Mekanika: Majalah Ilmiah Mekanika

Design, Production Cost, and Air Flow Distribution of Biomass Pellet Furnace

Heru Sutanto[1], Suyitno[1*], Wibawa Endra Juwana[1], Tito Gusti Nurrohim[1]

[1]Faculty of Engineering, Sebelas Maret University, Jl. Ir. Sutami 36 A, Surakarta, Indonesia

*suyitno@uns.ac.id

Abstract Biomass attracts a great deal of attention because it is converted into green fuels in the form of pellets. The furnace is needed to burn pellets to generate heat of up to 300 kW. In addition to meeting the heat capacity needs of small and medium-sized industries, furnaces must also be competitive in terms of price. The purpose of this study is therefore to obtain details of the cost of manufacturing the furnace and the model of air flow that occurs in the furnace. This study employs a forward and reverse engineering approach, beginning with determining load and capacity, drawing, determining the bill of materials and bill of manufacturing, numerical modelling of airflow with ANSYS FLUENT, fabrication, and final testing. The outcome revealed that the cost of production of the furnace included manufacturing costs, assembly costs, machining and repair costs. The findings revealed that the key portion of the cost of the furnace was the material cost of 77%. The findings of the simulation showed that the total pressure difference of up to 850 Pa and had to be resolved by air-supplying blowers. The gas velocity ranged from 2 to 10 m/s and increased significantly near the exit to 42 m/s.

1 Introduction

There is a growing need for pollution-free energy sources. The use of fossil fuels as an energy source has adversely affected the cleanliness of the environment through exhaust emissions. In addition, the limited supply of fossil fuels [1] has sparked the growth of renewable energy technology and the quest for alternative energy sources, such as biomass. Biomass content continues to be renewed as long as the ecosystem in which it is preserved and can be used as a renewable source of energy production [2].

Woods, derived in particular from the Kaliandra (Calliandra calothyrsus) genus, have become a favourite to cultivate into pellets due to their superior properties. Kaliandra woods have a strong growth, sturdy, specific gravity of 0.5-0.8, easy to dry, easy to burn, and calorific value of 4200 kcal/kg [3]. Compared to dry wood, Kaliandra wood biomass pellets have a higher density [4].

Sutanto et al.

In the meantime, biomass furnaces have been widely produced. Burning furnaces are a special device for converting energy from biomass. It is important to be able to convert biomass materials into usable energy. Wood pellet fuels are burned in the combustion chamber to generate heat energy. A fuel-matching combustion system is installed on the burner. The combustion chamber plays an important role in the process of converting biomass energy, thus requiring the design of a combustion chamber that is capable of efficient combustion [5]. A rocket type of pellet fuel stove has been designed [5] and has developed various furnace forms to obtain a common reference configuration for fuel pellet furnaces. Moreover, fourteen household pellet furnace experiments using the water boiling test (WBT) procedure have been conducted [6], which concluded that the furnaces were capable of improving fuel efficiency and lowering combustion exhaust emissions. Unfortunately, only a few researchers have reported the cost of manufacturing a furnace.

In addition to cost, the fuel burning process is a critical element in the furnace. The combustion mechanism is influenced by fuel as well as air. The supply of air must satisfy the needs of fuel combustion in order to achieve efficient combustion [7]. However, there is no precise information on the production cost and the gas distribution in the furnace, since each furnace is very specific, depending on the creativity of the designer and the manufacturer. Therefore, the study aims to obtain details on the cost of producing the furnace and the air flow model that exists in the designed furnace.

2 Methods

2.1 Materials

The primary feedstocks are wood pellets of the Kaliandra variety. The properties are shown in the Table 1. Kaliandra wood pellets have a diameter of 1-2 cm and a length of 2-3 cm.

