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Effect of Airflow Rate on Biomass Gasification Stove Performance Using Rice Husk and Sawdust Pellets

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ABSTRACT

Indonesia has great potential in utilizing biomass as a renewable energy source, especially for household needs. Biomass gasification stoves can increase energy efficiency while being environmentally friendly. This study analyzes the effect of air flow rate variations on the performance of biomass gasification stoves fueled by a mixture of rice husk and sawdust biopellets. The experimental method uses variations in air flow rates of 3 m/s, 4 m/s, 5 m/s, 6 m/s, and 7 m/s with the Water Boiling Test (WBT) tool to measure parameters such as flame temperature, CO and CO2 emissions, thermal efficiency, Specific Fuel Consumption (SFC), and combustion efficiency. The results showed that an air flow rate of 6 m/s produced optimal performance with the highest flame temperature (786°C), maximum thermal efficiency (61.80%), and lowest CO emissions (20 ppm). Combustion efficiency reached 94.38% with the lowest SFC (0.53 kg/h). Meanwhile, the flow rate of 3 m/s had a lower thermal efficiency (44.04%). This study concludes that the regulation of air flow rate is very important to achieve efficient and environmentally friendly biomass combustion, thus making a significant contribution to the development of renewable energy technology, especially biomass stoves.

Keywords: *Biomass; Thermal efficiency; Renewable energy; Gasification stove; Water boiling test.*

1. INTRODUCTION

Indonesia has diverse energy resources with considerable potential to fulfill energy needs, especially in the household sector. With high energy consumption, Indonesia is also committed to implementing efficient and environmentally friendly solutions. In this context, renewable energy sources such as biomass have become a major focus due to their abundance and development potential. According to the International Energy Agency [1], global energy demand increases by 1.7% by 2023, which reinforces the importance of technological innovation to meet energy needs sustainably.

Energy plays an important role in daily life, including for cooking, which is a basic need for many people. In many regions, biomass such as rice husk and sawdust is still a common source of energy used by households [2]. However, the traditional use of biomass is often inefficient and has negative impacts, such as pollutant emissions and high fuel consumption. Biomass gasification stoves are a viable solution, as they can improve combustion efficiency and reduce fuel consumption [3].

The performance of biomass gasification stoves is highly dependent on airflow rate, as air acts as both an oxidizing agent and a regulator of thermochemical reactions. An optimal airflow rate enhances combustion efficiency by ensuring complete biomass conversion into flammable gases, whereas excessive airflow may cool the reaction zone or prematurely deplete fuel before full gasification [4]. Previous studies have examined the impact of airflow rate on stove performance. Research by found that increasing airflow accelerates biomass combustion but reduces effective flame duration. Meanwhile, demonstrated that higher airflow rates improve energy and exergy efficiency by optimizing biomass-to-gas conversion [5]. However, excessive airflow can reduce thermal efficiency due to reaction zone cooling and incomplete combustion [6]. Additionally, airflow variations influence exhaust emissions, where insufficient airflow leads to incomplete combustion (high CO emissions), while excessive airflow increases turbulence, destabilizing the flame [7].

This study analyzes the effect of varying airflow rates (3–7 m/s) on the performance of a biomass gasification stove using rice husk and wood dust biopellets. The objective is to determine the optimal airflow rate for achieving stable flame conditions, maximum thermal efficiency, and

minimal emissions. The findings contribute to advancing renewable energy technology, particularly in optimizing biomass stoves for household applications.

2. MATERIAL AND METHODS

2.1 Material

This research was conducted from April 2025 to July 2025 at the Chemical Engineering Laboratory of Politeknik Negeri Sriwijaya. The tool used is a set of biomass gasification stoves. Test equipment such as scales, stopwatches, mercury thermometers, anemometers, and emission analyzers are certainly ready to use. The following is a picture of the biomass gasification stove and its components. The biomass stove can be seen in Figure 1.



Figure 1. Biomass Gasification Stove

2.2 Methods

This study used several research variables consisting of fixed variables and independent variables. The fixed variables in this study are fuel mass of 1 kg, fuel size of 2-5 cm and perfectly open primary and secondary air hole valves, while the independent variables in this study are the supply air flow velocity of 3 m/s, 4 m/s, 5 m/s, 6 m/s and 7 m/s. The fuels used were rice husk biopellets and teak wood powder biopellets with a mixing ratio of 50:50.

This research uses biomass fuel in the form of rice husk biopellets and sawdust biopellets obtained from Biomass Energy e-commerce. The fuels were then analyzed using the Proximate Analysis method (ASTM D7582-10) at the Chemical Engineering Laboratory of Politeknik Negeri Sriwijaya and Ultimate Analysis (ASTM D5373-16A) at PT Geoservices Coal Laboratory Palembang to determine fuel characteristics.

