AN EXPERIMENTAL STUDY ON THE DEVELOPMENT OF MULTIPURPOSE BIOMASS BURNER FOR COOKING STOVE AND THERMAL GENERATOR FOR HOUSEHOLD APPLICATION

Budhi Muliawan Suyitno*
Department of Mechanical Engineering, Faculty of Engineering, Universitas Pancasila, Srengseng Sawah Jagakarsa, DKI, Jakarta 12640, Indonesia, budhi.suyitno@univpancasila.ac.id
https://orcid.org/0000-0003-4384-0352

Ismail
Department of Mechanical Engineering, Faculty of Engineering, Universitas Pancasila, Srengseng Sawah Jagakarsa, DKI, Jakarta 12640, Indonesia, ismail@univpancasila.ac.id
https://orcid.org/0000-0001-7911-4163

Reza Abdu Rahman
Department of Mechanical Engineering, Faculty of Engineering, Universitas Pancasila, Srengseng Sawah Jagakarsa, DKI, Jakarta 12640, Indonesia, reza.a@univpancasila.ac.id
https://orcid.org/0000-0002-8047-6716

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Highlight
Two-in-one biomass burner for household application: cooking stove and heating system.

Abstract
The present study proposes a novel concept of a solid biomass burner for household applications. The designed biomass stove is a multipurpose burner that can be used as a cooking stove and thermal generator. It works as a basic model of a biomass cooking stove and is coupled with a coil heat exchanger for thermal generation. The experimental evaluation is conducted by using the time-to-boil (TTB) method to measure the effective energy that can be harnessed from the combustion process. It shows that the maximum temperature outlet from the coil heat exchanger is 62.2 °C. The effective energy uptake for the coil heat exchanger is 41.9%, whereas the overall energy uptake, including the kettle, is obtained by more than 50%. Therefore, the proposed model can improve the efficiency of solid biomass burners for household ware.

Keywords
alternative energy; biomass; burner; coil heat exchanger; cooking stove.

Introduction
Energy supply is a critical issue for humankind, particularly in the modern era when energy becomes a fundamental aspect of sustainable development. High dependency on fossil fuels leads to the risk of crisis energy since its non-renewable energy [1]. It motivates research for alternative fuel becomes mandatory. In the meantime, the exploration and reactivation of old oil well can be considered a short mitigation effort [2]. Harnessing clean energy is also crucial for the current situation. Thus, improving the renewable energy system such as solar and wind energy project increases nowadays [3]. It can be observed based on a statistical record of global utilization of solar and wind energy [4]. It improves significantly since the energy storage system becomes more reliable, supporting the dispatchability of the renewable energy system [5]. Moreover, a method to improve biomass utilization as an alternative and primary fuel is still necessary, particularly for remote regions with limited access to the main grid and renewable energy systems.

Biomass as solid fuel is considered the basic form of fuel stock that can be found across the globe. It is also considered the main fuel for primary energy sources for more than one-third of the population. It uses for the cooking process by using biomass stoves [6]. Also, solid biomass is essential for small to the large-scale factory for the production process [7]. Improving biomass combustion efficiency is essential to increase the net energy uptake from the combustion process. As a result, innovative methods such as thermo-electric converters and waste heat recovery system gains significant interest among researchers and industry practitioners. It allows the user to produce electricity or thermal energy for the heating purpose from the waste heat of the combustion

