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Comparison of the Performance of Biomass Briquette Stoves on Three Types of Stove Wall Materials

Zuryati Djafar[1*], Sallolo Suluh[2], Novriany Amaliyah[1], Wahyu H. Piarah[1]

[1] Mechanical Engineering Department, Faculty of Engineering, Universitas Hasanuddin, Jl. Malino, Bontomarannu, Kabupaten Gowa, Sulawesi Selatan 92171, Indonesia
[2] Mechanical Engineering Department, Faculty of Engineering, Indonesian Christian University Toraja, Makale, Kabupaten Tana Toraja, Sulawesi Selatan 91811, Indonesia

Corresponding Author Email: zuryatidjafar@unhas.ac.id

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ABSTRACT

The performance analysis of the biomass briquette stove has been carried out. The research was conducted with three variations of stove wall materials (clay, steel, and aluminum) and with several variations of shell diameter of the burning chamber (140mm, 150mm, 160mm, 170mm, and 180mm). The fuel used is coconut shell briquettes. The results showed that the maximum fire temperature of clay, steel, and aluminum stoves was obtained, respectively 798°C, 617°C, 508°C and thermal efficiency of 73.66% for clay followed by a steel stove of 38.98% and the lowest is obtained on an aluminum-based stove, which is only 11.49%. Furthermore, the diameter of the shell optimum is 180 mm for clay, 160 for steel, and 170 for aluminum.

1. INTRODUCTION

Biomass-derived from agricultural and plantation wastes has not been utilized optimally until now. The biomass can be made in the form of charcoal briquettes. In their research, Njenga et al. [1] stated that utilizing biomass in the form of briquettes has recycled charcoal into briquettes to increase the density of energy, reduce deforestation, and reduce Green House Gases (GHG) because of its low emissions.

The use of biomass stoves is widely used in rural area of Indonesia. In this research, the biomass used is coconut shell. Several studies have been conducted on the calorific value of biomass. In their research, Tanko et al. [2] investigated the physical properties of briquettes made from rice husk and coconut shell in different ratios were evaluated based on their thermo-physical properties. The calculated calorific values of the rice husk and coconuts shell are 16.51 MJ/kg and 18.60 MJ/kg. Yerizam et al. [3] reported characteristics of composite rice straw and coconut shell. It was found that rice straw fuel value is 1525.5 cal/gram while coconut shell has 7283.5 cal/gram of fuel value. Yuliah et al. [4] also stated that a mixture of rice husk and coconut shell briquettes produced a calorific value of 4966 kcal/kg at a mixture ratio of 50:50. Vivek et al. [5] also have researched a mixture of rice husk briquettes with coconut shell using Paper powder flour adhesive produced a calorific value of 4214.86 Kcal/kg.

In the utilization of biomass energy and the biomass briquette material, the type of stove material that works to transfer heat to the container (pan) needs attention. If the heat transfer to the container is not optimal, the resulting thermal efficiency will also less than optimal.

Several studies have been carried out previously, including Wang et al. [6], who modified the briquette stove combustion chamber by adjusting the secondary air duct and obtaining a thermal efficiency of 68%. Djafar et al. [7] have also modified the clay furnace combustion chamber and obtained a maximum thermal efficiency of 52.87%. Zhi et al. [8] modified the traditional coal briquette stove by adding a top cover and a galvanized chimney pipe. This modification can reduce particulate matter, organic carbon, and carbon black by 63%, 61%, and 98%, respectively. Harsono et al. [9] modified the stove combustion cylinder for bio-pellet by enlarging the hole in the combustion cylinder wall on the stove from 0.2 cm to 0.7 cm, with variations in the number of holes, namely 10, 30, and 40 holes. This research found that the optimum heat of 316.88 kJ was generated on the stove with 40 holes, the optimum thermal efficiency was 16.47% on the cylinder with ten holes.

In comparison, the lowest emissions are produced by a 40-hole cylinder. Syamsuri et al. [10] investigated the effect of adding fin on stove performance with variations in the diameter of corncob briquettes. Optimal cooking time and efficiency are obtained on stoves with fins for 1.5-inch diameter briquettes. Oyejidea et al. [11] modified the water hyacinth briquette stove by providing insulation around the combustion chamber, incorporating smoke rings on the stovetop surface, and adjusting the variable air supply to ensure sufficient air for complete combustion. The performance of the developed stove was evaluated, and the results showed that this briquette stove has an average thermal efficiency of 70.51%.

Sari et al. [12] analyzed the comparison of bio-briquette stoves with the combustion chamber wall material made of cement and glass wool insulation material. The results showed that stoves with glass wool coating material had 40% better efficiency than cement material. Wang et al. [6] developed a "clean burning" bio-briquette stove by adding a pyrolysis chamber to the combustion chamber and using calcium oxide and magnesium oxide additives. The results showed that the thermal efficiency of the stove increased to 68%, compared to 50% conventional stove. At the same time, the emissions of sulfur dioxide, nitrogen oxides, and carbon monoxide were also significantly reduced due to the addition of additives.

