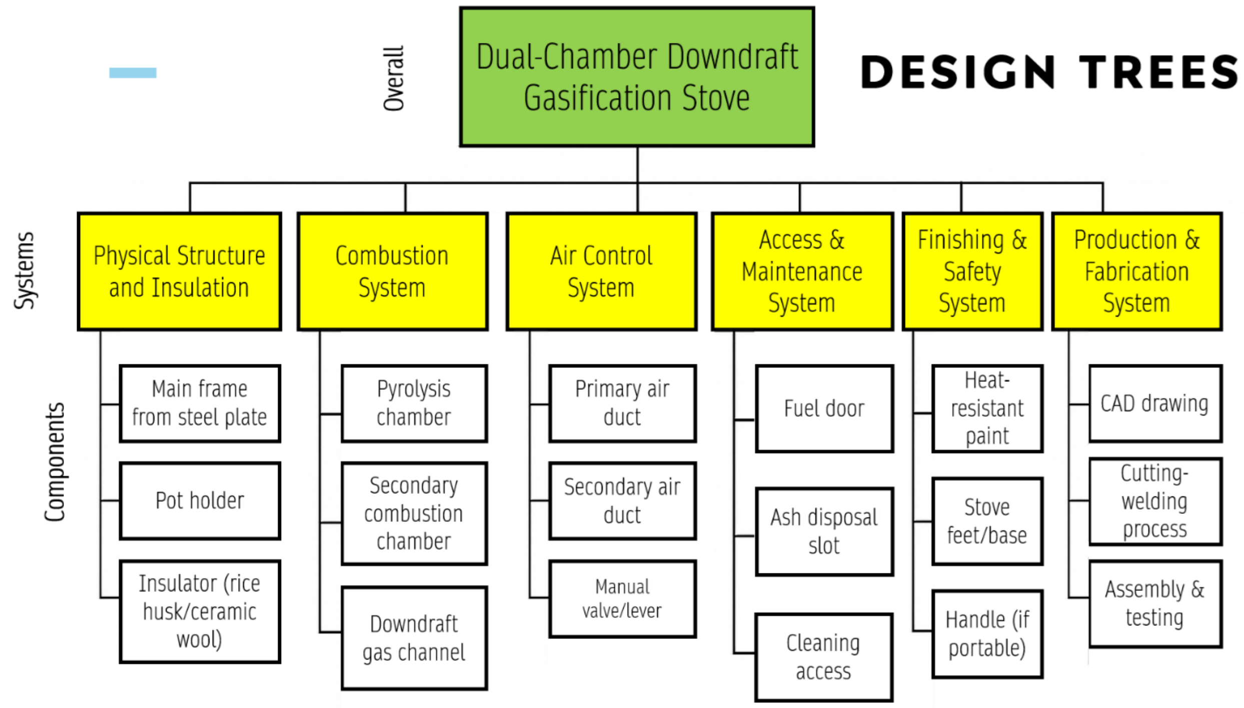

Figure 2: Design Tree of the Downdraft Gasification Stove

Figure 2 shows the Design Tree of the downdraft gasification stove system, illustrating the structural hierarchy from the main system level to individual components.

