Design and construction of a 25 kg plastic waste incinerator

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Abstract. The management of non-recyclable plastic waste in various Waste Banks and 3R Waste Transfer Stations (TPS 3R) in Sleman Regency provides the background for the development of this waste processing incinerator. This research aims to design and construct an incinerator prototype as a waste processing tool suitable for application at Waste Banks or TPS 3R facilities. This research also to obtain the specifications for the plastic waste combustor using the Quality Function Deployment (QFD) method. The results are expected to provide crucial insights for improving combustion efficiency and reducing exhaust emissions, thereby making the plastic waste combustion process more environmentally friendly and efficient. The designed waste processing capacity has a volume of 1 m³, equipped with a wet scrubber to eliminate exhaust pollutants before release into the atmosphere. The incinerator was designed with dimensions of 900 mm × 900 mm × 1000 mm. Combustion tests showed that the waste required 30 minutes to be completely burned and converted into ash. From an initial mass of 25 kg, the residual mass after combustion was 4.05 kg. The design and construction of the incinerator required a budget of Rp 37,373,200.00. This plastic waste incinerator design is expected to serve as a waste processing solution for both TPS 3R facilities and Waste Banks.

Keywords: design, construction, incinerator, plastic waste, efficient

1. Introduction

The management of waste, especially plastic waste that is not commercially viable, in waste banks and TPS 3R (Integrated Waste Management Centers/Recycling Centers) still depends on Final Disposal Sites (TPA). This pattern of waste handling, which relies on TPA, poses a problem. One of the solutions for waste management is incineration using a waste combustion installation called an incinerator. An effective tool for sustainable waste management is the incineration of solid waste through waste-to-energy (WTE) plants (Jiang et al., 2020). One of the ways to treat waste is by using incineration technology, and the device used is called an incinerator. The main advantages of using an incinerator are that it can drastically reduce waste volume, destroy pathogenic bacteria, and hazardous organic substances (Saragih & Herumurti, 2013). Waste treatment with an incinerator primarily aims to reduce the volume of the waste itself to the smallest possible extent, and also to process the waste so that it becomes not harmful to the environment and is chemically stable (Utami, 2016). The use of an incinerator can mitigate the negative impacts of open burning, such as smoke, odor, radiation, and heat produced by combustion, and also opens up efforts to utilize the heat energy resulting from the waste burning. The temperature achieved during the incinerator's combustion process can reach 1400°C, allowing the burned waste to turn into ash.

Based on the current waste problems occurring at waste management facilities, both in waste banks and TPS 3R, the resulting high volume of waste generation and the continued reliance on local TPA will lead to the accumulation of waste at the TPA, accelerating the spread of disease in the TPA area. Based on explanation above, the objectives of this research are to design and build a Plastic Waste Incinerator and to obtain the specifications for the plastic waste combustor using the Quality Function Deployment (QFD) method. This method allows increasing the customer satisfaction and improving the quality of every final product (Baczkowicz & Gwiazda, 2015).

2. Methods

2.1. Materials

This research was conducted in two stages: design and fabrication, as shown in the schematic diagram in Figure 1.

