Cost Analysis on Hydrogen Production from Biomass Gasification: Simulation Study on Rice Straw and Wood Pellet Conversion

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Abstract

This work studied the process of hydrogen production from biomass in Thailand, for instance, rice straw and wood pellet. The biomass gasification plant was simulated using the process simulation software Aspen Plus v.12.1. The sensitivity analysis was focused on the effects of significant operating conditions: gasification temperature and steam to biomass ratio (S/B ratio) on hydrogen production. The results were used to indicate the operating conditions that yielded the maximum amount of hydrogen production for each feedstock. The results revealed that 97.63 kg-H_2/hr was produced at gasification temperature of 700°C and S/B ratio of 1 for rice straw, while 83.33 kg-H_2/hr was produced at gasification temperature of 650°C and S/B ratio of 1 for wood pellet. Additionally, the cost analysis was studied and the results showed that the unit production costs of hydrogen production from rice straw and wood pellet gasification were 2.77 USD/kg-H_2 and 4.07 USD/kg-H_2, respectively.

Keywords: Aspen Plus, Biomass, Cost Analysis, Gasification, Hydrogen

Introduction

Around 34% of the Thailand population in 2023 was employed in the agricultural sector. Subsequently, a lot of agricultural residues is available as by-products and eliminated by open burning. Compared to burning, converting residues into renewable energy will be an opportunity to develop waste management systems within the concept of sustainable development, and reduce CO_2 emission from open burning (Dangprok et al., 2023).

Thai Government has adopted the Bio-Circular-Green Economic (BCG) model to promote sustainable development for economic development plan of 2021–2026, in which bioenergy was considered as one of targeted sectors (Edyvean et al., 2023).

Agricultural wastes are regarded as biomass, which can be used to produce hydrogen and biofuels. Unlike carbon-containing biofuels, hydrogen is a carbon-free molecule with no carbon emission from its combustion (Wilkinson et al., 2023). Based on the massive amount of agricultural waste and residues in Thailand, hydrogen production from biomass will act as a potential BCG model to support Thai economic development plans.

Moreover, the potential of economic and financial feasibility of hydrogen production from biomass gasification in Thailand should be evaluated. Therefore, cost analysis will be investigated to reveal the potential competitiveness of biomass-to-energy in an industrial-scale operation. In this study, hydrogen production from biomass gasification process model was developed via Aspen Plus simulation. The results from this study will be useful to support the development of renewable energy in Thailand.

Objectives

This study aimed to investigate the hydrogen production from biomass gasification process using Aspen Plus simulation, a chemical process simulator used in a large number of simulation study. The effects of biomass feedstock types and operating conditions on the amount of hydrogen yield were determined to identify the optimum operating conditions. Subsequently, the cost analysis of hydrogen production at optimum operating conditions was evaluated.

Concept Theory Framework

1. Biomass Gasification

Biomass gasification is a technology of thermochemical conversion of biomass. The basic principle is to heat the biomass feedstock under incomplete combustion conditions to produce syngas, which mainly consists of H_2 and CO (Wang, 2023). The reactions involved in the biomass-based gasification process are shown in Table 1.

Table 1: Reactions involved in the biomass-based gasification process (Rizvi et al., 2023)

Reaction name	Reaction	Standard heat of reaction, kJ/mol
Boudouard	$C+CO_2 \leftrightarrow CO$	+172.0
Char Partial Oxidation	$C+½O_2 \longrightarrow CO$	−111.0

Reaction name	Reaction	Standard heat of reaction, kJ/mol
Hydrogasification	$C+2H_2 \leftrightarrow CH_4$	−74.8
Steam Methane Reforming	$CH_4+H_2O \leftrightarrow CO+3H_2$	+206.0
Water-Gas	$C+H_2O \leftrightarrow CO+H_2$	+131.0
Water-Gas Shift	$CO+H_2O \leftrightarrow CO_2+H_2$	−41.0