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process [8]. Improving the quality of the conversion process from biomass to thermal energy is also necessary since it will produce more effective energy and reduce the emission ratio from the combustion process. For example, Rasoulkhani et al. compares the conventional and improved design of biomass stove for the combustion process. The study shows an acceleration of time-to-boil (TTB) using an improved design biomass stove by a value of 35% compared to the traditional mode [9]. The proposed method also can be combined by improving the fuel quality through pelletization. The solid biomass fuel as a pellet is preferable since it has a better surface area, improving the combustion process. It has better physical properties and reduces potential failure during storage [10]. Further improvement in biomass stoves implies the requirement to increase the energy conversion process from solid biomass fuel, particularly for household applications. Shaisundaram et al. suggest that the optimization process for conventional biomass stoves can increase the combustion efficiency and thermal generation from the stove [11]. It embeds the thermoelectric converter as an extra component that boosts the practical energy conversion from the combustion process, eventually increasing the effective net conversion. The method is also suitable as an electric generator for the remote region where the consumption of solid biomass fuel is high [12]. Biomass is also essential for subtropic and cold regions since it provides sufficient energy for heating [13]. Hou et al. describe the detailed aspect of converting solid biomass to household heating. The study combines the biomass system and solar energy to improve the readability of the green heating system [14]. The method is highly relevant to the development of thermal energy storage, which can be used to extend the effective working hour of the system to provide heat energy at night [15]. Ferla and Caputo specifically discuss the application of biomass for heating purposes in northern Italy. The study suggests the potential of biomass utilization and integration with district heating systems. Suitable optimization is suggested to promote a better energy uptake from solid biomass fuel and improve the system's operation for providing thermal energy [16].

Performance improvement of biomass stoves is mainly made by enhancing the thermochemical conversion. It is generally done by modifying the air intake system for the combustion process [17]. For instance, using pressurized air in the combustion chamber improves thermochemical conversion and boosts combustion [18]. Another aspect that should be considered is usability and acceptability from the consumer perspective since it relates to daily cooking and heating purposes for household applications [19]. Further study is also recommended in terms of reducing the drawbacks of conventional biomass open-stove which has low performance and high pollution compared to the closed-stove model [20]. Several studies report that improving the combustion chamber and energy uptake from the combustion process significantly reduces the pollution issue [21]. The application of biomass stoves can be combined for heating applications. Designing a biomass stove that can meet the criteria for both function, stove and heating, is advantageous for household application. The multipurpose biomass burner agrees with the recent trend where the 3E concept (energy, economic and environmental) becomes essential for developing biomass applications in a household environment [22]. The combined function of applying a multipurpose biomass burner is predicted to provide positive outcomes since it can be used as a stove for cooking and heating applications. Thus, the useful energy from the combustion process can be utilized better, reducing the cost and emission per unit of energy. Moreover, the concept of a multipurpose biomass burner can be improved for advanced application by embedding the system to a thermoelectric generator [23] and thermal energy storage [24] for a waste heat recovery system which significantly increases the effective energy conversion. Improvement on the equipment of energy conversion system is essential particularly for the feasibility of the energy conversion apparatus [25]. Also, using small scale pump reduces the energy consumption which help to increase the net energy balance from the burning process [26]. Therefore, the application of a multipurpose biomass burner is expected to boost energy conversion from solid biomass fuel. However, a limited study specifically addressed the concept of combining the biomass stove and heating generator for household applications. The present study proposes an innovative multipurpose biomass burner that is expected to be used as a cooking stove and heat generation as household ware. The proposed multipurpose burner is expected to be quickly adopted and gain a positive response for the user since it uses common material that is widely available and low-cost. As a preliminary study, the proof of concept is conducted experimentally to evaluate the effective performance of the proposed design. The concept of a multipurpose biomass burner is expected to become a fundamental basis for further improvement on the biomass burner for a household application that is also combined for district heating and hot water supply.

Methods

The basic component and conceptual design for the biomass burner was evaluated by using the first principal method. The heat utilization from the combustion process is specified for cooking and/or warm water supply, which can be applied for district heating by using liquid to air heat exchanger. In order to maximize the burning process, the air has to be supplied to the combustion chamber. Moreover, the fuel-feeding process can be done continuously without interfering with the cooking and burning process. These ideas were a fundamental aspect of building the multipurpose biomass burner.

