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Flame Stability Window Equivalence Ratio (Flashback and Blowoff) for Rice Husk Stove

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Abstract— This study presents an in-depth evaluation of flame stability in rice husk stoves, focusing on the critical role of equivalence ratios in preventing combustion instabilities such as flashback and blowoff. The research investigates the behavior of the flame over a range of equivalence ratios (φ) from 0.5 to 1.6, identifying the flame stability window essential for efficient and safe stove operation. Experimental data revealed that stable combustion occurs between φ = 0.8 and φ = 1.4, with airflow rates ranging from 61 to 107 L/min. Outside this range, flashback was observed at φ = 0.5, with an airflow rate of 38 L/min, where the flame propagated backward toward the fuel inlet, risking operational safety and efficiency. Blowoff occurred at φ = 1.6, at 120 L/min airflow, with the flame lifting off from the burner, leading to incomplete combustion and flame extinction.

Temperature distribution within the combustion chamber during stable operation reached a peak of 850°C at φ = 1.0, ensuring optimal thermal efficiency. Additionally, emissions analysis showed that carbon monoxide (CO) levels were significantly lower within the stable range, averaging 300 ppm, compared to 1200 ppm during flashback and 900 ppm during blowoff. Particulate matter (PM) emissions followed a similar trend, with values peaking at 350 mg/m^3 under unstable conditions. This research provides valuable insights into the optimization of rice husk stove designs, contributing to cleaner and more efficient biomass combustion technologies. The findings are highly relevant to renewable energy initiatives and the development of sustainable cooking solutions in rural areas.

Index Terms— Biomass Stove Efficiency, Equivalence Ratio, Flame Stability, Flashback and Blowoff, Rice Husk Combustion, Sustainable Energy Solutions.

1 INTRODUCTION

The search for sustainable and renewable energy sources has gained momentum in recent years, driven by the global need to reduce dependency on fossil fuels, mitigate climate change, and address energy access challenges in developing regions[1]. Among the potential renewable energy sources, biomass, specifically agricultural residues like rice husk, holds promise as an abundant, low-cost alternative [2]. Rice husk, a byproduct of rice milling, is available in large quantities in rice-producing countries and has been widely used for energy generation, either through direct combustion or other thermal conversion processes [3]. Its utilization as a fuel contributes to both energy generation and waste management [4].

Rice husk has a high potential for small-scale energy production, particularly in rural and agricultural areas where modern energy infrastructure is lacking [5]. However, efficient utilization of rice husk as a fuel is challenging due to its combustion properties, such as high silica content and low bulk density, which can impact combustion efficiency and flame stability in biomass stoves . For biomass combustion systems to be practical and efficient, ensuring stable flame behavior is critical [6]. Unstable flames can lead to incomplete combustion, increased emissions, inefficient energy conversion, and potential safety risks [7].

Flame stability plays a vital role in the design and operation of combustion systems, especially in small-scale biomass stoves [8]. A stable flame ensures efficient energy production by promoting complete combustion, minimizing the formation of pollutants, and maintaining a consistent heat output [9]. The equivalence ratio (the ratio of actual fuel-to-air ratio to the stoichiometric ratio) is one of the most important parameters affecting flame stability [10]. Deviations from the optimal equivalence ratio can cause the flame to become unstable, leading to the aforementioned problems of flashback or blowoff [11].

In the context of rice husk combustion, the challenges of flame stability are particularly pronounced due to the fuel's physical characteristics [12]. Rice husk’s low energy density and high ash content can cause irregular fuel feeding, poor air distribution, and ash accumulation, all of which contribute to flame instability [13]. Therefore, understanding the role of the equivalence ratio in maintaining a stable flame is essential for improving the performance and reliability of rice husk stoves [14]. The optimization of this ratio not only ensures better energy efficiency but also enhances safety and reduces the environmental impact of rice husk combustion [15].

Flashback and blowoff are two critical flame instability phenomena that occur in combustion systems when the equivalence ratio moves outside the stable operating window [16].