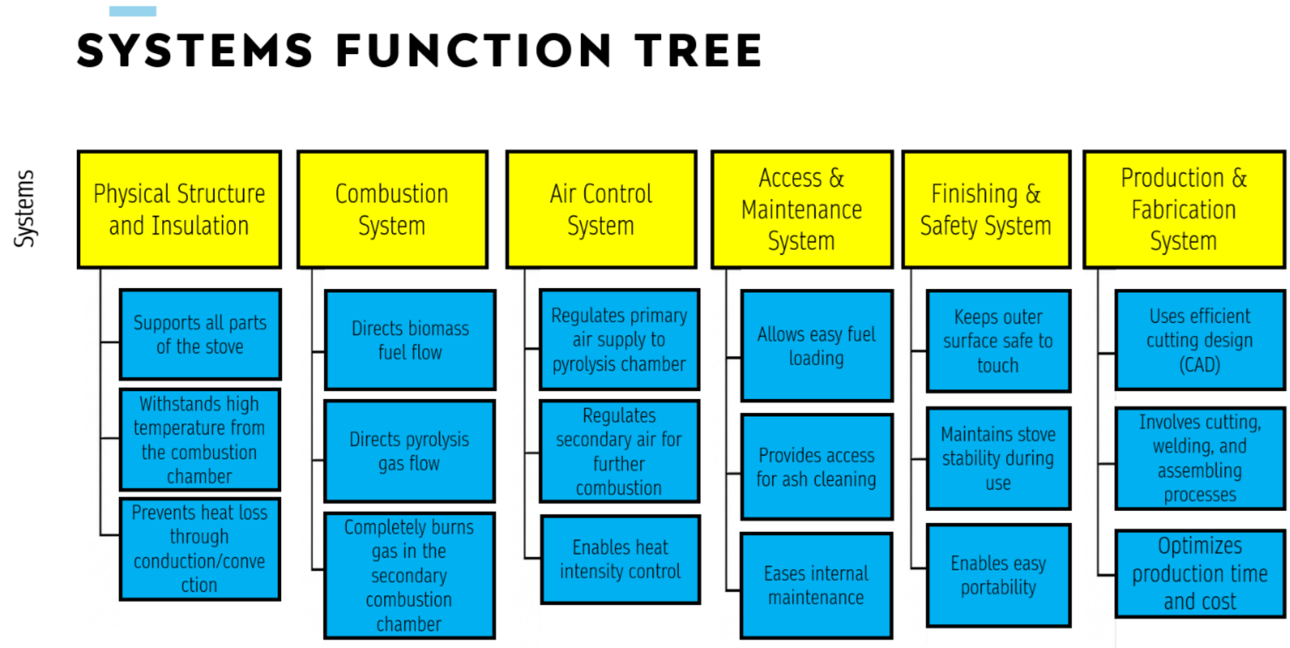

Figure 3: Function Tree of the Downdraft Gasification Stove

Figure 3 presents the Function Tree, which outlines the main functions of each subsystem. This helps in understanding how each component contributes to the overall system functionality.

