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Analysis of Hole Shape Modification and Airflow of Top-Lit Up Draft Stove to Enhance Thermal Efficiency

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ABSTRACT

The utilization of biomass energy, particularly from bio-pellet teak sawdust, is gaining attention as a renewable alternative to fossil fuels due to its environmental benefits. This study investigates the performance of a Top-Lit Up Draft (TLUD) stove fueled by bio-pellet teak sawdust based on SNI 7926:2013, focusing on the effects of airflow velocity and secondary air hole design on thermal efficiency, specific fuel consumption (SFC), and emissions (CO and CO_2). Experiments were conducted at Politeknik Negeri Sriwijaya from March to July 2025 using a Full Factorial Design (FFD). Results showed that the factory design achieved the highest thermal efficiency of 62.14% and the lowest SFC of 0.520 kg/h at 5 m/s. The modified design reached a peak thermal efficiency of 53.90% and an SFC of 0.558 kg/h at 4 m/s. The factory design also exhibited better CO and CO_2 emissions performance. These findings suggest that while modifying air holes showed minimal improvement, further research suggest to test modified hole design in other stove types to know the effect of enhance combustion efficiency and reduce emissions.

Keywords: *Biomass energy; Top-Lit Up Draft Stove; CO and CO_2 emissions; Specific fuel consumption; Thermal efficiency.*

1. INTRODUCTION

The utilization of biomass energy as a renewable source continues to be explored as a solution to the limitations of fossil fuels and the environmental challenges resulting from their use. Biomass, a sustainable resource, is particularly abundant in developing countries and can be transformed into energy through various technologies [1]. Indonesia, with its vast plantation and forestry sectors, has seen a significant increase in biomass production in recent years, making it a promising alternative energy source. According to the Central Bureau of Statistics [2], the country's biomass production continues to rise, indicating its potential to be widely utilized for energy generation.

The growing interest in biomass energy has led to the development of technologies such as the Top-Lit Updraft (TLUD) stove, which offers more efficient combustion compared to conventional stoves. TLUD technology optimizes staged combustion, where volatile gases produced from incomplete combustion, such as carbon monoxide (CO) and hydrocarbons, are re-burned in the secondary combustion zone. This results in higher thermal efficiency and reduced emissions of carbon monoxide and particulates, making TLUD stoves more environmentally friendly compared to traditional stoves [3].

Research by Hailu [4] highlighted the importance of fuel type in determining the performance of TLUD stoves. Hailu's study compared three types of fuel: eucalyptus wood, bamboo, and briquettes made from sawdust and cow dung. The study found varying stove efficiencies, with eucalyptus achieving 32.30%, sawdust-cow dung briquettes at 31.5%, and bamboo at 26.25%. When charcoal production was factored in, the efficiency increased to 53%. This study also showed that preheating the secondary air before combustion improved thermal efficiency by utilizing heat from the combustion chamber walls. However, the study did not explore how adjustments in airflow distribution could further improve thermal efficiency.

In another study, Scharler et al. [5] focused on emission optimization of TLUD stoves using Computational Fluid Dynamics (CFD) simulations. The study used forced draft TLUD stoves, equipped with a fan to enhance the mixing of volatile gases with air. The findings indicated that design modifications, such as adding a post-combustion chamber and optimizing primary air flow, could reduce CO emissions by up to 20 times,

achieving levels close to the best emission standards.

Another study by Zhang and Lee [6] emphasized that the design of secondary air holes, such as curved secondary air holes, could further improve combustion efficiency. Their CFD simulations showed that a curved design extended the residence time of volatile gases by 22%, reducing PM2.5 emissions by 30%. However, the increase in thermal efficiency was modest at only 2% due to heat dispersion in the vortex flow. The study also lacked experimental validation and did not account for fuel consumption or CO/CO_2 emissions.