Similarly, Orhevba et al. [13] have modified the stove with an insulin cylinder and produced a thermal efficiency of 57.4%. Deng et al. [14] compared a 2-chamber biomass stove with a top-lift updraft system (TLUD) biomass stove on various types of biomass briquettes. The research results found that the sensitivity to the type of fuel in a 2-chamber biomass stove is smaller than that of a TLUD stove, so this type is suitable for application to various types of biomass. Jetter et al. [15] reported testing ten types of biomass stoves using the water performance and boiling test (WBT) method. The results showed that stoves with lower mass components exposed to heat from biomass combustion tend to require less time to boil, better fuel efficiency, and lower pollutant emissions. Guerrero et al. [16] evaluated the effect of using an inert ceramic foam (silicon carbide) in the combustion chamber of a biomass stove. Porous ceramics are placed in the combustion chamber in three configurations (floor, wall, and roof). Preliminary firing tests show that the porous ceramic increases the firing rate and external surface temperature. The final combustion test results show that the particulate emission factor decreases by up to 20% for all configurations. The placement of porous ceramics on the combustion chamber walls showed a reduction in up to 61% emissions. Mac Carty [17] also investigated 50 stove designs to compare fuel use and the resulting CO and particulate emissions. It was found that the rocket-type stove can reduce fuel consumption by up to 33%, reduce CO emissions by 75%, and particulate emissions by 45% compared to traditional stoves. These results are due to lighter insulating materials in the combustion chamber.

Bantu et al. [18] developed a prototype charcoal stove using granite, stainless steel, and glass wool. This study reveals that the granite material has high thermal storage properties and can reduce fuel consumption by up to 78% regarding the type of open fire furnace. Rajesh et al. [19] investigated the flow and heat transfer model in a biomass stove with a diffuser-shaped combustion chamber made of ceramic. The combustion chamber is equipped with primary and secondary air inlets. The results showed that adding a diffuser in the combustion chamber increases the mass flow rate and total heat transfer through the stove. Murali et al. [20] investigated the addition of a catalytic combustor to a briquette stove using coconut shell briquettes, sawdust, and sugarcane. The results showed that adding a catalytic combustor could increase the calorific value and optimal combustion efficiency for coconut shell briquettes. Rasoulhkani et al. [21] compared the performance of a traditional stove used in Iran with a modified biomass stove made of 2 concentric metal cylinders equipped with two sets of primary and secondary air inlets using biomass from apple pruning waste. This study reports that the increase in flame and water temperature in the water boiling test (WBT) is almost the same. Still, biomass stoves generally have a better thermal efficiency of about 35%.

Similarly, the specific and total fuel consumption is 73% and 67% lower than traditional metal stoves. Mamuye et al. [22] compared two modified biomass stoves with traditional ones. This test was performed on a Merchaye stove made of clay and a Lakech stove made of sheet metal. Both Mercaye and Lakech emit significantly lower CO_2 ($P < 0.001$) than traditional metal stoves. Merchaye stoves use 222 g (32%) less fuel and Lakech stoves 164 g (23%) less fuel per day than traditional stoves. Both types of stove modifications have also been shown to reduce cooking time. Nicholas et al. [23] investigated an enhanced biomass furnace's thermal performance and emission characteristics using soil materials. This improved type of stove combines a high clay content soil with an organic binder in its combustion chamber and body construction.

The results showed that a mixture of materials containing a 1:1 ratio by volume of clay and high content straw as an organic binder was found to have thermal properties comparable to ceramic materials in more advanced furnace designs. Phusrimuang & Wongwuttanasatian [24] designed a biomass stove with a double-wall construction filled with rice husk ash as an insulator. The results showed that the thermal efficiency of conventional stoves was 15.17%, while the efficiency of new stoves was 21.21%. Fuel consumption is reduced by 15.20% (25.8 g/kg-product), equivalent to $190/year fuel cost savings. Ugochukwo et al. [25] designed a rocket briquette stove with metal materials for the body and combustion chamber and used teak wood ash (khaya grandifoliala) as an insulator. The thermal efficiency was 37.3% from the performance test, and the input and output energy of 2670kJ/kg and 99540.2kJ/kg was achieved by using an air blower that supplied secondary air to the stove. Otoo et al. [26] developed a cast aluminum biomass stove. The stove takes an average of 60 minutes to complete the water boiling test (WBT), the average fuel consumed by the stove is recorded at 639.50 g, and the energy released by the fuel is an average of 18033kJ. The overall performance of the stove is quite efficient compared to traditional stoves. Gloria et al. [27] investigated biomass stoves with different combustion chamber materials (Aluminum, ceramic clay, and mild steel). The energy efficiency, specific fuel consumption, and emission performance parameters of the three stoves indicate the ceramic clay combustion chamber as the material of choice in achieving the targets set by the International Organization for Standardization of biomass stoves. Umogbai et al. [28] developed the improved biomass cookstove from a cylindrical ceramic combustion chamber into a framed cylindrical metal. The average thermal efficiency was 76%, with a 3.9 g/min burning rate. The performance of a cooking stove improved with sawdust as an insulation material was assessed by Okino et al. [29]. The performance characteristics of a cooking stove improved with sawdust as insulation with a material thickness layer less than 6 cm.