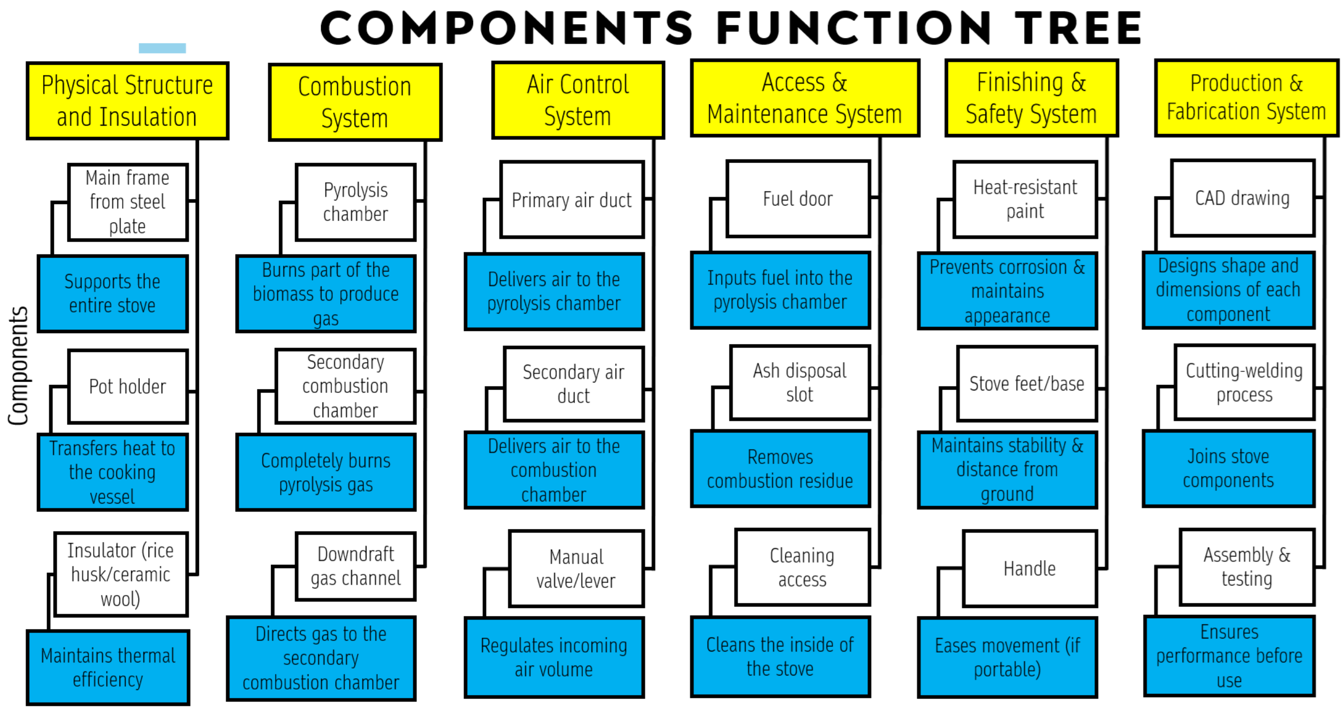

Figure 4: Component Function Tree of the Downdraft Gasification Stove

Figure 4 illustrates the relationship between functions and components, serving as the basis for identifying potential functional failures in each component.

This identification is essential for mapping potential failure modes in each component, forming the foundation for the FMEA process (Gupta & Kumar, 2021).

2.3. FMEA Procedure

The Failure Mode and Effect Analysis (FMEA) procedure in this study follows an engineering standard adapted to small-scale thermal systems (Liu et al., 2022). The main steps are as follows:

1) Identification of failure modes: Each component is analyzed to identify potential failure modes, such as cracking, air blockage, or incomplete combustion.
2) Risk assessment:
   a. S (Severity): The impact of failure on system efficiency and safety.
   b. O (Occurrence): The frequency of occurrence based on experience or historical data.
   c. D (Detection): The ability to detect the failure before it causes system damage.
3) Calculation of the RPN value:

$$RPN = S \times O \times D \ldots\ldots\ldots (1)$$

The higher the RPN value, the more critical it is to implement mitigation actions promptly.
Severity, Occurrence, and Detection scores are given on a scale of 1–10, following the MIL-STD-1629A standard practice (Wang et al., 2019).

2.4. Risk Priority Criteria

The Risk Priority Number (RPN) is used as the basis for determining components that require improvement. The categories used in this study are as follows:

1) RPN $\geq$ 150 : High risk → immediate improvement or redesign required.
2) RPN 100 – 149 : Medium risk → monitoring and minor design modifications needed.
3) RPN < 100 : Low risk → operational control or periodic inspection is sufficient.

This method allows researchers to focus on the components that are most critical in causing efficiency loss and potential operational disruptions, as also applied in other energy system FMEA studies (Singh et al., 2018; Wang et al., 2019).

3. Results and Discussion

3.1. System Structure and Function Analysis

The system analysis of the dual-chamber downdraft gasification stove begins with a structural and functional mapping approach to identify subsystems and key components. This approach involves three main diagrams: the Design Tree, the Function Tree, and the Component Function Tree, each providing a comprehensive overview of the physical structure, systemic functions, and interrelationships among elements.

Based on Figure 2 (Design Tree), the stove system is divided into six main subsystems: (1) structural and insulation system, (2) combustion system, (3) air control system, (4) access and maintenance system, (5) finishing and safety system, and (6) production and fabrication system. This classification facilitates the analysis of each subsystem's contribution to overall system performance and reliability.

Next, the Function Tree identifies the main function of the system, which is to convert biomass energy into thermal energy through gasification and combustion processes. This is further broken down into specific functions such as pyrolysis gas formation, secondary gas combustion, air supply regulation, user protection, and ease of maintenance access.

The Component Function Tree explains the relationship between physical components and the functions they serve. For example, the insulation wall functions as both a thermal shield and an energy efficiency preserver, while the air control valve plays a critical role in regulating combustion. This mapping is essential for risk and reliability analysis, as in Failure Modes and Effects Analysis (FMEA), since a single component may affect multiple functions and its failure can result in systemic consequences.

