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

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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 up to 300 kW of heat. In addition to meeting the heat capacity needs of small and medium-sized industries, furnaces must also be competitive in terms of price. Therefore, the purpose of this study is to obtain details of the costof manufacturing the furnace and the airflow model that occurs in the furnace. This study employs a forward and reverses engineering approach, beginning with determining load and capacity, drawing, determining the bill of materials and manufacturing, numerical modeling of airflow with ANSYS FLUENT, fabrication, and final testing. The outcome revealed that thefurnace's production cost included manufacturing costs, assembly costs,machining, and repair costs. The findings revealed that the critical portion of the cost of the furnace was the material cost of 77%. The simulation findings showed that the total pressure difference of up to 850 Pa had to be resolvedby 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 Calliandra (*Calliandra calothyrsus*) genus, have become a favorite to cultivate into pellets due to their superior properties. Calliandra woods have strong growth, a 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, Calliandra wood biomass pellets have a higher density [4].

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In the meantime, biomass furnaces have been widely produced. Burning furnaces are a particular devicefor converting energy from Biomass. It is essential 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 a vital role in 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 standard 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 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 particular, depending on the designer's creativity and the manufacturer. Therefore, the study aims to obtain details on the cost of producing the furnace and the airflow model in the designed furnace.

2 Methods

2.1 Materials

The primary feedstocks are wood pellets of the Calliandra variety. The properties are shown in Table 1. Calliandra wood pellets have a 1-2 cm diameter 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 sulfur	%	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

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 can consume 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.

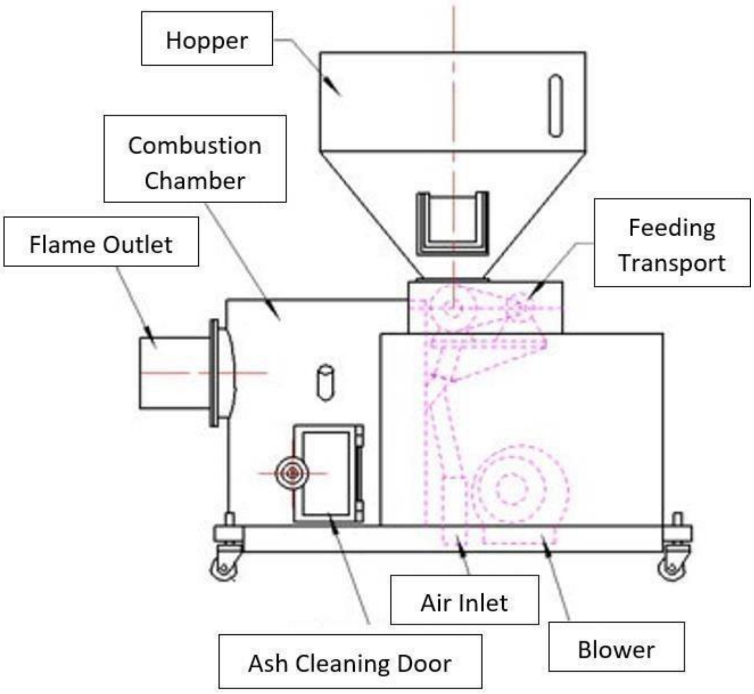


Figure 1. The initial design for a biomass pellet furnace

From the initial model of biomass pellet furnaces, the price of materials was calculated, the production method and cost were determined, and the operational 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 airflow 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 discretization method, initializing, running, and post-processing are just a few of the steps involved in airflow 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 calculates the air specifications based on the Air-Fuel Ratio (AFR) needed to burn biomass pellets (see Equation 1).

$$C_{8,7}H_{12,5}O_{6,4} + 8{,}625(O_2 + 3{,}76N_2) \rightarrow 8{,}7CO_2 + 6{,}25H_2O + 32{,}43N_2 \quad (1)$$

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 AFR greater than AFR stoichiometry will also be performed to produce an impression of air distribution in the combustion chamber.

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 Results and Discussion

3.1 Design, manufacturing, and assembly

The air requirement can be calculated based on the chemical reaction of combustion, i.e., $\frac{8.625(32+3.76\times 28)}{8.7\times 12+12.5+6.4\times 16}$ X 75 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. The air from the blower is circulated via a perforated plate into the combustion chamber. A perforatedplate, which is the primary 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 feeds biomass pellets into the combustion furnace. The hopper shouldbe large enough to accommodate all of the fuel used so that the burner volume can be adjustedby 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.

