Design of A Pellet Waste Gasification Reactor for Optimizing Syngas Production as Bioenergy Fuel

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Abstract. Pellet waste gasification is a promising method for converting organic waste into useful bioenergy fuel. This process produces syngas, a mixture of carbon monoxide, hydrogen, and methane which can be used as an environmentally friendly alternative fuel. However, to maximize the efficiency and sustainability of this process, gasification reactor designs need to be refined. A common challenge in the biomass gasification process is clogging in the distributor section which is caused by the buildup of charcoal and tar solids, which hinders the flow of syngas and can stop the gasification process. In this research, a reactor design was created which was equipped with a crusher-type distributor module. Validation of the design was carried out by experiments on laboratory-scale reactors. This research provides a better understanding of the gasification process. The gasification reactor can use a shredder module as a substitute for the grate plate model distributor plate. The test results show that the produced syngas meet the requirements as bioenergy fuel, thereby increasing the potential for utilizing organic waste (pellet waste) as a renewable energy source.

Keywords: Bio-Energy Gasification, Syngas, Waste Pellet

1 Introduction

Currently, waste issues have become a common problem occurring in various regions of Indonesia. The volume of waste tends to increase in line with population growth and the rise in economic activities. However, efforts by local governments to manage waste often do not keep pace with the growth in waste volume. According to data from the National Waste Management Information System (SIPSN) managed by the Ministry of Environment and Forestry, in 2023, the total volume of waste generated across Indonesia reached 18.081 million tons per year, with only 66.93% of that amount being properly managed (SIPSN, 2023). Data from SIPSN also shows that organic waste, such as food scraps and biomass waste, still dominates around 54% of the total national waste, and in some regions, the percentage can reach over 60%. For example, a study in Denpasar City in 2023 showed that the waste entering the Suwung landfill reached 920 tons per day, with nearly 60% being organic waste.

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One of the methods that has been implemented is converting organic waste and biomass into biofuel in the form of biomass pellets. These pellets can be used as an alternative to coal for various purposes. The process includes biodrying, shredding, and pelletization. The final product is a solid fuel with a calorific value or higher heating value (HHV) of around 3000-4000 kcal/kg, with this variation depending on the type and composition of the biomass used (Legino et al., 2019). In addition to being used directly as fuel to generate heat, waste pellets can also be utilized in gasification technology.

Gasification is a technology for converting carbon-containing biomass (whether solid or liquid) into combustible gas through partial oxidation at high temperatures (Basu, 2018). The gases produced in this process typically include CO, CO_2, N_2, O_2, H_2, and CH_4. The gasification of solid biomass occurs in conditions isolated from the surrounding air (limited oxygen) and under pressure relative to ambient pressure. The gas produced is called Syngas or Synthetic Gas.

The calorific value of the gas ranges between 1000 and 1200 kcal (Agustina et al., 2023). Syngas can be used as fuel for engines to drive electricity-generating generators. Gasification is an alternative within the framework of energy-saving and diversification programs. Additionally, gasification can help address waste management issues. There are three main components of a gasification system (Sharma et al., 2021), namely: a. The feedstock conversion unit is called the gasification reactor, b. The gas purification unit, c. The gas utilization unit.

In the gasification process of waste pellets in the reactor, several stages occur. First is drying: the pellets at the top position receive heat from the reduction process below, leading to the release of moisture. Second is torrefaction: at this stage, the pellets release volatile fractions, turning them into char. Third is pyrolysis: during this stage, decomposition occurs where cellulose compounds break down into gas, tar, and char. The fourth stage is reduction: in this stage, the char undergoes combustion until it turns into ash. The gas or syngas exiting the reactor is a combination of the gases produced at each stage.

Temperature is a crucial parameter in the gasification process. During the reduction stage, if the temperature is not sufficient for decomposition, the fuel will remain in the form of charcoal. Charcoal that binds with tar can cause clogging in the distributor plate and lead to operational failure. This issue is important to study further to design a distributor module capable of handling such hard charcoal. A possible design is to add a crusher module to replace the distributor plate, which would crush the charcoal into small particles and remove them to the ash collector. This would ensure smoother gasification operation even if the temperature is unstable.

2 Methodology

2.1 Experimental Stages

This research is an experimental study conducted by testing the design and construction of a laboratory-scale gasification reactor. The research is carried out in two stages:

1. Modeling and Simulation: Autodesk Inventor software is used to model and simulate the performance of the gasification reactor. With this model, various design scenarios and operational parameters can be explored to identify the optimal design.
2. Experimental Design: This involves creating a small laboratory-scale prototype of the reactor, focusing solely on the reactor component itself, and testing it with various configurations of air parameters and waste pellets as the gasifying agent and fuel. In this stage, supporting components such as the purifier, control systems, and hopper are not included.

