Research Article

Energy Analysis of Hydrogen Production from Biomass in Thailand

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Abstract

Hydrogen can be considered as a clean energy which can be produced from various domestic renewable resources. Biomass as an alternative energy can be used instead of fossil fuels, which are energy source that is limited and may become depleted. Biomass is the best source for hydrogen production as alternative energy in Thailand. Therefore, hydrogen production from biomass gasification is considered in this study. The purpose is to evaluate the energy performance of hydrogen production from biomass; rice husk and rice straw, in terms of energy and exergy analyses. The gasification process is simulated using the ASPEN HYSYS program. The results revealed that rice husk and rice straw can be used as raw materials for hydrogen production by gasification process. System's energy efficiencies are 33.45% and 35.56% for rice husk and rice straw feedstock, respectively. In addition, system's exergy efficiencies are 29.10% and 31.12% for rice husk and rice straw feedstock, respectively. Comparing these results with other hydrogen production methods such as steam methane reforming process and coal gasification process, energy and exergy efficiencies of the biomass-based hydrogen production process are relatively low. In order to increase energy and exergy efficiencies of the biomass gasification process, energy recovery technique should be applied.

Keywords: Biomass gasification; Energy analysis; Exergy analysis; Hydrogen production

1. Introduction

Renewable energy has become increasingly important for power generation. Because it offers better energy security and lower environmental impact compared to conventional energy sources [1]. Hydrogen is an attractive energy source because of clean and environmentally friendly fuel. Nowadays, researchers concentrate on electricity production by using hydrogen and fuel cells because the process produces higher efficiency than other types of electrical equipment [2]. Thus, hydrogen is an alternative energy that can be used as traditional renewable energy because of many benefits compared to the conventional combustion from vehicles or factories which causes fog, smoke and dust [3]. Hydrogen does not cause air pollution when it is combusted and it can also be used as fuel for households, internal combustion engines or turbines. Many sources of raw material can produce hydrogen such as algae, biomass, fresh water etc. [4]

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Biomass gasification process is an incomplete combustion that converts carbon-based solid by partial oxidation into a gaseous product, consisting of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), water (H_2O), methane (CH_4) and some light hydrocarbons [5]. Biomass is available in the form of energy and heat that can either be used to produce steam for industrial processes or as a fuel to produce electricity. Additionally, biomass gasification can consume many agricultural residues as raw materials such as wood chips, corn cobs, bagasse, palm shell, rice husk, rice straw, wood chip, coconut shell etc. [6]

Furthermore, Thailand is the world's number one rice exporter. Thus, biomass residues from rice paddies and the rice industry are available in large amounts which can be used to generate energy. From these points of view, biomass-based hydrogen production via gasification is studied in this work. The aim is to evaluate the performance of biomass gasification process in terms of energy and exergy analyses. The gasification of rice husk and rice straw is operated using the ASPEN HYSYS simulation program.

2. Materials and Methods

2.1 Biomass gasification

Biomass gasification is the conversion of biomass such as wood-waste and agricultural residues into a combustible gas that consists of carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2) and traces of methane (CH_4). This gaseous product is called syngas. Gasification reactions, series reactions with oxygen and additional gas phase reaction, are [7]

Pyrolysis or Devolatilizaton

$$\text{Biomass} \rightarrow \text{Char} + \text{Tars} + \text{Light gases} \qquad (1)$$

Boudouard reaction

$$C + CO_2 \rightarrow 2CO \quad \Delta H^o_{rxn} = +172 \text{ kJ/gmol} \qquad (2)$$

Heterogeneous water gas shift reaction

$$C + H_2O \rightarrow CO + H_2 \quad \Delta H^o_{rxn} = +131 \text{ kJ/gmol} \qquad (3)$$

Methanation reaction

$$C + 2H_2 \rightarrow CH_4 \quad \Delta H^o_{rxn} = -75 \text{ kJ/gmol} \qquad (4)$$