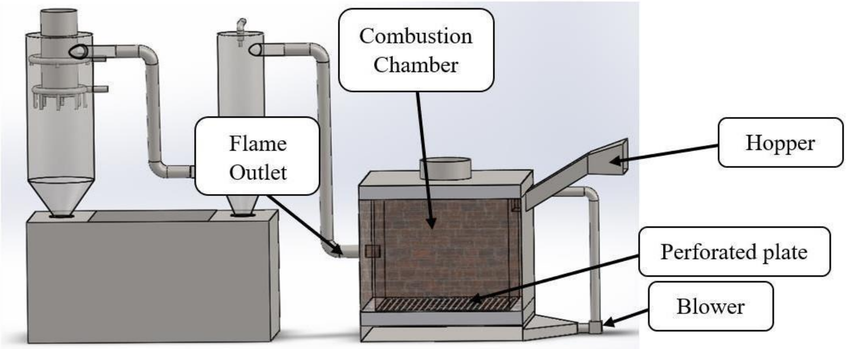


Figure 2. Design for the biomass pellet furnace

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 air inlet, fuel inlet, and fire outlet. The refractory brick is then attached to the plate using refractory cement and cut to size and shape. The coated plate is then welded on either side. The next step is to build a chimneywhere 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. The results of the design, manufacture, and assembly of furnacesare summarized in Table 2. The actual results of production are shown in Figure 3.

Table 2. The manufacturing process of wood pellet burner at a capacity of 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

Table 2. *Cont.*

Body	Parts	Materials	Manufacturing Process
Wet scrubber	Small cyclone	Carbon steel plate	Cutting, rolling, welding
Total Sulphur	Big cyclone	Carbon steel plate	Cutting, rolling, 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

Figure 3. The biomass pellet furnace

The furnace, made of carbon steel plate sheets, has a lifetime of 3-4 years [9]. On theother hand, the fire bricks 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 essential 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 anda replacement sprayer is installed once every two years. Previous research has shown that the fundamentalsof 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]. The furnace's lifetime can be extended even with improved material choices, but the investment expenses will rise. Enhance furnace lifeby 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 seven 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 production sequence. The material required 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.

Table 3. Bill of materials of wood pellet burner at a capacity of 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, 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 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 of the machining process

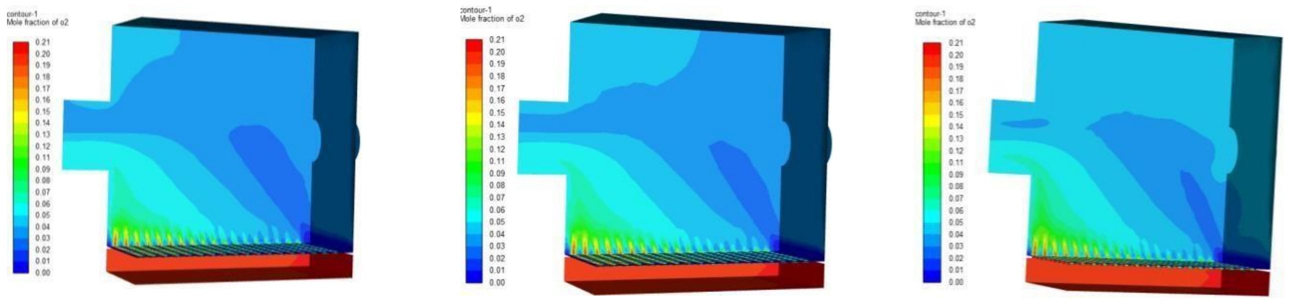
Parts	Machining process	Dimension (cm)	Cost (IDR)
Cover of combustion chamber	Bending	$L = 120$ (90)	300,000
Small cyclone	Roll	$D = 50$, $L = 150$	240,000
	Welding	$L = 150$	150,000
Big cyclone	Roll	$D = 65$, $L = 150$	300,000
	Welding	$L = 150$	150,000
Sprayer	Roll	$D = 50$	120,000
Total			1,260,000

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

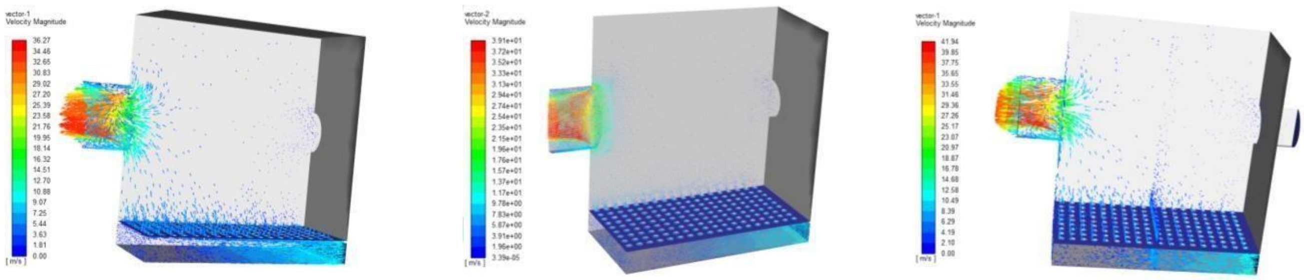
Air composed of 21% oxygen and 79% nitrogen is used for oxidizers and flows throughthe inlet side of the air. Oxygen is distributed in the combustion chamber, as shown in Figure 4. Oxygenis most commonly distributed in the middle and at the bottom of the combustion chamber. The greater theamount of air added, marked by excess air, the more it is noted that much of the oxygen flow to the front portion of the perforated plate. This can lead to more vigorous combustion of the front, and much heat is applied directly to the outlet portion of the combustion chamber.



