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Experimental Study of the Effect of Pressure and Temperature on the Performance Efficiency of a Mini Biomass Stove

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ABSTRACT: Access to efficient and clean cooking energy is a critical concern, particularly in rural regions where biomass burning is still widespread. This research conducts empirical tests with the aim of ascertaining the impacts of air pressure and initial fuel temperature on the thermal efficiency of the mini biomass cooker. A standard Water Boiling Test (WBT v4.2.3) was performed under different air pressures (10, 20, and 30 Pa) and different fuel temperatures (27°C, 40°C, and 60°C) to simulate different performance conditions. From the results, it was seen that as both air pressure and initial fuel temperature increased, the thermal efficiency greatly improved. The maximum thermal efficiency of 89.37% was obtained at 30 Pa and 60°C, which was also the lowest fuel consumption of 18.49 grams and the shortest boiling time of 8.11 minutes. The rise in flame temperature was solely due to a decrease in boiling time and improved heat transfer. These results validate that maximizing operational conditions like airflow and fuel preheating has the potential to enhance combustion efficiency significantly without any alteration in the design of the stove. This study offers beneficial knowledge for the design and optimization of biomass cooking stoves, making it easier to develop more efficient, cleaner, and more sustainable household energy sources

KEYWORDS: Thermal efficiency, Biomass stove, Airflow control, Fuel preheating, Renewable energy

INTRODUCTION

In recent decades, access to clean and sustainable energy has been one of the main concerns across the world, especially in relation to sustainable development and the reduction of greenhouse gas emissions (Sabie, 2022). It is about 2.6 billion people worldwide who still rely on traditional fuels such as wood, charcoal, and crop residues to cook daily, usually in low-efficiency and high-emission traditional cookstoves (Sedighi & Salarian, 2017). The incomplete combustion of these fuels is a major cause of indoor air pollution, deforestation, and a huge number of respiratory diseases, causing more than 3 million premature deaths annually (Orange et al., 2012). Improving the thermal efficiency and reducing emissions of biomass-based stoves are the basic means to contribute towards mitigating these negative impacts.

One such extensively researched technique is the development of improved cookstoves (ICS) that utilize new design and operating parameters such as airflow (pressure) and initial fuel temperature to improve thermal performance (Umogbai & Orkuma, 2011) (Bailis et al., 2007). Although there are designs that have registered efficiency improvements of up to 67% compared to conventional three-stone stoves (Umogbai & Orkuma, 2011), most studies still place more emphasis on structural design and type of fuel, as opposed to considering pressure and temperature dynamics as pertinent parameters for controlling performance.

The main question answered in this study is the disparity between the theoretical potential thermal efficiency of the biomass stoves and their performance under real conditions. Standard test methods like the Water Boiling Test (WBT) are likely to yield high variance in test results because of factors such as air pressure from the blower and starting temperature of fuel not systematically controlled (Orange et al., 2012) (Zhang et al., 2016). Also, the majority of the tests disregarded the complex interactions between airflow, temperature of the flame, and fuel type affecting heat exchange within the combustion chamber (Sedighi & Salarian, 2017).

Theoretically, the pressure generated by the blower is directed towards improving the oxygen diffusion rate in the combustion region, which rapidly oxidizes the fuel and raises the flame temperature (Rahmadani et al., 2020). On the other hand, the original temperature of the fuel affects the start time of the pyrolysis reaction, which is the first stage of energy conversion in biomass combustion systems (Aryanto et al., 2019). Sedighi & Salarian, (2017) recognized the significance of maintaining a balance between primary and secondary air supply to optimize the gasification process in TLUD and downdraft stoves. Mahmood et al. (2022) confirmed that through the application of primary and secondary air supply parameters, thermal efficiency could be increased without necessarily demanding significant structural modifications.

The novelty of this study is in the experimental method that isolates and quantitatively analyzes the influence of air pressure changes and fuel start temperature on mini biomass stoves' thermal efficiency, a stove that has not been well-addressed in recent literature. In comparison with the work by Umogbai & Orkuma (2011), which was based on comparing fuel usage and boiling time between three-stone stoves and ICS only, this research attempts to analyze the impact of dynamic parameters susceptible to modification in the course of the operation. Other than that, the current research also provides deeper knowledge concerning the relationship between flame temperature, time, and heat transfer efficiency that has not been highly unveiled in the traditional WBT procedure by Zhang et al (2016).