Based on previous studies, there is still a need for further innovation in TLUD stove design to improve combustion quality and thermal efficiency. This research proposes modifications in airflow distribution to improve the mixing of volatile gases from primary combustion with secondary air. This modification aims to improve the interaction between the volatile gases and air before combustion, enhancing combustion efficiency and reducing emissions [7]. The purpose of this study is to evaluate the effect of modified secondary air hole shapes and varying airflow rates on the thermal efficiency of TLUD stoves using teak sawdust fuel. The ultimate goal is to develop a more efficient TLUD stove that requires less fuel while achieving higher thermal efficiency.

2. MATERIAL AND METHODS

2.1. Material

The research was conducted from March to July 2025 at the Chemical Engineering Laboratory of Politeknik Negeri Sriwijaya. The first phase, from March to May 2025, involved preparing bio-pellet fuel (teak sawdust) and conducting proximate analysis. The second phase, from June to July 2025, focused on the TLUD stove experiments, data collection, and analysis.

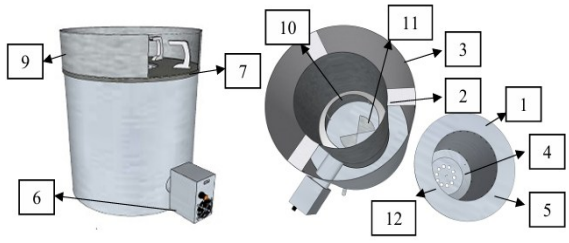


Figure 1. Top-Lit Up Draft Stove

The primary equipment used included a modified TLUD stove, which consists of several components as shown in the Figure 1: (1) the burning tube, (2) the inner tube, (3) the secondary air holes, (4) the primary air holes, (5) the air mixing section, (6) the stove support frame, (7) the fan, (9) the combustion chamber, (10) the air supply inlet, and (11) the exhaust outlet. This stove, designed for improved combustion efficiency, features a multi-stage combustion system. It includes air holes (28 primary and 28 secondary) and a fan for air mixing. The stove's specifications include a fuel capacity of 1 kg and a combustion tube with a height of 17.7 cm and top diameter of 12.8 cm.

Figure 2 illustrates the factory hole design, which has a set of evenly spaced secondary air holes that supply air for secondary combustion. Figure 3 shows the modified hole design, which features a curved geometry for the secondary air holes to enhance air mixing and distribution during secondary combustion.



Figure 2. Factory Hole Design



Figure 3. Modified Hole Design

Materials used in the research included 1 kg of bio-pellet teak sawdust and 2 kg of water. Test equipment such as thermoguns, anemometers, mercury thermometers, emission capture hoods, Tedlar bags, and a gas sampling pump.

2.2. Methods

The fixed variable in this study was the bio-pellet teak sawdust used as fuel in the TLUD stove, while the variable factors included airflow rates (4 m/s, 5 m/s, 6 m/s, and 7 m/s) and the shape of the secondary air holes (factory and modified design). The study used experimental observation to assess the performance of the stove with these modifications, focusing on airflow rates and air hole shapes with a fixed fuel amount of 1 kg of bio-pellets.

Moisture, ash, volatile matter, and fixed carbon content in the bio-pellets were analyzed using a Thermogravimetric Analyzer (TGA 701) following ASTM D7582-10 standards. The samples were heated in a crucible, and the mass change was measured to determine the water, volatile matter, and ash content.

The TLUD stove testing was performed according to SNI 7926:2013 standards to evaluate combustion efficiency, fuel consumption, and emissions. The stove was placed on a scale with an emission capture hood, and the bio-pellet fuel mass was recorded. The air flow rate was adjusted using the fan, and temperature and mass readings were taken to calculate fuel consumption and evaporated water mass.

CO and CO_2 emissions were analyzed based on ASTM D6331-16 and ASTM D3162-12 standards. Gas samples were collected using a gas sampling pump and Tedlar bags, and the emission concentrations were measured using a portable gas analyzer.

