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Performance and CO/CO_2 Emission of Three Different Biomass Stoves Fed With Coconut Shell Briquettes

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Abstract
The present work aims to investigate the performance of three different biomass stoves fed with coconut shell briquettes. The stoves' performance is evaluated in terms of fuel consumption rates, firepower, thermal efficiency, and pollutant emissions of C.O. and CO_2 using the Chinese Water Boiling Test (WBT) method. The clay stove (stove B) has the best performance compared to the concrete stove (stove A) and the metallic stove (stove C). The thermal efficiency of the clay stove is the highest among the threes. The stove A, B, and C's thermal efficiencies are 14.77%, 17.33%, and 14.88%, respectively. On the other hand, the fuel consumption rate and CO/CO_2 emission are the lowest in the clay stove. The fuel consumption rate of 0.54 kg/h and the CO/CO_2 emission of 0.11 is observed in the clay stove.

Keywords — *biomass, briquettes, performance, stove, thermal.*

I. INTRODUCTION

About 30% of the total energy consumed is attributed to households in developing countries. 90% of this energy is used for cooking and heating, and the majority comes from biomass fuel, especially in a rural area [1]. The biomass fuels are burned in traditional firewood stoves or improved biomass stoves. Compared to a conventional firewood stove, an improved biomass stove has better efficiency and lower emission. Many works in developing biomass stoves have been performed worldwide. Parmigiani *et al*., 2014 [2] designed and assessed a rice husk cookstove for a typical sub-Saharan setting. Wang *et at*., 2016 [3] and Sornek *et al*., 2016 [4] developed and investigated a clean-burning stove. Singh *et al.*, 2018 [5] developed a paddy straw combustor. Meanwhile, Sutar *el at*., 2015 [6] and Kumar *et al.*, 2013 [7] reviewed the design, development, and technological advancement of various cookstoves.

A biomass stove's performance can be evaluated in terms of thermal efficiency and flue gas emission [21]. The stove's performance can also be assessed in terms of fuel consumption rate and firepower [9]. The performance of the stove in terms of fuel consumption rates (FCR), firepower (P), and thermal efficiency (η_T) are calculated using Eq. (1) to Eq. (3), accordingly.

$$FCR = \frac{m_f}{\Delta t} \quad (1)$$

$$P = \frac{m_f LHV}{(\Delta t)} \quad (2)$$

$$\eta_T = \frac{m_w C_p \Delta T + m_v L}{m_f LHV_f} \quad (3)$$

where m_f is the mass of feedstock burnt (kg), Δt is the duration of the test (s), LHV is the lower heating value of the feedstock, M.W. is the mass of water in the pot (kg), $c_{p,w}$ is the specific heat of water, ΔT is the temperature difference of water before and after the test, m_v is the mass of water vapour, and h_v is latent of evaporation of water.

The stove's performance can be affected by air supply mode and airflow rate, which depend on the stove design. An effect of primary air supply mode on biomass stove performance has been investigated worldwide [10-14]. By comparing natural draft and force draft stove, it was evident that high efficiency and low emission of incomplete combustion can only be achieved with high controllability of the air flow in the different phases of combustion [11]. Performance and emission of the stove increased with the use of force draft primary and secondary air. The use of force draft mode resulted in better control of air mixing ratio and gross flow rates of primary and secondary air that significantly increased efficiency and reduced emission [10]. According to Suresh *et al*. 2016 [13], the use of force draft significantly reduced emission of particulate $PM_{2.5}$ and C.O. in the flue gas of biomass combustion.

The performance of a biomass stove also depends on feedstock type and feedstock properties [15-19]. The feedstock's sphericity influenced fuel conversion through the particle's grain and the overlap of particles in the bed [16]. Moisture content in a feedstock has to be considered to obtain high efficiency of the stove. Extremely dry or over-wet fuel inhibited combustion efficiency [17].

Three different biomass stoves are tested on coconut shell briquettes using Chinese Water Boiling Test method in the present work. The stoves and the briquettes are obtained from the traditional market in Yogyakarta, Indonesia. The work aims to study stove design on fuel consumption rates, firepower, thermal efficiency, and pollutant emissions of C.O. and CO_2. Since various biomass stoves are available in the local market, it is important to figure out the stove's performance to select the stove properly.

II. MATERIALS & METHODS

A. Design of the stove and fuel properties

Fig. 1 displays a photograph of the stoves which are investigated in the present work. Those stoves are bought from the local market in Yogyakarta, Indonesia. Each stove has a specific design, including the material used, size, and primary and secondary air inlets. Stove A, B, and C are made from concrete, clay, and steel plates. All the stoves have a primary air inlet at the combustion chamber at the lower part of the stove. Meanwhile, stove A and stove B without secondary air inlet, and stove C has a secondary air inlet at the upper part of the stove.

Stove A Stove B Stove C

Fig 1: Photograph of the stoves

The stoves are tested using a feedstock of coconut shell briquettes. The briquettes are obtained from the local market in Yogyakarta, Indonesia. The briquettes have an average size of 3 x 3 x 5 cm. The proximate properties, lower heating value, and the briquette photographs are presented in Table 1.