Table 1. Proximate and ultimate analysis of wood pellet

Parameters	Unit	Basis	Results
Total moisture	%	ar	6.41
Ash content	%	adb	1.12
Volatile matter	%	adb	77.82
Total sulphur	%	adb	0.06
Gross calorific value	kcal/kg	adb	4339
Net calorific value	kcal/kg	adb	4010
Chlorine (Cl)	ppm	adb	498.75
Ultimate Analysis			
Carbon	%	adb	46.80
Hydrogen	%	adb	5.61
Nitrogen	%	adb	0.26
Oxygen by difference	%	adb	47.33

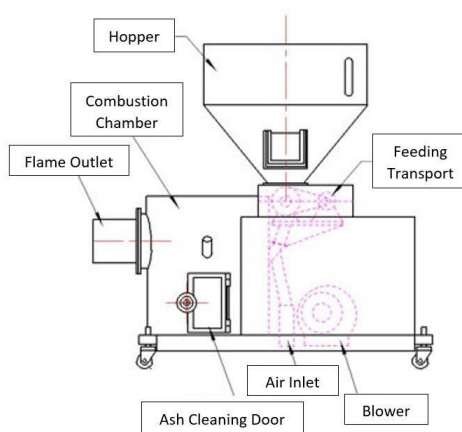adb = air dried basis, ar = as received

Sutanto et al.

Figure 1. Initial design for a biomass pellet furnace

## 2.2 Design, Manufacturing, and Cost of Furnace

The combustion furnace was designed using proximate and ultimate results. The sum of energy that reaches the furnace was calculated using calorific values. The furnace is capable of consuming the pellets at a capacity of 75 kilograms per hour. The fuel inlet (hopper), air inlet (blower), combustion chamber, and outlet are the four major components of the furnace. A perforated plate was used to direct air from the blower into the combustion chamber. Figure 1 depicts the preliminary design of the biomass pellet furnace.

From the initial model of biomass pellet furnaces, the price of materials was calculated, the production method and cost were determined, and the operating and maintenance process and cost were also determined. As a result, production cost information from the furnace can be generated during this design process. Improvements have been made to the initial model, especially the placement of the hopper, which is not on the top, as this would exacerbate the process of transporting feedstock content.

2.3 Air Flow Simulation

The next step is a cold simulation to assess the perforated plate's capacity to distribute air. ANSYS FLUENT software was used to conduct the air-flow simulation. Creating three-dimensional geometry, meshing, defining boundary conditions on geometry, checking mesh quality, determining the properties of the material used, determining the flow model used, determining the method of discretization, initializing, running, and post processing are just a few of the steps involved in air flow simulation. The mesh type of unstructured triangle was utilized in this investigation. The standard k-epsilon was used to set the viscosity model. The mass flow inlet for air and fuel was the boundary condition established. The pressure outlet was specified as a boundary condition on the outlet side. The SIMPLE schema served as the foundation for the simulation.

The following reaction equation is used to calculate the air specifications based on the air fuel ratio (AFR) needed to burn biomass pellets.

$$C_{8,7}H_{12,5}O_{6,4} + 8,625(O_2 + 3,76N_2) \rightarrow 8,7CO_2 + 6,25H_2O + 32,43N_2 \tag{1}$$
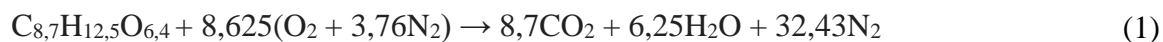
The combustion reaction is a heat-producing oxidation chemical reaction between fuel and oxidizer. As long as the oxygen or air source satisfies the requirements for stoichiometric reactions, complete combustion happens. According to equation 1, the amount of air used to burn 1 kg of biomass pellets is 5.37 kg.

With a stoichiometric AFR, all fuel components can be converted to CO_2 and H_2O, leaving no residual fuel [8]. Cold simulation of airflow distribution at AFRs greater than AFR stoichiometry will also be performed in order to produce an impression of air distribution in the combustion chamber.

Sutanto et al.