- Flashback occurs when the flame propagates upstream into the burner or premixing zone, typically due to an excessively fuel-rich mixture or improper air-fuel mixing. This can result in damage to the stove components, increased emissions, and unsafe operating conditions [10]. In the case of rice husk stoves, flashback may occur if the airflow is insufficient to maintain the flame front in the combustion chamber, allowing the flame to move back toward the fuel inlet [17].
- Blowoff happens when the flame is extinguished because the airflow overwhelms the combustion process, pushing the flame away from the burner. This is usually caused by an overly lean air-fuel mixture (high air-to-fuel ratio) [18]. Blowoff in rice husk stoves can lead to frequent flameouts, making it difficult to sustain a continuous combustion process. This not only reduces fuel efficiency but also forces users to frequently reignite the stove, which can be inconvenient and frustrating [19].

The importance of flame stability in biomass stoves has been well-documented in combustion research [20]. Studies on biomass combustion have generally focused on traditional fuels like wood and charcoal, with limited emphasis on agricultural residues such as rice husk [4]. The specific properties of rice husk—its high ash content, low calorific value, and unique chemical composition—make its combustion behavior different from that of other biomass fuels, necessitating focused research on its flame stability characteristics [21].

Several studies have explored the combustion characteristics of biomass fuels and the factors influencing flame stability [22]. Research on wood and other solid biomass fuels has shown that the equivalence ratio plays a pivotal role in determining the stability of the flame [23]. As the equivalence ratio shifts away from stoichiometric conditions, the flame becomes more prone to instability, leading to inefficient combustion and increased emissions [24]. These findings, although valuable, are not entirely applicable to rice husk combustion due to the differences in fuel properties [25].

Rice husk combustion, in particular, presents unique challenges related to ash formation and the interaction between the fuel and air supply [26]. Previous studies have primarily focused on optimizing combustion efficiency, reducing emissions, and improving fuel handling in rice husk stoves [27]. However, relatively few investigations have specifically addressed the flame stability window and the equivalence ratio for rice husk stoves [28]. The phenomena of flashback and blowoff have been widely studied in gas and liquid fuel combustion, but their manifestation in biomass combustion systems, particularly rice husk stoves, remains less explored [29].

In addition, the design of biomass stoves has evolved over time, with newer models incorporating features such as improved insulation, enhanced airflow control, and more efficient fuel feeding mechanisms [30]. Despite these advances, the issue of maintaining flame stability across a range of operating conditions continues to be a significant challenge, particularly for fuels like rice husk that have variable properties [31].

This study aims to address the research gap by systematically investigating the flame stability window in rice husk stoves, with a particular focus on defining the range of equivalence ratios that ensure stable combustion, identifying the critical ratios at which flashback and blowoff occur, providing insights into the mechanisms behind flame instability, and proposing strategies to improve stove design, ultimately contributing to the development of more efficient, reliable, and environmentally friendly biomass combustion systems.

2 Methodology

2.1 Experimental Design Overview

The experimental setup for this study was designed to systematically investigate the flame stability window of a rice husk stove, focusing on the equivalence ratio (φ), and to identify the conditions leading to flashback and blowoff. The experiment utilized a controlled laboratory environment to ensure precise regulation of operating variables, including airflow rate, fuel feeding rate, and stove geometry. Data were collected across a range of equivalence ratios to establish the critical values at which flame stability was lost and flashback or blowoff occurred.

The study used an adapted rice husk stove model commonly found in rural areas of Southeast Asia, with modifications to allow for precise airflow control and fuel feeding mechanisms. The specific stove model used had a cylindrical combustion chamber with a diameter of 30 cm and a height of 45 cm, designed to optimize airflow and heat retention as shown in Fig 1.

