CHEMICAL ENGINEERING TRANSACTIONS

VOL. 43, 2015

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Chief Editors: Sauro Pierucci, Jiří J. Klemeš

ISBN 978-88-95608-34-1; **ISSN** 2283-9216

DOI: 10.3303/CET1543251

Performance Improvement of Biomass Gasification and PEMFC Integrated System–Design Consideration for Achieving High Overall Energy Efficiency and Power-to-Heat Ratio Variation

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A proton exchange membrane fuel cell (PEMFC) has received considerable attention as an alternative power generation device. Using biomass to produce hydrogen via a gasification process makes the integrated system of the PEMFC and biomass gasification a potential power production technology. In this study, the performance of the biomass gasification and PEMFC system is theoretically analyzed. Two important operational issues of the system, i.e., waste heat recovery and response to variation in power-to-heat ratio, are considered. The capacity of the PEMFC system is selected to cover a daily residential power demand of 100 kW. In the proposed system, useful heat from the biomass processing and PEMFC is recovered for use in space heat or water heating in household. The simulation result shows that the PEMFC stack efficiency of the proposed system is around 47 to 57 %. The efficiency of the combined heat and power system is in range of 68 to 93 %, which is based on biomass input energy and recovered heat from the exhaust gas released from an afterburner. In addition, it is found that a regulation of the flow rate of biomass to the gasifier and afterburner is a key parameter in the PEMFC-based system to achieve the system requirement when the power-to-heat ratio is changed. The result indicates that the power-to-heat ratio of the designed system varies from 0.06 to 0.75.

1. Introduction

In the past decades, the power generation based on a fuel cell technology has been received a tremendous attention due to its high efficiency, compared to a conventional thermal power plant. A proton exchange membrane fuel cell (PEMFC) is one of the main types of fuel cells. It is operated at low temperatures and provides a cleaner choice for power generation via the electrochemical reaction between H_2 and O_2. Although PEMFC produces only water and heat as byproducts, a H_2 production process involves CO_2 emissions in some extents (Authayanun et al., 2013). Recently, use of renewable resources (i.e., biomass) as H_2 sources becomes more interesting.

Gasification process is the efficient way to convert biomass into H_2-rich gas with the lower amount of greenhouse gas emission (Figueroa et al., 2013). Syngas produced from the biomass gasification is mainly included H_2 and CO. When using steam as a gasifying agent, the syngas heating value is around 10-20 MJ/Mm^3 while the H_2 concentration is 30-60 vol. % (Mathieu and Dubuisson, 2002). The syngas with this H_2 concentration range is possible to be used as a fuel for fuel cell (Puala et al., 2013). However, steam gasification is an extremely endothermic process. To operate gasifier at self-sustainable operation, additional heat has to be applied to the gasifier in order to undergo the gasification reactions (Chutichai et al., 2013). Basically, a CO removal step is necessary to treat the syngas from the gasifier for PEMFC applications because PEMFC catalysts have the very low tolerance to the CO level in a fuel gas (Postole and Auroux, 2011).

Please cite this article as: Chutichai B., Arpornwichanop A., 2015, Performance improvement of biomass gasification and pemfc integrated system: design consideration for achieving high overall energy efficiency and heat to power ratio variation, Chemical Engineering Transactions, 43, 1501-1506 DOI: 10.3303/CET1543251

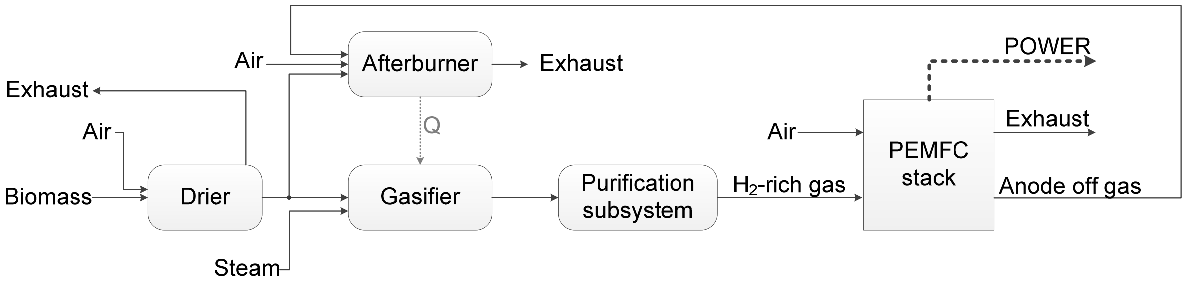

Figure 1: Schematic diagram of the biomass gasification and PEMFC integrated system