Performance testing of the biomass stove was conducted using the cold start Water Boiling Test (WBT) method. The test procedure included placing the stove on a scale connected to the emission suction hood, refueling, and heating water in a sealed pot equipped with a thermometer. Parameters such as water temperature, fuel consumption, and mass of evaporated water were recorded every minute until the water boiled and the temperature dropped 3°C from the boiling point. The boiling point was adjusted to the height of the location using the formula Td = 100 - h/300, where h is the height of the location from sea level in meters.

CO and CO_2 gas emission measurements were conducted using a calibrated gas analyzer. The measurement process involves taking gas samples using a gas sampling bag, reading the gas concentration after the flow has stabilized for 15 seconds, and recording the results in ppm. Calculation of specific fuel consumption (SFC) was carried out using the formula:

$$S_C = \frac{\Delta mk}{\Delta t} \quad (1)$$

The calculation of combustion efficiency is done using the formula:

$$\eta_C = 1 - \frac{NCO}{NCO2} \quad (2)$$

The thermal efficiency of the stove takes into account the mass of water, temperature change, mass of water vapor, and calorific value of the fuel calculated based on the equation:

$$\eta_T = \frac{maCp\Delta T + \Delta maL}{\Delta mkLHV} \quad (3)$$

Where:

η_T :Thermal efficiency (%)
m_a :Water mass (kg)
Cp :Specific heat of water (4,1866 kJ/kg°C)
ΔT :Water temperature difference (°C)
Δm_a :Mass of evaporated water (kg)
L :Calor of evaporation of water (2268 kJ/kg)
Δm_k :Mass of fuel used (kg)
LHV :Lower Heating Value(kJ/kg)

All calculations and data analysis were carried out in accordance with SNI 7926:2013 standards to ensure the validity of the research results.

3. RESULTS AND DISCUSSIONS

Data for calculations and discussions will be derived from observation data in the form of Water Boiling Test (WBT) test results, which are based on the outcomes of experiments on biomass gasification stoves.

3.1 Effect of Air Flow Rate on Flame Temperature

Biomass combustion occurs in two stages (1) pyrolysis (decomposition of the fuel into gas) and (2) combustion of the gas into heat. A minimum temperature of 500°C is required for the biomass (hemicellulose, cellulose, lignin) to decompose completely, provided there is sufficient air supply. This study analyzed the effect of air flow rate on the average flame temperature taken every 2 minutes using a thermogun during the Water Boiling Test (WBT). The graph shows that increasing the air flow rate has a significant effect on the flame temperature.

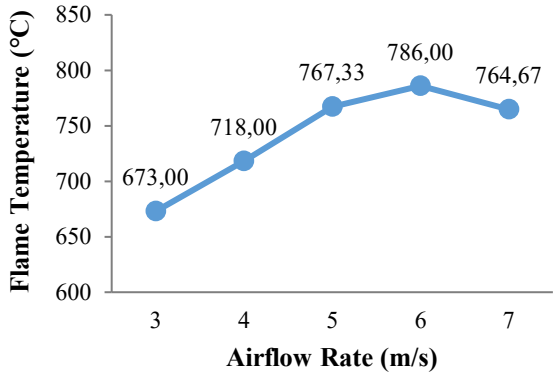


Figure 2. Effect of Air Flow Rate on Flame Temperature

The greatest temperature (786°C) is produced at an optimal velocity of 6 m/s, which strikes the perfect balance between oxygen supply, turbulence, and fuel residence time in the combustion zone, leading to nearly total oxidation of volatiles. The temperature decreases as the air flow rate decreases. This results in less than ideal combustion and an uneven distribution of oxygen because of decreased turbulence. Uneven oxygen delivery can lower efficiency, and too low air velocity also restricts combustion stability [8].

As the air flow rate is increased, more syngas is produced, which leads to more CO_2 and charcoal as well as increased oxygen availability in the oxidation zone [6]. Three distinct phases were observed during the 30-minute burn: (1) a bright orange flame and high temperature during the initial phase (0–10 min), which was caused by the intense combustion of CO and H_2 from fast pyrolysis; (2) a transition phase (10–20 min), which was primarily characterized by the combustion of charcoal; and (3) a final phase (20–30 min) with a blue-orange flame, which indicated clean combustion of residual CH_4 and H_2. The gasification process is indicated by the flame's color changing from orange, which represents the burning of carbon particles and CO, to blue, which represents the full combustion of CH_4 and H_2 [8].