The relevance of this study arises from the need to develop scientifically sound, experiment-based data that will form the basis for designing biomass stoves better suited to addressing local needs and prevailing fuel conditions, especially relating to clean energy technology adoption at the household level, in the rural and peri urban environments. Therefore, the main objective of this study is to experimentally investigate the influence of air pressure and initial fuel temperature on the thermal efficiency of mini biomass stoves. It is anticipated that this study shall not only make theoretical contributions to the discipline of energy engineering and heat conversion but also have practical contributions in terms of design parameters that can be implemented at the community level towards enhancing the use of more efficient, clean, and sustainable renewable energy.

METHOD

A. *Experimental Design*

This study employed a quantitative experimental design through direct testing of a mini biomass stove under controlled laboratory conditions (Ambara, 2025). The objective was to evaluate the impact of air pressure differences and fuel initiation temperature on the thermal efficiency of the stove. Testing was conducted using the standard Water Boiling Test (WBT) version 4.2.3, widely employed in testing the efficiency of biomass stoves (Yuliati & Hamidi, 2019).

The experimental procedure utilized two independent variables: fuel starting temperature (room temperature, 40°C, and 60°C) and air pressure (supplied by a blower with three speeds: low, medium, and high). The dependent variable for this study was thermal efficiency. The treatment combinations were repeated three times to give an average value and minimize possible bias in the readings

B. *Equipment And Materials*

1. Small Biomass Stove: Modified version of the downdraft type, with a heat-resistant metal combustion chamber.
2. Energy Source: Wood pellets having a moisture level of between 10 and 12 percent.
3. Blower: Adjustable speed 12V DC blower.
4. T-type thermocouple: For the measurement of flame temperature.
5. Digital scale (accuracy 0.01 g): For measuring the fuel weight.
6. Stopwatch: To track the boiling time.
7. Thermal Hygrometer: To record the starting temperature of the fuel, and the state outside.

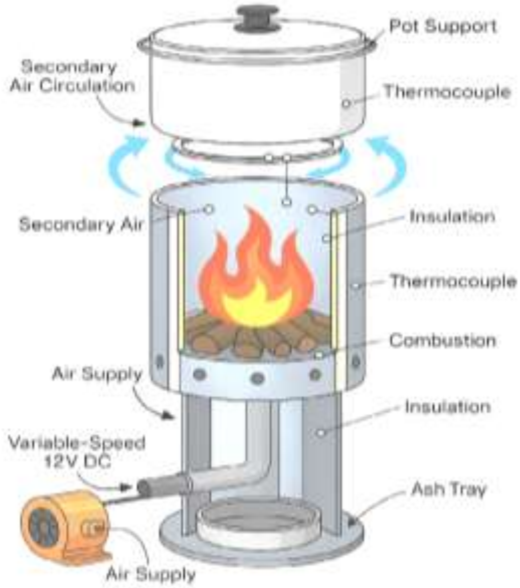

Figure 1. Cross-sectional Diagram of the Biomass Mini Stove Experimental Setup

C. *Testing Procedure*

The testing procedure begins with weighing 500 grams of wood pellets that will serve as fuel for each treatment. One liter of water was prepared in a standard, high thermal conductivity metal pot for uniform heat distribution for heating. A heater was utilized prior to testing to set the initial fuel temperature until a predetermined temperature was reached. Then, the blower was switched on with speed adjusted based on the treatment variation, i.e. low, medium, or high. The stove was lit, and the time when it was started and the initiation of the process of heating the water were recorded. The test continued with monitoring the temperature of the water until it reached the boiling point, which is 100°C. Once the water came to a boil, the operation was halted and the remaining fuel weighed in order to figure out how much was consumed during the experiment.

D. *Data Analysis*

The efficiency of heat is determined by relating the energy the water receives to the energy obtained from the burning of fuel. The formula for this equation is adopted from Jetter et al (2012), the formula is as follows :

$$\eta = \frac{m.C_p.\Delta T}{m_b.HHV} \times 100\% \dots (1)$$

Where:

H : Thermal efficiency (%)
M : Mass of water (kg)
Cp : Specific heat of water (4,186 kJ/kg°C)
ΔT : Water temperature rise (100°C)
Mb : Mass of fuel used (kg)
HHV : Calorific value of fuel (wood pellets ≈ 19 MJ/kg)

While the fuel consumption rate is calculated by the formula quoted from L'orange and Willson, 2011 as follows

$$\dot{m}_b = \frac{m_{b_{beginning}} - m_{b_{end}}}{t} \dots (2)$$

The data and analysis findings that have been obtained will be presented graphically together with their interpretation to reflect the real situation that is present in accordance with the research results.