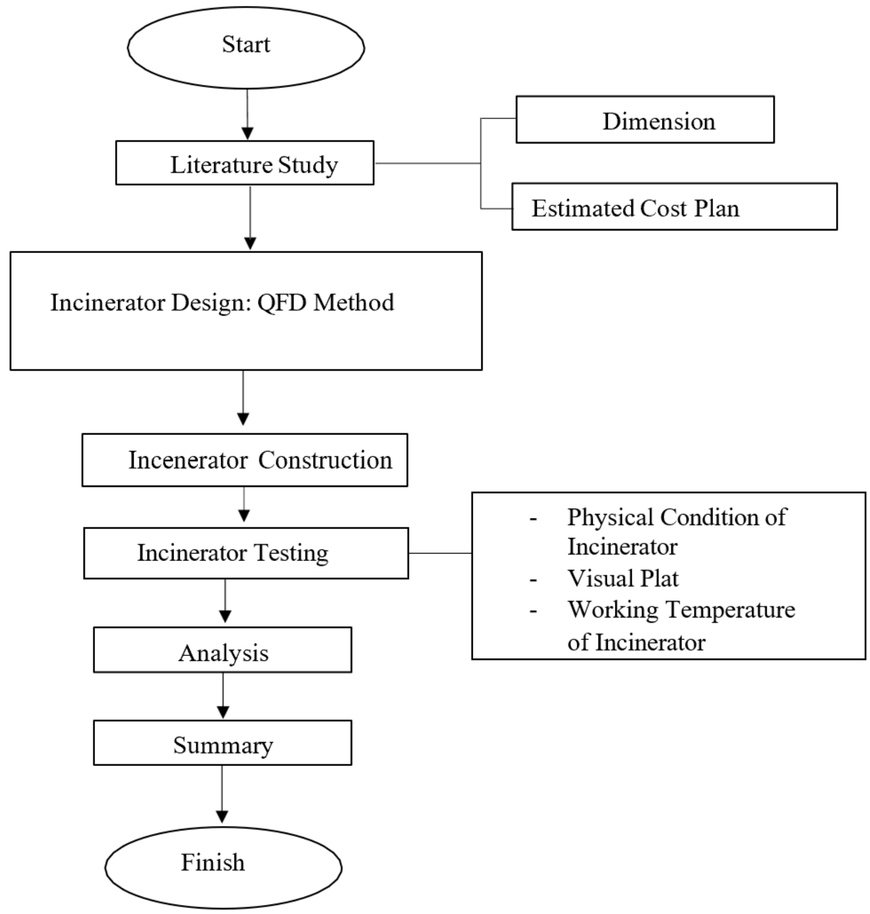

Figure 1. Scematic process of incenerator design and construction

The design stage comprised several steps, including defining the incinerator criteria, constructing the House of Quality (HOQ) using the Quality Function Deployment (QFD) matrix, and determining the optimal incinerator variant. This was followed by the detailed design phase, which involved performing calculations across various supporting aspects to ensure the final design aligns with its intended function and objectives. The use of QFD can simultaneously reduce design time by 40% and save design costs by 60%, while maintaining and improving design quality. Other benefits gained from the use of QFD include reducing costs, increasing revenue, and reducing production time (Baczkowicz & Gwiazda, 2015). The incinerator design was developed using CAD software, adhering to the required 25 kg capacity specification. To ensure ease of fabrication, the unit was designed in a cuboid shape. The combustion chamber dimensions are 900 x 900 x 1200 mm. The chimney height of the unit is 3 m. The combustion chamber shape is cuboid (cube-like). The picture of incenerator design is shown in Figure 2.

The fabrication process of the waste incinerator involved several steps, including constructing the combustion chamber, installing refractory bricks and cement, establishing the air intake system, creating the exhaust gas filtration system, and installing the waste burner ignition system.

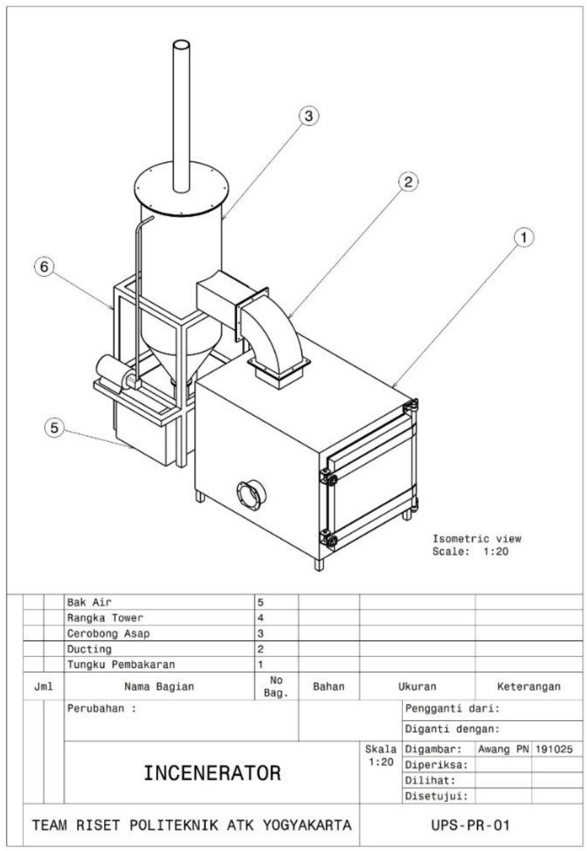

Figure 2. Design of Incinerator

2.2. Incenerator Design

The main components of this system are the combustion chamber, the air filtration chamber (scrubber), and the ash residue drawer. The available space for waste processing has a volume of

1 m^3.

