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Analysis of Biomass Gasification and PEMFC Integrated Systems for Power Generation: A Combined Heat and Power Approach

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A proton exchange membrane fuel cell (PEMFC) is expected to play a significant role in the next energy generation system. The purpose of this study is to evaluate the performance and the feasibility of an alternative combined heat and power (CHP) system based on biomass gasification and PEMFC processes for residential applications satisfying thermal and electrical demands. A model of the integrated CHP system is employed to analyze its performance under different operating conditions. The system is designed for the electrical load of 5 kW. The simulation results show that the gasification process can produce the synthesis gas having the hydrogen content of around 25-35 mol.% and the high heating value of 4-10 MJ/Nm^3. A purification process consisting of a water gas shift reactor and a preferential oxidation reactor is also necessary in order to reduce the concentration of CO in the synthesis gas to be lower than 10 ppm for PEMFC. The useful heat in the high-temperature synthesis gas derived from the gasifer is recovered and used in the purification step and thus the efficiency of the fuel processor is enhanced. Effect of a load level on the performance of PEMFC is investigated. The results of the system evaluation indicate that the total efficiency of the PEMFC-based cogeneration system is 92 % and the electrical efficiency is 22 %.

1. Introduction

Since a traditional power and heat generation uses fossil fuel and causes environmental problems, a more practical cogeneration system has been being developed. Fuel cell is one of the potential and attractive technologies that offer the prospect for a combined heat and power (CHP) system. Power generation by fuel cells is clean because water and heat are only the products from the electrochemical reaction of hydrogen and oxygen. However, this green energy system can be realized when the raw material used for hydrogen production is renewable.

Biomass gasification is a promising process to directly convert biomass, a renewable resource, into hydrogen-rich gas. Using steam as a primary gasifying agent seems to be effective because the synthesis gas produced has the high heating value (HHV) of around 10–20 MJ/m^3 and contains 30-60 vol.% H_2 (Mathieu and Dubuisson, 2002). However, the required heat input owning to an endothermic gasification reaction is a major drawback of the steam gasification. In practical, an air-steam gasification can be applied to solve such a problem by partial combustion of biomass with air, but the

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product gas obtained from this process has a lower amount of H_2 (10-25 vol.%) and lower HHV of 4-10 MJ/m^3 and is diluted by nitrogen in air (Mehrdokht and Mahinpey, 2008).

In view of a small CHP system utilized for residential application which requires low temperature heat loads, a proton exchange membrane fuel cell (PEMFC) is suitable for this application. It provides high electrical efficiency, high reliability and high flexibility of a load following system. The PEMFC based cogeneration system has higher efficiency than the traditional power generation because heat and electricity are generated and utilized closer to user. Various studies on PEMFC systems have been conducted during the past decades. The chemical and thermodynamic aspects of PEMFC electrical characteristics were studied by Yan et al. (2006) and Moreira and Silva (2009). Even the design and the analysis of fuel cell-based CHP systems are subjects of interest (Gencoglu and Ural, 2009; Oh et al., 2012), the study on a PEMFC system integrated with a biomass gasification is quite limited.

The aim of this study is focused on the performance evaluation of biomass gasification and PEMFC integrated system to generate thermal energy and electricity for a residential application. A model of the PEMFC integrated system is developed and employed to investigate its performance with respect to key operating parameters. The system is designed for a fixed electrical load of 5 kW that covers a power demand for residential applications, including electrical auxiliary facilities and recoverable heat for general usage.

2. System Description

Figure 1 shows a schematic diagram of the biomass gasification and PEMFC integrated system, which consists of three sections: (1) a fuel processor to convert biomass into a H_2-rich gas, (2) the PEMFC stack to generate electricity from the electrochemical reaction of hydrogen and oxygen. This system is designed to produce 5 kW of electrical power.

2.1 Fuel Processor

A fuel processor is the largest section of the whole PEMFC system due to a complexity of the fuel conversion process including the purification process of a hydrogen fuel for PEMFC. The fuel processor comprises three major units: (1) a biomass gasifier which converts biomass into H_2-rich gas, (2) high and low temperature water-gas shift reactors (HTS and LTS) where CO is removed by reacting with steam to produce CO_2 and additional H_2 and (3) a preferential oxidation reactor (PROX) where the remaining CO in the H_2 feed is reduced to an acceptable level for PEMFC applications (< 10 ppm).