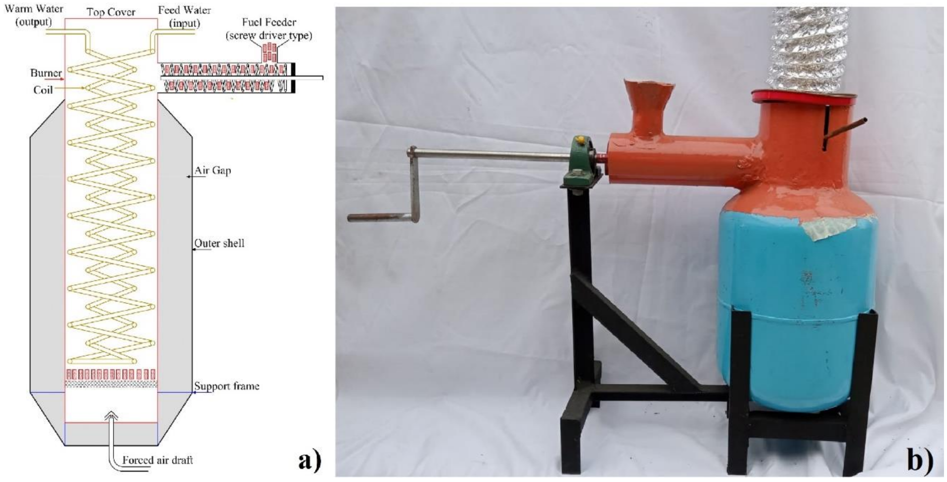

Figure 1. a) Schematic design for multipurpose biomass burner, b) Photograph of the prototype. *Source: Author.*

The developed prototype for a multipurpose biomass burner is presented in Figure 1. The prototype uses a screw-driver fuel feeder mechanism. The mechanism is operated manually and can be further developed for automation using a motor drive. The feeder is installed on the edge upper side of the combustion chamber to supply the fuel continuously during the combustion process. At the top of the burner, a flat metal sheet can be placed for cooking. The flat metal sheet can maximize heat distribution during the cooking process. The designed burner is equipped with an outer shell filled with air that reduces the heat losses from the combustion chamber to the environment. A metal tube hose is installed at the bottom part of the combustion chamber to supply fresh air for the combustion process. The compressor supplies fresh air, which can be adjusted to control the combustion process.

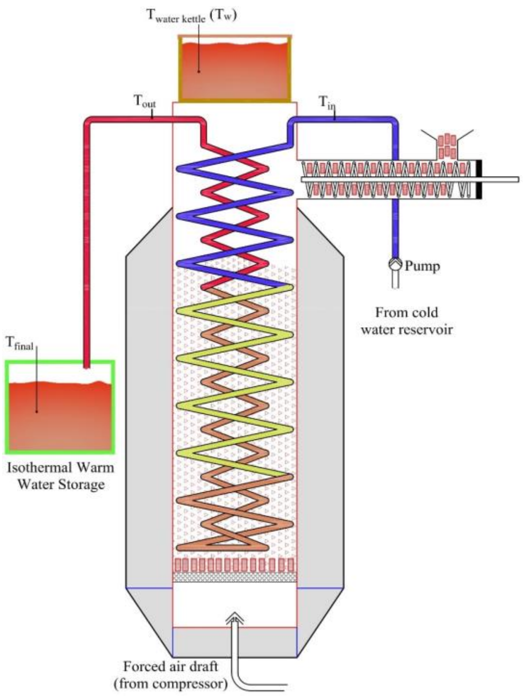

Figure 2. Schematic of experiment test by using time-to-boil (TTB) method. *Source: Author.*