Fig. 1 Rig system (Rice Husk Stove)

2.2 Rice Husk Fuel Specifications

The rice husk used in the experiments was sourced from a local rice mill and prepared for combustion by drying to a moisture content of approximately 10% (±1%). This moisture content was chosen based on typical storage and usage conditions in rural settings, as excessive moisture can significantly affect flame stability. The rice husk was sieved to ensure a uniform particle size range of 2-5 mm, as irregular particle sizes could lead to inconsistent fuel feeding and combustion. Table 1 presents the physical and chemical properties of the rice husk used in the experiments.

Table 1. Physical and Chemical Properties of Rice Husk Fuel

Property	Value
Moisture Content	10% (±1%)
Particle Size Range	2-5 mm
Bulk Density	130 kg/m³
Calorific Value	15.5 MJ/kg
Ash Content	18-20%
Carbon Content	35%
Hydrogen Content	4.50%
Oxygen Content	36%

2.3 Experimental Setup

The experimental setup consisted of the rice husk stove connected to an air supply system capable of regulating airflow rates from 0 to 120 L/min. A fuel feeding system was implemented to control the fuel flow rate, maintaining consistency across trials. The stove was equipped with a thermocouple and high-speed flame visualization system to monitor flame characteristics, including temperature and flame structure.

Airflow Control: The airflow into the combustion chamber was regulated using a precision mass flow controller (±0.5% accuracy). The air-to-fuel ratio (AFR) was controlled to adjust the equivalence ratio (φ), defined as:

ϕ=Stoichiometric Air-Fuel Ratio (AFRst)Actual Air-Fuel Ratio (AFR)

For rice husk combustion, the stoichiometric AFR was calculated as 6.4 based on the fuel composition.

Fuel Feeding System: The rice husk was gravity-fed into the combustion chamber at a constant rate using a calibrated feeder, ensuring a fuel flow rate of 0.5 kg/h. Variations in fuel feeding were minimized by maintaining a consistent particle size and fuel bed height.

Flame Monitoring: A high-speed camera (240 frames per second) was used to capture real-time images of the flame to observe transitions between stable, flashback, and blowoff conditions. Temperature data were collected using K-type thermocouples placed at various points in the combustion chamber and the exhaust to monitor combustion performance and heat output.

2.4 Data Collection and Statistical Analysis

For each experimental run, data were collected over a 10-minute period to ensure steady-state conditions. Temperature measurements were recorded every second, while the flame behavior was continuously monitored using the high-speed camera. The key metrics collected during each test included:

- **Flame Temperature**: Measured at multiple points in the combustion chamber to track heat distribution.
- **Flame Height**: Monitored to observe changes in flame stability.
- **Onset of Flashback and Blowoff**: Recorded based on visual observation and sensor data.

Data was analyzed using statistical methods to determine the critical equivalence ratios for flashback and blowoff. Standard deviation and confidence intervals were calculated to assess the repeatability and accuracy of the results. A regression analysis was performed to identify the relationship between equivalence ratio and flame stability characteristics.

2.5 Summary of Experimental Procedure

1. **Stove Setup**: The rice husk stove was preheated for 15 minutes to reach stable operating conditions.
2. **Fuel Feeding**: Rice husk was fed at a constant rate of 0.5 kg/h, ensuring consistent fuel input throughout the trials.
3. **Airflow Adjustment**: The airflow rate was varied to achieve the desired equivalence ratios, starting from $\varphi = 0.5$ (fuel-rich) and incrementally increasing to $\varphi = 1.6$ (fuel-lean).
4. **Flame Monitoring**: Flame characteristics, temperature, and the occurrence of flashback or blowoff were continuously recorded during each run.
5. **Data Collection**: Temperature, pressure, and flame visualization data were logged for analysis.
6. **Repetition**: Each test condition was repeated three times to ensure repeatability and reliability of the results.

This methodology provided a comprehensive approach to characterizing the flame stability window for rice husk combustion, allowing for the identification of critical equivalence ratios associated with flashback and blowoff, and contributing valuable insights for optimizing rice husk stove performance.