The oxygen distribution in the furnace, air speed from the entrance, within the furnace, to the output side, and the pressure inside the furnace were all examined as key simulation factors. The contours of oxygen concentration, speed, and pressure were the output of the ANSYS FLUENT post processing procedure. The oxygen concentration, pressure, and velocity contour were the flow field for that iteration in the steady state.

3. Result and Discussion

3.1 Design, Manufacturing, and Assembly

The air requirement can be calculated based on the chemical reaction of combustion, i.e., $\frac{8.625x(32+3.76x28)}{8.7x12+12.5+6.4x16}$ $x75$ kg/h = 405 kg/h. Meanwhile, the air supply is provided by a blower, with the following blower power requirements: 405 kg/h x 1 hour / 3600 s x 9.81 m/s² x 2,000 m = 169 W. In reality, the blower was selected to have a rated power one level above 169 W.
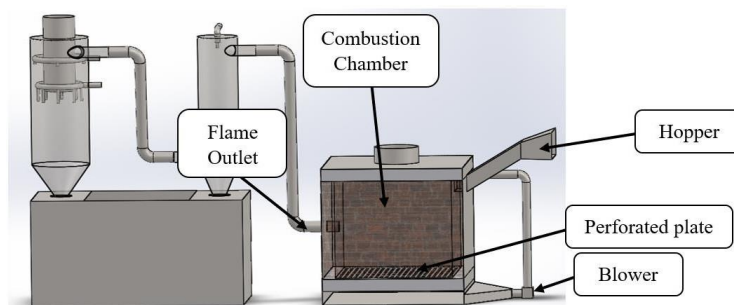

Figure 2. Design for the biomass pellet furnace

The air from the blower is circulated via a perforated plate into the combustion chamber. A perforated plate, which is the main material of the fixed bed component, is made from a carbon steel plate with a thickness of 4 mm and a hole diameter of 8 mm.

Moreover, the hopper is used to feed biomass pellets into the combustion furnace. The hopper should be large enough to accommodate all of the fuel that would be used, so that the burner volume can be adjusted by the scale and shape of the hopper. The bottom of the hopper is narrowed and made of steel plate. The fuel delivery part of the combustion chamber is attached to the bottom hole. Figure 2 depicts a sketch of the modified furnace.

Table 2. Manufacturing process of wood pellet burner at a capacity 75 kg/hour

Body	Parts	Materials	Manufacturing Process
Combustion chamber	Cover of combustion chamber	Carbon steel plate	Cutting, bending, welding
	Insulation	Fire brick	Civil work
	Fuel inlet	Carbon steel plate	Cutting and welding
	Air inlet	Carbon steel plate and carbon steel pipe	Cutting and welding
	Exhaust or outlet	Carbon steel plate	Roll and welding
	Chimney system	Carbon steel plate	Cutting, bending, welding
Wet scrubber Total Sulphur	Small cyclone	Carbon steel plate	Cutting, roll, welding
	Big cyclone	Carbon steel plate	Cutting, roll, welding
	Sprayer system	Carbon steel pipe, sprayer	Cutting, roll, welding, thread cutting
	Water container	Sand, cement, roll steel, and brick	Civil work
	Exhaust pipe	Carbon steel pipe	Welding and flange

Sutanto et al.

The shape of the furnace is a cube with a combustion chamber size of 1 x 1 x 1 m. The outside of the combustion chamber is composed of a steel plate. There are three holes in the steel plate for air inlet, fuel inlet, and fire outlet. The refractory brick is then attached to the plate using refractory cement, which has been cut to size and shape. The coated plate is then welded on either side. The next step is to build a chimney where the fire comes out using a steel plate filled with refractory cement. The need for a cyclone-shaped smoke filter with two filtering steps using water as a filter medium. The hopper, the combustion chamber and the chimney were assembled together. The results of the design, manufacture and assembly of furnaces are summarized in Table 2. The actual results of production are shown in Figure 3.