3. RESULTS AND DISCUSSIONS

Based on the experimental results of the TLUD biomass stove, observation data were obtained from the Water Boiling Test (WBT) to be used for calculation and discussion. The experiments were conducted based on SNI 7926:2013, and the data presentation follows a Full Factorial Design (FFD) covering all combinations of airflow rates and secondary air hole shapes. The calculation data are shown in Table 1.

Table 1. Full Factorial Design Experimental Data

Hole Geometry	v (m/s)	t_b (s)	T_{avg} (°C)	CO (ppm)	CO_2 (ppm)	η (%)	SFC (kg/h)	$η_c$
Factory Design	4	660	740.73	126	543	54.45	0.54545	0.7680
	5	623	752.10	52	575	62.14	0.52006	0.9096
	6	578	736.03	58	399	47.38	0.74740	0.8546
	7	549	793.63	28	356	43.02	0.85246	0.9213
Modified Design	4	645	736.07	163	439	53.90	0.55814	0.6287
	5	584	742.80	108	522	50.84	0.67808	0.7931
	6	576	750.07	50	201	40.75	0.81250	0.7512
	7	532	782.77	27	216	38.27	1.01504	0.8750

3.1 Effect of Airflow Velocity on Average Temperature

To further understand the combustion characteristics, the relationship between airflow velocity and the average flame temperature was analyzed. The results are shown in Figure 4, where the performance of both the factory and modified designs can be compared.

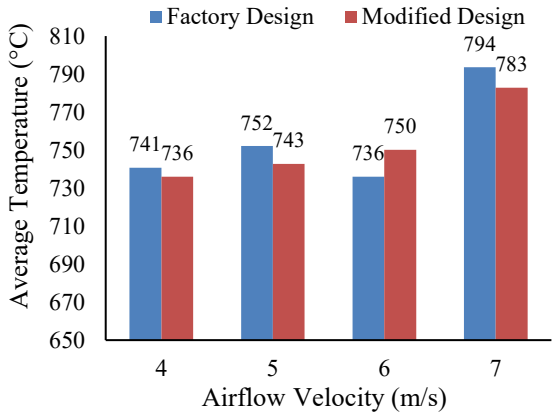


Figure 4. Effect of Airflow Velocity on Average Temperature

Based on the data in Table 1 and Figure 2, increasing airflow velocity raised the flame temperature, peaking at 7 m/s. The factory design reached 793.63°C, while the modified design reached 782.77°C. At 5 m/s, the factory design recorded a temperature of 752.10°C, higher than the modified design at 742.80°C. This can be attributed to the factory design's better mixing of volatile gases with oxygen, enhancing combustion [7].

At 4 m/s, both designs were nearly identical, but as the airflow velocity increased to 6 m/s and 7 m/s, the factory design maintained higher temperatures (766.80°C and 793.63°C) compared to the modified design (758.53°C and 782.77°C). This suggests that the factory design performs better in maintaining higher temperatures at greater airflow velocities, consistent with findings by Yang et al. [8] and Thompson & Witter [9], who emphasized the importance of good air distribution in improving combustion efficiency and maintaining high temperatures.

3.2 Effect of Airflow Velocity on Thermal Efficiency

The influence of airflow velocity on thermal efficiency was examined to evaluate how changes in air supply affect heat transfer performance. The results are illustrated in Figure 5, comparing the factory and modified designs under varying airflow conditions.