2. Cost Analysis

The total capital investment (TCI) consists of installed direct equipment costs, indirect costs, tax and working capital. The operating costs include raw material, utilities, labor, and maintenance costs. The software Aspen Process Economic Analyzer (APEA) is used to estimate the capital cost and operating costs for the process plant. APEA is integrated to Aspen Plus simulation and used to estimate costs of the designed model. The annuity techno economic assessment method is used to estimate the unit production cost using the equation as follows (Fivga & Dimitriou, 2018). The unit production cost will be considered as the key financial indicator to compare the feasibility of each feedstock. Cost analysis is conducted based on the assumption of the exception of transportation and storage cost (Fivga & Dimitriou, 2018 and AlNouss et al., 2020).

$$ACI = TCI \times \frac{r \times (1 + r)^N}{(1 + r)^N - 1}$$

$$\text{Unit production cost (USD/kg)} = \frac{\text{ACI + Operating cost (USD/yr)}}{\text{Annual hydrogen production (kg/yr)}}$$

where ACI is the annuity of the capital investment, r the interest rate and N the lifetime of the plant.

Materials and Methods

To study the operating conditions of the gasification process and the characteristics of different biomass feedstocks, Aspen Plus v.12.1 was used to design and optimize the gasification process. The process flowsheet of the biomass gasification was presented in Fig. 1. Proximate and ultimate analysis of biomass were entered for the stream BIOMASS component attributes as presented in Table 2. The non-conventional stream of biomass was pyrolyzed by the DECOMPOS block (RYield reactor). Biomass gasification was simulated by the GASIFIER block (RGibbs reactor) where the gasifying agent was added to the reactor as stream STEAM1. Gasification temperature was varied between 600°C - 1000°C and mass flow rate of gasifying agent was varied depending on the steam to biomass (S/B) ratio between 0.4 - 1. Separator were used for hydrogen purification to obtain hydrogen gas as the final product. The system was operated under atmospheric pressure and the mass flow rate of BIOMASS was 1000 kg/hr.

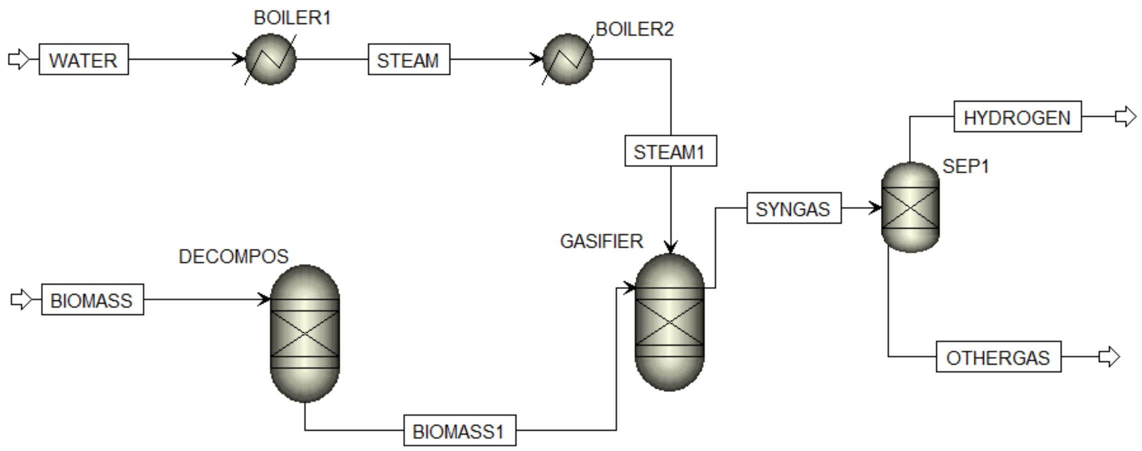


Figure. 1: Aspen Plus model flowsheet for hydrogen production from biomass gasification

Table 2: Proximate and ultimate analysis of rice straw (Luque & Speight, 2014) and wood pellet (Charis, Danha, & Muzenda 2019)

Biomass	Moisture	FC	VM	ASH	C	H	O	N	S
Rice straw	14.10	16.90	77.30	5.80	49.31	8.52	22.12	12.42	1.83
Wood pellet	3.79	19.21	76.78	4.01	41.47	5.15	52.15	1.23	0

To study the feasibility of biomass gasification in large industrial scale, the preliminary cost of the biomass gasification plant was evaluated using Aspen Process Economic Analyzer (APEA). The cost analysis was performed at optimum conditions which maximize the mass flow rate of hydrogen. The cost estimation for the production with different feed types (rice straw and wood pellet) was conducted and the feasibility among the two feed types can be compared. Critical parameters and their values for this economic analysis were presented in Table 3.