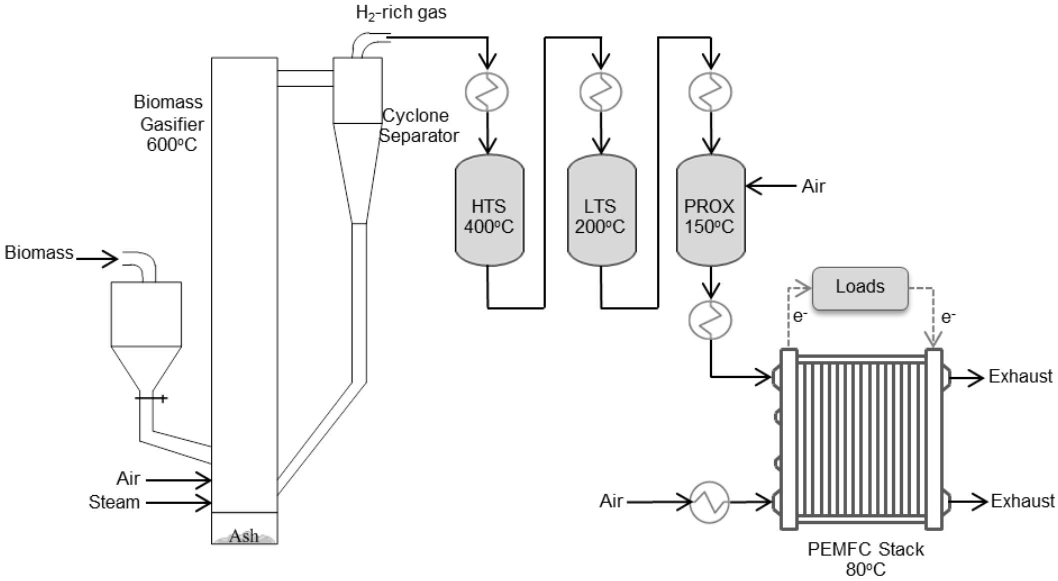

Figure 1: Schematic diagram of the biomass gasification and PEMFC integrated system.

Table 1: Gasification Reactions

Biomass gasification		
Heterogeneous reactions:		
Char partial combustion	$C + 0.5O_2 \leftrightarrow CO$	ΔH^0_{298} = -111 kJ/mol
Boudouard	$C + CO_2 \leftrightarrow CO$	ΔH^0_{298} = +172 kJ/mol
Water-gas	$C + H_2O \leftrightarrow CO + H_2$	ΔH^0_{298} = +131 kJ/mol
Methanation	$C + 2H_2 \leftrightarrow CH_4$	ΔH^0_{298} = -75 kJ/mol
Homogeneous reactions:		
CO partial combustion	$CO + 0.5O_2 \leftrightarrow CO_2$	ΔH^0_{298} = -283 kJ/mol
H2 partial combustion	$H_2 + 0.5O_2 \leftrightarrow H_2O$	ΔH^0_{298} = -242 kJ/mol
Water-gas shift	$CO + H_2O \leftrightarrow CO_2 + H_2$	ΔH^0_{298} = -41 kJ/mol
Steam-methane reforming	$CH_4 + H_2O \leftrightarrow CO + 3H_2$	ΔH^0_{298} = +206 kJ/mol
Water-gas shift reactor (HTS, LTS)		
Water-gas shift	$CO + H_2O \leftrightarrow CO_2 + H_2$	ΔH^0_{298} = -41 kJ/mol
Preferential oxidation reactor (PROX)		
CO oxidation	$CO + 0.5O_2 \leftrightarrow CO_2$	ΔH^0_{298} = -283 kJ/mol
PEMFC stack		
Anode	$H_2 \rightarrow H^+ + 2e^-$	
Cathode	$0.5O_2 + H^+ + 2e^- \rightarrow H_2O$	
Overall	$H_2 + 0.5O_2 \rightarrow H_2O$	ΔH^0_{298} = -286 kJ/mol

Table 2: Biomass Composition

Material	Proximate Analysis (wt.%)				Ultimate Analysis (wt.%)				HHV
	MC	VM	ASH	FC	C	H	O	S	(MJ/kg)
Sawdust	6.11	79.5	3.7	16.8	45.76	6.74	47.42	0.08	18.47

Table 3: Design specification and operation conditions of PEMFC stack

Number of cell	50 cell	Operating temperature	80 °C
Area	0.072 m^2/cell	Operating pressure	1 atm
Electric power	5 kW	Fuel utilization	80 %
Thermal power	7.7 kW	Oxygen utilization	50 %
Operating voltage	0.7 V/cell		

In this study, chemical equilibrium, steady state condition, zero-dimensional model and uniform temperature are assumed. The composition of the product gas from the gasifier, water gas shift reactor and preferential oxidation reactor, which consists of H_2, CO, CO_2, CH_4 and H_2O, is determined from the minimisation of the Gibbs free energy using a flowsheet simulator Aspen Plus.