Based on several studies about the type of biomass fuel briquette and modification of the stove, this study was made to obtain the best thermal efficiency value from 3 wall materials by modifying the addition of variations in the diameter of the sleeve in the combustion chamber of the biomass briquette stove.

2. EXPERIMENTAL PROCEDURES

In this study, three types of briquette stove materials were used, namely clay, steel, and aluminum with thermal conductivity values of 2,3 W/m℃, 43 W/m℃, 202 W/m℃, and with the exact stove dimensions, namely: height 300 mm, inner wall diameter 200 mm, briquette holder distance from stove base 10 mm. The biomass briquette used was coconut shell in a wasp nest with 145 grams as many as nine briquettes. This form is used because it has a larger flame surface. The shell is made of an aluminum plate with a thickness of 0.9 mm and five variations in diameter: 140 mm, 150 mm, 160 mm, 170 mm, and 180 mm (see Figure 1). The pan used has a capacity of 5 liters made of aluminum. The data measured were: fire temperature (Tf) in the combustion chamber, secondary combustion chamber temperature (Tsc), stove wall temperature (Tsw), shell temperature (Ts), pan wall temperature (Tpw), water temperature (Tw), and ambient air temperature (Ta). The experimental setup can be seen in Figure 2.

Figure 1. The shell of burning chamber

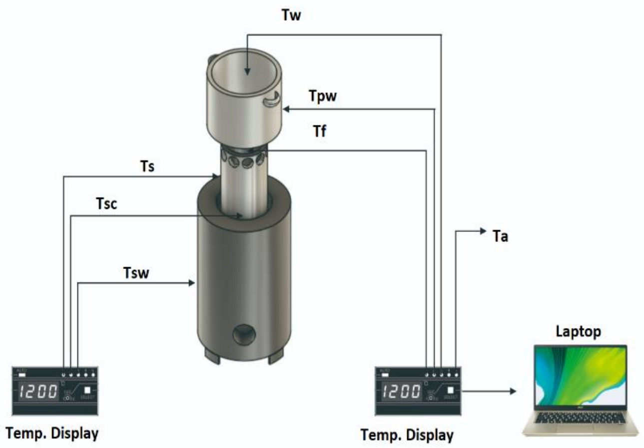

Figure 2. Experimental installation

3. RESULTS AND DISCUSSION

The experimental results can be seen in the following graphs:

3.1 Fire temperature

In Figure 3, the fire temperature in the combustion chamber is highest in the stove that uses clay, then for those made of steel and the last one made of aluminum. For those made of clay, the best temperature occurs at the shell of the diameter of 180 mm, than those made of 170 mm aluminum, and then 160 mm steel. Furthermore, for the clay stove, the stable temperature is close to 800℃, and for aluminum, it is close to 500℃, and for steel, it is around 400℃. This phenomenon indicates that the higher the thermal conductivity of the material of a stove, the greater the heat released to the surroundings so that the lower the temperature of the combustion chamber.

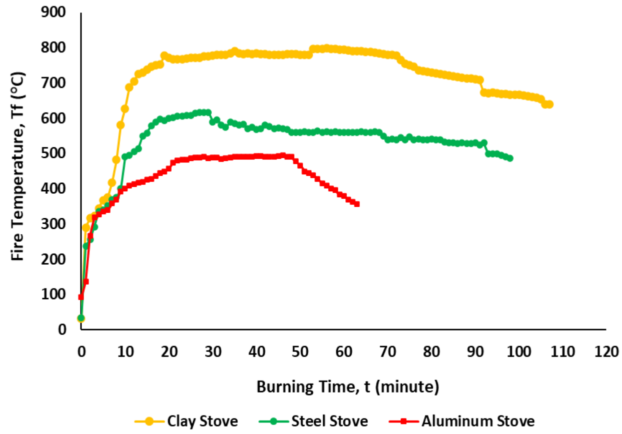

Figure 3. Fire temperature history

3.2 Stove wall temperature

Figure 4 shows the temperature of the outer wall of the stove. The highest temperature occurs in the stove made of aluminum, followed by a steel stove and clay. This result further strengthens the findings from the review in Figure 3, which says that clay stoves will be better able to retain heat in the primary combustion chamber than other materials (Aluminum and steel). The presence of a larger temperature difference concerning the ambient temperature also indicates a greater heat release.