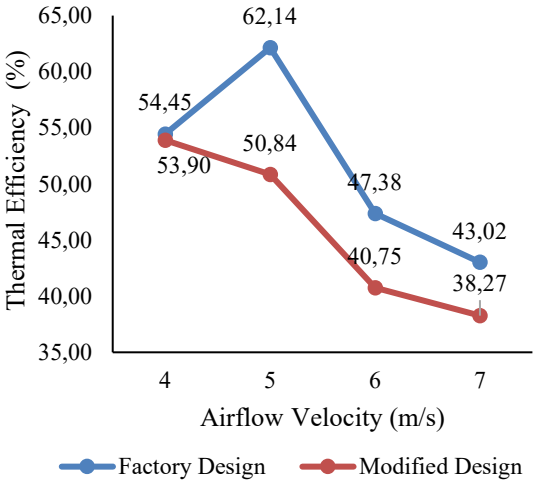


Figure 5. Effect of Airflow Velocity on Thermal Efficiency

Based on Table 1 and Figure 3, thermal efficiency increased with airflow up to 5 m/s for the factory design (62.14%), while the modified design peaked at 4 m/s (53.90%). Beyond this point, efficiency decreased, especially at 7 m/s, where the factory design reached 43.02%, and the modified design dropped to 38.27%. This drop suggests overcooling, where excess air absorbs heat before it can be transferred to the load [12].

The factory design maintained more stable efficiency at higher flow rates, supporting more efficient heat transfer. This aligns with Scharler et al. [5], who found that poor air distribution leads to lower efficiency. In contrast, Rebryk et al. [10] observed that thermal efficiency can remain above 60% with proper insulation, even at high airflow.

3.3 Effect of Airflow Velocity on Specific Fuel Consumption

To assess the impact of airflow on fuel utilization, specific fuel consumption (SFC) was measured at different airflow velocities. Figure 6 presents the comparison between the factory and modified designs, Shows how airflow variations influence the rate of fuel usage. Based on Table 1 and Figure 4, specific fuel consumption (SFC) increased with airflow velocity. The lowest SFC for the factory design was 0.520 kg/h at 5 m/s, while the modified design's lowest was 0.558 kg/h at 4 m/s. At 7 m/s, the modified design's SFC rose sharply to 1.015 kg/h, while the factory design increased to 0.852 kg/h. This indicates that the modified design is more sensitive to airflow changes, leading to higher fuel consumption.

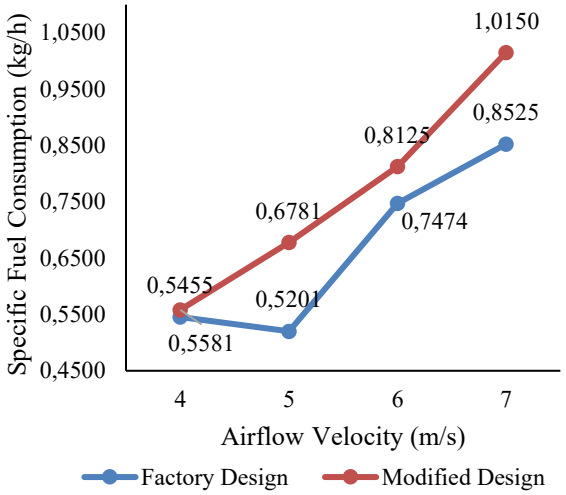


Figure 6. Effect of Airflow Velocity on Specific Fuel Consumption

The factory design allows for better combustion by providing sufficient residence time for volatile gases, leading to lower fuel consumption [15]. In contrast, the modified design expels gases before full combustion, requiring more fuel to maintain temperature. These findings align with Scharler et al. [5], who noted significant fuel consumption increases when air supply is poorly controlled, but differ from Fetene et al. [11], who found that heat recovery systems could keep fuel consumption low, even at higher airflows.

3.4 Effect of Airflow Velocity on CO Emission

Carbon monoxide (CO) emissions were analyzed to evaluate combustion quality under different airflow velocities. Figure 7 illustrates how the factory and modified designs responded to changes in airflow, providing insights into the effectiveness of air distribution in reducing CO levels.

The data from Table 1 and Figure 4 show that increasing airflow velocity reduces CO emissions. At 4 m/s, the factory design emitted 126 ppm, lower than the modified design at 163 ppm. As airflow increased to 5 m/s, CO emissions dropped to 52 ppm for the factory design and 108 ppm for the modified design. At 7 m/s, emissions were similar for both designs, with the factory design at 28 ppm and the modified design at 27 ppm, indicating lean combustion. However, the factory design maintained lower CO emissions overall due to more efficient oxidation of volatile gases, while the modified design suffered from poor air

distribution, causing incomplete combustion and higher CO levels [14].