RESULTS AND DISCUSSION

A. Result

The following table provides measurement data of flame temperature, boiling time, fuel consumption, and thermal efficiency for various air pressure and fuel starting temperature combinations.

Table 1. Summary of Experimental Results

Air Pressure (Pa)	Initial Fuel Temp (°C)	Flame Temp (°C)	Boiling Time (minutes)	Fuel Consumption (g)	Thermal Efficiency (%)
10	27	918.47	15.16	202.48	8.16
10	40	935.23	13.77	167.66	9.86
10	60	945.79	12.77	125.31	13.19
20	27	968.93	12.84	141.34	11.69
20	40	972.42	10.09	102.75	16.08
20	60	974.38	8.99	83.14	19.87
30	27	1004.42	9.89	110.66	14.93
30	40	1017.74	10.07	55.75	29.64
30	60	1024.56	8.11	18.49	89.37

1. ***Pressure and Temperature Effect on Thermal Efficiency***

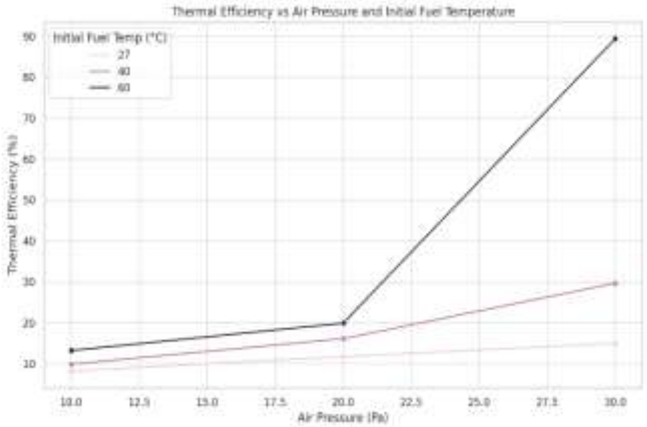

Figure 2. Effect of Air Pressure and Initial Fuel Temperature on Thermal Efficiency

The second graph demonstrates an increasing trend of thermal efficiency with increasing air pressure supplied by the blower, and with increasing initial temperature of fuel, increasing efficiency achieved.

The maximum efficiency was achieved at the operating condition of 30 Pa pressure and 60°C starting temperature with a reading of 89.37%, and the minimum efficiency was achieved at 10 Pa pressure and 27°C temperature with a reading of 8.16%. This is in line with research by Sedighi & Salarian, (2017) who concluded that the increase in air pressure increases the process of diffusion of oxygen, thereby improving the quality of combustion.

2. ***Relationship between Flame Temperature and Boiling Time***

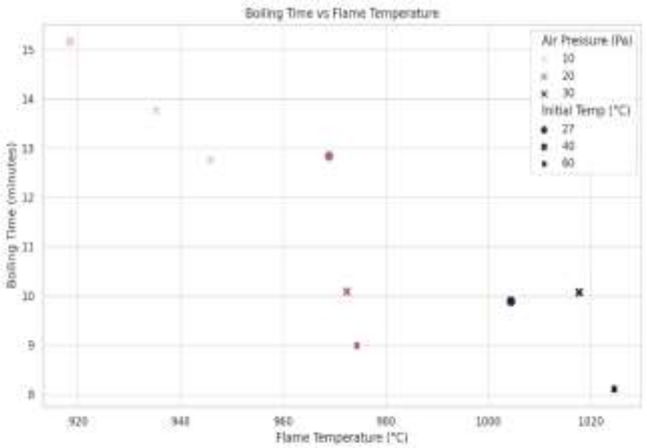

Figure 3. Relationship Between Flame Temperature and Boiling Time

The third graph illustrates the inverse relation between boiling time and flame temperature: the greater the flame temperature achieved by the stove, the less time it will take for water to boil. This is consistent with basic principles of thermodynamics as well as with the results of a study by Orange et al. (2012), on the necessity to develop operating parameters for minimizing the heating time.