2.2 Material

The fuel used is solid waste, which is commonly found in daily life and has a solid form, distinct from other types of waste such as liquid or gas waste. Solid waste is typically produced from various human activities, including household, industrial, commercial, and institutional activities. The solid waste to be used has undergone prior processing, including shredding, drying, fermentation, and pellet formation. The process of converting waste into pellets involves a series of steps to transform solid waste into fuel.

Figure 1. Solid waste is processed into pellets as fuel

Pellet Waste is the management of waste into an energy source. The process of waste treatment is relatively simple and easy. After being sorted, waste that has been separated from stones, glass, and iron is then subjected to the "*peuyeumisasi*" process or piling process with a bioactivator for seven days. Next, the waste is fed into a shredder machine, and the results are molded in a pellet-making machine. The final product can be used as fuel (Brunner et al., 2021).

Efforts to address waste management issues have been undertaken by the Klungkung Regional Government in collaboration with Indonesia Power (IP) by launching the Local Waste Processing Site (TOSS) program. Waste is directly processed into briquettes and pellets using the "*peuyeumisasi*" method. The pellets, which are small round shapes, contain 2500 - 4000 kcal/kg of calories (Fadli et al., 2019) and can then be utilized in large-scale power generation by being mixed with coal. The technology

applied involves combustion, where the pellets serve as fuel, and the heat generated is used to heat a boiler that produces steam to drive the power plant's turbines.
The processing of waste into pellets has also been carried out by the Denpasar City Government at the Kesiman Kertalangu Integrated Waste Management Site (TPST). Test results, Table 1, shows that the energy content in the pellets reaches 4816 – 5293 kcal/kg (Pratama et al., 2019). This indicates that waste has a significant energy content and its potential as a new renewable energy source.

Table 1. Proximate analysis test results of waste pellets in Denpasar city

Parameters	Unit	AR (As received)	DB (Dry Basis)
Total Moisture	% wt	9.01	---
Ash Content	% wt	14.46	15.89
Volatile Matter	% wt	65.91	72.43
Fixed Carbon	% wt	10.62	11.68
Total Sulfur	% wt	0.17	0.19
Gross Calorific Value	Kcal/kg	4816	5293

Source: Pratama et al., 2019

2.3 Gases Analysis

The performance of the gasification reactor is evaluated based on the quality and quantity of the syngas produced. Syngas is a combustible gas that contains elements of hydrogen, oxygen, and carbon in the form of compounds such as CO_2, CO, CnHm, CH_4, and H_2. The percentage composition of these gas compounds influences the heat value generated. The higher the heat value, the more energy can be produced. The heat value depends on the quality of the fuel and the configuration of the gasification process parameters within the reactor. The gas content in the syngas will be tested using a Gas Analyzer, specifically the Portable Infrared Syngas Analyzer Gasboard-3100P as shown in Figure 2.

Figure 2. Portable infrared syngas analyzer Gasboard-3100P

3 Result and Discussion

There is less oxygen present throughout the biomass gasification process than is necessary in theory for full combustion. Under these circumstances, O_2 reacts with volatile materials and charcoal components because it is taken mostly by the more reactive elements, that is, volatile materials, and partially by the charcoal. The incomplete oxidation results in a significant amount of CO and H_2, along with a small amount of CH_4. This mixture of gases is referred to as producer gas or syngas. To increase the heating capacity or calorific value and improve the combustion characteristics of the gas produced from the gasification process, the amount of H_2 needs to be increased. By increasing the amount of H_2 in syngas, the heating capacity and calorific value will improve, making it more efficient for various applications, including as fuel for power generation, industrial heating, or as a feedstock in chemical production. This means that further research and technology development are necessary to enhance gas production and improve the quality of the gas produced from the gasification process.

The reactor can be classified depending on the biomass gasification technology. The simplest and oldest type of gasifier is the fixed-bed gasifier. The design and construction of this gasifier are the simplest compared to other types, and this type of gasifier does not require complicated biomass preparation and feeding, gasification control with varying parameters, or gasification agents such as oxygen. Based on the feeding method, gasifiers are classified into two types: updraft gasifiers and downdraft gasifiers. The two basic inputs for gasification are biomass and the gasification agent. In an updraft gasifier, air as the gasification agent is introduced from the bottom, and the fuel is fed from the top, while in a downdraft gasifier, both air and fuel enter from the top. There are several limitations with this technology, including the presence of a significant amount of hydrocarbons (tar) in the product gas, which necessitates product gas cleaning, heat recovery from the product gas, and a long residence time of several hours, as well as lower carbon conversion efficiency (i.e., 80–90%) (Sharma et al., 2021).