3.2. Identification of Failure Modes

Based on the analysis of the structure and operation of the gasification stove, several major failure modes have been identified that potentially reduce the system's thermal efficiency. These failure modes are grouped by component, as shown in Table 2:

Table 2: Failure Modes and Their Effects on the System

System	Component	Failure Mode	Effect on System
Structure & Insulation	Steel frame	Cracks, deformation due to high heat	Unstable frame, safety hazard
	Pan holder	Warped, uneven	Uneven heating, unstable cookware
	Insulator (husk/ceramic wool)	Burnt, loss of insulation	Reduced thermal efficiency, heat leaks from the stove
Combustion System	Pyrolysis chamber	Incomplete combustion, blockage	Suboptimal gasification, excessive smoke
	Secondary combustion chamber	Insufficient heat for complete combustion	High emissions, low efficiency
	Downdraft gas channel	Blocked or leaking	Gas flow disrupted, combustion process fails
Air Control System	Primary air channel	Blocked, leaking, incorrect dimensions	Inadequate air supply, poor combustion
	Secondary air channel	Same as primary	Secondary combustion not achieved
	Control valve/lever	Jammed, unresponsive	Cannot regulate air supply, system unresponsive
Access & Maintenance	Fuel door	Loose, damaged	Air leakage, uncontrolled flame
	Ash disposal slot	Blocked	Ash buildup, airflow and gas flow disrupted
	Cleaning access	Limited, difficult to open	Difficult maintenance, reduced performance
Finishing & Safety	Heat-resistant paint	Peeling, rust	Poor aesthetics, corrosion risk
	Stove legs/base	Unstable, broken	Stove may tip over, risk of injury
	Handle (if portable)	Detached, loose	Risk during transport
Production & Fabrication	CAD drawing	Inaccurate design	Poor component fit during assembly
	Cutting & welding process	Untidy, weak joints	Air/gas leakage, unstable structure
	Assembly & testing	Incomplete, untested	Stove fails to operate properly, unsafe to use

3.3. Severity, Occurrence, Detection Assessment and RPN Calculation

Each failure is assessed using three parameters: Severity (S), Occurrence (O), and Detection (D), each rated on a scale from 1 to 10. These values are multiplied to obtain the Risk Priority Number (RPN). The assessment results are shown in Table 3:

Table 3: FMEA Analysis Results of the Dual-Chamber Gasification Stove

System Function	Potential Failure Mode	Effect of Failure	S	Cause of Failure	Preventive Measures	O	Detection Method	D	RPN
Combustion System	No secondary combustion	Excess smoke, inefficient heat	9	Poor secondary air, design flaw	Basic CFD airflow design test	5	Prototype performance testing	4	180
Air Control System	Valve jammed or clogged	Flame out, hard to control	8	Ash buildup, rusted hinge	Easy-to-clean valve design	4	Routine visual inspection	5	160
Structure & Insulation	Heat leaks from stove	Reduced efficiency, hot surface	7	Worn insulation, poor materials	Use insulation rated >1000°C	3	Surface temperature monitoring	4	84
Access & Maintenance	Door difficult to open/clean	Operation disruption	6	Loose hinge, poor ergonomics	Quick-lock access door	3	Opening test during assembly	3	54
Safety & Portability	Stove easily tips over	Injury risk, fire hazard	10	Unstable frame, unbalanced weight	Wide legs, low center of gravity	2	Stability test (4 directions)	3	60
Production & Fabrication	Loose joint connections	Air/gas leaks, poor performance	7	Inaccurate welding and cutting	Welding jig and quality control	3	Pressure/leak testing	3	63