For the station power generation like the biomass gasification and PEMFC integrated system, it has the ability to generate both heat and power simultaneously (combined heat and power (CHP) system) without dependence on the grid which allows for better fuel management (Francios et al., 2012). One of the major advantages of the fuel cell-based CHP system over other power generation technologies is ability to response to the rapid change in power and heat demands (Colella, 2003).

The parameter corresponding to the electric and thermal power produced in the CHP system is the power-to-heat ratio (Savola and Fogellholm, 2006). High power-to-heat ratio means the CHP system has a fast response to the energy demand with high fuel efficient. An ability to regulate the power-to-heat ratio that leads to higher total system efficiency also results in lower pollutant emissions. The effective way to achieve the goal of a variable power-to-heat ratio is to vary the amount of solid biomass in the H_2 production process to alter the amount of the fuel feeding to the PEMFC (Colella, 2002).

In this study, the biomass gasification and PEMFC integrated system performance is evaluated, considering the heat and combined power approach. The goal of this study is to investigate the ability of this PEMFC-based system to regulate the power-to-heat ratio and to analyze the effect of primary parameters of power production on the system energy efficiency. The biomass gasification and PEMFC integrated system is simulated via a commercial process simulator, Aspen Plus®. To regulate the power-to-heat ratio, the ratio of reactants flowing to the fuel cell is varied.

2. Process description

In this study, a PEMFC-based cogeneration of heat and power with variation in a heat-to-power ratio is proposed. The integrated system of biomass gasification and PEMFC consists of three main parts: (1) H_2 production, (2) PEMFC stack and (3) afterburner. The H_2 production process including a biomass gasification and a purification process converts solid biomass into H_2-rich gas.

Figure 1 shows a schematic diagram of the biomass gasification and PEMFC integrated system. Biomass used in the simulation is sawdust. Proximate analysis shows that it contains 79.5 wt.% of volatile matter, 16.8 wt.% of fixed carbon and 3.7 wt.% of ash. Ultimate analysis indicates that it includes 45.8 wt.% of carbon, 6.7 wt.% of hydrogen, 0.1 wt.% of nitrogen and 47.4 wt.% of oxygen. Wet solid biomass is dried in a drier to reduce a moisture using hot air. The moisture content of the biomass leaving the drier is set to 5 wt.% (Doherty et al., 2009). Biomass is then split into two streams for H_2 production process and heat production in a burner. Regarding the H_2 production process, biomass is fed into the gasifier to react with steam to generate H_2-rich syngas. Gasifier is operated at temperature of 700 °C and atmospheric pressure. The steam-to-biomass ratio is unity based on mass flow rate of biomass fed into gasifier. Carbon loss is assumed to be 2 wt.% of input biomass (Li et al., 2004). Syngas produced from this step mainly contains H_2, CO, CO_2, CH_4 and steam. Due to the poisoning effect of CO on the PEMFC catalyst, CO has to be removed and its concentration has to be less than 10 ppm (Postole and Auroux, 2011). The purification process consists of two water-gas shift reactors: high- and low-temperature water gas shift (HTS and LTS) reactors. These reactors not only reduce the CO concentration but also enhance the H_2 production. Preferential oxidation reactor is also employed as the concentration of H_2 leaving the water-gas shift reactors is still higher than an acceptance level. A cooling unit is applied to control the inlet gas temperature of each purification unit. The efficiency of the H_2 production process is equal to 83 %, based on the energy in H_2 produced to the energy in biomass fed into the gasifier (Chutichai et al., 2013). The produced H_2-rich gas is then used as a fuel for electricity production via PEMFC.