As seen in Figure 1, the coil heat exchanger is located directly in the combustion chamber. It uses a dual-coil heat exchanger to improve the heat transfer rate from the combustion process. A copper tube ($Ø_{in}$ 0.5 cm, $Ø_{out}$ 0.61 cm) was used as suitable media for absorbing the heat by using the working principle of a recuperative heat exchanger. It allows the unmixed heat transfer process between cold and hot fluid. The height of the coil is 30 cm with the number of turns 40, where the inside/outside coil ratio is 0.6 (11.4 cm and 6.8 cm, respectively). The detailed dimension for the coil is taken from [27]. The designed coil is expected to achieve the primary function of developing a multipurpose biomass burner. Experimental evaluation was taken to observe the function of the prototype multipurpose biomass burner. As seen in Figure 2, the test was conducted using the time-to-boil method to measure the amount of useful energy absorbed by the kettle and coil heat exchanger during the combustion process. The kettle was filled with water (mass of 3 kg and temperature of 19 °C) and placed at the combustion chamber's top. The temperature increment of the water was measured by a thermocouple (Type K). During the same heating process, the pump distributed water from the cold reservoir (19 °C) and flowed to the coil heat exchanger at a mass flow rate of 2–10 g/s (interval 2 g/s). The outside temperature of the water from the coil heat exchanger was measured by a thermocouple (T_{out}). The warm water from the coil was collected in well-insulated water storage. The water temperature inside the storage is defined as the final temperature from the coil (T_{final}). The combustion process used solid fuel biomass with a lower heating value (LHV) of 17.45 MJ/kg and moisture content (MC) of 14.8%. The combustion process was set for 20 minutes using 0.75 kg of solid fuel. The air from the compressor was supplied to the combustion chamber at a pressure of 2 bar. The burning process for biomass stove is a complex thermochemical conversion which affected by quality of the fuel, properties of the air (temperature and pressure) and temperature gradient with the surrounding [28]. The designed experiment was taken under these considerations by repeating the process for five times and error of measurement (5%). By measuring the temperature increment for the stored water from the coil heat exchanger and kettle, the effective energy from the combustion process can be defined precisely.

Results and discussion

The variation of the mass flow of water through the coil heat exchanger is set as the basis point to observe the temperature increment for the water in the kettle (T_w) and from the coil heat exchanger (T_{final}). As seen in Figure 3, the temperature profile of the water in the kettle shows a different final temperature. The highest final temperature for the kettle is obtained at a mass flow rate of 2 g/s for the coil. Then, the final temperature tends to decrease as the mass flow rate increases on the coil side. Therefore, it implies that the change in mass flow rate on the coil side effects the kettle's energy uptake. The energy from the combustion is absorbed on the coil in the first place then to the kettle. It makes the kettle absorbs a smaller quantity of the heat energy from the combustion. The temperature increment during the combustion process is relatively linear, with a minor fluctuation for the mass flow rate of 6 g/s and 10 g/s. The fluctuation is generally caused by inadequate thermal distribution during the combustion process.

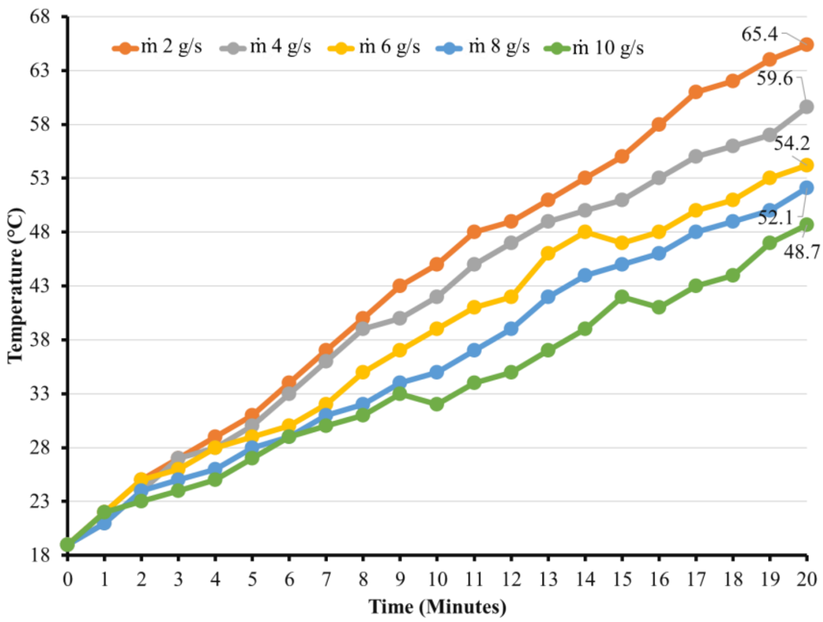

Figure 3. Profile temperature of the water inside the kettle (T_w). *Source: Author.*

