An Evaluation of A Solid Biomass Cook Stove in Small Household Industry

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Abstract. This paper presents the design of solid biomass natural convection stove test with that solid biomass as fuel in one of the small household industries. Corncob, coconut shell and wood chips waste were utilized using the stove with combustion chamber diameter of 15 cm and the height of 45 cm. The performance test of the stove includes combustion flame temperature, visual flame color and water boiling test as well as economic evaluation. The results of the test showed the start-up time of 10.55-16.34 min, the specific fuel consumption (Sc) of 0.51 to 0.76 kg/h, with the thermal efficiency (ηth) of 20-21% has a maximum fire power of 22.97 kW and 8.76 kW using coconut shells and wood chips, respectively. The biomass consumption cost for boiling water was about IDR 130-300/kg of water. The biomass utilization for frying fish gave a higher profit margin of IDR 1,500/kg fish compared to LPG. From this study, the performance test is met to the Indonesian National Standard of biomass stove (SNI 7926:2013) and suitable for the households, especially small household industries in rural areas. Further study related to CO and particulates emissions will be conducted in an attempt to improve this biomass stove design. Life cycle assessment of the used of solid biomass for heat production will be studied as well.

1. Introduction
Biomass a renewable energy resource used for cooking in small household industries in West Bandung District, West Java, Indonesia. In this rural area recorded at least 23 small household industries. Each industry uses approximately 34.2 kg/day of liquid petroleum gas (LPG) to fulfill the daily energy needs. Recently, LPG is no longer easy to come in term of high fuel cost and availability. LPG is utilized in combination with solid biomass as their main fuel for cooking. About 70% of the LPG consumption is replaced by the solid biomass as fuel using conventional biomass stove in these industries. Corncob, coconut shell and wood chips as the solid biomass residues of agriculture crops are used as main fuel for the production process and meanwhile LPG as a secondary fuel for smaller tasks such as frying fish crackers as a result of their products. In 2015, the biomass energy potential from agriculture waste of corncob, wood chips, and coconut shell are 48,629 G Wh, 205,581 G Wh, and 6,758 G Wh, respectively [1, 2] and will continue to increase every year. As an illustration of corn production in West Bandung district is about 11,960 tons/year with about 50% of it as corncob waste (13.03 G Wh/year). Despite its enormous potential, the utilization of solid biomass waste such as corncobs has not yet been fully utilized as fuel. Some of the solid biomass of corncobs, wood, coconut shell is used as heating by burning on the ground, while the rest is disposed of as waste.

Most people in these household industries, cooking is performed on the open fire, usually enclosed between the three or more stones fire in U-shape which act as pot supports as a traditional solid biomass stove. Poor combustion will negatively affect thermal performance of this traditional
stove. Incomplete combustion and low heat transfer efficiency (ratios of energy entering the pot to that liberated by combustion) will decrease the stove efficiency. In general, such combustions fire have a thermal efficiency of no more than 10% compared to the above 20% obtained by using a properly designed solid biomass cooking stove [3, 4]. Low heat transfer efficiencies is a significant factor affect stove’s efficiency, while energy loss due to incomplete combustion is about 8% of total energy input [3, 5]. However, the incomplete combustion of solid biomass fuel will release harmful emissions and affect high levels of indoor air pollution. The emissions are associated with serious adverse health effects that causing the acute respiratory problem. The harmful emission includes CO, unburned hydrocarbons, and NOx.

Many designs, construction, and testing of the improved solid biomass stove are reported by researchers. Although, the development of solid biomass cooking stove is not the earliest technologies. Unfortunately, there today exist no clear-cut internationally accepted design standards for solid biomass cooking stove [3, 5, 6, 7]. This is due to a lack of knowledge and understanding in combustion science and stove design. The currently available local solid biomass stoves do not represent the best in modern engineering design. This local solid biomass stove has a low efficiency and consequently high emissions from unburned fuel.

