Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 79 (2015) 430 – 435

Energy Procedia

2015 International Conference on Alternative Energy in Developing Countries and Emerging Economies

Energy Efficiency Analysis in An Integrated Biomass Gasification Fuel Cell System

Woranee Paengjuntuek[a*], Jirasak Boonmak[a], Jitti Mungkalasiri[b]

[a]*Chemical Engineering Department, Engineering Faculty, Thammasat University, 99 Klong Luang, Pathumthani 12120, Thailand*
[b]*MTEC, National Science and Technology Development Agency, 114 Klong Luang, Pathumthani 12120, Thailand*

Abstract

Biomass gasification for power generation has received considerable attention as a partial substitute for fossil fuels power generation. Gasification is the incomplete combustion that converts a carbon-contain feedstock into syngas including hydrogen, methane, carbon monoxide, carbon dioxide, water and other gaseous hydrocarbons. To increase power efficiency, fuel cell is one of the most suitable ways to combine with biomass gasification especially solid oxide fuel cell (SOFC). SOFC is considered as the most encouraging fuel cell type due to its high power generation efficiency and long term stability. Therefore, to obtain higher energy efficiency, gasification process should be operated with highly efficient power generation as SOFC. The combined cycle is called integrated biomass gasification fuel cell (BGFC) system. Furthermore, to measure a system performance, energy analysis should be evaluated. In this study, Aspen plus 7.2 is used to perform an integrated biomass gasification fuel cell system with rice straw feedstock for power generation. The results show that at the optimal operating condition, the electricity production is 1395.61 kW with 69.38% total energy (combined heat and power) efficiency.

Peer-review under responsibility of the Organizing Committee of 2015 AEDCEE

Keywords: Biomass gasification; Energy efficiency; Fuel cell; Power generation system

1. Introduction

According to the population growth in Thailand, there is not sufficient electricity and also energy consumption. Furthermore, using fossil fuels have negative environmental impacts due to greenhouse gas emissions and air pollution problem. Therefore, biomass is a renewable and sustainable source to produce environmentally friendly energy. Biomass is also considered as an ideal energy source for gradually

* Corresponding author. Tel.: +662-564-3001 ; fax: +662-564-3024.
E-mail address: pworanee@engr.tu.ac.th.

Peer-review under responsibility of the Organizing Committee of 2015 AEDCEE
doi:10.1016/j.egypro.2015.11.514

replacing fossil fuels. Moreover, agricultural residues in Thailand such as rice straw, bagasse, palm empty bunch and cassava rhizome have increased in recent year. Biomass residues can also use for domestic heating and industrial cogeneration. In Thailand, rice straw is one of the main agricultural residues and estimated to be about 26 Mt/year. In addition, the capital cost of rice straw power generation is low [1-2].

Considering environmental issues, biomass gasification for power generation has received considerable attention as a partial substitute for fossil fuels power generation. Because it is more environmentally friendly and it provides a profitable way to dispose wastes. In addition, the energy efficiency of biomass gasification can be greatly enhanced when operating with highly efficient power generation systems as fuel cells. Among fuel cell types, solid oxide fuel cell (SOFC) is the most suitable candidate for biomass power technologies because of high efficiency, fuel flexibility, tolerance to fuel contaminants and its operating temperature close to biomass gasification process [3]. The combined cycle of renewable energy sources and innovative power generation technology are called an integrated biomass gasification fuel cell (BGFC) system. Several researches have reported that an integrated BGFC system is established to have higher power generation potential than biomass gasification combined cycle (BGCC) system [4]. Therefore, the purpose of this study is to evaluate an energy efficiency of an integrated biomass gasification fuel cell system with rice straw feedstock in order to purpose sustainable way for electricity production in Thailand.

Nomenclature

E	energy transfer
Q	thermal energy or heat
W	mechanical work or electricity

Greek letter

η	efficiency (%)

Subscripts

in	input
mass	mass transfer
out	output

2. Biomass Gasification

Gasification is the partial oxidation of carbonaceous material achieved by limiting the amount of oxygen. For biomass gasification, it is an incomplete combustion of biomass that converts biomass into a combustible gas consisting of carbon monoxide (CO), hydrogen (H_2), traces of methane (CH_4) and unused product like tar and dust. The mixture is called producer gas or syngas.