Combustion reaction

$$2C + O_2 \rightarrow 2CO \quad \Delta H^o_{rxn} = -111 \text{ kJ/gmol} \qquad (5)$$

$$CO + \tfrac{1}{2}O_2 \rightarrow CO_2 \quad \Delta H^o_{rxn} = -283 \text{ kJ/gmol} \qquad (6)$$

$$C + O_2 \rightarrow CO_2 \quad \Delta H^o_{rxn} = -394 \text{ kJ/gmol} \qquad (7)$$

Stream methane reforming reaction

$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad \Delta H^o_{rxn} = +206 \text{ kJ/gmol} \qquad (8)$$

Water gas shift reaction

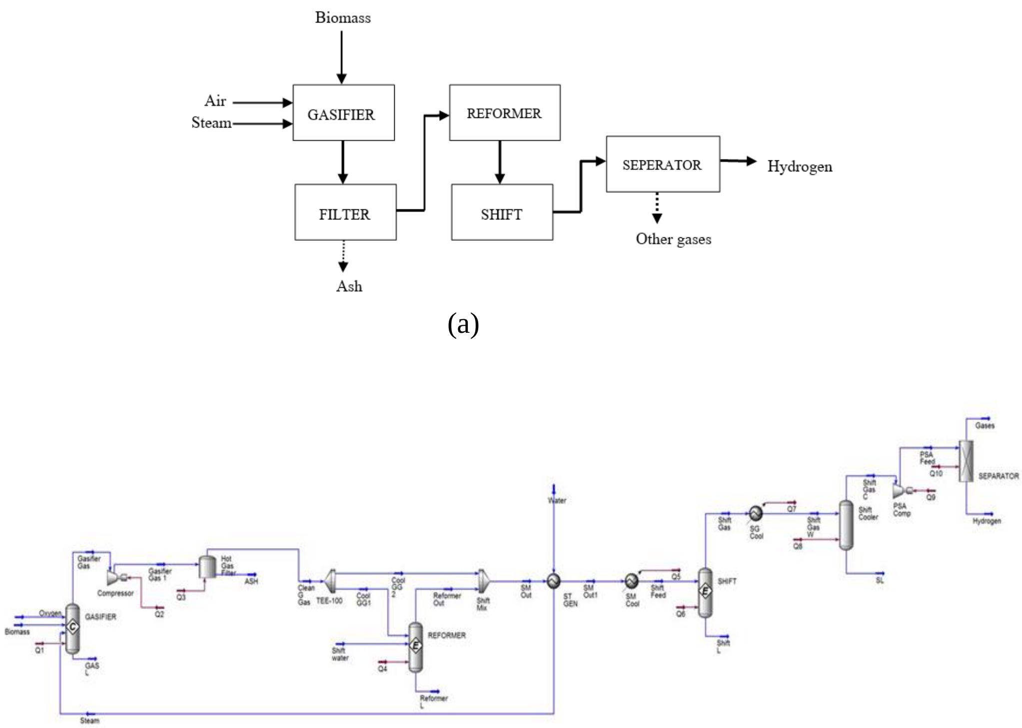
$$CO + H_2O \rightarrow CO_2 + H_2 \quad \Delta H^o_{rxn} = -41 \text{ kJ/gmol} \qquad (9)$$

2.2 Simulation of hydrogen production from biomass

Since, biomass residue from rice paddies and the rice industry in Thailand are available in large amounts, rice husk and rice straw are chosen as a raw material to produce hydrogen. The HYSYS process design and simulation program is used to develop the gasification process in this study as presented in Figure 1. The gasification process is developed using GTI proprietary gasifier model [8]. In addition, the gasification process operates at thermodynamic equilibrium conditions, thus a Gibbs reactor is used in the simulation. The main unit operations of gasification are gasifier, reformer, shift reactor and separator. The key operating variables are air to biomass ratio, stream to biomass ratio, process temperature and pressure. The compositions of biomass from Thailand institute are provided in Table 1.

Table 1. Ultimate and proximate analysis of rice husk and rice straw in Thailand [6].