Figure 4 presents the coil side's profile temperature, measured in the outlet temperature (T_{out}), as seen in Figure 2. The temperature is increased gradually until it reaches the peak point and decreases moderately. The study uses a finite amount of fuel since it is crucial to understand the nature of the system to absorb heat from combustion, both in the coil and kettle side. Using this approach allows for evaluating the characteristic of temperature distribution properly. For instance, all temperature profile shows a significant temperature increment for 10 minutes. The highest temperature is obtained by a mass flow rate of 10 g/s with a peak temperature of 62.2 °C. Contrary to that, the lowest peak temperature is obtained at 59.3 °C when using a mass flow rate of 2 g/s, which occurs after 16 minutes (approximately). It demonstrates that a higher mass flow rate has a better energy uptake and leads to a higher temperature. The mass flow rate of 10 g/s also shows the highest final temperature compared to the other.

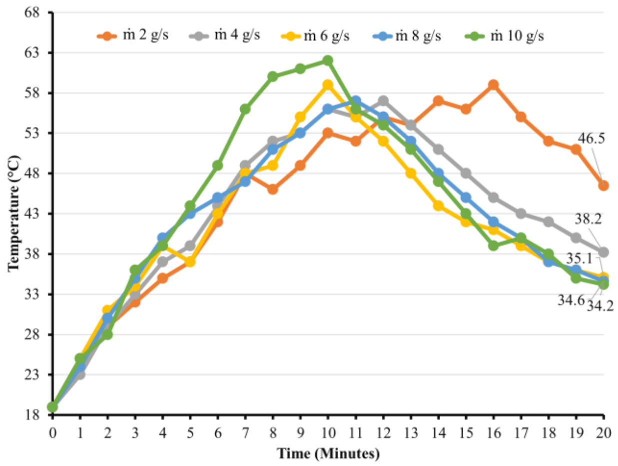

Figure 4. Profile temperature of the outlet from the coil heat exchanger. *Source: Author.*

The heat from the combustion that is absorbed by water for the coil side involves combination heat transfer. The copper body absorbs the heat from hot fluid (air from combustion) and transfers it to the working fluid (water). A low mass flow rate leads to slower heat diffusion, reducing the temperature increment rate. It also disturbs the flow within the coil, which can be observed by the temperature fluctuation during the slow mass flow rate. Increasing the mass flow rate improves the temperature and promotes a stable temperature distribution [29]. It makes the heat exchange process excellent. The plot provides essential information as a higher temperature is more desirable for heating, such as an air heater. The maximum temperature can be improved by using a lower specific heat capacity for the working fluid (i.e., thermal oil) since it improves the heat transfer effectiveness for liquid-to-air heat exchangers [30].

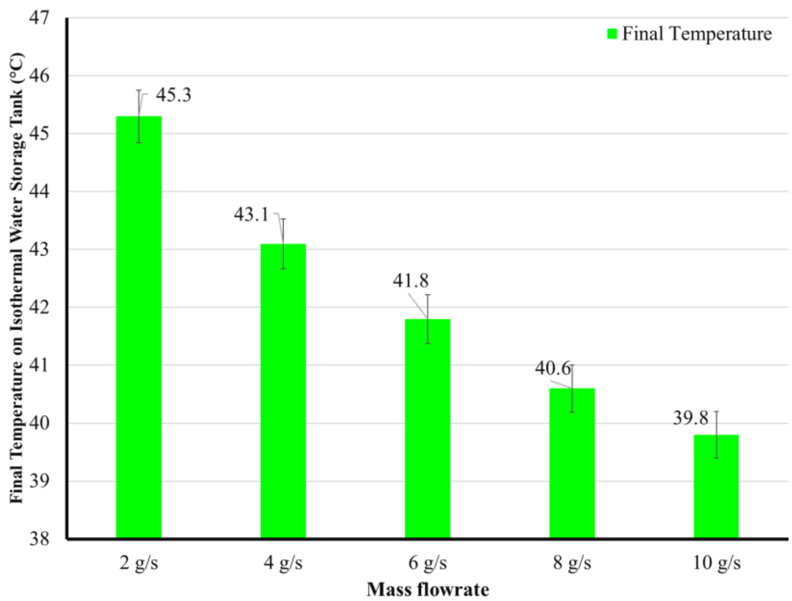

Figure 5. The final temperature on the isothermal warm water storage. *Source: Author.*