PEMFC stack generate electricity (and heat) via the electrochemical reactions between H_2 and O_2. PEMFC is run at temperature of 80 °C and atmospheric pressure. Electricity production is designed to cover the energy demand for residences at 100 kW (full load). The nominal voltage and current density are approximately 0.7 V and 200 mA/cm^2, respectively (Chutichai et al., 2012). Oxygen utilization is set to be 50 % while fuel utilization

Table 1: Operating parameters

Gasifier		
Gasifier operating pressure	1	bar
Gasifier operating temperature	700	°C
Carbon Conversion (Li et al., 2004)	98	%
Gasifying agent	steam	
Steam temperature	200	°C
Steam-to-biomass ratio (Chutichai et al., 2013)	1	
Purification subsystem		
Reactors operating pressure	1	bar
HTS operating temperature	400	°C
LTS operating temperature	200	°C
PROX operating temperature	120	°C
PROX O_2/CO ratio	1.5	
Proton Exchange Membrane Fuel Cell (PEMFC)		
PEMFC operating pressure	1	bar
PEMFC operating temperature	80	°C
Number of cell	500	Cells
Area	0.14	m^2/cell
Fuel utilization	80	%
Oxygen utilization	50	%
Power production (full load)	100	kW
Nominal operating voltage	0.7	V/cell
Afterburner		
Afterburner operating pressure	1	bar
Afterburner operating mode	adiabatic	

is at 80 %, meaning that there is unreacted-H_2 leaving the stack and it can be combusted in an after burner to generate useful heat.

Considering the second stream of biomass which is used as a fuel in the afterburner, this fuel is co-fired with unreacted H_2 from the PEMFC to produce useful heat at atmospheric pressure. Heat generated from the afterburner is supplied to the endothermic gasification reactions in the gasifier via the flue gas. If the heat supplied to the gasifier is sufficient for achieving its self-sustainable conditions, the excess heat is considered as the useful heat that can be recovered for water or space heating applications. The system operating conditions of each unit are given in Table 1.

As mentioned above, the input biomass is divided into two streams: one is for the electricity production and the other is for the heat production. To manage the power-to-heat ratio, the biomass feeding ratio is varied in response to a change in the individual energy demands.

3. Results and discussion

The biomass gasification and PEMFC integrated system is analyzed. The power-to-heat ratio of the system is varied owing to a change in the split fraction of biomass feed. When the power-to-heat ratio is changed, the amount of H_2 fed into PEMC is also changed, affecting the ability to produce syngas, electric power and thermal power of the system.

The expressions of the energy efficiency related to the combined heat and power PEMFC-based system are defined as follows:

$$\eta_{PEMFC} = \frac{\text{electrical energy produced from PEMFC (kW)}}{\text{energy in } H_2 \text{ fed in PEMFC (kW, LHV basis)}} \quad (1)$$

$$\eta_{s} = \frac{\text{energy in syngas produced from } H_2 \text{ production step (kW)}}{\text{energy in biomass (kW, LHV basis)}} \quad (2)$$

$$\eta_{h} = \frac{\text{net useful thermal power (kW)}}{\text{energy in biomass (kW, LHV basis)}} \quad (3)$$

$$\eta_e = \frac{\text{net electric power (kW)}}{\text{energy in biomass (kW, LHV basis)}} \quad (4)$$

$$\eta_{total} = \eta_e + \eta_h \quad (5)$$

3.1 Power-to-heat ratio

In this study, the ratio of biomass and gasifying agent that fed into gasifier is varied to enhance the amount of H_2-rich gas producing and flowing to the fuel cell stack in response to a variation in the power-to-heat ratio. The amount of useful heat from the afterburner is also affected by varying this biomass ratio. For instance, during a period of high thermal demand, a greater fraction of the biomass is intentionally combusted to produce a varying level of thermal energy relative to the total energy output of the system. The afterburner is also used to combust the anode off gas from PEMFC.