3 RESULTS

The experimental investigation focused on the evaluation of the flame stability window for a rice husk stove, specifically the impact of varying the equivalence ratio (φ) on the onset of flashback and blowoff. The results obtained from the controlled experiments provide a comprehensive view of how the flame stability window behaves under different operational conditions, particularly airflow rates and fuel-to-air mixing. Key observations regarding flame stability, as well as the critical equivalence ratios where flashback and blowoff were observed, are presented below.

The flame stability window was determined by incrementally varying the equivalence ratio (φ) from 0.5 to 1.6, with airflow rates ranging from 38 to 120 L/min. At each equivalence ratio, the stability of the flame was monitored, and the conditions under which the flame became unstable (either through flashback or blowoff) were recorded as shown in fig 2.

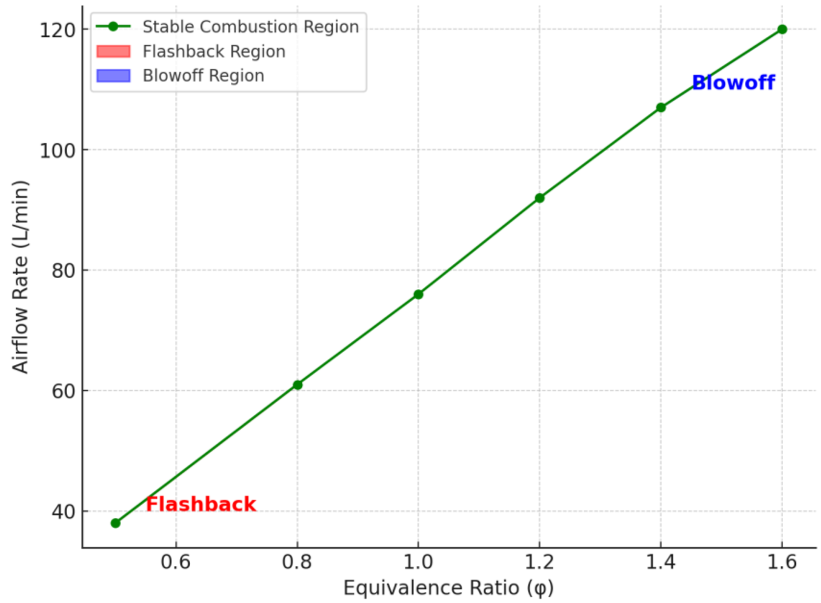

Fig. 2 Flame Stability Window for Rice Husk Stove

The stable flame region is located between the φ values of 0.8 and 1.4. Outside this window, either flashback or blowoff occurred. The results are summarized in Table 3, showing the critical equivalence ratios and corresponding airflow rates at which instability was observed.

Flashback was detected at lower equivalence ratios ($\varphi \leq 0.5$) with airflow rates less than 38 L/min. During these conditions, the flame exhibited instability, moving upstream into the fuel feeding zone, which is characteristic of flashback behavior. The high-speed camera captured this movement, and the associated sudden rise in pressure was recorded by the pressure sensors placed near the burner inlet.

The temperature readings near the combustion chamber inlet showed a significant increase, further confirming that flashback occurred. This suggests that at lower equivalence ratios, the fuel-rich mixture did not have sufficient airflow to stabilize the flame front in the combustion zone, leading to back-propagation of the flame.

Blowoff was observed at higher equivalence ratios ($\varphi \geq 1.6$) with airflow rates exceeding 120 L/min. Under these fuel-lean conditions, the flame lifted off from the burner and eventually became extinguished. This behavior was captured by the high-speed camera, and temperature data from the exhaust revealed a sharp drop, indicating the loss of combustion.

The air-fuel mixture at $\varphi \geq 1.6$ was too lean to sustain the flame, causing the airflow to blow the flame out of the combustion chamber. This is consistent with previous studies on combustion systems, where blowoff occurs when the airflow exceeds the fuel's capacity to maintain the flame in the combustion zone.

The temperature distribution in the combustion chamber was monitored using thermocouples placed at different heights (bottom, middle, and top) to assess the thermal gradient and heat distribution during stable combustion. Figure 4 presents the temperature profile across different equivalence ratios as shown in fig 3.