Commonly, the aimed of the improvements are to increase the stove thermal efficiency, such as improved air/fuel mixing and secondary air to combust the biomass fuel more completely which resulted in lower pollutant emissions. Therefore, the challenge of designing a solid biomass cooking stove is not only a technical issue but a social issue as well. The improvement of a solid biomass stove in this work is undertaken on the economics, environmental, and health considerations. Another goal is to be flexible to different types of solid biomass and ease of operation. The LPG needs of the all small household industries in the rural area can be replaced with solid biomass waste. In present work, the modification on the existing solid biomass stove designs was conducted by providing sufficient air to enhance the complete combustion, it means to increase combustion flame temperature. The high combustion flame temperature can reduce the level harmful air pollution and increase combustion efficiency. The solid biomass stove performance was evaluated according to some of the parameters required by the National Standardization Agency of Indonesia (BNSi) for biomass stove (SNI 7926: 2013) [8].

2. Biomass Resource in Indonesia

Most of the biomass in Indonesia is crop residues from non-edible plant parts as remain of by-products after crop processing, such as pilling, milling, and extraction. These biomass residues and can potentially be used as energy source in the household and small industry sector for cooking in the rural area [9]. These residues contribute significantly up to 5% energy consumption in Indonesia in 2025 as one of new and renewable energy resources [2, 9]. Table 1 shows the total biomass residue production in the year 2015 from some provinces in Indonesia [2]. The estimation of biomass base new and renewable energy potential derived of agricultural and plantation from solid residues are approximately 399,536 GWh.

| Region         | Rice husk | Corncob | Wood chips | Coconut shell |
|---------------|-----------|---------|------------|---------------|
| Jawa          | 65,652    | 26,534  | 5,053      | 1,532         |
| Sumatera      | 36,292    | 8,103   | 41,785     | 2,243         |
| Kalimantan    | 13,298    | 715     | 68,649     | 381           |
| Bali, Nusa Tenggara | 7,486 | 5,039   | 3,309      | 399           |
| Sulawesi      | 15,304    | 7,705   | 19,275     | 1,613         |
| Maluku        | 322       | 474     | 7,789      | 558           |
| Papua         | 213       | 59      | 59,721     | 32            |
| Total Potential (GWh) | 138,568 | 48,629  | 205,581    | 6,758         |

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In Indonesia, agricultural residues vastly meet the household energy demands in rural areas, for example, the potential energy of corn cob, coconut shell and wood chips from agricultural plantations in West Bandung District were estimated 1.413 GWh, 0.196 GWh and 5.973 GWh in a year respectively [9]. In this region, around 80 percent of the economic activities are based on agriculture about 84% of those solid biomass residues are used as a renewable energy source. These residues are utilized as fuel using a conventional simple stove in the household and small industry sector for cooking [9] and the remains are used for several others purposes. The typical agricultural residues fuel has the ultimate analysis by mass as carbon content is 30 to 50%, hydrogen is around 6%, oxygen is 30 to 45%, nitrogen is around 2% and HHV is about 17 MJ/kg [4, 6, 7], [9 -12]. According to the report, the energy in about 4 kg of the solid biomass of agricultural residues approximately substitutes about ±1 kg of LPG [9,10].

3. Solid Biomass Combustion

In order to convert solid biomass into useful heat energy, it has to undergo combustion. This process is used every day in households and small household industries for heating and/or cooking. Solid biomass combustion is a process in which the fuel is burnt with the oxygen from the air at sustainable elevated temperatures to release heat in burners. This combustion process is a complex interaction of physical and chemical processes and affected by the physicochemical properties of the fuel (size, shape, density, moisture content, fixed carbon content, volatile matter, etc.), quantity and mode of air supply (primary and secondary air), and the conditions of the surroundings (temperature, wind, humidity, etc.) [3, 13].