The biomass split fraction is defined as the mass fraction of biomass utilized as H_2 source and the biomass utilized as afterburner fuel. High biomass split fraction results in the more H_2 and electricity produced; therefore, the power-to-heat ratio of this system is enhanced as shown in Figure 2. At the design condition, the biomass split fraction is around 0.87 where 100 kW of electricity is produced and the power-to-heat ratio is equal to 0.75. The ideal burner of this method would have a huge turndown ratio to handle with a large variation in fuel flow rates (Colella, 2003). The result shows that by varying the biomass split fraction between 0.14 and 0.87, the power-to-heat ratio is regulated in range of 0.06 to 0.75.

3.2 Performance of PEMFC stack

Performance of the PEMFC is defined as an ability of the stack to convert energy in H_2 into electricity as shown in Eq(1). Figure 3 shows that the PEMFC stack efficiency (η_{PEMFC}) is directly related to the power production and cell potential. Since the PEMFC is designed to generate 100 kW of electricity (full load), changing the power production means changing the operating point in the polarization curve. At a higher current density operation, the higher potential losses are distinguished resulting in the reduction in cell potential. An increase in the power production by increasing the operating current density leads to a decrease in the cell potential (Figure 3). Additionally, the greater power production level results in the lower PEMFC efficiency. This means, for the certain amount of power produced, the fuel cell stack generates electricity with high efficient at significantly a lower power output. For the power production in range of 20 to 100 kW, cell potential varies from 0.7 to 0.85 V while the PEMFC efficiency is 47 to 57 %.

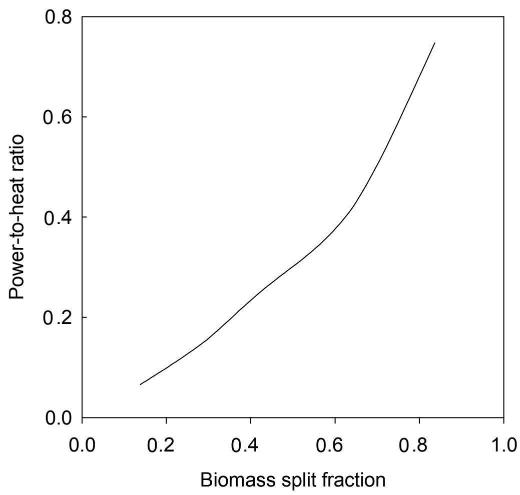

Figure 2: Power-to-heat ratio of the biomass gasification and PEMFC system

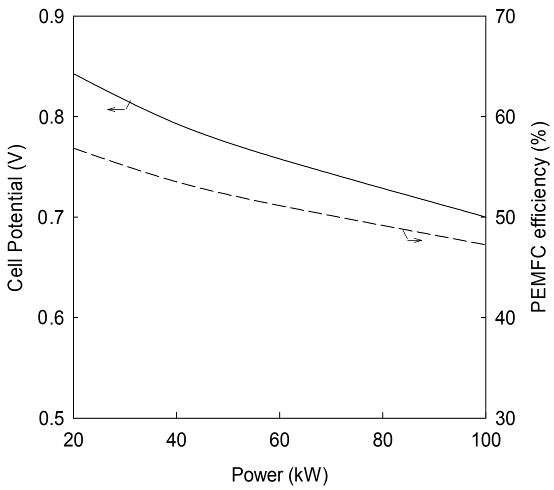

Figure 3: Effect of power production on cell potential and PEMFC efficiency

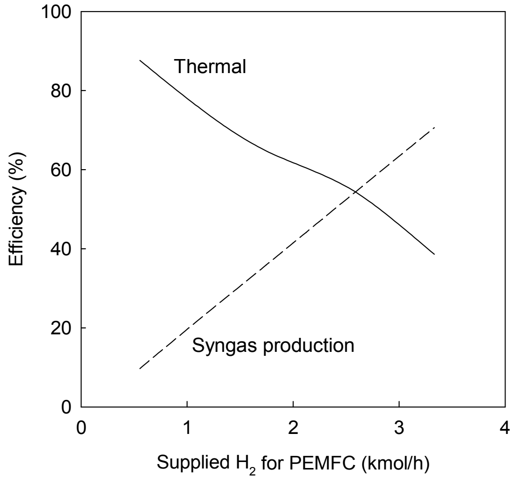

Figure 4: Effect of supplied H_2 for PEMFC on syngas production efficiency and thermal efficiency