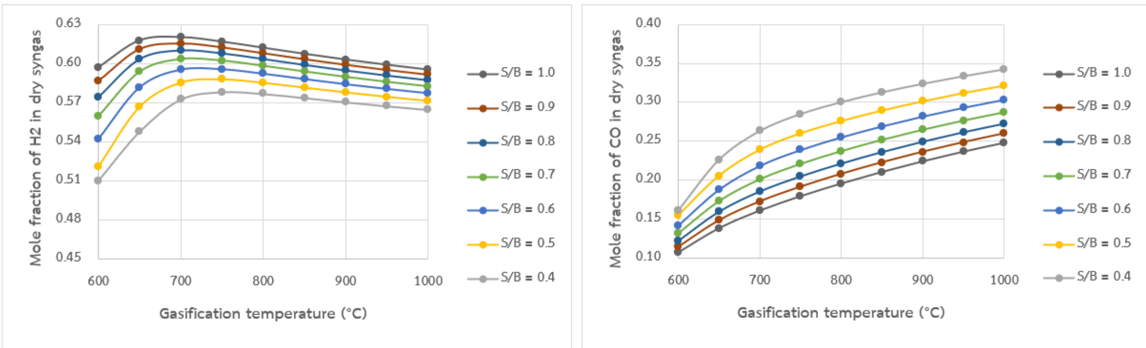
Table 3: Critical parameters and their values for cost analysis

Parameters	Values	Parameters	Values
Plant Economic Life	20 years	Operating hours per period	8766 hr/year
Construction Period	1 year	Biomass flowrate	1000 kg/hr
Starting Year of Construction	2024	Price of rice straw	0.042 USD/kg
Interest rate	20 %	Price of wood pellet	0.106 USD/kg

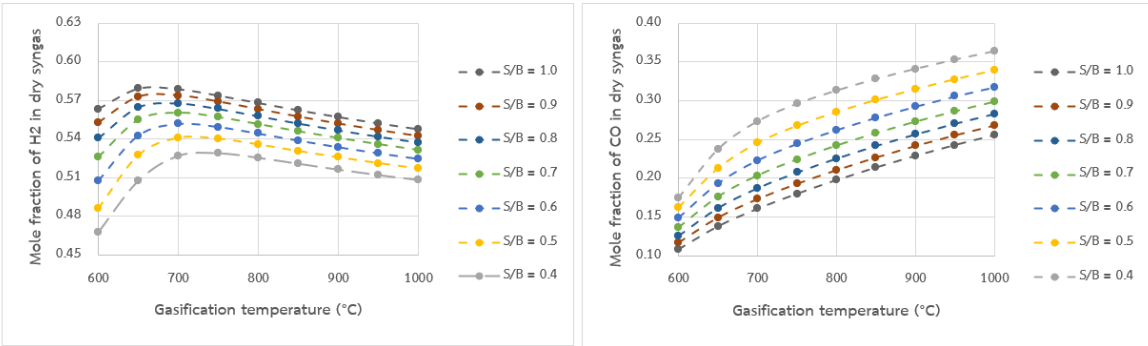
Results

1. Gasification: Effect of Operating Conditions on Hydrogen Production

The parametric study was performed to determine the effects of operating conditions on the performance of the gasifier. The gasification temperature and steam to biomass ratio (S/B ratio) were evaluated. The results of the mole fraction of dry syngas composition were analyzed. The outputs were the syngas composition of H_2 and CO as shown in Fig. 2.