Solid biomass fuels are primarily composed of carbon, hydrogen, and oxygen. Ideally, all hydrogen and carbon would split off and combine with the oxygen in the air to create water vapor, carbon dioxide, and heat. Flame temperatures can exceed 2000°C, depending on the heating value and moisture content of the fuel (the fuel characteristics), the amount of air used to burn the fuel and the design, configuration and construction of the solid biomass stove. The high-flame temperature is closely related to thermal efficiency and tends to increase it. This condition can be achieved when complete combustion occurs, which lowers losses and extracts all of the energy from the biomass as fuel. In practice, to obtain perfect combustion is very difficult due to various factors. The technical factors that may affect perfect combustion are fuel/air ratio, mode of fuel supply, and primary and secondary air supplies. The perfect fuel to air ratio is needed for the stoichiometric combustion takes place. In practice, in order to achieve complete combustion, it is necessary to increase the amount of air to the combustion process to ensure the burning of all of the biomass fuel. The amount of air that must be added to make certain all energy will be retrieved is known as excess air. Typical excess air required for various stove design is in the range of 5% to 50% [4], depending on the fuel properties and the stove configuration.

4. Biomass Stove Design

The design of this solid biomass stove was developed to be implemented in a small household industry by consideration to enhance the combustion quality. The natural convection mode is a basic principle design of this stove [14, 15] with the aims to increase efficiency and reduce emissions. Providing the sufficient air for combustion by the adequate draft for enhancing the combustion process. A proper air-fuel ratio can increase combustion efficiency. The primary and secondary combustion air ports on the stove will affect to fuel consumption rate, power fire, combustion flame temperature as well as thermal efficiency. Consequently, the stove geometry, stove size, loading fuel door, combustion air inlet ports/holes and grate (fuel bed) in stove design must be able to ensure in accommodation of combustion air properly.

Based on the considerations of a solid biomass stove as described above, solid biomass stove was designed by using selected parameters as follows; a stove was constructed using mild steel sheet with 8 mm thickness. The total stove height was 45 cm with a height of 35 cm combustion chamber. The external diameter and internal diameter stove were 15 cm and 13.5 cm, respectively. The loading fuel door size of 7cm x 13 cm, equipped with 12 and 40 holes of primary and secondary air inlet with a diameter of each hole was 2 cm and 8 mm, respectively, Figure 1. This improved biomass cooking
stove and its implementation have the potential impacts to decrease exposure indoor air pollution, reduce the dependence of the LPG fuel and household industrial cost (fuel substitution and economic aspect).

![Figure 1. Sketch of improved biomass stove and visualized flame](image)

5. Experiment

Corncobs, coconut shells and wood chips waste were used as fuel for evaluating a solid biomass cook stove in a small household industry in West Bandung District. Such biomass is very abundant in this area, but it is very less in its use as an energy resource. The modified of a conventional natural draft biomass stove with the specification as described in the above subsection was used in this study. This stove design was not equipped with a blower, therefore the need of combustion air was supplied to the chamber due to the natural draft. This air flows due to the difference in density, the low-temperature zones on the stove will have greater air density than in higher ones. The combustion air will move naturally from low temperatures to high temperatures. The adequacy of secondary air for complete combustion of biomass pyrolysis gases due to the presence of air intake through secondary air holes.

The three kinds of biomass waste as feedstock for testing biomass stove were cut into small pieces and store in a dry place for further use. Elements and proximate analysis were carried out before testing by using the method suggested by ASTM. The physical and thermal properties of biomass feedstock used for evaluating the stove performance as well as economic evaluation. The measured parameters during the study were boiling time, start-up time, flame temperature, thermal efficiency, air flow rate, and biomass consumption. From the results of this stove, performance test study is expected to fulfill some of the parameters set by the Indonesian National Standard of biomass stove (SNI 7926:2013). While other parameters such as CO and particulates emissions will be conducted in an attempt to improve this biomass stove design in further study.