The average waste density at management sites is 342.61 kg/m. If multiplied by the available combustion chamber volume of 0.972 m^3, the theoretical capacity of the incinerator chamber is calculated to be 219.27 kg. However, the operational capacity, the amount of waste that can be inserted in a single burn, is limited to 25 kg. The incinerator chamber must maintain negative pressure to prevent back pressure, which could cause damage to the chamber walls. To achieve negative pressure in the combustion chamber, the gas flow within the chamber must be efficient and provided with sufficient space. Therefore, the maximum amount of waste that can be loaded in a single combustion cycle is limited to 25 kg. This condition leaves an effective capacity of 194.27 kg for the air flow required to sustain the combustion process (Mamat, 2008).

3. Result and Discussion

3.1. Construction of the combustion chamber

Perfect combustion (of waste) is influenced by the amount of air required for the combustion process in the incinerator (Martana et al., 2017). The combustion chamber was designed and manufactured with dimensions of 900 x 900 x 1200 mm. The Combustion chamber is lined with SK-34 refractory bricks. Refractory cement was also utilized, with Tekchnocast LW 12 serving as the refractory insulation and Teknocast TC-140 acting as the adhesive material between the bricks. The temperature in the incinerator combustion chamber can reach approximately 1,100 ℃ (Susastrio et al., 2020). In waste feeding, the incinerator receives waste, usually via a conveyor system or hopper. This purpose is to maintain a constant and controlled flow of waste into the combustion chamber (Bhikuning, 2024). The combustion chamber is shown in Figure 3.

Figure 3. Construction of combustion chamber

3.2. Installation of refractory bricks and cement

The refractory bricks and cement are required to line the external iron structure of the combustion chamber. Fire-resistant bricks have an advantage in terms of refractoriness value, which is influenced by the constituent components such as SiO_2, Al_2O_3, and other compounds (Pranaka, 2022). This lining also functions as the primary layer of the combustion chamber directly exposed to the flame. As illustrated in Figure 4, the brick layer is positioned inside the combustion chamber framework.

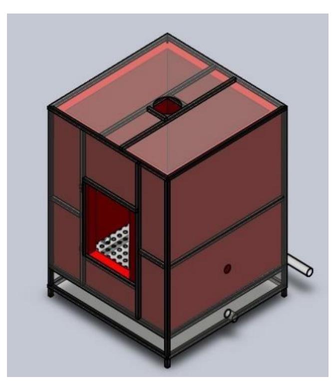

Figure 4. Installation of refractory bricks and cement

3.3. Fabrication of the exhaust gas filtration system

The exhaust gas filtration system functions to remove emission residues generated from waste combustion in the combustion chamber. The design and fabrication of this section include a filter housing integrated with a water scrubber. The filter housing is cylindrical, with a diameter of 40 cm and a length of 250 cm. The exhaust gas filtration system is shown in Figure 5.

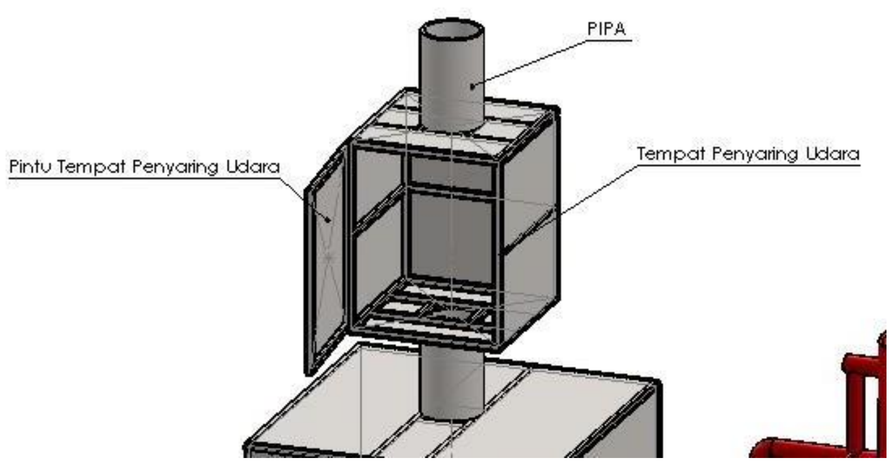

Figure 5. The exhaust gas filtration system

3.4. Installation of the Waste Burner Ignition System

The igniter serves to strike the initial flame into the burner. Once the main flame is ignited, the igniter flame is extinguished. The burner requires fuel to operate, which is stored inside the fuel tank. To ensure fuel flow to the burner, the tank is positioned higher than the burner. Therefore, the design and manufacturing of this section cover the burner mounting and the fuel tank assembly. The Burner system is shown in Figure 6.