TABLE 1
Proximate properties of coconut shell briquettes

Proximate	(wt. %)
FC	62.31
VM	7.61
MC	5.70
Ash	24.38
HHV (cal/g)	5159.21

B. Experimental work

The stoves' performances are tested with coconut shell briquettes using the water boiling test (WBT) method. The tests are conducted in the WBT facility in the Laboratory of Manufacture-Department of Mechanical Engineering-Institut Sains & Teknologi AKPRIND. As shown in Fig. 2, the experimental setup consists of the stove, a water pot, a flue gas duct, a hood, thermocouples, an infrared thermometer, a CO/CO_2 sensor a data logger. Chinese WBT procedure is adopted in the present work. The stove is operated for a particular amount of the feedstock. The data of temperatures are collected from the briquettes' initiation until all amounts of the briquettes are completely burnt. The water temperatures in the pot (T_w) and temperature of the flame (T_f) are measured using K-type thermocouples and logged in a Graptech Data Logger. The temperature of the external surface of the stove is measured using an infrared thermometer. The concentration of C.O. and CO_2 in the flue gas is analyzed using a gas analyzer.

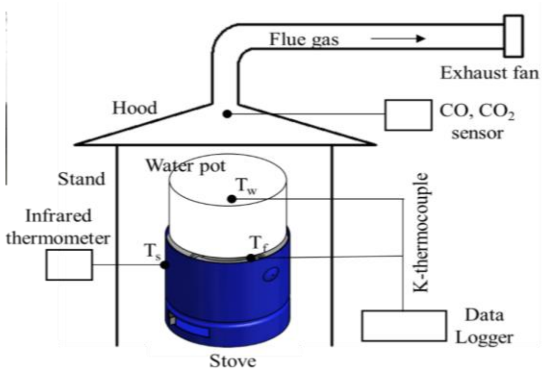

Fig 2: Schematic diagram of the experiment setup

III. RESULTS & DISCUSSION

A. Temperature profile

Fig. 3 to Fig. 5 present water temperature profiles in a boiling pot and temperature profiles of a flame, respectively. The temperatures are measured till the flame in the stove extinguishes. The time required to reach the boiling temperature of the water is the fastest in stove A. In contrast, the slowest time to reach the boiling temperature is observed in stove C. The required time to reach a boiling point is 25, 45, and 65 minutes for stove A, B, and C. The fastest boiling temperature achieved in stove A is due to the highest heat released during briquettes combustion in stove A as indicated by the flame temperature profile in Fig. 4. From Fig. 4, it can be observed that maximum flame temperatures of stove A, B, and C are 637.6°C, 420.2°C, and 568°C, respectively. The maximum flame temperature is obtained in 30 minutes for stove A, 50 minutes for stove B, and 55 minutes for stove C.

Meanwhile, from Fig. 5, it can be observed that the temperature of the outer body of the stove C is much higher than the same as stove A and B. This is because the stove C has no insulator. More heat from briquette combustion is transferred to stove C's outer wall and more heat losses to the surrounding. As shown in Fig. 3 to Fig. 5, the briquettes' combustion rate is the fastest in stove A, followed by stove C, and then stove B. One kg of the briquettes is consumed within 75 minutes, 90 minutes, and 110 minutes in stove A, B, and C, accordingly.