During biomass gasification, the material is heated to a high temperature with atmospheric pressure, which causes a series reactions as [5]

$C + 0.5O_2$	$\leftrightarrow$	CO	$\Delta H^{o}_{rxn} = -111\ kJ/mol$
$C + H_2O$	$\leftrightarrow$	$CO + H_2$	$\Delta H^{o}_{rxn} = +131\ kJ/mol$
$C + CO_2$	$\leftrightarrow$	$2CO$	$\Delta H^{o}_{rxn} = +172\ kJ/mol$
$C + 2H_2$	$\leftrightarrow$	CH_4	$\Delta H^{o}_{rxn} = -75\ kJ/mol$
$CH_4 + 0.5O_2$	$\leftrightarrow$	$CO + 2H_2$	$\Delta H^{o}_{rxn} = -36\ kJ/mol$
$CO + 0.5O_2$	$\leftrightarrow$	CO_2	$\Delta H^{o}_{rxn} = -283\ kJ/mol$
$H_2 + 0.5O_2$	$\leftrightarrow$	H_2O	$\Delta H^{o}_{rxn} = -242\ kJ/mol$
$CO + H_2O$	$\leftrightarrow$	$CO_2 + H_2$	$\Delta H^{o}_{rxn} = -41\ kJ/mol$
$CH_4 + H_2O$	$\leftrightarrow$	$CO + 3H_2$	$\Delta H^{o}_{rxn} = +206\ kJ/mol$

In this work, gasification process is studied via process simulation with rice straw feedstock. The composition of rice straw after primary pyrolysis or devolatilization is shown in Table 1.

Table 1. Composition of rice straw (after primary pyrolysis or devolatilization) [4]

Components	*kg/kg rice straw*	Components	*kg/kg rice straw*
Total devolatilization	0.9600	H_2	0.0016
Total gas	0.4760	CH_4	0.0241
Tar	0.4840	C_2	0.1227
Char	0.0400	CO	0.2164
		CO_2	0.0308
		H_2O	0.0804

3. Fuel Cell

A fuel cell is an electrochemical energy conversion device which directly converts one part of chemical energy into electrical energy by consuming hydrogen-rich fuel and oxidant. At the cathode, oxygen is reduced by the incoming electrons to produce oxygen anions that are conducted through the electrolyte to the anode where they electrochemically combine with the adsorbed hydrogen to form water and heat as a by-product and release electrons to the external circuit. The electrochemical reactions as follows [6]

At the anode: $H_2 + O^{2-} \rightarrow H_2O + 2e^-$

At the cathode: $1/2O_2 + 2e^- \rightarrow O^{2-}$

Overall reaction: $H_2 + 1/2O_2 \rightarrow H_2O$ +Heat + Electricity

Solid oxide fuel cell (SOFC) is one of the most potential fuel cell types for stationary application or transportation systems. It can produce clean energy at high efficiency and low pollution emission. In addition, SOFC operates at very high temperatures, typically between 500 and 1000°C. At these temperatures, it does not require expensive platinum catalyst material. Moreover, SOFC is fuel flexibility which means that both hydrogen and syngas obtained from biomass gasification can be optionally used as a feedstock. They are also relatively resistant to small quantities of sulphur in the fuel [3].

4. Integrated Biomass Gasification Fuel Cell System

Gasification is one of the best conversion routes for producing a renewable energy from biomass feedstock. However, biomass gasification cannot give high energy efficiency; therefore, solid oxide fuel cell (SOFC) should be combined in order to obtain higher energy efficiency. An integrated biomass gasification fuel cell or BGFC system contains 6 main units as shown in Fig.1. These are gasifier, cyclone, heat recovery steam generator (HRSG), gas clean up, steam turbine, and fuel cell (SOFC). The system generates electricity from two ways; the turbine unit and fuel cell unit. The parameters for fuel cell simulation are referenced by [7]. The electrical output from fuel cell is predicted by electrochemical model [4].