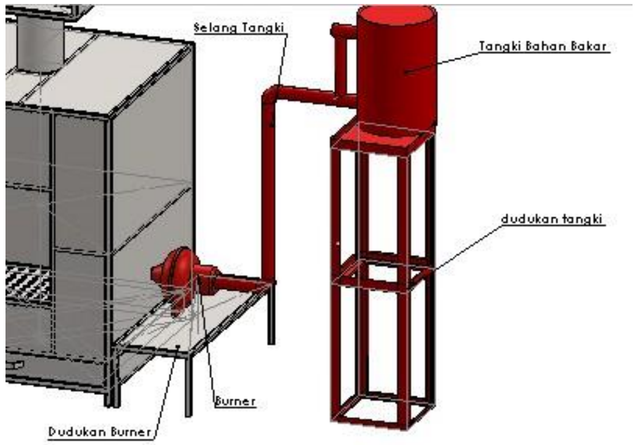

Figure 6. waste burner ignition system

The diesel fuel tank that is shown in Figure 7 utilized a container previously used for chemicals, which was then modified to function as the incinerator's fuel storage.

Figure 7. The fuel tank

3.5. Mass flow rate of air and combustion fuel

The designers of the incinerator must know the amount of air needed for complete combustion, anticipated flue gas composition, air flow rate and exit temperature in order to control the emissions and toxic gases formed (Omari et al., 2015). Air velocity measurements were taken at the blower outlet, precisely where the flow enters the pipe, using an anemometer. Data was recorded over a duration of 30 seconds for each distinct blower valve opening (setting).

Assuming an air density $\rho_{air} = 1.2$ kg/m^3, the preceding calculations successfully yielded the mass flow rate of air values for all valve openings, as presented in the Table 1.

Table 1. Mass flow rate of air

Q_{air} (m^3/s)	v_{air} (m/s)	A_{blower} (m^2)	M_{air} (kg/s)
0,0108	6,81	1,58 x 10^{-3}	0,0129
0,0208	8,76	2,38 x 10^{-3}	0,0250
0,0311	9,80	3,17 x 10^{-3}	0,0373

3.6. Determination of The Mass Flow Rate of Waste Fuel

The fuel mass flow rate in this waste combustion process was determined by considering two components: the waste being combusted and the supplementary diesel fuel. Accordingly, the total fuel mass flow rate was calculated as the sum of these two contributions. The mass flow rate of the waste component was obtained from the difference between the initial waste mass (before combustion) and the final residual mass (after combustion), divided by the combustion duration, which was 5 minutes for the 5 kg test and 30 minutes for the 25 kg test, as presented in Table 2. In contrast, the mass flow rate of the diesel fuel component was determined from the total volume of diesel consumed during the combustion process over the corresponding time interval.

Table 2. Final waste weight

Q_{air} (m^3/s)	Final waste weight (kg)	
	5 kg	25 kg
0,0108	0,60	4,80
0,0208	0,40	4,50
0,0311	0,30	4,10

Following the calculations performed, the resulting mass flow rate of waste values for all air valve openings are presented in the Table 3.

Table 3. Mass flow rate of waste values

Q_{air} (m^3/s)	m_{waste} (kg)	
	5 kg	**25 kg**
0,0108	0,00244	0,00561
0,0208	0,00256	0,00570
0,0311	0,00261	0,00581

3.7. Determination of the Air-Fuel Ratio (AFR)

The air–fuel ratio (AFR) is defined as the mass ratio of air to fuel during the combustion process. This value was determined from the mass flow rate of air and the mass flow rate of the combustion fuel, which were obtained from previous calculations and are presented in Table 4.