Figure 3. The biomass pellet furnace

The furnace, made of carbon steel plate sheets, has a lifetime of 3-4 years [9]. The fire bricks, on the other hand, can survive for 20 years. This fire brick acts as heat insulation, preventing the carbon steel plate component from coming into direct touch with the fire. As a result, the fire brick will extend the lifetime of the furnace [6]. Furthermore, because there are no moving parts, the combustion furnace has a lifetime of more than ten years. Blowers, wet scrubbers, wet scrubber pumps, and spray nozzles are examples of important elements that require frequent maintenance and even replacement. The life of the furnace's wet scrubber and spray components will be extended if maintenance is performed once every three months and a replacement sprayer is installed once every two years. Previous research has shown that the fundamentals of stove life in general can be employed for up to five years. According to various studies, the minimum predicted lifetime of a furnace with proper maintenance is five years [10]. Even with improved material choices, the furnace's lifetime can be extended, but the investment expenses will rise. Enhance furnace life by up to two years, increase net present value (NPV), internal rate of return (IRR), and benefit-to-cost ratio. The suggested upgraded furnace with better quality steel cladding results in a 20% increase in investment costs, with a service life of up to 7 years.

3.2 Bill of Materials

The bill of materials (BOM) covers the costs of purchasing materials, manufacturing procedures, installations, and repairs organized in a sequence of production. The material requirement for a furnace capacity of 75 kg/h is shown in Table 3. The material cost is 77% of the overall cost of furnace production.

Sutanto et al.

Table 3. Bill of materials of wood pellet burner at a capacity 75 kg/hour

Parts	Materials	Volume	Unit	Price (IDR)	Total (IDR)
Cover of combustion chamber	Carbon steel plate, thickness 4 mm	4	sheet	785,000	3,140,000
Insulation	Fire brick	300	Pieces	4,200	1,260,000
	Fire cement	300	kg	1,500	450,000
Fuel inlet	Carbon steel plate, thickness 4 mm	1	sheet	785,000	785,000
Air inlet	Carbon steel pipe, diameter 3 inch	0.25	Pieces	650,000	162,500
	Carbon steel plate, thickness 4 mm	1	sheet	785,000	785,000
Combustion gas outlet	Carbon steel plate, thickness 4 mm	0.5	sheet	785,000	392,500
Chimney system	Carbon steel pipe, diameter 4 inch	0.25	Pieces	910,000	227,500
Small cyclone	Carbon steel plate, thickness 4 mm	2	sheet	785,000	1,570,000
Big cyclone	Carbon steel plate, thickness 4 mm	2.5	sheet	785,000	1,962,500
Sprayer system	Carbon steel pipe diameter 1.5 inch	1	Pieces	230,000	230,000
	Sprayer diameter ¼ inch	14	Pieces	15,000	210,000
Water container	Sand	0.5	Truck	1.700,000	850,000
	Cement	8	Unit	43,000	344,000
	Clay brick	500	Pieces	43,000	516,000
	Roll steel	12	Pieces	910,000	2,730,000
TOTAL					15,965,000

In addition to working with machines, the method of producing parts often uses manual methods. Machining work, such as rolling and bending, can use machining facilities. Budget criteria for machining jobs, such as Table 4. The machining cost is 6% of the overall cost of furnace production.

Assembly is the final stage in the sequence of production processes. The assembly stage is designed to integrate furnace parts and wet scrubber components. In addition to assembly, maintenance needs are also required in order to maintain good furnace efficiency. The assembly and maintenance requirements are shown in Table 5. The assembly and maintenance costs are 77% of the overall cost of furnace production.