Figure 5 displays the final temperature (T_{final}, Figure 2) for the water from the coil heat exchanger. It shows that a lower mass flow rate has the highest final temperature within the storage tank. The final temperature for a mass flow rate of 2 g/s is 45.3 °C, whereas the mass flow rate of 10 g/s has a relatively lower final temperature

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of 39.8 °C. Since the mass flow rate of 2 g/s delivers a smaller capacity during the test (the final mass of the water in the storage tank is 2.4 kg), the final temperature of the storage tank is relatively higher. It allows the system to reach a higher final temperature since the water capacity is smaller than the mass flow rate of 10 g/s (approximately 20.76 kg). Improving such performance for the indirect heating system using biomass stove is can be considered as important aspect which help to increase the economic feasibility of biomass heating system [31]. Thus, the result can be used for further consideration on the designation of the usage for the water from the coil heat exchanger.

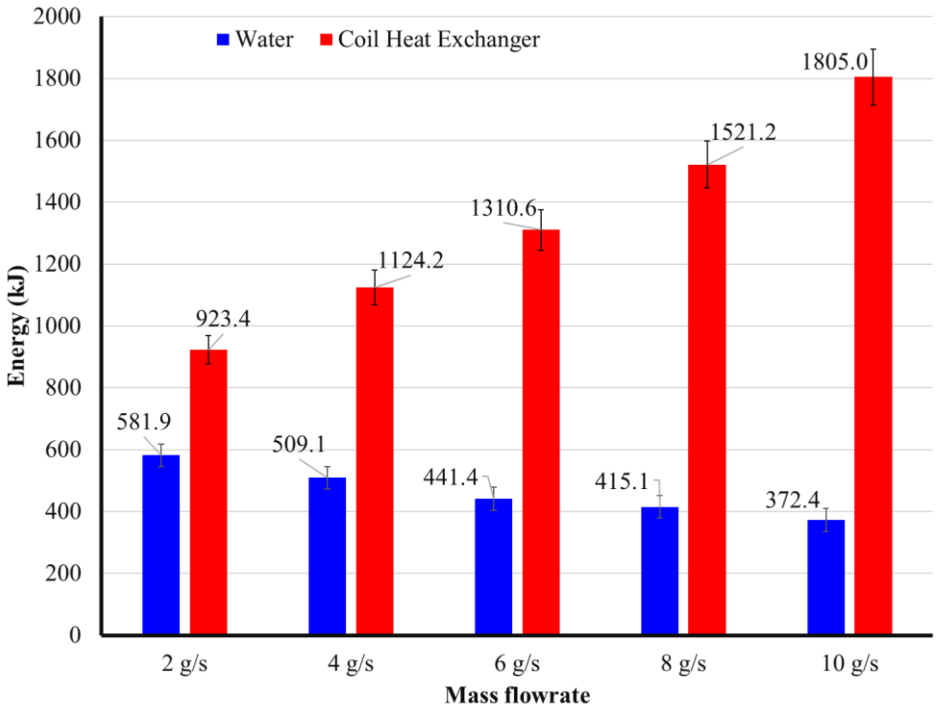

Figure 6. The absorbed heat energy for the water in the kettle and coil heat exchanger. *Source: Author.*

The total energy extracted from combustion on the kettle and coil side is plotted in Figure 6. Using the isothermal storage tank allows for estimating the amount of energy extracted by the coil heat exchanger. It can be seen clearly that the extracted energy for the kettle and coil is opposite. It shows that the net energy balance for the system has a limitation. It explains that the temperature profile for both sides shows an inverse characteristic. It implies that the energy distribution from the combustion only can be absorbed at a certain level. Therefore, using more than two systems that absorb the heat of combustion is preferable as it can improve the net energy balance. It helps to increase the overall usage of solid fuel biomass where the system can produce more energy which reduces the consumption cost and model for distribution, particularly for the rural and mountain area which has limited access to the feedstock [32]. The proposed design is also suitable for high altitude design where the needs of heating source is relatively high while in the same time requirements for energy cooking process is also high [33].