Table 4. Mass flow rate of air and fuel

Q_{air} (m^3/s)	m_{air} (kg/s)	m_{waste} (kg)	
		5 kg	**25 kg**
0,0108	0,0129	0,00244	0,00561
0,0208	0,0250	0,00256	0,00570
0,0311	0,0373	0,00261	0,00581

The data presented in Table 4 is input into the following Equation (1) to calculate and determine the AFR value.

$$AFR = \frac{\dot{m}_{air}}{\dot{m}_{waste}} \quad (1)$$

Table 5. AFR value for 5 kg of waste

Air Flow Rate (m^3/s)	AFR
0,0108	5.29
0,0208	9,77
0,0311	14,29

Table 6. AFR Value for 25 kg of Waste

Air Flow Rate (m^3/s)	AFR
0,0108	2,30

Air Flow Rate (m^3/s)	AFR
0,0208	4,39
0,0311	6,42

The correlation between the mass flow rate of air and the mass flow rate of fuel, based on the final weight of the waste, and how this influences the magnitude of the AFR. Specifically, the greater the air mass flow rate and the smaller the fuel mass flow rate, the higher the resulting air-to-fuel ratio as shown in Figue 8. Conversely, if the air mass flow rate is smaller than the fuel mass flow rate, the resulting air-to-fuel ratio value will be lower.

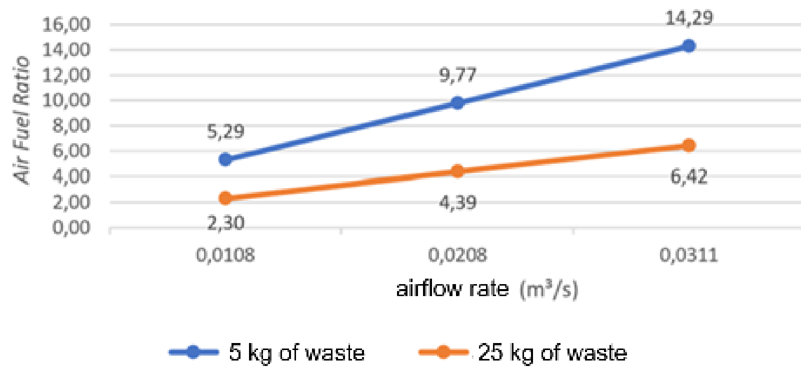

Figure 8. AFR value based on air flow rate

3.8. Emission Testing

The combustion testing was conducted to evaluate the incinerator's operational readiness, based on research utilizing 25 kg capacity unit that is shown in Figure 9. A 25 kg sample of waste was incinerated. The combustion process lasted for 30 minutes, resulting in an ash residue of 4.80 kg and reaching a peak temperature of 1060.75 °C. Subsequent tests were conducted to evaluate the effectiveness of the Electrostatic Precipitator (ESP). Three tests were performed with the ESP turned off, and three were performed with the ESP turned on. A reduction in the emission values for each substance in the exhaust gas exiting the chimney was observed when the ESP was activated. Specifically, the exhaust gas showed a 43% reduction in CO concentration, an 18% reduction in HC, 10% reduction in CO_2, and 9% increase in the O_2 level. The filters utilized in the ESP exhaust gas scrubbing process were stainless steel plates. This material was chosen because stainless steel offers good durability at high temperatures and possesses sufficient electrical conductivity. The temperature within the ESP reaches 400℃; using non-heat-resistant materials would lead to corrosion, thereby shortening the filter's lifespan. Figure 10 shows one of the ESP filter plates in its condition prior to the combustion tests.

Figure 9. The incenerator for 25 kg capacity

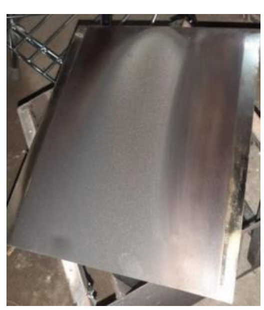

Figure 10. The ESP Filter plate before the filtration process

Under conditions prior to filtration (or: precipitation), it can be observed that the plate is still relatively clean, and there is no visible dust adhering to the plate. ESP Filter plate after the filtration process can be shown in Figure 11. Visually, there is a significant difference in the physical appearance of the filter plate. The plate has yellowed, and a large amount of dust is adhering to it that is shown in Figure 11.

Figure 11. ESP Filter plate after the filtration process

4. Conclusions

The conclusions drawn from this study on the design and construction of a 25 kg plastic waste incinerator indicate that a waste combustion unit with a nominal capacity of 25 kg was successfully designed and fabricated using the Quality Function Deployment (QFD) method. The available waste processing chamber has a volume of 1 m^3. Therefore, the incinerator dimensions were determined to be 900 × 900 × 1200 mm. The results of the combustion tests showed that the air–fuel ratio (AFR) is strongly influenced by the relative mass flow rates of air and fuel. An increase in the air mass flow rate combined with a decrease in the fuel mass flow rate resulted in a higher AFR value. Conversely, when the air mass flow rate was lower than the fuel mass flow rate, the resulting AFR decreased.

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