A common issue encountered during the operation of downdraft gasification is clogging or blockage at the bottom, specifically at the distributor plate between the combustion chamber and the ash bin. This is caused by the high tar content of biomass, which leads to the binding and hardening of the charcoal fraction. One of the gasification technologies developed uses a grate-type distributor plate which consists of several plates that move relative to each other, as shown in Figure 3. This design allows ash to pass through the gaps between the plates. However, the clogging that forms can block these gaps, leading to reactor failure.

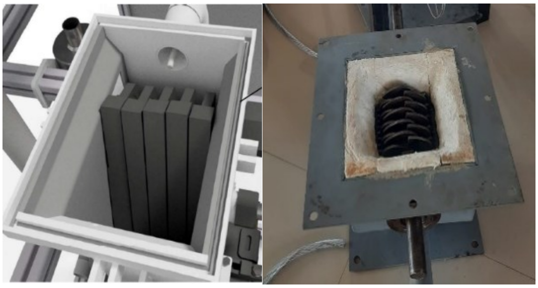

Figure 3. Grate-plate and shredder-type distributor

To address this issue, there is a need for a new distributor model that can better handle clogging and optimize the gasification process to produce optimal syngas. One technique that can be adopted is replacing the grate with a shredder module, as shown in Figure 3. High-quality, heat-resistant shredder blades can be applied. The clogging that forms will be shredded and simultaneously directed to the ash collector. In this context, operational parameters such as rotational speed, dimensions, period, and the volume of air as the gasification agent must be considered to ensure the gasification reactor operates optimally (Hermanuloh, 2015).

3.1 Design of Gasification Reactor

This study utilizes a shredding concept consisting of 10 blades, each with a thickness of 5 mm, arranged on a single shaft. To facilitate the cutting process, the module is equipped with stators on both sides, with gaps matching the thickness of the blades. Each stator is mounted using two small shafts attached to the reactor cover. The blade shaft is fitted with bushings at both ends, which are also attached to the reactor cover. One end of the shaft is connected to a servo motor that provides rotational motion. The design of the shredder module is shown in Figure 4 below.

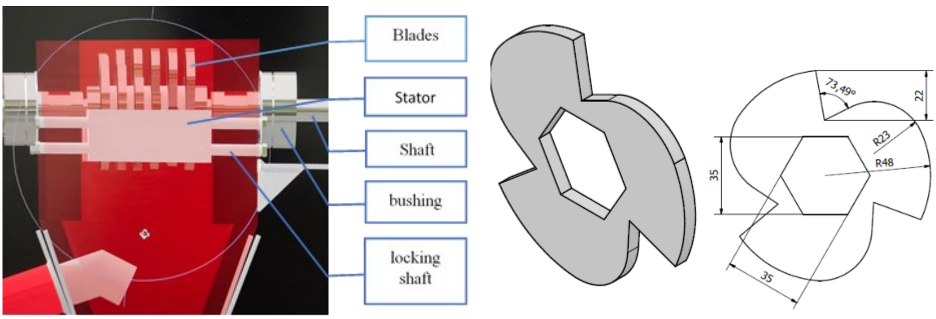

Figure 4. Shredder module using rotating blades

The design of the shredder module is then integrated into the overall reactor design. The gasification reactor consists of four main parts; (1) Feeder Section; Equipped with an input feeder, a sight glass, and an input for hot air. The hot air is sourced from a compressor and passed through a pipe fitted with an ignitor (a cylindrical electric heater). (2) Combustion Chamber; This is where the fuel is burned. (3) Charcoal Shredder Module; Positioned to process the charcoal. (4) Ash and Charcoal Collector; Located at the bottom, where the ash and charcoal are collected. The shredder module has an output hole for the syngas resulting from the combustion. All parts of the reactor are connected with flanges secured by bolts at several points. To ensure the reactor is completely airtight, high-temperature silicone seals are added between the flanges. The design of the gasification reactor is shown in Figure 5 below.