3.Fuel Consumption and Energy Efficiency

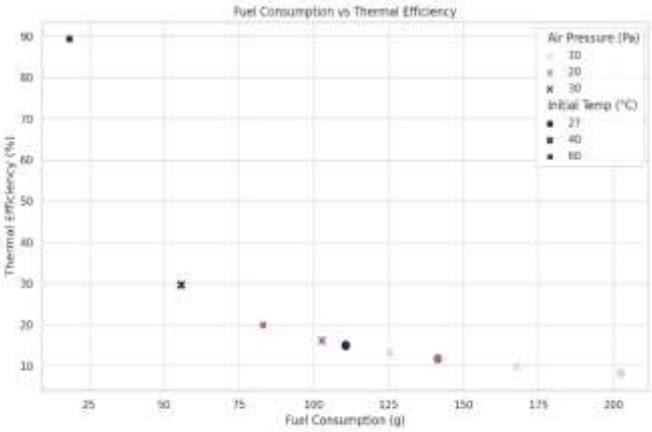

Figure 3. Correlation Between Fuel Consumption and Thermal Efficiency

There is a strong relationship between fuel consumption and thermal efficiency. Fuel consumption is substantially decreased when the engine is operated at higher temperatures and pressures. As an example, under severe conditions (30 Pa, 60°C), 18.49 g of fuel is sufficient to boil water by heating, whereas at the lowest pressure and temperature, 202.48 g is consumed. This shows that high efficiency can be achieved with the proper control of airflow and fuel thermal initial conditions.

B. Discussion

The results of this study show that increased air pressure and increased fuel ignition temperature significantly improve the thermal efficiency of the mini biomass stove. The results can be described in thermodynamic and biomass combustion kinetic terms. A higher temperature of the flame supports the oxidation reaction, while higher air pressure from the blower increases oxygen supply, reduces the area of incomplete combustion, and accelerates the process of chemical energy transformation into thermal energy. The combined effect of these two factors creates ideal conditions for efficient and clean burning.

The peak efficiency reached was 89.37% when the pressure was 30 Pa and the initial temperature was 60°C, showing tremendous potential in working conditions maximization without requiring elaborate structural redesigning. This is several times the published value of efficiency by Umogbai & Orkuma (2011), where the highest efficiency for ICS stoves tested was a mere 67%. This comparison verifies that pressure and temperature control strategies are making a real contribution to efficiency gains.
Orange et al (2012), investigations demonstrated that biomass stove testing outcomes are highly dictated by controllable variables such as the airflow speed and fuel water content. For this purpose, the original high fuel temperature plays a triggering function of lowering the initial pyrolysis reaction's activation energy, thus increasing the combustion process at a faster rate and saving fuel. This concept is compatible with the original Arrhenius principle, on the basis of which an increase in temperature equals an exponential increase in the velocity of chemical processes.

In general, the considerable decrease in water's boiling time under conditions of high temperature and pressure demonstrates that heat energy is transferred more intensively to the hot medium, i.e., water, with less heat lost to the environment. This outcome is consistent with the research findings of Aryanto et al (2020), which reported how the efficiency of the stove can be increased up to 51% through air outlet design and air supply factor, although the obtained efficiency is still not close to the highest value observed in this study.

The consequences of these findings for the design of future biomass stoves are of critical practical importance to rural and developing nations that have not yet abandoned the use of biomass as a major energy source. Through the use of flexible air pressure regulators and fuel preheating (i.e., with waste heat recovery), the fuel consumption and cooking times can be reduced while reducing emissions.

At work, these findings can form a foundation for the design of a control system founded on the utilization of a simple microcontroller for the regulation of the blower rate according to existing operating conditions. This will see application in the development of smart biomass stoves that have the ability to adapt to user needs and the characteristics of locally available fuels.

C. Research Limitations

The work was conducted in a laboratory environment under limited fuel ignition temperature and air pressure. User properties, shape of the combustion chamber, air humidity levels, and fuel type are not taken into account in the analysis. The outcome should therefore be confirmed through field experiments on a household scale (Kitchen Performance Test) to better understand the efficiency of biomass stoves in normal usage.

CONCLUSIONS

In this study, it has been demonstrated empirically that air pressure change and fuel ignition temperature have significant effects on the thermal efficiency and overall performance of the mini biomass stove. Test results indicated that the combination of air pressure at 30 Pa and fuel initial temperature at 60°C produced the highest thermal efficiency of 89.37%, the lowest reduction in fuel consumption of 18.49 g, and the shortest time to boil 1 liter of water of 8.11 minutes. The resulting flame temperature at this condition was also the highest at 1024.56°C. The findings validate that the biomass burning performance is highly dependent on the rate of oxygen supply and the thermal state of the fuel upon starting the combustion process. An increase in air pressure boosts the oxidation reaction and reduces the heat loss through incomplete burning, while an increase in initial fuel temperature improves the pyrolysis reaction and the generation of heat energy.

Compared to the findings of previous studies, the achieved efficiency in this study is a remarkable improvement, while illustrating the technical contention that optimization of operating conditions could be a viable strategy in the development of more efficient and cleaner biomass stove technology without requiring basic structural modifications.

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