(a) Rice straw



(b) Wood pellet

Figure. 2: Effects of operating conditions on syngas composition (a) rice straw and (b) wood pellet

In this study, the gasifier temperature was varied from 600°C - 1000°C. The temperature has caused a significant effect on the chemical reactions' equilibrium state. As the increase in temperature, the endothermic reactions e.g. water-gas reaction ($C + H_2O \leftrightarrow CO + H_2$ +131.0 kJ/mol) was enhanced, led to an increase in molar concentration of H_2 and CO. However, the shift the chemical equilibrium according to Le Chatelier's principle affected the molar concentration of H_2 differently from CO. The molar concentration of H_2 initially increases before decreasing as the temperature rises from 600°C to 1000°C. This trend was observed in both types of biomass feedstocks. Furthermore, rice straw produced hydrogen at the highest mole fraction between 700°C and 750°C while wood pallet produced hydrogen at the highest mole fraction between 650°C and 700°C, which is slightly lower than rice straw.

Additionally, the effect of S/B ratio on syngas composition was investigated. As an increase in the amount of gasifying agent, steam (H_2O), the water-gas reaction ($C + H_2O \leftrightarrow CO + H_2$) and water-gas shift reaction ($CO + H_2O \leftrightarrow CO_2 + H_2$) were enhanced. An increase in S/B ratio led to an increase in molar concentration of H_2 due to water-gas reaction. On the other hand, an increase in S/B ratio led to a decrease in molar concentration of CO due to water-gas shift reaction. This trend was observed in both types of biomass feedstocks. Therefore, the optimum S/B ratio that led to the maximum molar fraction of H_2 for rice straw and wood pellet gasification was considered to be S/B ratio = 1. The effect of operating conditions on hydrogen and syngas composition from the simulation study were compared with the results from the biomass gasification in laboratory scale (Song et al., 2012). It was found that, the results of both studies were in an agreement.

Since, the cost analysis was required for assessing the feasibility of biomass gasification and the hydrogen production rate was one of the significant values that affected the annual hydrogen production of the process. In Fig. 3, the mass flowrate of hydrogen (kg-H_2/hr) was presented to indicate the operating conditions that yielded the highest amount of hydrogen production for each feedstock types. For rice straw, the optimum condition was at gasification temperature of 700°C and S/B ratio of 1 produced 97.63 kg-H_2/hr. For wood pellet, the optimum condition was at gasification temperature of 650°C and S/B ratio of 1 produced 83.33 kg-H_2/hr. The amount of annual hydrogen production would be calculated based on the basis operating hours of 8766 hr/yr.

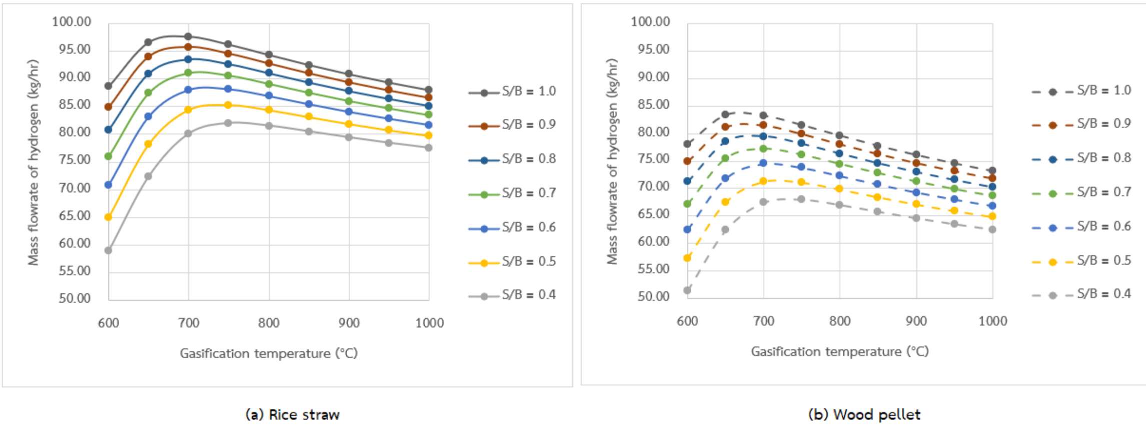


Figure. 3: Effects of operating conditions on mass flow rate of hydrogen (a) rice straw and (b) wood pellet