Table 4. Cost for machining process

Parts	Machining process	Dimension (cm)	Cost (IDR)
Cover of combustion chamber	Bending	L = 120 (90)	300,000
Small cyclone	Roll	D = 50, L = 150	240,000
	Welding	L = 150	150,000
Big cyclone	Roll	D = 65, L = 150	300,000
	Welding	L = 150	150,000
Sprayer	Roll	D = 50	120,000
Total			1,260,000

Sutanto et al.

Table 5. Cost of assembly and maintenance

Activity		Volume	Cost (IDR)	Total (IDR)
Assembly	Flange	8	45,000	360,000
	Bolt mounting	16	15,000	240,000
Maintenance	Sprayer	14	15,000	210,000
	Blower	1	2,200,000	2,200,000
	Water pump	1	560,000	560,000
Total				3,570,000

3.3 Air Flow Distribution in the Furnace

Air composed of 21 per cent oxygen and 79 per cent nitrogen is used for oxidisers and flows through the inlet side of the air. Oxygen is distributed in the combustion chamber, as can be seen in Figure 4. Oxygen is most commonly distributed in the middle and at the bottom of the combustion chamber. The greater the amount of air added, which is marked by excess air, the more it is noted that much of the oxygen flows to the front portion of the perforated plate. This can lead to more vigorous combustion of the front and a lot of heat is applied directly to the outlet portion of the combustion chamber.

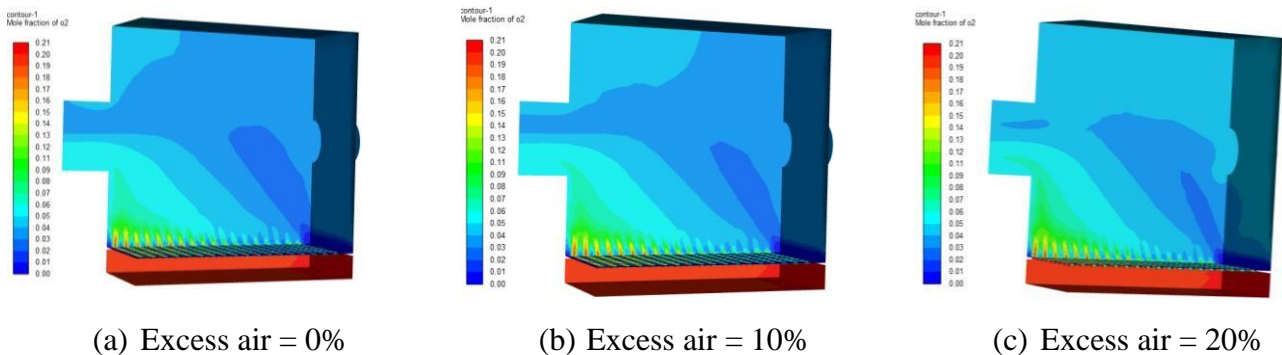(a) Excess air = 0%   (b) Excess air = 10%   (c) Excess air = 20%

Figure 4. Oxygen flow in the combustion chamber

The gas velocity in the combustion chamber and close to the perforated plate for different excess air can be seen in Figure 5 and Figure 6. The air flows at a speed of 7-11 m/s in the inlet chamber and then the speed in the combustion chamber decreases due to the wider area. In the surrounding portion of the outlet, the gas is experiencing a rise in velocity due to a decrease in density due to an increase in combustion temperature. The gas speed at the outlet is around 25-42 m/s, depending on the excess air. Figure 6 indicates that the perforated plate is very capable of spreading air to all the cross-sections on it. The speed difference above the perforated plate at the front and back of the air inlet path is 1-2 m/s.
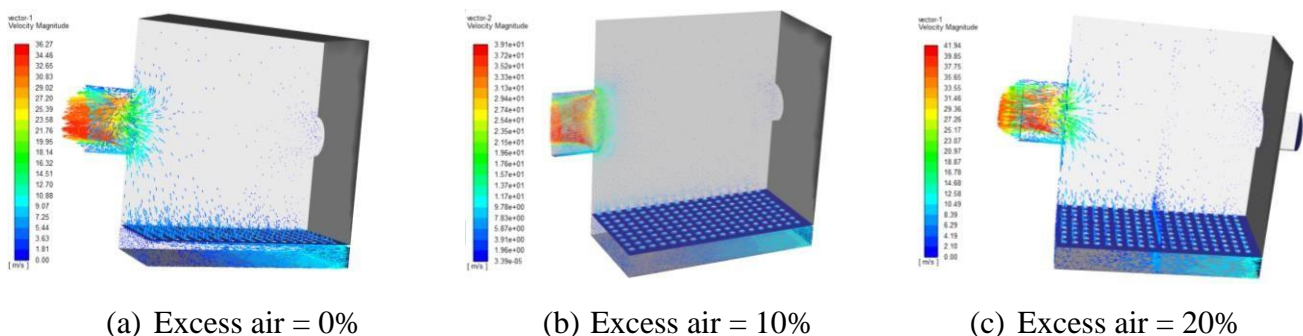