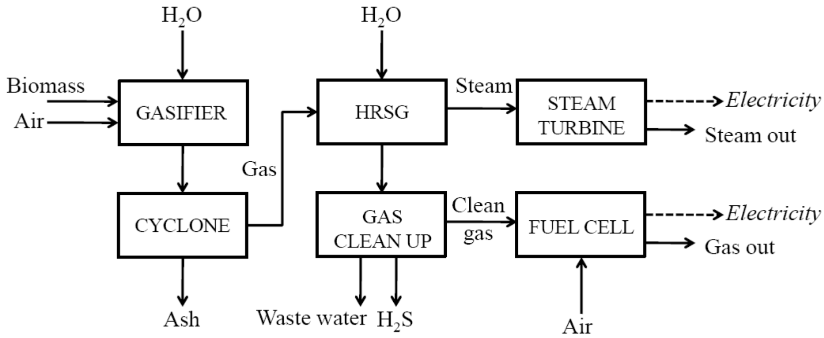

Fig. 1. The process flow diagram of BGFC system.

5. Energy Analysis

Energy analysis is an important tool to establish the short-term feasibility of a system. Energy efficiency, η, is a generic term used to measure the performance of a system. It is an indicator to quantify changes in energy.

Total energy (combined heat and power) efficiency of the BGFC is defined by the ratio of delivered usable energy to the energy input [8] as

$$\eta_{tot} = \frac{\sum W_{out} + \sum Q_{out}}{\sum E_{mass,in} + \sum Q_{in}} \tag{1}$$

For electrical efficiency :

$$\eta_{el} = \frac{\sum W_{out}}{\sum E_{mass,in} + \sum Q_{in}} \tag{2}$$

For thermal (heat) efficiency :

$$\eta_{th} = \frac{\sum Q_{out}}{\sum E_{mass,in} + \sum Q_{in}} \tag{3}$$

6. Results and Discussion

Integrated biomass gasification fuel cell (BGFC) system is a significant cooperation for simultaneous heat and material integration between the gasification and the SOFC systems to generate electricity. The study is carried out by using Aspen plus v.7.2. The simulated rice straw BGFC system is shown in Fig.2.

In our previous study, the optimal operating conditions for maximum electrical power generation of the BGFC system were evaluated. The results revealed that at 205.35 kg rice straw/hr, 2.0 air to biomass ratio, 1.3 steam to biomass ratio, 1000˚C gasifier temperature, 1 bar gasifier pressure, 1000˚C fuel cell temperature and 5 bar fuel cell pressure, the maximum electrical powers generated from steam turbine and SOFC fuel cell were 3.79 kW and 1391.82 kW, respectively [7].

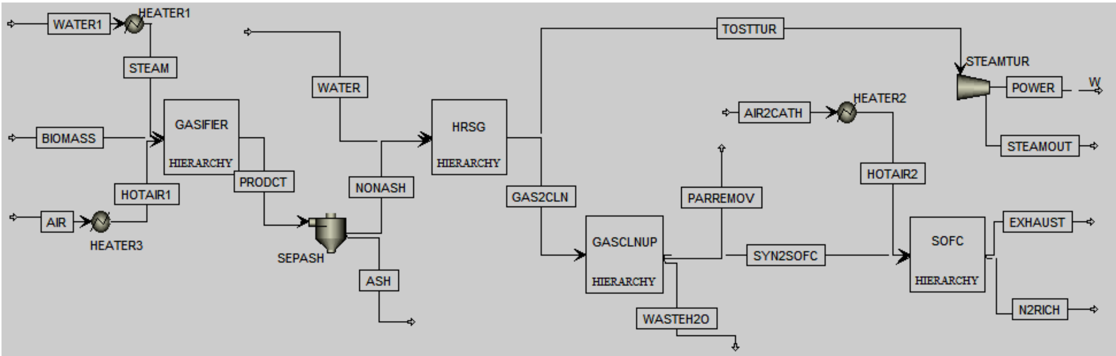

Fig. 2. Aspen simulation of the BGFC power generation system

Energy flows of the simulated BGFC system are illustrated in Table 2. It can be seen that major energy flow supplied to the system is biomass and water. The BGFC performance is evaluated in terms of total efficiency, eq.(1), electrical efficiency, eq.(2) and thermal efficiency, eq.(3). The results revealed that the BGFC system with rice straw feedstock has 39.55% electrical efficiency, 29.83% thermal efficiency and the total energy efficiency is 69.38%. Many variables affect the overall system's energy efficiency including the type of biomass, its moisture content and operating conditions. In addition, the total energy efficiency of the BGFC is significantly higher than biomass gasification combined cycle (BGCC) system (42.23%) [4].