The biomass weight of about 0.5-1.5 kg was used in the test to measure the startup time and the fuel consumption. Specific fuel consumption, $S_c$ was calculated using the equations below [8]:

$$S_c = \frac{\Delta m_k}{\Delta t}$$

where $\Delta m_k$ is the fuel mass that has been burned during the test (kg) and $\Delta t$ is the duration of the test. The fuel (biomass) consumption was determined by evaporating a known quantity of water which is recommended as standard water-boiling test [8, 9, 16]. The consumption of fuel was also evaluated by
frying a quantity of food until cooked. In the current work, to compute the thermal efficiency, experiments were conducted to study energy consumed for boiling amount of water at atmospheric pressure (at about 100 °C) and for frying amount of food until cooked (at the boiling point of cooking oil, about 250 °C). The weight measurement was done using a digital strain gauge base weighing balance and the temperature, while the temperature of water and frying oil, as well as surface flame temperature of flue gas combustion, were measured using a digital thermocouple Krisbow-KW06-283. The secondary air flow rate on secondary holes inlet for fuel combustion air was measured using a digital anemometer Krisbow-KW06-653. The experiments were repeated three time and thermal efficiency was determined by measuring the amount of heat absorbed by the fuel, and dividing by the total amount of fuel used. The ratio of energy used for cooking with heat energy available in the fuel was defined as [17]:

\[
\text{Thermal efficiency} = \frac{\text{Heat utilized}}{\text{Heat supplied}} \quad (2)
\]

The experiment results of the above parameters have to meet some of the following standards (SNI 7926: 2013); the maximum of specific fuel consumption, \( S_c \) is 1kg/hr, and the minimum thermal efficiency, \( \eta_{th} \) is 20%. Another additional requirement parameter is power output of about 2.5 to 5 kW or equivalent to 0.5 to 1.0 kg/hr of biomass fuel consumption with a heating value of 18 MJ/kg.

The output power of biomass cooking stove output is a measured of the total energy produced by the fuel during one hour. The output power was calculated by using equation [18]:

\[
P_o = \frac{F_{Sc} \times H_{cf} \times \eta_{th}}{3600} \quad (3)
\]

where \( P_o \) is the output power (kW), \( F_{Sc} \) is consumption rate of biomass (kg), \( \eta_{th} \) is the thermal efficiency and \( H_{cf} \) is the fuel calorific value (kJ/kg). In this experiment, the power was also evaluated as a ratio of the biomass energy consumed by the stove per unit time (in kW) as fire power (\( F_p \)) and mathematically expressed as [5].

\[
F_p = \frac{(m_c \times H_{cf})}{(60 \times (t_f - t_i))} \quad (4)
\]

where \((t_f - t_i)\) is the duration of the specific experiment phase. The experiment was conducted with both cold and warm start conditions. The cold start begins with the stove at room temperature, while the warm start, a fire was reset immediately after cold start phase.

6. Results and discussion
6.1 Biomass properties as fuel

Table 2 shows the proximate analysis, the ultimate analysis and the calorific value of some selected agricultural biomass waste. The structural components and chemical elements of biomass are influence factors on combustion characteristics and thermal utilization. These components and elements depending on the origin and type of biomass. C, H, and O are the main elements of these solid biomass waste. In this work, the calorific values were estimated using Dulong’s formula based on elements composition. The calorific values of corncob, coconut shell, and wood chip were obtained about 17275 kJ/kg, 20890 kJ/kg and 18321 kJ/kg, respectively. The higher content of C and H increase to the calorific values, while the O content decreases the calorific value. The C content of coconut shell is higher than those of corncob, it means the slightly higher calorific value of coconut shell [19]. The lower calorific value of wood chip was influenced by H content due to the formation of water (moisture) [19]. The ash content also decreased the net calorific value, moisture and ash absorb some of the heat.
Since the value of this biomass calorific values is still within the range of calorific values of biomass in general. It is reasonable to be used as the basis for calculating the parameters for evaluating the performance of the natural draft stove.