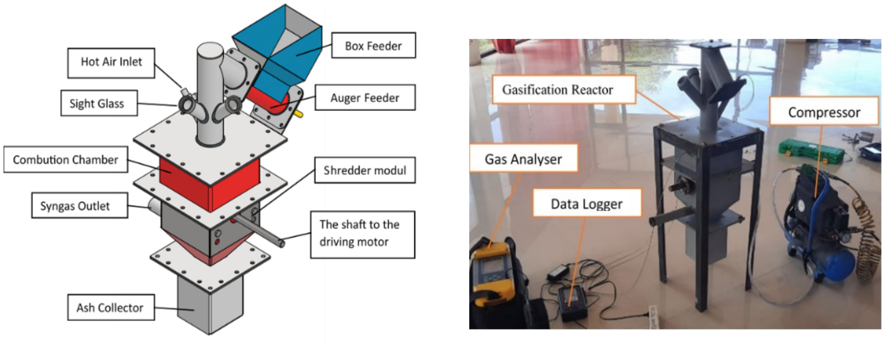

Figure 5. Gasification reactor design and experiments set up

3.2 Gas Composition Analysis in Syngas

Reactor testing aims to determine the syngas produced. The experiment was carried out five times with the testing scheme as in Figure 6. The syngas composition was detected using Portable Infrared Syngas Analyzer Gasboard-3100P, which can detect gas content percentages including CO, CO_2, CH_4, H_2, O_2, and N_2, as well as the gas calorific value LHV in MJ/m^3. The graph of the first test results is presented in Figure 6 and results from experiments carried out five times, are shown in Table 2.

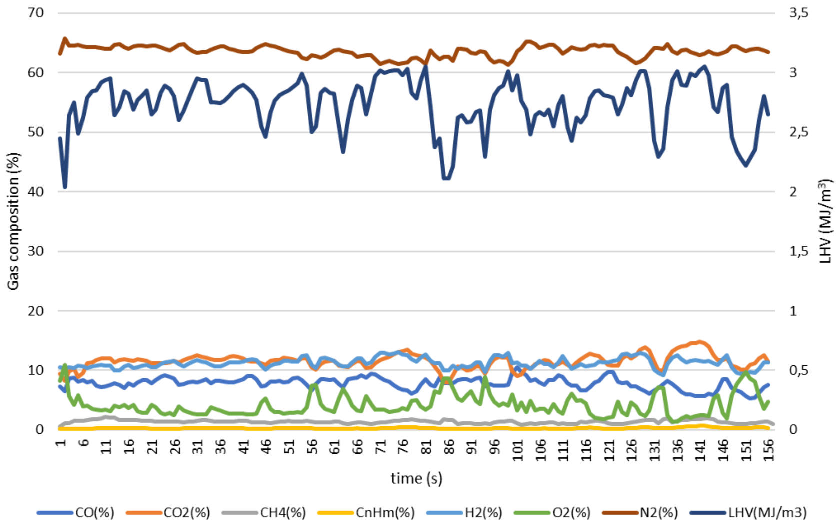

Figure 6. Gas composition in syngas from experimental

Table 2. Test result data

Exp	Gas Composition						Gas composition in syngas	LHV
	CO (%)	CO_2 (%)	CH_4 (%)	H_2 (%)	O_2 (%)	N_2 (%)	CO + CH_4 + H_2 (%)	(MJ/m³)
1	8.06	11.72	1.39	11.33	5.67	69.75	20.78	2.77
2	8.53	8.05	0.9	9.22	8.17	65.5	18.65	2.2
3	9.83	9.73	1.19	9.7	4.66	64.73	20.72	2.62
4	11.45	7.72	0.8	9.62	1.09	65.05	21.87	2.66
5	7.57	7.41	1.08	8.55	4.13	74.66	17.2	2.13
Average	9.09	8.93	1.07	9.68	4.74	67.94	19.84	2.48

Of the six gases that appeared, N2 showed the highest value, reaching 67.94%, due to an excess air supply into the reactor. This is also indicated by the presence of 4.74% unreacted O2. Therefore, this reactor needs to be optimized, particularly in controlling the air supply to achieve stoichiometry.

Based on Table 2, it can be seen that syngas consisting of CO, CH4, and H2 have an average value of 19.84%. This value is quite high as a parameter requirement for success as a bioenergy fuel as stated by other researchers. (Narega et al., 2022) (Azeem et al., 2019). Likewise, the LHV value with an average of 2.48 MJ/m3 shows a sufficient value and meets the requirements for bioenergy.

4 Conclusion

Testing of the gasification reactor design using waste pellet fuel has been conducted. The gasification reactor can use a shredder module as a substitute for the grate plate model distributor plate. The test results show that the produced syngas meet the requirements as a bioenergy fuel.

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