Preliminary plant design of thermochemical conversion for rice straw-based second-generation bioethanol production in West Java

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Abstract. Thermochemical conversion is selected in the design of a rice straw-based bioethanol production plant. This study examines the gasification and catalytic synthetic process technologies of rice straw into ethanol. The size of rice straw was reduced and dried before entering the gasification reactor to convert into syngas. The clean gas goes to the mixed alcohol synthesis process in a plug flow reactor with CuO/ZnO as a catalyst. The product is then purified through several separation methods, i.e., column distillation, stripping, and absorption. The controlled parameters for this plant are temperature, flow rate, pressure, level, and concentration. The paper describes the piping instrumentation diagram with a graphical representation of the equipment, piping, and instrumentation. A Heat Exchanger Network analysis achieves an efficiency of 34.4%. The electricity required is fulfilled by turbine expander for about 1,493 kW, and the rest of it is provided by PLN, besides an emergency generator sets. The capacity of this plant is 100,000 kL/year.

1. Introduction

Southeast Asian countries have many to offer in terms of biomass feedstocks resources for producing bioethanol, including oil palm empty fruit bunch [1,2], rice straw [3], sugarcane bagasse [4,5], durian skin [6], algae [7], and waste paper [8]. Besides oil palm industries, the possible lignocellulosic resource in Indonesia is from rice straw, as rice is the main course of Indonesians. The composition of rice straw usually is 34.2–40.6% cellulose, 19–20.6% hemicellulose, 12.3–16.7% lignin, 7.8–20.3% ash, and silica (silicon dioxide or SiO₂), and 16–19.3% extractives [3]. Indonesia's rice harvest area in 2019 is estimated at 10.68 million hectares, with rice production in 2019 estimated at 54.60 million tons of dry unhusked rice [9]. The rice straw in Indonesia is abundant. However, studies on plant design for rice straw to bioethanol are limited. Another study in this conference examines the technological aspects of rice-straw based bioethanol plant. This study examines the preliminary design for the rice straw-based bioethanol production plant.
2. Materials and Methods

2.1. Materials
The source of biomass used in this plant design is rice straw. The composition of the rice straw was determined as 12.4% ash, 39.2% cellulose, 23.5% hemicellulose, 36.1% lignin, and 1.83% moisture, based on Hans et al. [3].

2.2. Production Capacity
The production capacity for this plant is determined through a market analysis. The supply and demand for bioethanol production capacities were obtained from the Ministry of Energy and Mineral Resources [10].

2.3. Plant Location Selection
The plant location is selected based on the consideration of primary and secondary factors. The primary factors include communication and electricity infrastructure, availability of raw material, transportation, and labor forces. The secondary elements include government policy and physical aspects of the location.

2.4. Process
The main processes are gasification and catalytic synthetic. The cellulose is dried and goes to the gasification chamber producing carbon monoxide (CO), hydrogen (H\textsubscript{2}), and traces of methane (CH\textsubscript{4}). Other contaminants produced must be treated. Catalytic synthesis is the primary process to convert the syngas into ethanol by a metal catalyst like modified methanol catalysts (Cu/Zn and Cu/Mn-based), modified molybdenum sulfide catalysts, and modified molybdenum oxide catalysts. Rice straw is gasified to syngas, followed by catalytic conversion to produce ethanol and others (such as C3-C4 alcohols). The process simulation was done in Unisim Design. The biomass was modeled as hypothetical components based on Wooley and Putsche data. Ash also modeled with the theoretical element as Unisim's database does not contain ash's properties data. The other components were also added from the unisim database to begin the simulation. The energy network is analyzed and designed by using a Heat Exchanger Network (HEN) analysis method.

3. Results and Discussion

3.1. Production Capacity
Based on the Sustainable Development scenario, the national final energy demand in the year 2025 is 154.7 MTOE, while the bioethanol portion is assumed as 25% of the 23% New and Renewable Energy targeted in 2025 [8]. This means 8.89 MTOE bioethanol is needed in 2025. The supply was calculated based on the same source with the national New and Renewable Energy supply is 13.4 MTOE, and the bioethanol targeted amount is 20%, which makes the supply of bioethanol is 2.68 MTOE. One of the biggest bioethanol producers in Indonesia, PT Sampoerna TG Ethanol, produces about 0.375 MTOE per year (1,200 kL/day). Because the new plant is new, we target a smaller capacity than the benchmark. The capacity production is 0.100 MTOE (300 kL/day) of bioethanol, or merely 3.73% of the bioethanol supply targeted in 2025.

3.2. Plant Location
The district where the most significant rice production in Indonesia, which means produce the highest rice straw too, is in Indramayu, West Java. The rice straw production is between 12 to 15 tons per hectare per harvest cycle. The government has set a policy for Indramayu as the industrial zone. There are a lot of industrial areas in West Java, including the one in Losarang-Kandanghaur, Indramayu, which has available communication and electricity. Transportation infrastructure in this area is very well established as the Indramayu district is one of the busiest hubs in West Java. The presence Cipali (Cikopo-Palimanan) highway helps the mode of transportation around Java Island. Indramayu has a population of around 1.8 million inhabitants (2,300 people per km\textsuperscript{2}) [11]. With support from the high population surround, Indramayu undoubtedly provides enough labor force.
3.3. Process

The overall process and unit are illustrated in Figure 1.