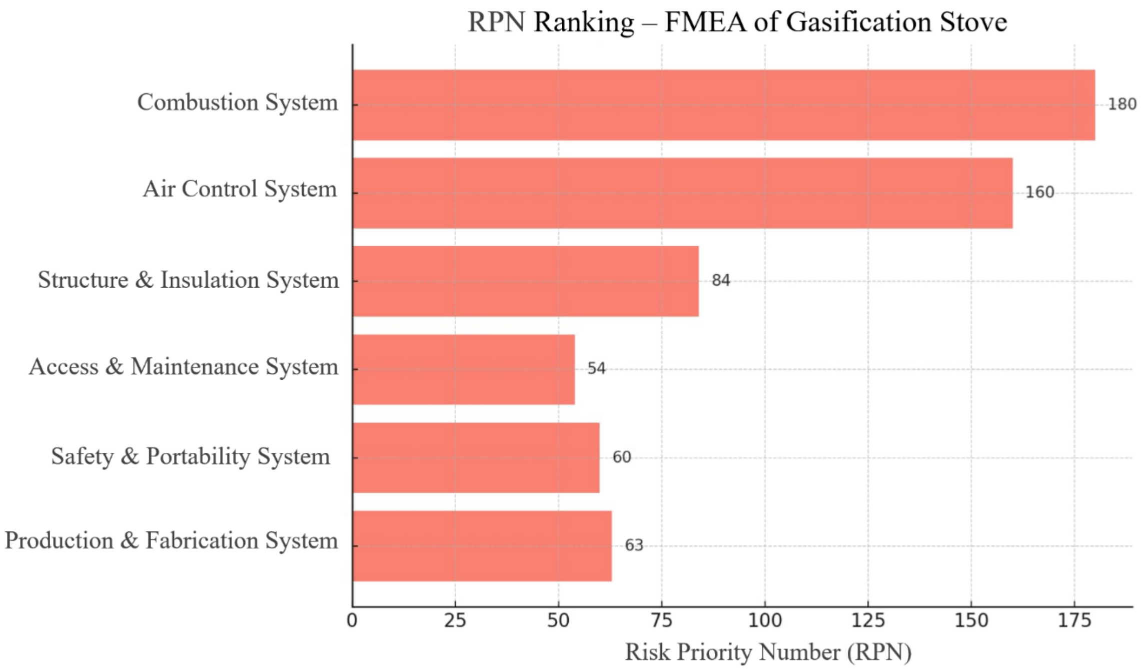

Figure 5: RPN Ranking Chart – FMEA of Gasification Stove

3.4. Results Interpretation

The failure mode analysis using the Failure Mode and Effects Analysis (FMEA) approach revealed that the highest risk is found in the combustion system, with a Risk Priority Number (RPN) of 180. Failure in the secondary combustion leads to increased smoke emissions and reduced thermal efficiency. A basic Computational Fluid Dynamics (CFD) simulation indicates that the distribution of secondary air needs to be optimized to ensure complete pyrolysis and oxidation, in line with the findings of Zhang et al. (2020).

In the air control system, an RPN of 160 is attributed to valve malfunction due to ash accumulation and hinge corrosion. Although the valve has been redesigned for easier cleaning, preventive measures such as the use of anti-corrosive materials and sensor-based automation as suggested by Wang et al. (2018) are still necessary to improve reliability. Meanwhile, the structure and insulation system recorded an RPN of 84, with the potential risk of heat leakage to the outer surface. The use of materials such as ceramic wool (>1000°C) has proven effective in maintaining thermal efficiency and user safety, as noted by Li & Tan (2016).

On the other hand, the access and maintenance system showed a relatively low RPN (54), but still requires attention to ergonomics, prompting the adoption of a quick-lock system to facilitate servicing and cleaning. The safety and portability system, despite having the highest severity level (S = 10), showed a low RPN (60) due to the implementation of wide-legged design and low center of gravity, in compliance with ISO 19867-1:2018 standards. As for the production and fabrication system, issues with welding joints and cutting precision resulted in an RPN of 63, which has been addressed through the use of jigs and quality control procedures, supporting Luo et al. (2022)'s findings on the importance of fabrication accuracy in thermal device performance. These findings emphasize that design interventions based on risk analysis can significantly improve system reliability and enhance safety standards in portable thermal equipment.

4. Conclusion

Based on the FMEA analysis of the downdraft gasification stove with dual combustion chambers, the following conclusions can be drawn:

1) The highest failure risk lies in the combustion system (RPN 180), due to suboptimal secondary air distribution, followed by the air control system (RPN 160) due to potential valve blockage and corrosion.
2) Other systems, such as insulation structure, maintenance access, safety, and fabrication, have RPN values below 100, indicating medium to low risk. However, they still require design improvements and quality control.
3) The application of the FMEA method is effective in identifying improvement priorities for critical components that affect system efficiency and safety.
4) Technical recommendations include optimizing airflow design using CFD simulations, using high-temperature-resistant insulation materials, applying a quick-lock system for maintenance access, and enforcing quality control in the production process.

Through risk-based interventions, the thermal efficiency, reliability, and safety of the stove can be significantly improved, making it an appropriate technological solution for the sustainable utilization of biomass energy.

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