3.2 Effect of Air Flow Rate on Specific Fuel Consumption (SFC)

By comparing the amount of fuel used (in grams or kilograms) and the amount of time it takes to boil water (Boiling Time), the SFC value can be calculated. The lower the SFC value, the higher the ability of the stove to convert fuel energy into heat.

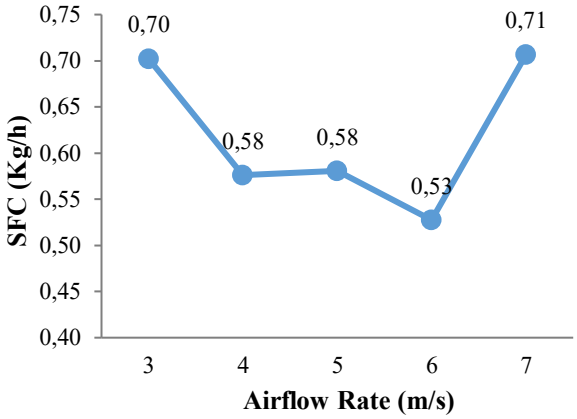


Figure 3. Effect of Air Flow Rate on Specific Fuel Consumption (SFC)

The results show a clear relationship between airflow velocity and combustion efficiency in biomass stoves, as indicated by the Specific Fuel Consumption (SFC) pattern. The optimal velocity of 6 m/s resulted in the lowest SFC of 0.51 kg/h, indicating the most efficient combustion condition. At this condition, an ideal balance is achieved between oxygen supply, flow turbulence, and fuel residence time in the combustion zone, allowing for almost complete oxidation of the fuel. Increasing airflow velocity is directly proportional to fuel consumption, but only to a certain extent before it decreases efficiency. [10]

Decreasing the air velocity to 3 m/s causes an increase in SFC to 0.71 kg/hr. This is due to insufficient turbulence for optimal mixing of oxygen and fuel, resulting in incomplete combustion. Conversely, increasing the speed to 7 m/s also decreased the efficiency because the residence time of the fuel was too short to react completely with the excess oxygen. At low flow rates, the air turbulence in the combustion chamber is still minimal so that the mixing of oxygen and fuel is uneven. This causes some of the fuel to not burn completely, so the efficiency drops and the SFC rises and when the air flow rate is increased, turbulence increases and mixing becomes better [11].

The SFC value obtained in this study (0.51-0.73 kg/h) meets the SNI 7926:2013 standard for biomass stoves (<1 kg/h) [12], indicating the feasibility of the tested stove design.

3.3 Effect of Air Flow Rate on Thermal Efficiency

Thermal efficiency is the main parameter in evaluating the performance of biomass gasification stoves, with a minimum standard of 20% according to SNI 7926:2013.

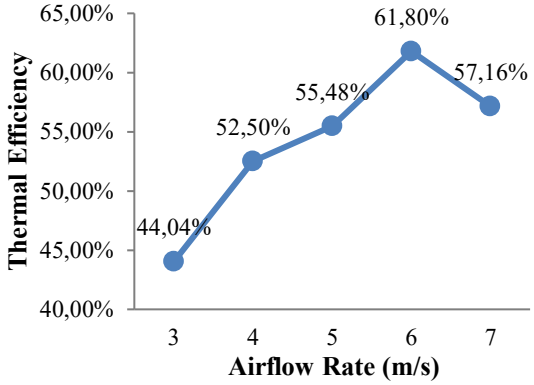


Figure 4. Effect of Air Flow Rate on Thermal efficiency

The results show that the thermal efficiency of biomass stoves is strongly influenced by the air flow rate with a consistent pattern. At an air flow rate of 3 m/s, the thermal efficiency reached 44.04%, a value that already meets the SNI 7926:2013 standard (minimum 20%) [12] and is much higher than traditional biomass stoves which generally range from 20-25%. Increasing the air flow rate to 6 m/s caused a significant increase in thermal efficiency to a peak of 61.80%. However, when the flow rate was increased to 7 m/s, the thermal efficiency actually decreased to 57.16%.

Efficient air flow velocity of 6 m/s. This optimal condition is achieved through three main mechanisms, (1) adequate air supply for complete combustion of the biomass stove thermal constituents peaking at 61.80% volatile pamponents, (2) optimal turbulence that creates homogeneous mixing between fuel and oxygen, and (3) combustion temperature stability that improves heat transfer [6,13]. This proves the advantages of modern stove design through effective insulation systems and balanced air distribution [14]. However, increasing the flow rate to 7 m/s decreased the efficiency to 57.16% due to the cooling effect of the reaction zone and too short gas residence time [8]. These results emphasize the importance of precision regulation of air supply to achieve a balance between oxygen supply and combustion stability.