Figure 1. Process flow diagram 1.
3.3.1. Gasification
Biomass feedstocks that are already dried enter the gasification process to produce syngas. The medium of the gasification process is synthetic olivine (calcined magnesium silicate) consisting of Enstatite (MgSiO$_3$), Forsterite (Mg$_2$SiO$_4$), and Hematite (Fe$_2$O$_3$). A small amount of MgO is added to the fresh olivine. The MgO rejects the potassium present in biomass as ash by forming ternary eutectic with the silica. This ternary eutectic has a high melting (~2,370°F/1,300°C) point, thus sequestering it. The formation of K$_2$SiO$_3$, which has a low melting point (~930°F/500°C), would cause the bed media to become solidified. Potassium carry-over from the gasifier to downstream processes is also significantly reduced with the addition of MgO. The biomass ash is assumed to contain 0.2 wt % potassium. The gasifier and char combustor remain in heat balance by producing (gasifier) and burning (char combustor) enough char to satisfy the energy requirements of the operation. If the gasifier temperature is lower than the equilibrium temperature, then more char is formed, and more heat is generated by char combustion. This results in more heat transfer from the combustor to the gasifier, thus bringing the gasifier temperature up toward equilibrium. The gasifier temperature is 1,596°F (869°C), and the char combustor temperature is 1,808°F (987°C).

\[
\begin{align*}
(biomass \text{ volatiles } \text{char}) + H_2O & \rightarrow CO + H_2 \\
(biomass \text{ volatiles } \text{char}) + CO_2 & \rightarrow 2CO \\
(biomass \text{ volatiles } \text{char}) + H_2 & \rightarrow CH_4 \\
CO + H_2O & \rightarrow CO_2 + H_2 \\
CO + 3H_2 & \rightarrow CH_4 + H_2O
\end{align*}
\]

3.3.2. Water Gas Shift Reaction
According to the specification of reactor synthesis alcohol, the ratio H$_2$/CO that resulted from the gasification reaction is not enough for ethanol production. The ratio of H$_2$/CO to become around 2 can be increased by using the water-gas shift reaction. The water-gas shift reaction converts CO and H$_2$O to become CO$_2$ and H$_2$. It makes the number of CO decrease, while the number of H$_2$ increase.

3.3.3. CO$_2$ Removal
After the water gas shift reaction, there is still more CO$_2$ in syngas. CO$_2$ must be removed from the syngas because CO$_2$ is not needed for the alcohol synthesis process. CO$_2$ is removed by the absorption mechanism that uses an amine solvent. Our plant uses MDEA as an absorbent to remove CO$_2$. In general, the amine absorption mechanism needs some equipment like the absorption column and the regenerator column.

3.3.4. Alcohol Synthesis
Cooled low-pressure syngas enters a four-stage centrifugal compressor system where the pressure is increased to approximately 2,000 psi (107 bar). The overall stoichiometric reaction for alcohol synthesis is summarized in equation 6.

\[ n \text{ CO} + 2n \text{ H}_2 \rightarrow C_nH_{2n+1} + 1 \text{ OH} + (n-1) \text{ H}_2O \]

Light hydrocarbons, methyl esters, and aldehydes are produced in smaller quantities through similar chemical routes. The stoichiometry suggests an optimum H$_2$/CO ratio of 2.0. However, CuO/ZnO catalysts have significant water gas shift activity and generate H$_2$ and CO$_2$ from CO and H$_2$O, as shown in equation 7.

\[ \text{CO} + H_2O \rightarrow H_2 + CO_2 \]

Heat must be removed from the reactors because the synthetic reaction is exothermic. Steam is generated at 1336 psi and 581 °F (305 °C).

3.3.5. Alcohol Separation
Cooled crude alcohols are de-pressurized and degassed in a flash separator. Before it enters the flash separator, crude alcohol is expanded by two series expanders to decrease its pressure. Ethanol exit
the distillation column as the top product and its pump to the adsorption column to dehydrate water to reach purity until 99% mole.

| Components     | Rice Straw [kg/h] | Ethanol Product [kg/h] |
|----------------|-------------------|------------------------|
| Ash            | 3,150.2           | 0.0                    |
| Cellulose      | 8,736.0           | 0.0                    |
| Hemicellulose  | 5,237.0           | 0.0                    |
| Lignin         | 8,045.0           | 0.0                    |
| Hydrogen       | 0.0               | 0.0                    |
| CO₂            | 0.0               | 0.0                    |
| H₂O            | 0.0               | 1,244.0                |
| Methane        | 0.0               | 0.0                    |
| Ethane         | 0.0               | 0.0                    |
| Ethanol        | 0.0               | 12,298.0               |
| **TOTAL**      | **25,168.2**      | **13,543.0**           |

The overall mass efficiency of ethanol = ethanol produced/biomass feed = 12,298/25,168 = 48.86%.

3.3.6. Energy Analysis

Preheaters, steam generators, and super-heaters are integrated to generate the steam. The recycled process condensate is combined with makeup water. Electricity is generated using two-stage steam turbines, with intermediate reheat, to meet the demands of the plant. The first stage turbine drops the steam pressure from 1321 psi to 350 psi. The second stage turbine drops the pressure from 345 psi to 3.5 psi, and the steam inlets to both turbine stages are preheated to 1000 °F.
the plant area, an office area, which has a total electricity requirement is about 4,703 kW. The turbine expander fulfills the power required for about 1,493 kW, and PLN provides the rest of it. There is also emergency electricity using generator sets. The fuel utility is used by the boiler, which needs fuel about 170 kg.

4. Conclusion

Our plant is planning to fulfill 10% of the demand in Indonesia, which leads to our plant capacity, which is 100,000 kilolitres per year. The proposed ethanol production is using thermochemical conversion through biomass gasification and synthetic catalytic process. The overall mass efficiency is 48.86%. The achieved efficiency from Heat Exchanger Network is 34.41%.

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