Figure 4. Stove wall temperature history

3.3 Water boiling ability

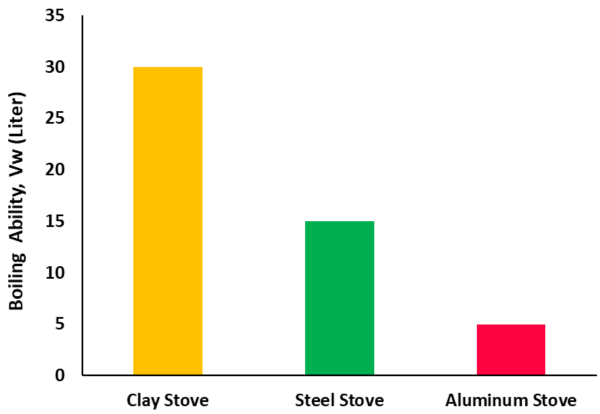

Figure 5. Ability to boil water

Figure 5 shows the ability to boil water (Vw) for the same amount of packaged fuel (1.30 kg) on three types of stove materials and the pan used with a capacity of 5 liters of water. The stove made of clay was capable of boiling water in six pans, while those made of steel were three pans, and those made of aluminum were only one pan. Again, this result shows that stoves with lower conductivity materials will be better at keeping heat energy from being wasted as losses are more utilized to boil water.

3.4 Briquettes used

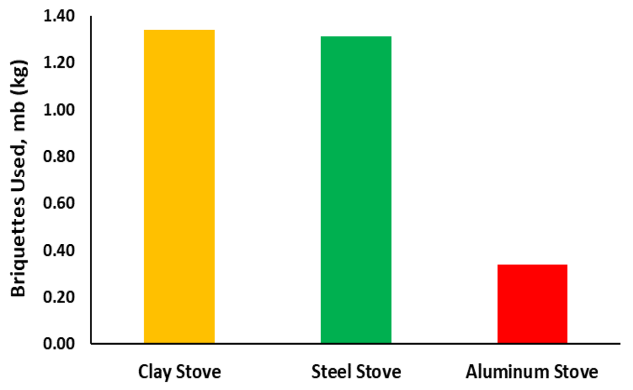

Figure 6. Mass of briquettes used

Figure 6 shows the mass of briquettes that burnt out on each stove. 1.26 kg of briquettes burned for the clay stove and then 1.24 kg of steel stove. And for an aluminum stove, only 0.34 kg. In the aluminum stove, not many briquettes are burned out because the combustion chamber conditions are not optimal to keep the combustion process going due to the relatively low temperature.

3.5 Thermal efficiency

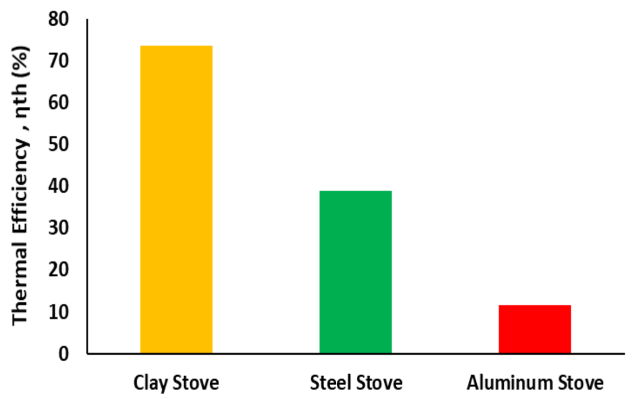

Figure 7. Thermal efficiency of stoves

Thermal efficiency describes the amount of heat utilized from a fuel. Figure 7 shows that the most superior thermal efficiency is produced at 73.66% on a clay-based stove, followed by a steel stove of 38.98%, and the lowest is obtained on an aluminum-based stove, which is only 11.49%. This is because the best combustion conditions occur in clay stoves. The thermal conductivity properties of clay stoves reduce wasted heat compared to stoves with steel and aluminum base materials.

4. CONCLUSION

Using three types of stove wall materials, the maximum fire temperature of clay, steel and aluminum stoves was obtained, respectively 798℃, 617℃, 508℃. The highest ability to boil water also occurs in 30 liters of clay stoves, 15 liters of steel stoves, and 5 liters of aluminum stoves. The best maximum thermal efficiency also occurs in clay stoves at 73.66%, followed by steel stoves at 38.97%, and finally aluminum stoves at 11.49%. These results also show that the stove wall material with a smaller thermal conductivity performs better.

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