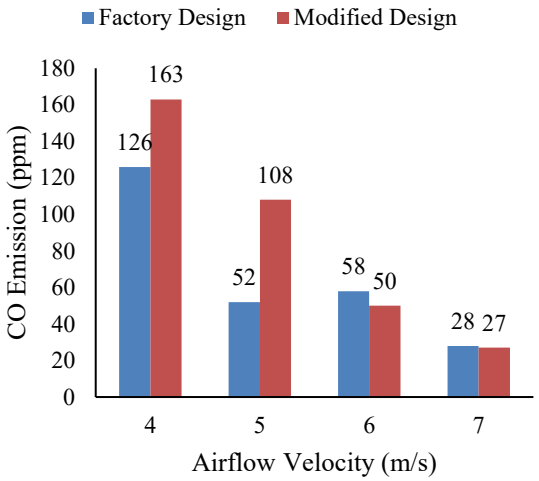


Figure 7. Effect of Airflow Velocity on CO Emission

These findings support Scharler et al. [5], who noted that precise air-to-fuel ratio control reduces CO emissions, but contrast with Rebryk et al. [10], who found that inadequate secondary reaction zones could result in high CO emissions despite increased airflow.

3.5 Effect of Airflow Velocity on CO_2 Emission

To further evaluate combustion completeness, CO_2 emissions were measured at different airflow velocities. Figure 8 shows the comparison between the factory and modified designs, Shows how airflow variations influenced the extent of fuel oxidation.

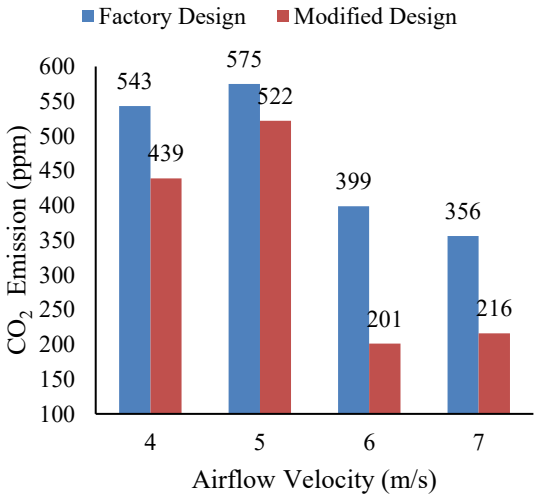


Figure 8. Effect of Airflow Velocity on CO_2 Emission

The data in Table 1 and Figure 6 show that CO_2 emissions in the TLUD stove decreased as airflow velocity increased, with the highest emissions at 5 m/s (575 ppm for the factory design and 522 ppm for the modified design). At 7 m/s, emissions decreased to 356 ppm for the factory design and 216 ppm for the modified design. The drop in CO_2 at high velocities is due to overcooling and reduced residence time, which limits complete oxidation [13].

The factory design showed more stable CO_2 emissions, as it better maintained combustion efficiency. In contrast, the modified design's unstable air distribution led to higher CO emissions and a less efficient conversion of CO to CO_2. These results align with Scharler et al. [5], who noted that controlling the air-to-fuel ratio improves CO_2 conversion, but differ from Rebryk et al. [10], who found that gasifier designs with good heat recovery could still maintain higher CO_2 emissions at high airflow.

4. CONCLUSIONS

The results show that the use of modified air holes did not significantly improve the performance of the TLUD stove, particularly in terms of CO and CO_2 emissions and flame temperature. The factory design consistently outperformed the modified design, achieving a maximum thermal efficiency of 62.14% at 5 m/s and a specific fuel consumption (SFC) of 0.520 kg/h, compared to 53.90% and 0.558 kg/h for the modified design at 4 m/s. Airflow velocity had a more significant effect on thermal efficiency and fuel consumption. These findings suggest that further investigation is needed into the use of modified air holes in different stove types to assess their potential impact on combustion efficiency and emissions.

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