Nevertheless, energy flow data of the BGFC system in Table 2 also presented that energy loss occurs in the BGFC system. A large portion of the energy loss is from the exhaust. Moreover, the BGFC operation produces large quantities of waste heat and steam. Therefore, energy efficiency of the BGFC system can be improved by recovering the waste heat and unused steam in order to reduce energy consumption in the system.

7. Conclusion

The aim of this study is to evaluate the energy performance of biomass power generation system. A process simulation for the integrated biomass gasification fuel cell (BGFC) system is performed.

Table 2. Energy flows of the BGFC power generation system

Stream/Unit	Mass flow rate (m, kg/hr)	Energy Input (kW)		Energy Output (kW)		
		Energy flow ($E_{mass,in}$)	Heat (Q_{in})	Energy flow ($E_{mass,out}$)	Heat (Q_{out})	Work (W_{out})
BIOMASS	205.35	832.92				
WATER1	266.96	1175.00	-	-	-	-
AIR	410.71	0.00	-	-	-	-
WATER	101.43	447.22	-	-	-	-
ASH	19.58	-	-	1.22	-	-
WASTEH2O	208.36	-	-	913.89	-	-
PARREMOV	0.32	-	-	0.05	-	-
STEAMOUT	101.43	-	-	327.22	-	-
EXHAUST	587.96	-	-	1127.78	-	-
N2RICH	1015.36	-	-	211.94	-	-
HEATER1	-	-	335.87	-	-	-
HEATER2	-	-	276.94	-	-	-
HEATER3	-	-	122.47	-	-	-
GASIFIER	-	-	36.96	-	190.93	-
HRSG	-	-	301.54	-	230.43	-
STEAMTUR	-	-		-	-	3.79
SOFC	-	-		-	631.37	1391.82

The results revealed that at the optimal operating conditions with 205.35 kg rice straw/hr the total power generation from steam turbine and SOFC is 1395.61 kW. In addition, the BGFC system has 39.55% electrical efficiency, 29.83% thermal efficiency and 69.38% total energy efficiency. However, large quantities of waste heat and steam are produced, thus an effective way to increase the system's energy efficiency is to recover waste heat and unused steam.

Acknowledgement

The authors would like to acknowledge the support from Engineering Faculty and Thammasat University Scholarships.

References

[1] Delivand MK, Barz M, Garivait S. Overall analysis of using rice straw residues for power generation in Thailand-project feasibility and environmental GHG impact assessment. *J Sustain Energy & Envi Special Issue* 2011;39-46.

[2] Shafie SM, Mahlia TMI, Masjuki HH. Life cycle assessment of rice straw co-firing with coal power generation in Malaysia. *J Energy* 2013;**57**:284-294.

[3] Suranat W, Hiroshi I, Motohiro S, Hideo Y. Performance evaluation of an integrated small-scale SOFC-biomass gasification power generation system. *J Power Sources* 2012;**216**:314-322.

[4] Sadhukhan J, Zhao Y, Shah N, Nigel N. Performance analysis of integrated biomass gasification fuel cell (BGFC) and biomass gasification combined cycle (BGCC) systems. *Chem Eng Sci* 2010;**65**:1942–1954.

[5] Bhawasut C, Suthida A, Suttichai A, Amornchai A. Performance analysis of an integrated biomass gasification and PEMFC (proton exchange membrane fuel cell) system: Hydrogen and power generation. *Energy* 2013;**55**:98-106.

[6] Seitarides T, Athanasiou C, Zabaniotou A. Modular biomass gasification-based solid oxide fuel cells (SOFC) for sustainable development. *Renewable and Sustainable Energy Reviews* 2008;**12**:1251-1276.

[7] Jirasak B, Woranee P. Optimal operation analysis of IGFC system. *Thammasat Int Sci and Tech*. 2014;**19**:52-59.

[8] Ertesvag IS. Exergetic comparison of efficiency indicators for combined heat and power. *Energy* 2007;**32**:2038-2050.