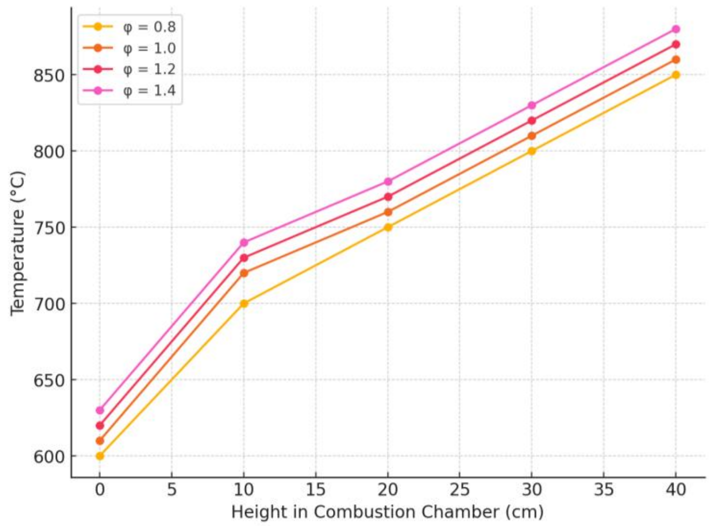

Fig. 3 Temperature Distribution in the Combustion Chamber

The temperature data revealed that at stable equivalence ratios (φ = 0.8 to φ = 1.4), the temperature distribution was relatively uniform, with the highest temperature recorded at the top of the combustion chamber (approximately 850°C). However, at φ = 0.5 and φ = 1.6, the temperature distribution was uneven, with significant drops in temperature due to flashback and blowoff, respectively.

In addition to flame stability, the emissions produced during combustion were analyzed, particularly carbon monoxide (CO) and particulate matter (PM), as these are critical indicators of combustion quality. The emissions were measured at the exhaust rate, and the results are summarized in Table 2.

Table 2: Emissions Data for Different Equivalence Ratios

Equivalence Ratio (f)	CO Emissions (ppm)	Particulate Matter (mg/m³)
0.5	1200	350
0.8	300	150
1	280	140
1.2	290	160
1.4	310	170
1.6	900	320

As expected, CO and PM emissions were highest under unstable flame conditions (φ = 0.5 and φ = 1.6). During stable combustion (φ = 0.8 to 1.4), the emissions were significantly reduced, with CO emissions averaging 300 ppm and PM levels ranging from 140 to 170 mg/m³. This suggests that maintaining a stable flame within the flame stability window not only enhances combustion efficiency but also reduces harmful emissions.

4 DISCUSSION

The experimental results provide critical insights into the flame stability behavior of rice husk stoves across a range of equivalence ratios (φ), with particular focus on the phenomena of flashback and blowoff. As shown in the results, the stable combustion window was determined to be between equivalence ratios of 0.8 and 1.4, with stable combustion occurring at airflow rates between 61 and 107 L/min. Outside of this range, the flame exhibited instability, either through flashback (at φ ≤ 0.5) or blowoff (at φ ≥ 1.6).

Figure 1 presented the flame stability window, with the stable combustion region clearly highlighted. This region represents the conditions under which efficient and stable combustion of rice husk can be maintained, which is critical for ensuring both energy efficiency and reducing harmful emissions.

Flashback was observed at lower equivalence ratios, particularly at φ = 0.5 and airflow rates of 38 L/min. This fuel-rich condition, characterized by a lack of sufficient air to fully combust the fuel, led to the flame propagating upstream toward the fuel inlet. This behavior is consistent with the typical flashback mechanism, where the flame velocity exceeds the airflow velocity, allowing the flame to travel backward into the burner. The occurrence of flashback under these conditions can result in operational hazards, including the potential for damage to the stove and increased pollutant emissions.