For further observation, Figure 7 presents the ratio of effective energy absorbed by the water from the coil side and water inside the kettle. The ratio is obtained from the amount of energy from the water and the total mass of the fuel times its lower heating value (LHV). In addition, the LHV for the solid fuel is obtained under an ideal combustion process within the apparatus (bomb calorimetry) which uses excess oxygen. For the actual combustion within the burner, the theoretical oxygen ratio in the air is roughly 21%, which means the maximum energy that can be harnessed from the solid fuel is only 21%. The actual combustion process also interacts with the environment, which is considered heat loss even though using air gap between the combustion chamber and the environment with the help of the outer shell reduces the heat losses during the combustion (Figure 2). However, for simplification, the heat loss from combustion is neglected and the total maximum energy is only plotted based on the ratio of 21% oxygen in the air. Promoting a higher efficiency burning process lead to a significant improvement on the fuel consumption that in the same time reducing the air pollutant [34]. It also promotes a better cooking process where the method can be adopted easily in conversion process from open-air biomass stove to a cleaner cooking process [20].

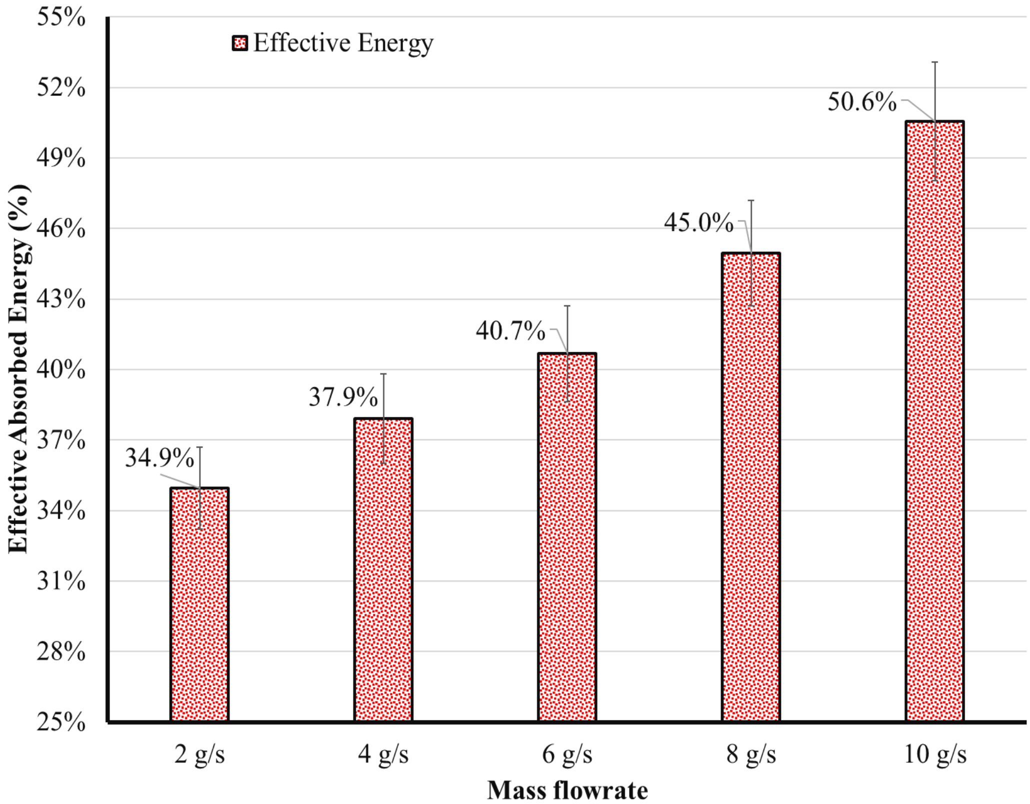

Figure 7. The ratio of effective energy absorbed by the water on the kettle and coil side. *Source: Author.*

