Research Article

Optimal Operation Analysis of IGFC System

Jirasak Boonmak and Woranee Paengjuntuek*
Department of Chemical Engineering, Faculty of Engineering, Thammasat University, Rangsit Campus,Khlong Nueng, Khlong Luang, Pathumthani, 12120, Thailand

Jitti Mungkalasiri
MTEC,NationalScience and Technology Development Agency,
Klong Nueng, KlongLuang, Pathumthani, 12120, Thailand.

Abstract

Electrical energy consumption in Thailand increased annually which affects to decrease amount of fossil fuels, an important source of power generation. Thus, biomass, waste from agricultural product, is considered as an alternative source of power generation. Integrated biomass gasification combined cycle is common process for transformation and utilization of biomass to produce electrical energy. However efficiency can be greatly enhanced by using fuel cell technology. Solid oxide fuel cell (SOFC) has received considerable attention in this research because SOFC can operate effectively at the same condition with gasification process. As a result, integration between SOFC and biomass gasification processes can make the high overall plant efficiency. This research studies co-operation system of biomass gasification and power plant technology that called IGFC (integrated gasification fuel cell). This research aims to find the optimal operating conditions in order to make highest power efficiency from rice straw. The operating variables considered include temperature and pressure of gasifier and SOFC, air-to-biomass ratio and steam-to-biomass ratio. Aspen plus is used to perform a simulation in this study. In order to make highest power efficiency, the optimal operating conditions are 3.4 of air-to-biomass ratio, 0.6 of steam-to-biomass ratio, 1000 ˚C of temperature of gasifier, 1000 ˚C of fuel cell temperature, 1 bar of gasifier pressure and 0.5 bar of fuel cell pressure. This condition can generate net power output is 651.35 kW and efficiency is 59.17 %

Keywords: Biomass gasification; Electrical energy; Power generation; Solid oxide fuel cell.

1. Introduction

The utilization of biomass is widely well-known and important to the reduction of global warming. Biomass, which is environment-friendly, can replace fossil fuels for thermal and electricity applications. Biomass gasification appear to be important alternatives to conventional heat and power generation systems, specifically in countries with available feedstock, higher oil prices and shortages of existing supplies [1-3].

Most the biomass gasifiers operating for power generation today are combined either with gas engine or with gas turbine based combined cycles. The energy efficiency of a biomass gasification process can be greatly enhance if combined with high efficiency power generation systems, such as solid oxide fuel cell (SOFC). Moreover both gasifiers and SOFCs operate effectively at elevated temperatures of around 500–1000 ˚C and atmospheric

***Correspondence** : pworanee@engr.tu.ac.th

pressures, so it can be provide opportunities for process integration [4-7]. This work studies co-operation system of biomass, rice straw, gasification and power plant technology called IGFC (integrated gasification fuel cell) and aims to find the optimal operating conditions in order to produce highest power efficiency. Commercial program as Aspen plus is used to perform a simulation in this study.

2. Biomass gasification process

2.1. Gasification

Biomass gasification is the conversion of solid fuels (biomass) such as wood, wood-waste, rice straw and agricultural residues into a combustible gas. Combustible gas consists of carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2) and traces of methane (CH_4). This mixture is called producer gas or syngas. Gasification reactions, series reactions with oxygen and additional gas phase reaction, are [8-10]:

$$2C(s) + O_2 \rightarrow 2CO_2 \qquad \Delta H^o_{rxn} = -221.31\ kJ/gmol$$

$$C(s) + O_2 \rightarrow CO_2 \qquad \Delta H^o_{rxn} = -393.98\ kJ/gmol$$

$$C + H_2O \rightarrow CO + H_2 \qquad \Delta H^o_{rxn} = +131.00\ kJ/gmol$$

$$C + 2H_2 \rightarrow CH_4 \qquad \Delta H^o_{rxn} = +75.00\ kJ/gmol$$

$$2CH_4 + O_2 \rightarrow 2CO + 4H_2 \qquad \Delta H^o_{rxn} = -71.44\ kJ/gmol$$

$$CH_4 + H_2O \rightarrow CO + 3H_2 \qquad \Delta H^o_{rxn} = +206.20\ kJ/gmol$$

$$2CO + O_2 \rightarrow 2CO_2 \qquad \Delta H^o_{rxn} = -566.65\ kJ/gmol$$

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad \Delta H^o_{rxn} = -41.21\ kJ/gmol$$

$$2H_2 + O_2 \rightarrow 2H_2O \qquad \Delta H^o_{rxn} = -484.23\ kJ/gmol$$

2.2. Fuel cell principle

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 [11]. 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 in such a cell can be summarized as follows [6,7]:

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

3. Simulation of IGFC system

Simulation of the IGFC system is undertaken in Aspen Plus 7.2. The parameters for IGFC simulation are shown in Table 1. The simulated IGFC process is composed of 6 main units illustrated in Fig. 1. Gasifier unit under consideration consists of two interconnected operation which are steam gasification and char combustion. The syngas (PRODUCT steam) rich in hydrogen from the steam gasifier passes through cyclone for Ash elimination (ASH stream) to give an excellent feedstock to the SOFC. HRSG unit is a heat exchanger. The hot nonash syngas (NONASH stream) which is at about 900°C exchanges heat with water (WATER stream). Steam turbine unit is an isentropic expansion causing turbine work output (POWER stream) which applies this power to generate electricity. Clean up unit is for syngas cleaning. SOFC unit composed of anode and cathode. Air (HOTAIR2 stream) is fed into cathode to separate rich N_2 (N2RICH stream) from O_2. The left over O_2 goes through the anode to continue reaction with syngas to obtain the product gas (EXHAUST stream). SOFC unit produces more efficient power than STEAMTUR unit by calculating enthalpy and entropy of product gas (EXHAUST stream).

The lists of Aspen plus models which are used in simulations of each section are also summarized in Table 2. The basis of the energy efficiency studies for the IGFC system is a power generation about 600 kW from the SOFC, based on 85% clean syngas utilization in the SOFC [4]. Basis for feedstock flow rates is 205.35 kg/hr of rice straw and its composition is provided in Table 3. The NRTL method is approximate for this analysis and stream type is “MIXNC”. The system operates under steady-state conditions and all steams are well mixed. Operating temperature and pressure of fuel cell are uniform and constant [12-14]. Reactants in fuel cell are assumed to be compressible ideal gases with the constant thermodynamic and electrochemical properties. No side reactions or electrode reactions (e.g., corrosion) occur in fuel cell. All of reacting species e.g. H_2, CO, CH_4 in syngas is the source of power generation from fuel cell [4]. Predicted electrical output from fuel cell by electrochemical model [11] as follows:

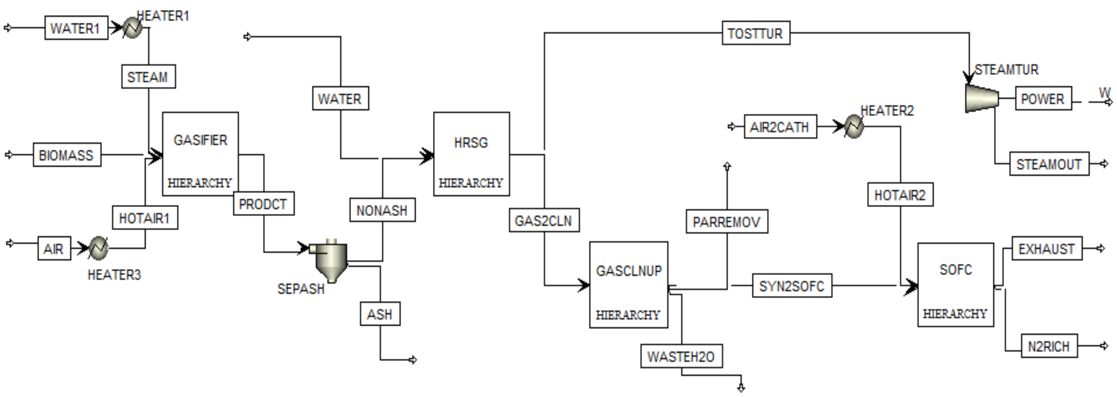

Fig.1. Aspen simulation of IGFC system.

$$P_{fc} = \frac{iA}{n_e F}\left(m - \frac{k}{RTd_1} m^2\right)$$

$$\eta_o = \frac{W_E + \Sigma Q_{TH}}{Q_{FUEL}}$$

where
P_{fc} is Fuel cell power
η_o is Fuel cell efficiency
ΣQ_{TH} is Net useful thermal outputs
Q_{FUEL} is Net energy input
W_E is Net power = Power from fuel cell + Power from turbine

$$d_1 = 2n_e sinh^{-1}\left(\frac{i}{2i_{0,a}}\right) + 2n_e sinh^{-1}\left(\frac{i}{2i_{0,c}}\right) - ln\left(1 - \frac{i}{i_{L,a}}\right) - ln\left(1 - \frac{i}{i_{L,c}}\right) + \frac{i n_e F L_{el}}{\sigma_0 R} exp\left(\frac{E_{el}}{RT}\right)$$

$$i_{0,a} = \gamma_a \left(\frac{p_{H2}}{p_0}\right)\left(\frac{p_{H2O}}{p_0}\right) \exp\left(-\frac{E_{act,a}}{RT}\right)$$

$$i_{0,c} = \gamma_c \left(\frac{p_{H2}}{p_0}\right)^{1/4} \exp\left(-\frac{E_{act,c}}{RT}\right)$$

$$m = -\Delta h^{\circ} + T\Delta s^{\circ} + RT\ln\left(\frac{p_{H2} p_{O2}^{1/2}}{p_{H2O}}\right) - RTd_1$$

Table 1. Parameters used in the SOFC model.