The reactions taking place in the biomass gasification are shown in Table 1. The model of the biomass gasification is derived from the study of Doherty et al. (2009) coupled with experimental data of Li et al. (2004). It is assumed that the sulphur is reacted to form H_2S. The residue carbon loss in ash is 2 % and heat loss from the gasifier is equal to 3 % of heat input. The efficiency of the cyclone separation is

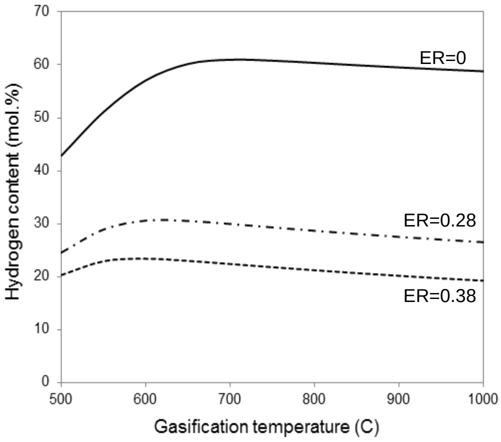

Figure 2: Effect of equivalence ratio (ER) on H_2 content in biomass gasification.

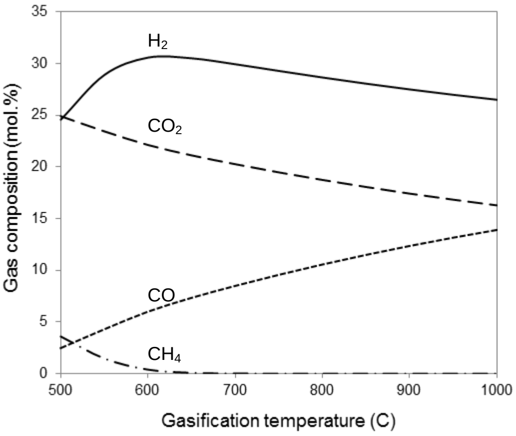

Figure 3: Effect of gasification temperature on product gas composition at ER=0.28.

85 % as reported by Zhang and Basu (2004). The input parameters of biomass are given in Table 2. The water gas shift reaction is occurred in the HTS and LTS reactors where CO in the product gas from the biomass gasifier is further reacted with steam to form H_2 and CO_2. The CO selective reaction is taken place in the PROX reactor. Here methane is treated as an inert along the purification steps.

2.2 PEMFC stack

PEMFC is a power generator device which converts the chemical energy in hydrogen into electric power via an electrochemical reaction as shown in Table 1. The electrochemical model of PEMFC proposed by Yan et al. (2006) is used in this study. Table 3 shows the specification and operating conditions of the PEMFC stack. All cells in the stack are connected in series and have the same electrical characteristics. Constant temperature and pressure operation is assumed. The hydrogen obtained from the biomass gasification is employed as a fuel for PEMFC to generate electricity.

3. Results and Discussion

3.1 Effect of temperature and ER on product gas composition

Simulation of the biomass gasification process is performed to investigate effect of key operating parameters such as gasification temperature, steam-to-biomass ratio (S/B), equivalence ratio (ER), and pressure. The ER is defined as the ratio of air fed into the gasifier to the stoichiometric amount of air required for a complete combustion. The results show that the most important parameters affecting the product gas composition are the gasification temperature and equivalence ratio (ER). When steam is only employed as a gasifying agent (ER = 0), the gasifier requires the highest energy supply. The introduction of air to the gasifier reduces the heat input. It is found that the gasifier can be operated without the requirement of an external heat at the ER of 0.38; heat obtained from the combustion of biomass and air is sufficient to supply for the biomass gasification process. However, H_2 content is reduced 20-30 % at this condition, as shown in Figure 2.

Effect of gasification temperatures on the product gas composition is shown in Figure 3. As the purpose of this unit is to produce the H_2-rich gas, the optimal operating temperature is in a range of 550-600 ^oC when the gasifier is run at the ER of 0.28. Under these conditions, the synthesis gas obtained contains H_2 around 28-32 mol.% and has the HHV of 5.0 MJ/Nm^3. However, high content of CO is observed (20-26 mol.%). Since the CO concentration in the product gas is over the operational constraint of the PEMFC, the product gas is further treated by the water-gas shift reactor (HTS and LTS) and the CO preferential oxidation reactor (PROX). The final product gas composition, which will be fed into the PEMFC stack, is indicated in Figure 4; it contains 30 mol.% H_2 and less than 10 ppm of CO.