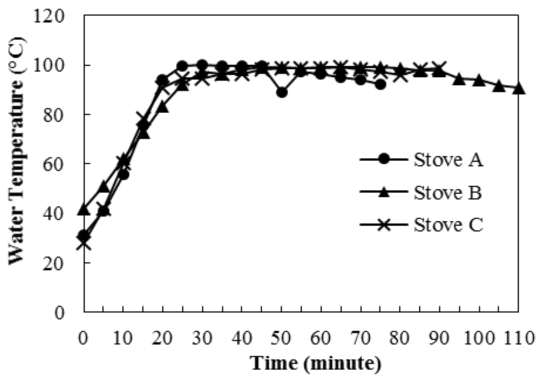

Fig 3: Temperature profile of the water

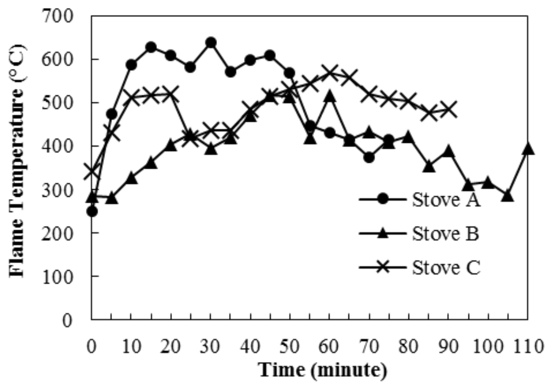

Fig 4: Temperature profile of the flame

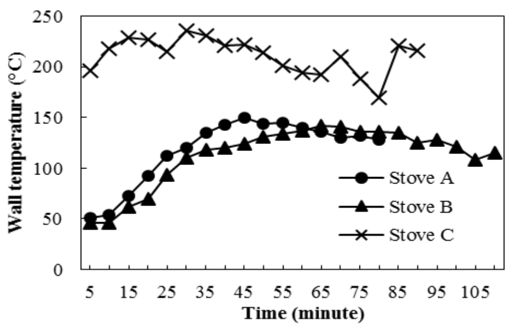

Fig 5: Stove temperature

B. Performance of the stoves

Fig. 6 to Fig. 9 present the stoves' performance in terms of fuel consumption rate, firepower, thermal efficiency, and CO/CO_2 emission. Fuel consumption rate (FCR) is the highest in stove A as shown in Fig. 6. This indicates the burning rate is the highest in stove A. The high burning rate is due to more air is drawn into the combustion chamber. This means that more oxygen available for combustion. Thus, results in an increasing the combustion rate of the briquettes. The primary air inlet of stove A is larger than that same of stove B. Increasing the amount of primary air at larger inlet results in enhancing combustion. Although the stove C has the largest primary air inlet, FCR is lower than FCR of the stove A. Since stove C has no insulator, more heat losses to the surrounding, this loss reduces flame temperature and results in a lower combustion rate. Compared to two other stoves, stove B has the lowest FCR. This is obviously due to stove B has the smallest primary air inlet. The mass flow rate of air entering the combustion chamber is lesser than that of stove A, and the stove C. Lesser amount of air reduces the combustion rate. Thus the lowest FCR is observed in stove B.

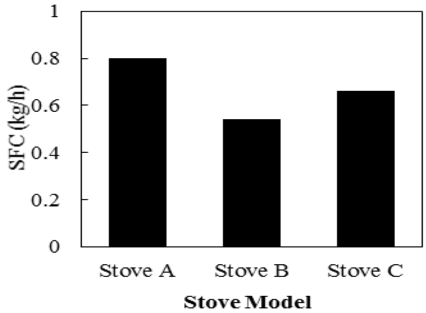

Fig 6: Specific fuel consumption

Firepower has a similar trend with the FCR trend, as indicated in Fig.7. Firepower increases as FCR increases, and vice versa, firepower reduces when CFR lowers. Higher FCR means that more feedstock is consumed at a particular time, and more heat is released during combustion. These affect in improving the firepower of the stove. The highest firepower is obtained in stove A, and the lowest is observed in stove B. The fire powers of the stove A, B, and C are 4.82, 3.28, and 4.01 kW at FCRs of 0.8, 0.54, and 0.66 kg/h, respectively.

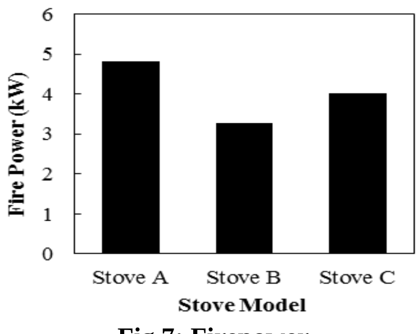

Fig 7: Firepower

In contrast, stove B has the highest thermal efficiency, among others, as displayed in Fig 8. It can be explained that heat is effectively used for heating the water in the stove B, and also less heat is lost to the surrounding through the body of the stove. The stove A, B, and C's thermal efficiencies are 14.77%, 17.33%, and 14.88%, respectively. According to Fig 9, it can be figured out that better combustion occurs in stove B. The lowers CO/CO_2 emission in stove B's flue gas indicates that complete combustion of the briquettes is achieved in the stove B. This is indicated by more amount of CO_2 is generated than C.O.

during combustion. The ratio of CO/CO_2 emission is 0.17, 0.11, and 0.15 for stove A, B, and C, accordingly.

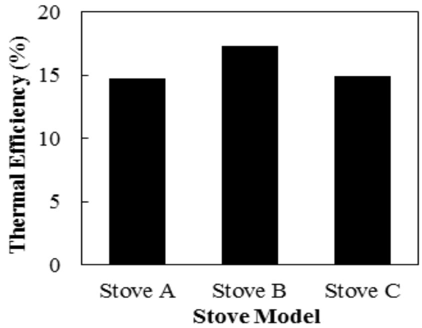

Fig 8: Thermal efficiency

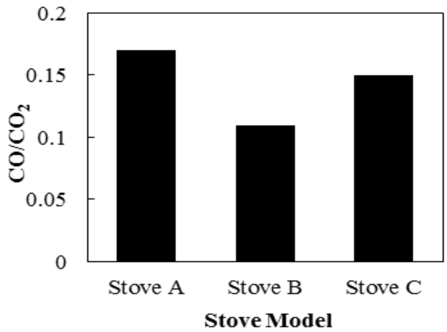

Fig 9: CO/CO_2 emission in flue gas

IV. CONCLUSIONS

Three different biomass stoves are tested on the feedstock of coconut shell briquettes using the water boiling test method. It can be concluded that the design of the stove influences the performance of the stove. The clay stove has the best performance compared to the concrete and metallic stoves. The thermal efficiency of the clay stove is the highest, among others. On the other hand, the fuel consumption rate and CO/CO_2 emission are the lowest in the clay stove. The clay stove is recommended to be used to get benefits in terms of performance and economic consideration.

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