(a) Excess air = 0%   (b) Excess air = 10%   (c) Excess air = 20%

Figure 5. Gas velocity in the combustion chamber

Sutanto et al.

| (a) Excess air = 0% | (b) Excess air = 10% | (c) Excess air = 20% |
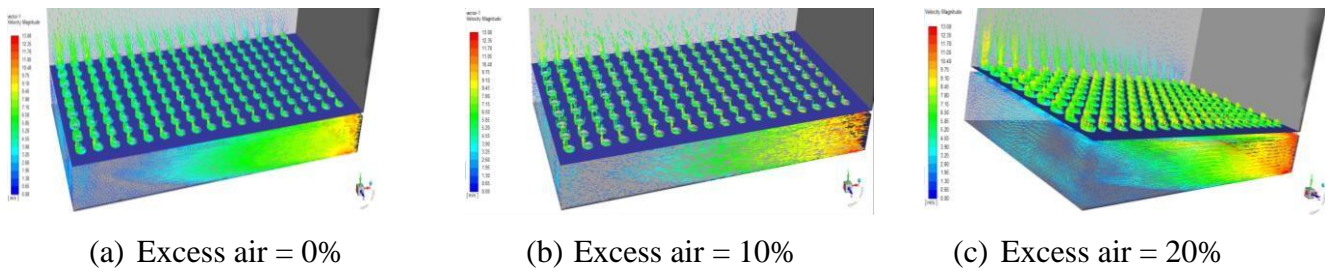
Figure 6. Gas velocity close to perforated plate

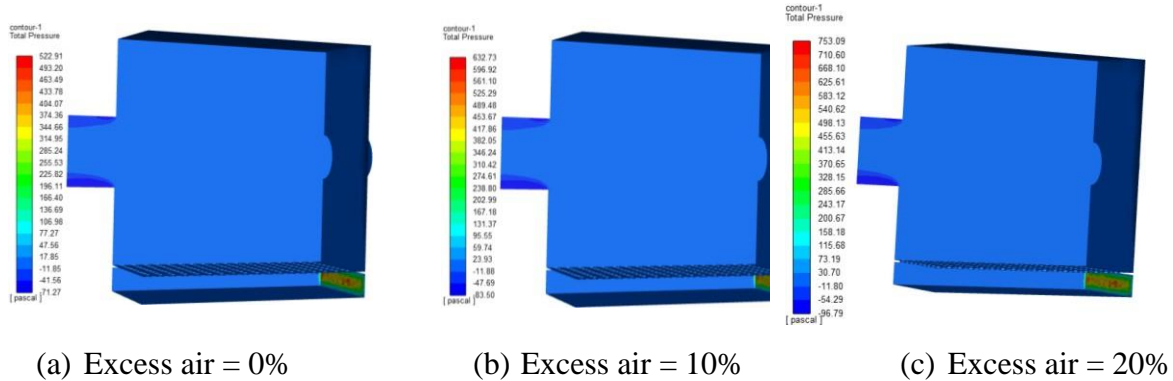| (a) Excess air = 0% | (b) Excess air = 10% | (c) Excess air = 20% |