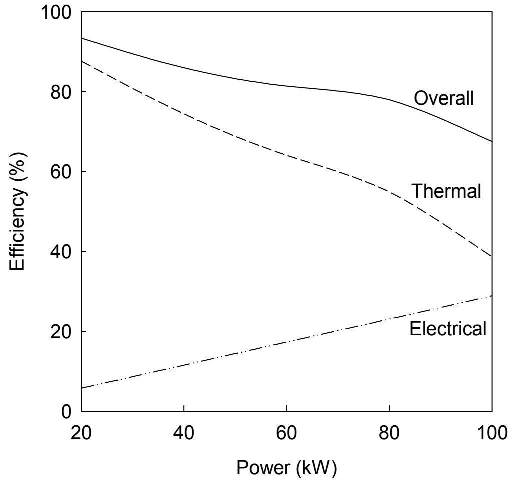

Figure 5: Electric, thermal and total efficiency of the integrated system

3.3 Hydrogen production

The simulation results reveal that syngas produced from gasifier contain 61 mol% of H_2, 18 mol% of CO, 20 mol% of CO_2 and trace of CH_4 and impurities (dry basis) with the heating value of 10.59 MJ/Nm^3. After the purification steps, the H_2-rich gas produced from H_2 production process contains 67 mol% of H_2. The heating value of the H_2-rich gas is around 10.27 MJ/Nm^3 (a medium quality gas). Using steam as a gasifying agent not only adds more hydrogen source into the gasifier but also shifts the reaction between carbon and steam to produce more H_2.

Syngas production efficiency (η_s) represents the system ability to convert energy in solid biomass into energy in synthesis gas (Eq(2)). Thermal efficiency (η_h) is calculated from the net useful thermal energy released from the system divided by net energy of input biomass (Eq(3)). Both the syngas production efficiency and the thermal efficiency are directly related to the amount of H_2 flowing into fuel cell stack as shown in Figure 4. The more H_2 is required, the more biomass is converted into power. On the other hand, the net thermal power decreases with an increase in H_2 production rate because less biomass is fed into afterburner to generate heat. In this study, PEMFC requires H_2 of 0.55 to 3.33 kmol/h to generate the electric power of 20 to 100 kW. Syngas production is in range of 10 to 71 % while thermal efficiency is in range of 39 to 88 %

3.4 Energy efficiency of integrated system

Electric efficiency (η_e) represents an ability of the system to convert energy in biomass into electric power (Eq(4)). The performance of combined heat and power system is defined by the total efficiency (η_{total}), which is the net useful power (i.e. electric and thermal power) produced from the system divided by the input biomass energy (Eq(5)). It is illustrated in Figure 5 that a change in power production has an effect on the system performance. The electrical efficiency is increased with increasing the power production because a greater amount of energy in biomass is converted into electricity to meet the power demand. On the other hand, the thermal efficiency is affected by a change in power production because less biomass is combusted. In addition, although increasing power production may imply that more unreacted H_2 flows into afterburner and then be oxidized, the thermal energy released owing to the anode off gas combustion is still low and does not have a strong effect on thermal efficiency. Consequently, the thermal efficiency declines faster than an inclination of the electric efficiency. The system performance is likely to drop when the power production increases because the system produces heat with less efficient.

4. Conclusions

This study shows that the biomass gasification and PEMFC integrated system is the effectively combined heat and power (CHP) generation system. A power-to-heat ratio is the parameter indicating the ability to response to the rapidly change in energy demand. The CHP system with a wide range of the power-to-heat ratio consumes fuel more efficient. The power-to-heat ratio can be controlled by varying the amount of biomass feeding to the power generation section. The result indicates that this PEMFC-based system has the power-to-heat ratio in a range of 0.06 to 0.75. The power produced from the proposed system is between 20 to 100 kW with the system electric efficiency of 6 to 29 %. Biomass and unreacted H_2 is used as fuel and combusted in the afterburner where thermal energy is mainly generated. The total efficiency of this system is around 68 to 93 %.

Acknowledgements

The support from the Thailand Research Fund and the Ratchadaphiseksomphot Endowment Fund of Chulalongkorn University is gratefully acknowledged.

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