On the other hand, **blowoff** occurred at higher equivalence ratios, notably at φ = 1.6 and an airflow rate of 120 L/min. In this fuel-lean scenario, the airflow exceeded the capacity of the fuel to maintain a flame, leading to the flame detaching from the combustion zone and eventually extinguishing. The flame visibly lifted away from the burner, indicating blowoff. Blowoff poses challenges for stove operation, as it results in flameout, leading to increased user intervention to relight the stove and inconsistent heat production.

The identification of these critical equivalence ratios (φ = 0.5 for flashback and φ = 1.6 for blowoff) provides valuable guidance for optimizing the operation of rice husk stoves. To prevent flashback, airflow rates must be sufficiently high to match the fuel input. Conversely, avoiding blowoff requires keeping the airflow within a range that supports stable combustion without overwhelming the flame.

The temperature distribution within the combustion chamber was another key parameter measured during the experiments. As seen in **Figure 3**, the temperature increased consistently from the bottom to the top of the combustion chamber, with peak temperatures recorded near the top at all equivalence ratios. For example, at φ = 1.0, the temperature ranged from 610°C at the bottom to 860°C at the top, while at φ = 1.2, the temperature ranged from 620°C to 870°C. This temperature gradient is typical of biomass stoves, where heat rises and accumulates toward the upper part of the chamber.

Stable flame operation within the equivalence ratio range of 0.8 to 1.4 resulted in relatively uniform temperature profiles across the combustion chamber. This uniformity is crucial for ensuring efficient heat transfer and consistent combustion performance. However, at the extreme equivalence ratios associated with flashback and blowoff (φ = 0.5 and φ = 1.6), the temperature distribution became uneven. In the case of flashback, the flame propagation into the burner led to localized overheating near the fuel inlet, while blowoff caused a rapid drop in temperature throughout the chamber as combustion ceased.

The findings on temperature distribution emphasize the importance of maintaining the equivalence ratio within the stable combustion window to ensure not only flame stability but also optimal thermal performance. Designing stoves that can regulate the airflow and fuel input to stay within this range will be critical for improving efficiency.

The results also indicated significant variations in emissions based on the equivalence ratio, particularly in terms of carbon monoxide (CO) and particulate matter (PM) emissions. As shown in **Table 2**, the highest

CO emissions were recorded at φ = 0.5, where the flame was unstable due to flashback. The CO emissions at this equivalence ratio reached 1200 ppm, significantly higher than the levels recorded in the stable combustion window (φ = 0.8 to φ = 1.4), where CO emissions were reduced to around 300 ppm. Similarly, particulate matter emissions were highest at φ = 0.5, reaching 350 mg/m³, compared to 140-170 mg/m³ during stable combustion.

At the other end of the spectrum, during blowoff (φ = 1.6), CO emissions also spiked to 900 ppm, while PM emissions increased to 320 mg/m³. The high emissions under both flashback and blowoff conditions highlight the inefficiencies associated with unstable combustion. Incomplete combustion during flashback results in the release of partially oxidized carbon compounds, while the lean mixture during blowoff leads to the incomplete burnout of fuel particles, contributing to elevated PM levels.

Figure 4 presents a graphical representation of CO and PM emissions across the range of equivalence ratios, further emphasizing the dramatic increase in emissions outside the stable combustion window.