Figure 7. Total pressure distribution in the combustion chamber

Figure 7 shows the distribution of total pressure within the furnace. At 0 per cent air excess, the total pressure difference is 600 Pa, which does not accurately account for the loss of pressure due to pellet and ash piles in the combustion chamber. The higher the excess air causes the total pressure to rise. At 20% excess air, the difference in total pressure is 850 Pa. So, in the design step, using the head assumption for the blower of 2000 Pa was enough to overcome the pressure losses that occurred.

4. Conclusion

The furnace for biomass pellets with a capacity of 75 kg/h has been designed and installed. Production costs, material costs, machining costs, assembly costs and maintenance costs may have already been determined. Air supply at an air fuel ratio of 5.37 with excess air from 0 to 20 per cent has also been studied for oxygen distribution, velocity and total pressure that may occur in the combustion chamber. The total amount of pressure, up to 850 Pa, must be overcome by air-supplying blowers. The gas velocity varies from 2-10 m/s and drastically increases nearby the outlet, up to 42 m/s. Experimental tests and flow-heat simulations are necessary to learn more about the performance of the furnace.

5. Acknowledgement

References

1. S. Proskurina, E. Alakangas, J. Heinimö, M. Mikkilä, and E. Vakkilainen, "A survey analysis of the wood pellet industry in Finland: Future perspectives," *Energy*, vol. 118, pp. 692–704, 2017.
2. D. Sjoding, E. Kanoa, and P. Jensen, "Developing a wood pellet/densified biomass industry in Washington State: opportunities and challenges," *Tech. Assessment, Washingt.*, 2013.
3. K. A. Hendarto, D. Syamsuwida, N. Yuniarti, N. W. Siregar, A. Aminah, Y. Nugraheni, D. D. N. Cahyono, and A. R. Hidayat, "Farmers' economic perceptions of demonstration plot development of kaliandra (Calliandra calothyrsus Meisner) biomass energy at Parungpanjang research forest: findings from a focus group discussion," in *IOP Conference Series: Earth and Environmental Science*, 2020, vol. 415, no. 1, p. 12013.
4. J. Swithenbank, Q. Chen, X. Zhang, V. Sharifi, and M. Pourkashanian, "Wood would burn," *Biomass and*

Sutanto et al.

     bioenergy, vol. 35, no. 3, pp. 999–1007, 2011.

5.   M. P. Kshirsagar and V. R. Kalamkar, "Application of multi-response robust parameter design for performance optimization of a hybrid draft biomass cook stove," *Renew. Energy*, vol. 153, pp. 1127–1139, 2020.

6.   J. J. Jetter and P. Kariher, "Solid-fuel household cook stoves: Characterization of performance and emissions," *Biomass and Bioenergy*, vol. 33, no. 2, pp. 294–305, 2009.

7.   A. Zhou, Y. Tu, H. Xu, Y. Wenming, F. Zhao, S. K. Boon, and P. Subbaiah, "Numerical investigation the effect of air supply on the biomass combustion in the grate boiler," *Energy Procedia*, vol. 158, pp. 272–277, 2019.

8.   C. Erlich and T. H. Fransson, "Downdraft gasification of pellets made of wood, palm-oil residues respective bagasse: experimental study," *Appl. Energy*, vol. 88, no. 3, pp. 899–908, 2011.

9.   T. Koyuncu and Y. Pinar, "The emissions from a space-heating biomass stove," *Biomass and Bioenergy*, vol. 31, no. 1, pp. 73–79, 2007.

10.   T. Mink, "Methods for generating market intelligence for improved cookstove dissemination: A case study in Quetzaltenango, Guatemala." *Humboldt State University*, 2010.