As seen in Figure 7, using a higher mass flow rate contributed to a higher ratio of effective energy from the combustion. Using a coil heat exchanger in the combustion chamber promotes a higher energy uptake, making the system more effective in harnessing the combustion heat. Furthermore, the rest of the combustion energy is absorbed by the water within the kettle. Thus, the system can provide a higher effective energy by using two different methods for absorbing the heat of combustion. Moreover, the combined system such as with photovoltaic will produce a significant improvement on electrical consumption and energy for cooking process in rural area [35]. The heat from the coil heat exchanger can be further processed for a specific application which makes the multipurpose biomass burner advantageous as it can provide more energy from the solid biomass fuel. Therefore, the multipurpose biomass burner can be considered an effective method for advanced utilization of solid biomass fuel through combustion.

Impact

Solid biomass fuel is the primary energy source for more than one-to-third of the world's population, particularly those who live in remote areas. Using biomass as fuel in household application is commonly used for cooking and heating by an open stove cook with low combustion efficiency. Providing a better biomass burner should be done by considering the cost and process of developing a novel biomass burner. The study presents the concept and prototype of a multipurpose biomass burner that society can quickly develop. The dual function of the designed burner is expected to help society with daily heating supplies such as warm water and district heating. The energy from combustion can be utilized higher than a single model. Thus, the effective energy from the combustion process of solid biomass fuel can be harnessed productively and reduce the cost per unit of energy. Furthermore, putting the coil heat exchanger in the combustion chamber improves the heat exchange process and provides a better net energy uptake from the combustion. Owing a higher performance for biomass stove is essential both for the environment and society. The fuel consumption will reduce significantly which reduces the economic cost of the solid fuel biomass. The heat energy can be taken for heating process which account more than 35% annual energy consumption, particularly for the cold and high-altitude region. In the same manner, reducing the fuel consumption leads to a lower air pollutant which slowing down the air pollution process. Also, promoting a higher efficiency burning process makes the burning process more effective which reduces the emission process. The study presents a specific recommendation that can be used for further development and modification depending on the burner's specific and operation characteristics. Therefore, multipurpose biomass burners for household applications can be implemented in society.

Conclusions

A multipurpose biomass burner is developed to meet the cooking process and heating application criteria. The heat from the combustion of solid fuel biomass is absorbed effectively by a coil heat exchanger located in the combustion chamber. Mass flow rate plays a critical role in effective heat transfer where a mass flow rate of 10 g/s can absorb heat effectively five times greater than 2 g/s. The excess heat from the combustion is also absorbed by the kettle located at the top of the combustion chamber. It allows for adding more effective energy, up to 8.6%. Thus, the combined method, coil heat exchanger and kettle, provide a sufficient energy uptake from the combustion by a value of 50.6%. The method improves the effectiveness of the combustion process from solid fuel biomass by a higher effective energy than can be utilized from combustion. It is suitable to improve the effective energy density, indirectly reducing the cost and gas emission from the combustion process. The highest water temperature from the coil heat exchanger is obtained at 62.2 °C. The test uses water as a working fluid with a high specific heat capacity. Therefore, using thermal oil with a lower specific heat capacity would improve the temperature outlet from the coil heat exchanger. A higher outlet temperature is desirable for the heating process, such as district heating and dryer. The study implies that the designed multipurpose biomass burner can be further developed by focusing on the aspect of the combustion process and suitable pressure/air draft to the combustion chamber. Moreover, improving the emission control system and waste heat recovery from the burner can provide higher energy efficiency with lower emission.

Conflict of interest

There are no conflicts to declare

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