Parameters	**Value**
Ambient pressure (bar), p_0	1
Partial pressure of H_2 ; H_2O, $p_{H2}; p_{H2O}$	0.80 ; 0.20*
Partial pressure of O_2 ; N_2 , $p_{O2}; p_{N2}$	0.21 ; 0.79
Number of electrons participating in the reaction, n_e	2
Pre-factor for anode exchange current dinsities (A/m^2), γ_a	5.5 ×10^8
activation energy of anode (J/mol), $E_{act,a}$	1.0 ×10^5
limiting current densities of anode (A/m^2), $i_{L,a}$	2.99 ×10^4
Pre-factor for cathode exchange current dinsities (A/m^2), γ_c	7.0 ×10^8
Activation energy of cathode (J/mol), $E_{act,c}$	1.2 ×10^5
Limiting current densities of cathode (A/m^2), $i_{L,c}$	2.16 ×10^4
Thickness of electrolyte (μm), L_{el}	20
Activation energy for ion transport (J/mol), E_{el}	8.0 ×10^4
Reference ionic conductivity (S/m), σ_0	3.6 ×10^7
Ratio of the internal resistance to the leakage resistance, k	1/100
Faraday constant (C/mol), F	96485
Universal gas constant (J/mol K), R	8.314
Standard molar enthalpy change (J/mol), Δh°	-112665*
Standard molar entropy change (J/mol K), Δs°	-4.09*

* From Aspen simulation results at nominal operating conditions

Table 2. Aspen model list of each section.

Section	Aspen model list
HEATER1,2,3	Heater
GASIFIER	Sep, RGibbs, Mixer
SEPASH	SSplit
HRSG	Heater, HeatX
STEAMTUR	Compr
GASCLNUP	Flash2, Sep2
SOFC	Sep, Sep2, Mixer, RGibbs

Table 3. Composition of rice straw after primary pyrolysis/devolatilisation.

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

* Total devolatilization is amount of volatile matter (tar and volatile gases) of rice straw after pyrolysis

** Total gas is sum of volatile gas (H_2, CH_4, CO, CO_2 and H_2O) of rice straw after pyrolysis

4. Results and discussions

The objective of this work is to study operating variables that affect power performance of IGFC system. In addition, the optimal operating condition is determined for producing highest power efficiency. The operating variables and significant ranges for this study are gasifier temperature at 500-1000 ˚C, gasifier pressure at 0.5-5 bar, fuel cell temperature at 500-1000 ˚C, fuel cell pressure at 0.5-5 bar, air-to-biomass ratio at 2.0-4.0 and steam-to-biomass ratio at 0.6-2.0. The effect of operating variables to power generation (from fuel cell and steam turbine), net power generation and power efficiency is considered. The sensitivity results in Fig. 2-4 are studied at nominal conditions of 3.65 air-to-biomass ratio, 1.32 steam-to-biomass ratio, 950˚C of gasifier temperature, 800˚C of fuel cell temperature, 5 bar of gasifier pressure and 1 bar of fuel cell pressure.

4.1. Effect of air-to-biomass and steam -to-biomass ratio

The increase of air-to-biomass and steam-to-biomass ratios shows a similar tendency as Fig. 2. Gas products and their heat will increase, so steam produced from HRSG has high temperature and pressure. As a result, power generation from steam turbine has increased. In contrast, at higher air-to-biomass and steam-to-biomass ratios make the power generation from fuel cell extremely decrease because the increase of steam partial pressure and the decrease of H_2 partial pressure are inverse proportion to the fuel cell power generation (describe by electrochemical model). Net power, sum of power from steam turbine and fuel cell, and efficiency are follow the same trend with fuel cell power generation since fuel cell is the main power generation of IGFC system. However, the steam-to-biomass ratio has stronger effect than air-to-biomass ratio.