3.4 Effect of Air Flow Rate on Combustion Efficiency

For all biomass components to be fully decomposed into heat energy, the ideal combustion process requires a balance between fuel and oxygen supply. Too low an airflow rate leads to incomplete combustion as there is not enough oxygen, leading to large carbon monoxide (CO) emissions and energy waste.

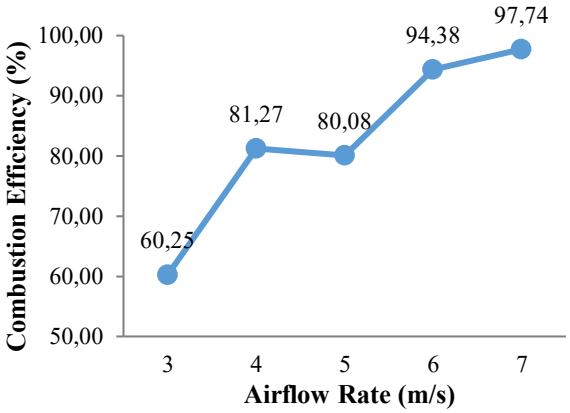


Figure 5. Effect of Air Flow Rate on Combustion Efficiency

The efficiency of biomass combustion depends on the air flow rate, with an optimal pattern at 6-7 m/s. At 3 m/s, the efficiency is only 60.25% due to lack of oxygen [14]. Increasing to 4 m/s pushes the efficiency up to 81.27%, but excess turbulence at 5 m/s lowers it to 80.08%. The optimum point is reached at 6-7 m/s (94.38-97.74%), where adequate air supply ensures near-complete combustion with minimal CO emissions [15]. This finding emphasizes the importance of adjusting the air flow rate to balance oxygen supply and flame stability.

3.5 Effect of Air Flow Rate on CO Emissions

At high concentrations, which is a colorless and odorless deadly gas, CO can cause serious poisoning and even death because CO can bind to hemoglobin in the blood 200 times more strongly than oxygee. When the air-fuel ratio is not ideal or the combustion temperature is too low to ensure full oxidation of carbon to CO2, incomplete combustion is the main cause of CO emissions in biomass stoves.

This problem has been successfully overcome by the two-stage combustion system in modern biomass stoves, which consists of pyrolysis and oxidation with primary and secondary air supply.

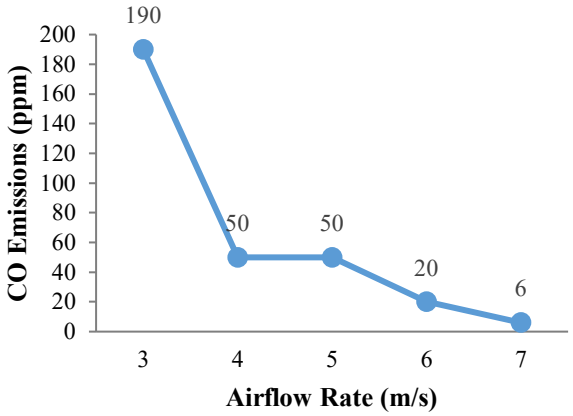


Figure 6. Effect of Air Flow Rate on CO Emissions

The results showed that the two-stage combustion system in modern biomass stoves significantly reduced CO emissions. The measured CO emissions ranged from 6-190 ppm, far below the maximum limit of SNI 7926:2013 of 67,000 ppm [12]. At an airflow rate of 3 m/s, CO emissions were relatively high (190 ppm) due to inadequate oxygen supply. However, by increasing the airflow rate to 7 m/s, CO emissions were reduced to 6 ppm, indicating almost complete combustion.

This reduction in CO emissions was influenced by four main factors: (1) sufficient oxygen availability to oxidize CO to CO_2, [16] (2) good air turbulence for fuel and oxygen mixing, (3) sufficient residence time in the combustion zone [19], and (4) high temperatures (>500°C) that accelerate the oxidation reaction [17]. These findings are in line with previous studies showing the importance of maintaining an optimal air-fuel ratio and high combustion temperature to minimize CO_2 emissions.

4. CONCLUSIONS

The air flow rate was shown to determine the performance of the biomass gasification stove. At 6 m/s, the highest flame temperature (786C), lowest SFC (0.51 kg/h), highest thermal efficiency (61.80%), and minimal CO emissions (20 ppm) were achieved due to the optimal balance between oxygen supply, turbulence, and fuel residence time. However, above 6 m/s (7 m/s), thermal efficiency drops due to reaction zone cooling although combustion efficiency remains high (97.74).

This study confirms the importance of airflow rate regulation for household-scale biomass stove optimization, both in terms of energy efficiency and environmental friendliness. The results provide a scientific basis for the development of more effective biomass gasification technology.

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