Biomass	Rice husk	Rice straw
Proximate analysis		
Ash, %	12.65	10.39
Volatile Matter, %	56.46	60.70
Fixed Carbon, %	18.88	18.90
Ultimate Analysis		
Carbon, %	37.48	38.17
Hydrogen, %	4.41	5.02
Sulfur, %	0.04	0.09
Chlorine, %	0.09	-
Ash, %	12.65	10.39
Other Characteristic		
Bulk Density, kg/m3	150	125
HHV, kJ/kg	14755	13650
LHV, kJ/kg	13517	12330



(a)

(b)

Figure 1. Biomass-based hydrogen production process (a) process block diagram (b) process simulation via ASPEN HYSYS.

2.3 Energy and exergy analyses

Since hydrogen is the desired product in the process, the system performance can be evaluated in terms of energy efficiency (η) and exergy efficiency (ψ) at steady-state operation [9]. The energy (*E*) or first law efficiency of a system is defined as the ratio of energy output to the energy input to system. The energy efficiency can be calculated as [10]

$$Energy\ efficiency\ (\eta) = \frac{\dot{E}_{H_2} + \dot{W}_{net}}{\dot{E}_{air} + \dot{E}_{biomass} + \dot{E}_{water}} \quad (10)$$

The exergy (*Ex*) or second law efficiency is defined as the ratio of exergy output to the exergy input to system. Exergy is used to define the maximum possible work potential of a system. The concept of exergy is the consideration of energy quality. Exergy can be expressed by the sum of physical and chemical exergy as [9]

$$Ex = Ex^{ph} + Ex^{ch} \quad (11)$$

The physical exergy can be defined as

$$Ex = (H - H_0) - T(S - S_0) \quad (12)$$

The chemical exergy can be calculated for an ideal gas mixture as

$$Ex^{ch} = \sum_i x_i (Ex_i^{ch} - RT \ln x_i) \quad (13)$$

Here, x_i is the mole fraction and Ex_i^{ch} is the standard chemical exergy of component *i*.

In an exergy analysis, the temperature and pressure of the reference environment are usually taken as 298.15 K and 0.101 MPa, respectively. The exergy efficiency can be calculated as [10]

$$Exergy\ efficiency\ (\psi) = \frac{\dot{E}x_{H_2} + \dot{W}_{net}}{\dot{E}x_{air} + \dot{E}x_{biomass} + \dot{E}x_{water}} \quad (14)$$

Where

$\dot{E}_{H_2}$ and $\dot{E}x_{H_2}$ are energy and exergy rates of hydrogen, respectively

$\dot{W}_{net}$ is the net work rate (produced work – consumed work)

$\dot{E}_{air}$ and $\dot{E}x_{air}$ are energy and exergy rates of air, respectively

$\dot{E}_{biomass}$ and $\dot{E}x_{biomass}$ are energy and exergy rates of biomass, respectively

$\dot{E}_{water}$ and $\dot{E}x_{water}$ are energy and exergy rates of water, respectively

3. Results

In this work, the system performance is evaluated via process simulation. Biomass gasification mathematical model was validated using the results obtained from Lau (2002) [8]. Hydrogen is the desired product from the biomass gasification process. The important parameters affected the biomass gasification process efficiency are air to biomass ratio, steam to biomass ratio, gasification temperature and pressure. From this point of view, the optimal operating conditions in terms of maximum hydrogen yield are evaluated. The results revealed that the optimal operating conditions are shown in Table 2 [6]. Hydrogen production rates from rice husk and rice straw are 1513 kg/hr and 1526 kg/hr, respectively. In order to use energy more efficiently, energy and exergy analyses of the biomass-based hydrogen production process should be evaluated. The energy and exergy flow rates of rice husk and rice straw feedstock are compared as demonstrated in Table 3 and 4. They revealed that the main energy and exergy flows supplied to the system are biomass and energy consumption.

Table 2. Optimal operating conditions of the biomass gasification process.