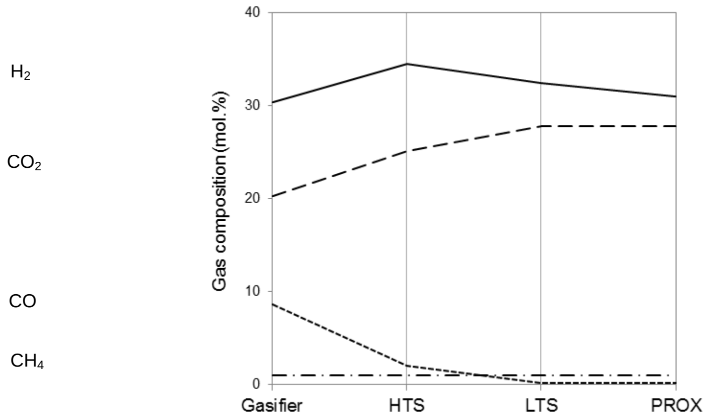

Figure 4: Gas composition at the outlet of gasifier, HTS, LTS and PROX.

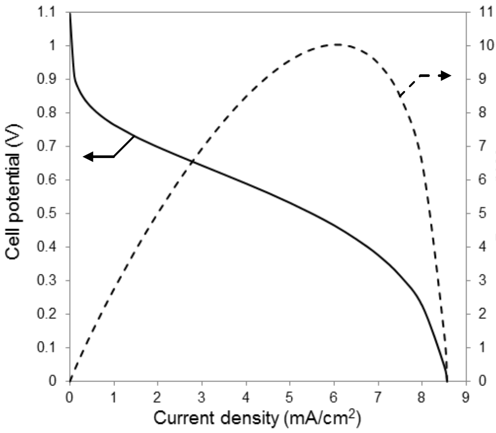

Figure 5: Polarization curve of PEMFC.

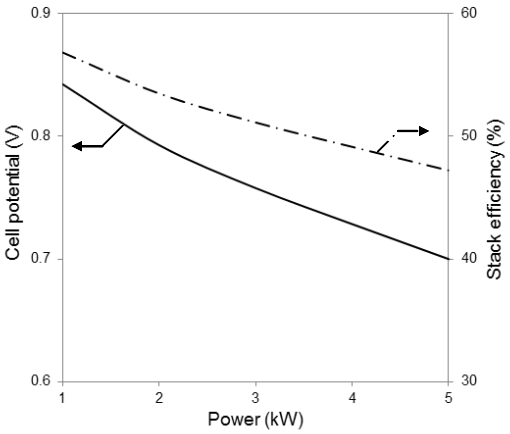

Figure 6: Effect of load level on PEMFC.

3.2 PEMFC Performance

The electrical characteristics of PEMFC are shown in Figure 5. The polarization curve shows the effect of internal losses in fuel cell as a function of load level. At the design condition where the PEMFC is operated at 0.7 V, it is found that the generated current density is equal to 1.98 mA/cm^2 and 5 kW of electrical power is produced. Since the fuel cell stack efficiency is directly proportional to the fuel cell potential, a decrease in the load level results in an increase in the fuel cell potential and stack efficiency as illustrated in Figure 6. At the design condition of 5 kW, the stack efficiency is 47.23% based on the energy of the synthesis gas fed to the PEMFC stack.

3.3 Efficiency of PEMFC System

An efficiency of the biomass gasification and PEMFC integrated system is analyzed. The power and heat generated by the PEMFC system are considered. It is found that under the optimal operating conditions as discussed above, the PEMFC system has the total efficiency of 92 % (total useful power and thermal energy) based on the HHV of biomass and the electrical efficiency of 22 %, as reported in Table 4. The thermal energy obtained from the PEMFC system is found to be a low grade heat, which can be utilized in a space heating.

Table 4: Efficiency of the biomass gasification and PEMFC integrated system

Total efficiency	91.87 %
Electrical efficiency	21.73 %
Thermal efficiency	70.15 %
PEMFC stack efficiency	47.23 %
Fuel processor efficiency	57.50 %

4. Conclusions

In this study, a biomass gasification and PEMFC integrated system was proposed for combined heat and power cogeneration. Simulations of the PEMFC system were performed to analyze the effect of operating parameters on its performance. The biomass gasification was coupled with a water-gas shift reactor and preferential oxidation reactor to purify a synthesis gas obtained from the gasifier. It was found that when the gasifier is operated the optimal operating temperature of 550-600 ^{o}C and the ER of 0.28, the synthesis obtained contain 30 mol.% of H_2 with the efficiency of 57%. The PEMFC stack generates electricity and low grade heat with the efficiency of 47-60 %. The total efficiency of the PEMFC system is around 92 %. The biomass gasification and PEMFC integrated system is an attractive way to produce clean power and heat for residential application with high efficiency.

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