(a) (b) (c)

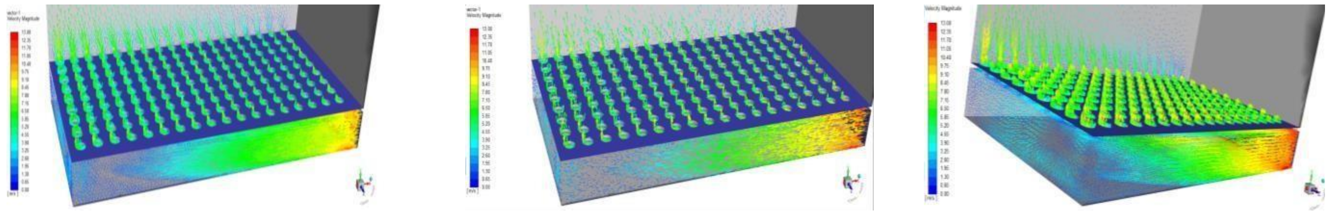
Figure 4. Oxygen flow in the combustion chamber: (a) Excess air = 0%, (b) Excess air = 10%, and (c) Excess air = 20%

The gas velocity in the combustion chamber and close to the perforated plate for different excess air can be seen in Figures 5 and Figure 6. The air flows at a speed of 7-11 m/s in the inlet chamber, and then thespeed in the combustion chamber decreases due to the broader area. In the surrounding portion of the outlet,the gas is experiencing a rise in velocity due to a decrease in density due to increased 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 can spread air to all the cross-sections on it. The speed differenceabove the perforated plate at the front and back of the air inlet path is 1-2 m/s.



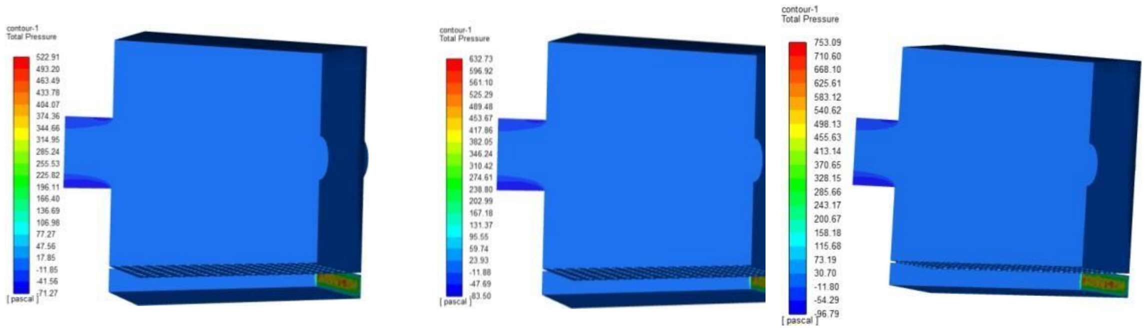
(a) (b) (c)

Figure 5. Gas velocity in the combustion chamber: (a) Excess air = 0%, (b) Excess air = 10%, and (c) Excess air = 20%



(a) (b) (c)

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



(a) (b) (c)

Figure 7. Total pressure distribution in the combustion chamber: (a) Excess air = 0%, (b) Excess air = 10%, and (c) Excess air = 20%

Figure 7 shows the distribution of total pressure within the furnace. At 0% air excess, the total pressure difference is 600 Pa, which does not accurately account for the pressure loss 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. Therefore, in the design step, using the head assumption for the blower of 2000 Pa was enough to overcome the pressure losses.

4 Conclusions

The furnace for biomass pellets with 75 kg/h has been designed and installed. Production, material, machining, assembly, and maintenance costs may have already been determined. Air supply at an air-fuel ratio of 5.37 with excess air from 0-20% has also been studiedfor oxygen distribution, velocity, and total pressure 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 furnace's performance.

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