| Characteristic | Corncob | Coconut shell | Wood chip |
|----------------|---------|---------------|-----------|
| Ultimate Analysis (%) |         |               |           |
| C              | 45.01   | 47.89         | 51.28     |
| H              | 6.45    | 6.09          | 7.23      |
| O              | 46.3    | 45.75         | 46.78     |
| N              | 0.26    | 0.22          | 0.28      |
| S              | 0.11    | 0.05          | 0.34      |
| Ash            | 1.87    | 7.56          | 18.65     |
| Proximate Analysis: |         |               |           |
| Moisture Content (% wb) | 10.6   | 6.51          | 7.30      |
| Volatile Matter (% db) | 75.52  | 68.82         | 76.75     |
| Fix Carbon (% db) | 22.61  | 18.03         | 14.82     |
| Calorific Value (kJ/kg) | 17275* | 20890*        | 36206**   |
| Bulk density (g/l) | 332.06  | 562.06**      | 362.06**  |

* Calculated by Dulong’s formula
** Experiment

6.2 Stove performance

Table 3 shows the values of some stove performance during hot start phase and cold start phase using a different kind of biomass fuel. Various fuel properties were found to affect the stove performance. Slightly lesser time (about 1 min.) was required to start up and to boil the water during hot start phase than in cold start. Coconut shell waste and wood chips waste provide longer start-up time of about 1 minute compared to corncob. This can be understood by the fact that the biomass fuel in the stove would be at slightly higher temperature than room temperature. This increases the amount of volatile vapor that would burn more easily. The higher volatile matter allows the fuel to ignite quickly into gas. This is due to heat transfer to the fuel and the fast combustion process occurs in the hot start phase than the cold start phase and due to the percentage of volatile matter content.

| Type of biomass | Weight (kg) | Start-up time (min.) | Operation time (min.) | Boiling time (min.) |
|-----------------|-------------|-----------------------|-----------------------|--------------------|
|                 | Hot start   | Cold start            | Hot start             | Cold start         |
| Corncob         | 0.50        | 10.55                 | 9.25                  | 12.78              |
|                 | 0.75        | 11.49                 | 11.25                 | 15.11              |
|                 | 1.00        | 12.14                 | 12.70                 | 16.37              |
|                 | 1.50        | 12.61                 | -                     | 18.14              |
| Coconut shell   | 0.50        | 12.11                 | 11.03                 | 14.09              |
|                 | 0.75        | 14.47                 | 13.25                 | 16.21              |
|                 | 1.00        | 14.79                 | 14.68                 | 18.19              |
|                 | 1.50        | 15.09                 | -                     | 19.55              |
| Wood chip       | 0.50        | 11.93                 | 12.30                 | 13.88              |
|                 | 0.75        | 14.07                 | 14.75                 | 16.69              |
|                 | 1.00        | 15.75                 | 15.98                 | 17.46              |
|                 | 1.50        | 16.34                 | -                     | 20.21              |

In addition, corncobs have a large number of void fractions to facilitate incoming combustion airflow and improve air and combustible elements mixing that enable good combustion. In this
experiment, there was no significant difference of operation time for the various amount of biomass in both hot and cold phase. This can be explained by the experiments that average of burning rate was found about 0.2 kg/min for all kinds biomass fuels.

The maximum flame temperature on the natural draft stove using three kinds of biomass fuel was about 1126 °C. The flame temperature of about 795-869 °C with reddish orange flame color was observed when corncob utilized as fuel. Whereas the utilization of coconut shells tends to produce orange bluish flame at the temperature of 706-963 °C and wood waste fuels also tend to produce bluish orange flame at the temperature of 912-1126 °C, as shown in Table 4. The flame temperature is affected by the type of fuel, the amount of fuel and air supplied. The high flame temperature determines the amount of released heat, as the flame temperature gets higher, the heat released by the fire increases. Different flame colors were influenced by some gas content in biomass fuel. The orange flame color was caused by a lot of CO and unburned of carbon particles. When more CO in the flue combustible gases closer to the red flame color. While the blue color on the flame indicates that a lot of combustible gases of CH₄ and H₂ [5]. In this work, the height and shape of the resulting flame tend to be unstable due to turbulent airflow.

| Type of biomass | Flame Temperature (°C) | Flame color       |
|-----------------|------------------------|-------------------|
| Corncob         | 795 – 869              | Reddish orange    |
| Coconut shell   | 706 – 963              | Orange            |
| Wood chip       | 912 – 1126             | Bluish orange     |