Operating variables	**Operating conditions**
Biomass feed rate	20830 kg/hr
Air to biomass ratio	0.30
Steam to biomass ratio	0.63
Gasifier temperature and pressure	1073 K, 792.9 kPa
Reformer temperature and pressure	1473 K, 689.5 kPa
Shift reactor temperature and pressure	473 K, 551.6 kPa
Separator temperature and pressure	366 K, 1482 kPa

Table 3. Energy and exergy flows of the biomass (rice husk) gasification process.

Rice husk	**Mass flow rate (kg/hr)**	**Energy flow rate (GJ/hr)**	**Exergy flow rate (GJ/hr)**
Input			
Biomass	20,830	433.06	505.85
Air	6,178	1.80	0.83
Water	13,150	5.79	15.30
Energy (LPG)	2,035	102.21	102.21
Output			
Hydrogen	1,513	181.61	181.66
Off-gas*	1,665	104.73	101.83
Ash	10,408	202.54	235.02
Energy		26.26	26.27

* Off-gas consists of CO_2, H_2O, H_2, CO, N_2, NH_3 and H_2S

Table 4. Energy and exergy flows of the biomass (rice straw) gasification process.

Rice straw	**Mass flow rate (kg/hr)**	**Energy flow rate (GJ/hr)**	**Exergy flow rate (GJ/hr)**
Input			
Biomass	20,830	405.34	470.35
Air	6,178	1.80	0.83
Water	13,150	5.79	15.30
Energy (LPG)	2,047	101.81	101.81
Output			
Hydrogen	1,526	183.17	183.22
Off-gas*	1,826	115.93	112.98
Ash	10,448	217.22	253.73
Energy		26.14	26.14

* Off-gas consists of CO_2, H_2O, H_2, CO, N_2, NH_3 and H_2S

Table 5. Energy and exergy efficiencies of biomass-based hydrogen production in Thailand.

Biomass	**Energy efficiency (%)**	**Exergy efficiency (%)**
Rice husk	33.45	29.10
Rice straw	35.56	31.12

In the biomass-based hydrogen production process, energy and exergy efficiencies as shown in Table 5 are 33.45%, 29.10% and 35.56%, 31.12% for rice husk and rice straw feedstock, respectively. There are many variables that affect the overall energy and exergy efficiencies as biomass type, the amount of hydrogen product and off-gas. In addition, the exergy efficiency of the system is lower than its energy efficiency; this means that the system has low energy quality. These values are reasonable because of low hydrogen product yield and a large amount of off-gas [11]. Moreover, the temperature and pressure differences of inlet (500.1 K, 1482 kPa) and outlet gases (366.33 K, 413.7 kPa) in the separation unit are the main cause of exergy loss in the gasification process.

From these results, they also demonstrated that energy and exergy efficiencies of the biomass-based hydrogen production process are relatively low compare to other methods such as steam methane reforming process (86.0% energy efficiency and 78.5% exergy efficiency) and coal gasification process (64.0% energy efficiency) [12]. Since production methods and fuel types affect the efficiencies of hydrogen production process.

In order to increase energy and exergy efficiencies of the hydrogen production from biomass gasification process, energy recovery technique should be applied. In the gasification process, reformer and shift reactor produce large quantities of waste heat. Therefore, energy efficiency can be improved by recovering the waste heat in order to reduce the energy consumption in the process.

5. Conclusion

Since hydrogen become a significant part of the energy economy of the future. In this study, hydrogen production from biomass gasification is evaluated via process simulation. The objective is to evaluate the energy performance of biomass gasification process using rice husk and rice straw in Thailand. The results showed that at the optimal operating conditions hydrogen production rates from rice husk and rice straw are comparable; 1513 kg/hr and 1526 kg/hr, respectively. Moreover, system's energy and exergy efficiencies are relatively low; 33.45% and 35.56% energy efficiencies and 29.10% and 31.12% exergy efficiencies for rice husk and rice straw feedstocks, respectively. They are reasonable due to less hydrogen production and a large amount of off-gas. Therefore, energy recovery techniques should be applied to increase energy and exergy efficiencies of the biomass-based hydrogen production process.

6. Acknowledgements

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7. References

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