2. Cost analysis of Hydrogen Production from Biomass Gasification

To determine the feasibility of biomass gasification on a large industrial scale, the cost estimation was performed at the optimum condition which maximized the mass flow rate of hydrogen. The detailed of cost analysis was shown in Table 4. Annual capital investment (ACI), operating costs and annual hydrogen production was determined in order to evaluate the unit production costs for each feedstock. The unit production cost was considered as a key financial indicator for comparing with product market prices in order to preliminarily assess the financial feasibility of the project. In this study, cost analysis is conducted based on the assumption of previous studies of Fivga & Dimitriou, (2018) and AlNouss et al., (2020). So, transportation cost, storage cost and inflation price of raw material, utilities, and labor costs are not considered in the calculation.

Table 4: Cost analysis for hydrogen production from (a) rice straw and (b) wood pellet gasification

	(a) Rice Straw	(b) Wood Pellet
Feedstock price (USD/kg)	0.042	0.106
Operating conditions		
Gasification Temperature (°C)	700	650
S/B Ratio	1.0	1.0
Operating hours (hr/yr)	8766	8766
Mass Flowrate of Hydrogen (kg/hr)	97.63	83.33
Annual Hydrogen Production (kg/yr)	8.56×10^5	7.30×10^5
Cost analysis		
Total Capital Cost (USD)	4.00×10^6	3.99×10^6
Total Operating Cost (USD/Year)	1.55×10^6	2.16×10^6
Total Raw Materials Cost (USD/Year)	3.71×10^5	9.35×10^5
Total Utilities Cost (USD/Year)	2.15×10^5	2.12×10^5
Annual capital investment (USD/Year)	8.21×10^5	8.20×10^5
Key Financial Indicator		
Unit production cost (USD/kg)	2.77	4.07

The results showed that the unit production costs of hydrogen from rice straw and wood pellet gasification were 2.77 USD/kg-H_2 and 4.07 USD/kg-H_2, respectively. This revealed that the unit production costs were significantly influenced by the difference in annual hydrogen production and operating costs of each feedstock, which the operating costs were affected by total raw material cost and total utilities cost. Since the total raw material cost for rice straw gasification was lower than the wood pellet gasification, then the operating costs for rice straw gasification were also lower than wood pellet gasification. Furthermore, the annual hydrogen production rate of rice straw gasification was higher than wood pellet gasification. Therefore, the unit production cost can be reduced by either the decrease of raw materials cost or the increase in annual hydrogen production rate.

Conclusions and Discussion

This work studied the potential of using biomass in Thailand as a feedstock for hydrogen production from biomass gasification. Rice straw and wood pellet were selected as the potential feedstocks. The simulation results indicated that the optimum operating conditions of rice straw gasification was a production rate of 97.63 kg-H_2/hr at gasification temperature of 700°C and S/B ratio of 1. And, the optimum operating condition of wood pellet gasification was a production rate of 83.33 kg-H_2/hr at gasification temperature of 650°C and S/B ratio of 1. Cost analysis for each feedstock was evaluated at the optimum operating condition. The results showed that the unit production costs of hydrogen from rice straw and wood pellet gasification were 2.77 USD/kg-H_2 and 4.07 USD/kg-H_2, respectively. Additionally, the unit production cost can be reduced by manipulated the technical factor as the hydrogen production rate and economic factor as raw materials cost.

To enhance the validation of the cost analysis model, factors such as plant location, transportation costs, and the availability of other feedstocks on hydrogen production from biomass gasification should be considered in further study. Since the agricultural waste and residues was differed based on regional geographic and the unit production cost was affected by the feedstock price, the appropriate selection of low-priced feedstock with high availability will improve the competitiveness of hydrogen price.

Since Thailand's highest career proportion is in the agricultural sector and a lot of agricultural residues, there is a potential to launch the hydrogen production from biomass gasification in Thailand. Furthermore, the open burning of agricultural residues, which leads to environmental effect as massive CO_2 emission, can be migrated by converting residues into feedstocks for hydrogen production from biomass gasification. Subsequently, converting residues into renewable energy will be an opportunity to develop waste management systems within the concept of sustainable development along with BCG model.

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