The other stove performance indicators were conducted by boiling 1 kg of water through calculations based on modified of water boiling test. The time required for boiling 1 kg of water about 3-4 minutes, with the consumption of biomass fuel 105-121 g (specific fuel consumption, Sₙ about 0.51 - 0.76 kg/hour). The use of coconut shell as fuel in this stove gave a shorter boiling time than corncobs and wood chips. This was influenced by the combustion process because of the greater the burning rate the greater the firepower and the amount of flammable gas produced. The higher of combustion quantity would cause the greater of heat combustion. It could be understood that utilized coconut shell as fuel would cause faster boiling of water. But in this case, the higher of the calorific value of fuel resulted in a little bit more energy lost to the environment, as well as the rate of evaporation of boiling water becomes larger, however no significant effect on thermal transfer efficiency.

| Parameters performance | SNI standard | Experimental data |
|------------------------|--------------|-------------------|
| Thermal efficiency, ηₙ (%) | Minimum 20   | 20 – 21           |
| Combustion efficiency, ηₑ (%)  | Minimum 0.96 or 0.04 | –                  |
| Specific fuel consumption, Sₑ (kg/jam) | Maximum 1   | 0.51 – 0.76       |
| Emission of CO (g/kg)        | Maximum 67   | –                 |
| Particulate emissions, PM 2.5 (mg/kg) | Maximum 1500 | –                 |

The performance of biomass stoves that represented as thermal efficiency is influenced by a number of factors. The first factor is insulation or coating along the combustion chamber. Insulation will minimize the rate of heat loss in the combustion chamber wall by conduction. There is also an adequate air supply factor, which will ensure the complete combustion of biomass [6]. The biomass utilization using this stove gave the thermal efficiency, ηₙ of about 20 - 21%. And a maximum fire power of 22.97 kW and 8.76 kW using coconut shells and wood chips, respectively.

From several evaluation parameters that have been accomplished, some of them have met the SNI standard requirements of SNI 7926: 2013. While the combustion efficiency (ηₑ), CO emissions and particulate emissions have not been measured yet. The more details of parameters are presented in Table 5.
6.3 Economic Studies

In the current work, the economical was evaluated by the implementation of the biomass stove in PT. Tiga Oscar Besaudara, in the area of West Bandung District. The economical was conducted on the basis of the used of biomass and excluding the investment of the stove. The economic calculation was based on the ratio of energy used for cooking/frying, as well as for boiling of water with heat energy available in the fuel. By the thermal efficiency of about 20%, the cost for boiling 1 kg of water about IDR 130-300/kg water. The price of this economical was still much cheaper than using kerosene stove, IDR 188/kg of water and LPG stove, IDR 250/kg of water. While the economic calculation of the biomass utilization for frying fish using this stove gave the difference between the benefit of the use of LPG and the use of biomass was IDR 1,500/kg fish.

7. Conclusions

The specific fuel consumption, \( S_c \), of solid biomass waste utilized using this stove was in the range of 0.51-0.76 kg/h. The coconut shells and wood chips utilization using this stove produced a maximum fire power of 22.97 kW and 8.76 kW, respectively and gave the maximum flame temperature was 1126 °C with a bluish orange flame. About 3-4 minutes was needed to boil 1 kg of water with thermal efficiency in the range of 20-21%. The average of burning rate was found about 0.2 kg/min for all kinds biomass fuels. The biomass waste utilization gave the most economical cost than the used of LPG. This stove performance have met some parameters of the SNI standard requirements of SNI 7926: 2013. By the results of this study, small industries in West Bandung District are suggested to utilize the biomass waste using this stove to substitute LPG needed.

8. Further study

Since the finding of the experiments is encouraging, work is in progress to measure CO and particulates emissions. The experiment is also being planned to improve this biomass stove design and scale up for the medium industrial needs. The estimation of the life cycle environmental impacts of the solid biomass combustion and to identify its benefits will also be studied. The data will be submitted in subsequent paper.

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