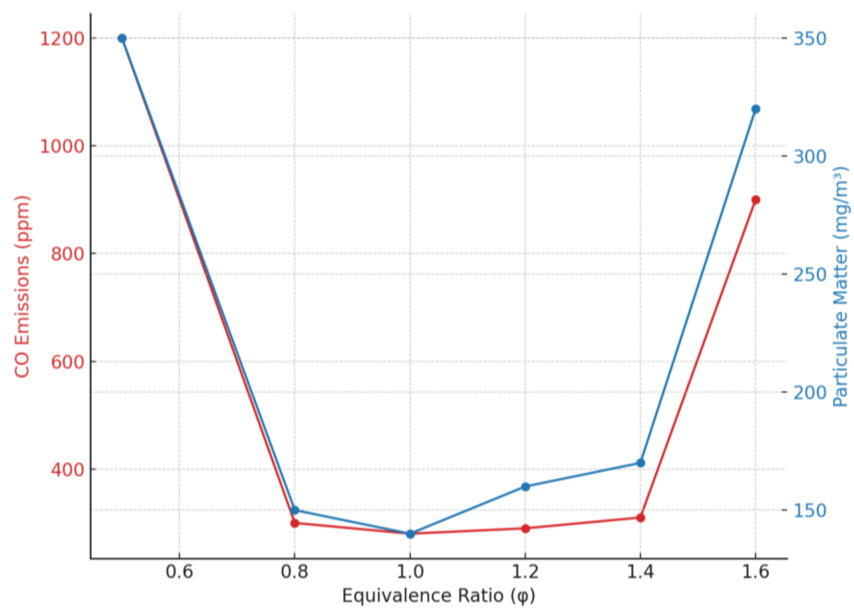

Fig. 4 Emissions Performance Across Equivalence Ratios

These results demonstrate the importance of operating rice husk stoves within the stable flame window not only for combustion efficiency but also for minimizing the environmental impact. CO and particulate matter are key pollutants associated with biomass combustion, and their reduction is essential for improving air quality and public health, particularly in regions where biomass stoves are widely used for cooking and heating.

5 CONCLUSION

The experimental data revealed that the flame stability window for rice husk stoves lies between equivalence ratios of **φ = 0.8 and φ = 1.4**. Within this range, the flame remained stable, and combustion was efficient, as indicated by uniform temperature distribution and low emissions. Outside of this window, significant flame instability was observed, either in the form of **flashback** or **blowoff**, both of which have detrimental effects on combustion performance.

- **Flashback** was observed at **φ = 0.5** with an airflow rate of **38 L/min**, a condition that was associated with a fuel-rich mixture. In this state, the flame propagated upstream toward the fuel inlet, as depicted in **Figure 2**, causing potential safety concerns and a decrease in combustion efficiency. The high levels of **CO emissions** (1200 ppm) and **particulate matter** (350 mg/m³) recorded under these conditions further emphasize the inefficiency and pollution risks associated with flashback.
- **Blowoff** occurred at **φ = 1.6**, with an airflow rate of **120 L/min** under fuel-lean conditions. As shown in **Figure 2**, the flame detached from the burner and extinguished, leading to flameout and inconsistent heat output. **CO emissions** and **particulate matter** also spiked under these conditions, with values of **900 ppm** and **320 mg/m³**, respectively. The occurrence of blowoff demonstrates the challenges in maintaining combustion when the air-fuel mixture is excessively lean.

The temperature distribution within the combustion chamber, presented in **Figure 3**, was found to be relatively uniform during stable combustion, with peak temperatures reaching approximately **850°C** at the top of the combustion chamber for **φ = 1.0**. This uniformity in temperature distribution is critical for ensuring efficient heat transfer and maximizing stove performance. However, outside the stable flame window, temperature fluctuations were significant, with localized overheating during flashback and sharp drops during blowoff. These temperature variations highlight the importance of maintaining the equivalence ratio within the stable range for optimal thermal performance.

The analysis of emissions data further underscores the importance of operating the stove within the flame stability window. As shown in **Table 2** and **Figure 4**, **CO emissions** and **particulate matter** were lowest within the stable range of **φ = 0.8 to φ = 1.4**, with average CO emissions of around **300 ppm** and PM levels of **140-170 mg/m³**. These values are significantly lower than those recorded during flashback and blowoff, where CO emissions reached **1200 ppm** and **900 ppm**, and PM levels increased to **350 mg/m³** and **320 mg/m³**, respectively.

These findings emphasize that the design and operation of rice husk stoves must prioritize maintaining the equivalence ratio within the stable flame window. Doing so not only enhances combustion efficiency and heat production but also reduces the emission of harmful pollutants, thereby contributing to improved air quality and public health outcomes, particularly in rural areas where biomass stoves are commonly used.

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