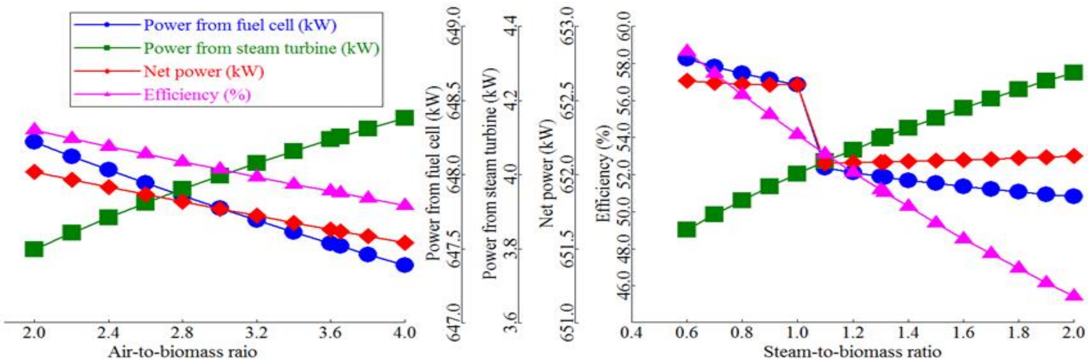

Fig.2. Sensitivity study at nominal condition of operating variables: (a) Effect of air-to-biomass ratio; (b) Effect of steam-to-biomass ratio.

4.2. Effect of gasifier and fuel cell temperature

Fig. 3 revealed that the increase of gasifier temperature hardly enhances the power generation from steam turbine but enhances power generation from fuel cell, because of the increase of hydrogen partial pressure and standard enthalpy, which are proportion to the fuel cell power generation (describe by electrochemical mode). However the increase of gasifier temperature has no significant influence on power efficiency, because the increasing of gasifier temperature requires more energy.

Moreover, the effect of fuel cell temperature and gasifier temperature quite follow the same trend but the fuel cell temperature does not affect the power generation from steam turbine. Fuel cell temperature has stronger impact to the power generation from fuel cell, because of the increase of standard molar entropy change, which are proportion to the fuel cell power generation (describe by electrochemical model). As a result, the increase of fuel cell temperature has strong influence on power efficiency.

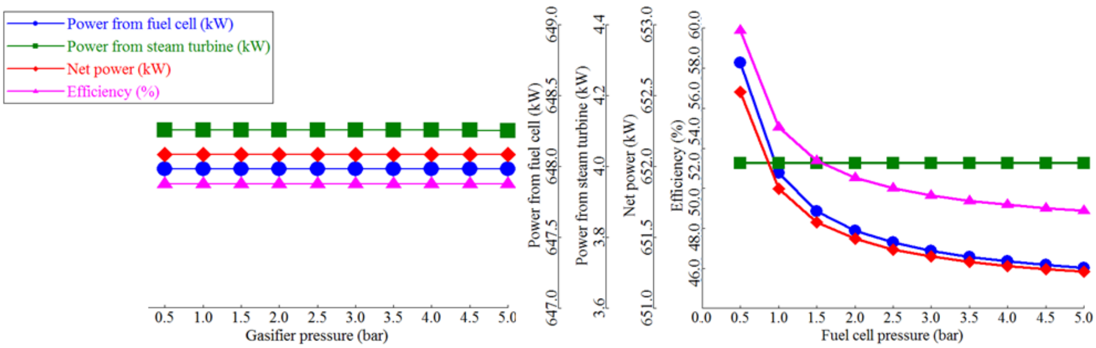

Fig.4. Sensitivity study at nominal condition of operating variables: (a) Effect of gasifier pressure; (b) Effect of fuel cell pressure.

4.4. Optimal operating condition analysis

In the optimal operating condition analysis, we consider operating variables that most affect power efficiency. So we firstly adjust steam-to-biomass ratio and adjust other operating variables to produce highest power efficiency. The optimal operating condition is showed in Table 4. At this condition, maximum fuel cell voltage, net power output and power efficiency are 0.4354 V, 651.35 kW and 59.17%, respectively.

Table 4. Optimal operating condition of IGFC system.

Operating condition	Optimal value
Air-to-biomass ratio	3.4
Steam-to-biomass ratio	0.6
Temperature of gasifier	1000
Temperature of fuel cell	1000
Gasifier pressture	1
Fuel cell pressure	0.5

5. Conclusion

This work aims to study operating variables that affect power performance of IGFC system, and to find the optimal operating conditions that produce highest power efficiency. Aspen plus is used to perform a simulation of IGFC system. This system based on 85% clean syngas utilization in the SOFC, feedstock flow rates is 205.35 kg/hr of rice straw, the NRTL method and stream type is “MIXNC” are selected for this analysis. It is assumed that the system operates under steady-state conditions, all steams are well mixed. Moreover, in fuel cell is assumed that all of reacting species in syngas are considered as H_2.

Simulation results indicated that optimal operating conditions that produce highest power efficiency are 3.4 of air-to-biomass ratio, 0.6 of steam-to-biomass ratio, 1000 ˚C of temperature of gasifier, 1000 ˚C of fuel cell temperature, 1 bar of gasifier pressure, 0.5 bar of fuel cell pressure. This condition can generate 651.35 kW of net power output and 59.17% of power efficiency.

6. Acknowledgement

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7. References

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