Simulation of Biomass Gasification with Proton Exchange Membrane Fuel Cell System

W. Mungkalasiri and J. Mungkalasiri

***Abstract*—The rapid growth increases the threat of global climate change. Biomass is a potential alternative to fossil fuel due to environmentally friendly fuel source. Therefore, power generation from biomass gasification integrated with fuel cell system is studied in this work. The objectives are to determine the amount of biomass feed needed to produce power output of 50 kW and the optimal operating conditions of both gasification process and proton exchange membrane (PEM) fuel cell. The power output of the system is targeted in order to determine the amount of hydrogen required for the PEM fuel cell. The operating conditions of PEM fuel cell are varied in terms of temperature, pressure, and relative humidity (RH). The amount of hydrogen is used to determine the amount of feed required via the biomass gasification modeled by the Aspen plus programs. The parameters that are studied include gasifier temperature, air to biomass ratio, and steam to biomass ratio. The results shown that optimal operating conditions of PEM fuel cell (50 kW) are 120°C, 3 atm and 100%RH and the hydrogen required is 2.320 kg/hr, whereas the optimal operating conditions of biomass gasification are 800°C gasifier temperature, 2.0 air to biomass ratio, and 2.0 steam to biomass ratio with biomass feed of 27.641 kg/hr**.

***Index Terms*—Biomass gasification, power generation, process simulation, proton exchange membrane fuel cell.**

I. Introduction

Most countries in the world have reduced amounts of domestic fossil fuel sources, especially coal, on the contrary to biomass. Biomass has been and will be one of the most significant renewable sources of energy because of its abundant and relatively low price compared to other energy sources. Moreover, biomass is a clean energy carrier as it produces no net emission of CO_2 when it is operated sustainably [1], [2]. As a result, biomass is converted to hydrogen via gasification process, then the hydrogen is further converted to energy by the use of certain technologies [3].

A fuel cell is acknowledged as one of the most promising energy systems and main bases for power sources since it can be integrated into a wide variety of applications. It is a leading candidate for power generation, due to its low pollution, simplicity in system design, environmentally friendly behavior, high efficiency and absence of moving parts. Among all widely known fuel cell types, proton exchange membrane (PEM) fuel cell is most seen as a potential backup technology for hybrid cars and spare power units [3], [4].

Manuscript received September 8, 2018; revised November 21, 2018.

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This study aims to investigate the characteristics of biomass gasification integrated with a PEM fuel cell by simulating the process, which is accomplished through the development of Aspen Plus process simulation program. The objectives are to determine the optimal amount of biomass (rice straw) required for the biomass gasification process and the amount of hydrogen required for the PEM fuel cell system of 50 kW. Moreover, determine the optimal conditions in terms of gasifier temperature, air to biomass ratio and steam to biomass ratio for the biomass gasification process and temperature, pressure and relative humidity for the PEM fuel cell system for 50 kW of power production.

II. Theory

A. Biomass Gasification

The production of generator gas (producer gas) called gasification, is partial combustion of solid fuel (biomass) and takes place at temperature of about 1000°C [5]. The reactions taking place in the gasifier can be summarized as

Partial oxidation: $C + 1/2O_2 \leftrightarrow CO$ (-268 MJ/kg mole)

Complete oxidation: $C + O_2 \leftrightarrow CO_2$ (-406 MJ/kg mole)

Water gas reaction: $C + H_2O \leftrightarrow CO + H_2$ (+118 MJ/kg mole)

Boudouard reaction: $C + CO_2 \leftrightarrow 2CO$ (-169 MJ/kg mole)

Water gas shift reaction: $CO + H_2O \leftrightarrow CO_2 + H_2$ (- 42 MJ/kg mole)

Methane formation: $CO + 3H_2 \leftrightarrow CH_4 + H_2O$ (- 88 MJ/kg mole)

B. Fuel Cell

A fuel cell is a device that generates electricity from a fuel by a chemical reaction. Every fuel cell has two electrodes, the anode and cathode, and an electrolyte, which carries electrically charged particles from one electrode to the other. There are six types of fuel cell that have emerged as viable systems for the present and near future. The applications and advantages on each type of fuel cells are shown in Fig. 1.

C. Proton Exchange Membrane Fuel Cell

PEM fuel cells operate at relatively low temperatures (below 100°C). Due to the relatively low temperatures and the use of precious metal-based electrodes, these cells must operate on pure hydrogen. PEM fuel cell cells are currently the leading technology for light duty vehicles and materials handling vehicles, and to a lesser extent for stationary and

doi: 10.18178/ijcea.2018.9.6.725

other applications.

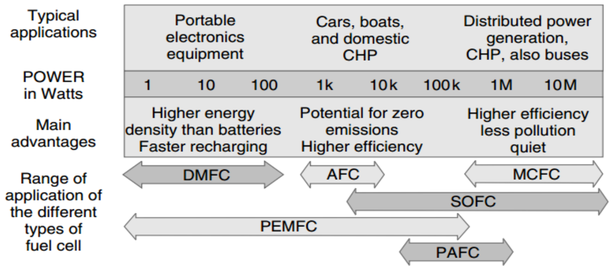

Fig. 1. Summary on the applications and main advantages of fuel cells of different types and in different applications [6].

The main advantage of PEM fuel cells is their high efficiency compared with other energy conversion devices. Another important advantage of PEM fuel cell, in contrast to other types of fuel cells, is the low operating temperature, allowing it to reach the operation point quickly. In addition, the cost of the materials is lower than for the high temperature fuel cells and their operation is safer. All these characteristics make PEM fuel cells particularly appropriate for applications in vehicles [7]. However, the main disadvantage of fuel cells is their high cost and the high production cost of hydrogen.

III. Methodology

In this work, an integrated system of biomass gasification with PEM fuel cell has been studied by process simulation and mathematical model calculation. Biomass gasification process is developed by the Aspen simulation program as shown in Fig. 2.

The mathematical model for the PEM fuel cell voltage and power density [8] are

$$V = V_{ref} + \Delta V_T + \Delta V_P + \Delta V_{RH} \quad (1)$$

in which all of the variables are functions of current density (I).

$$V_{ref} = 6.2173{\cdot}10^{-10}{\cdot}I^3 + 9.4139{\cdot}10^{-7}{\cdot}I^2 - 9.4002{\cdot}10^{-4}{\cdot}I + 0.8508 \quad (2)$$

$$\Delta V_T = (2.8904{\cdot}10^{-6}{\cdot}T - 3.5254{\cdot}10^{-4}) \cdot I \quad (3)$$

$$\Delta V_P = (3.0443{\cdot}10^{-13}{\cdot}I^4 - 1.8192{\cdot}10^{-10}{\cdot}I^3 - 1.7879{\cdot}10^{-7}{\cdot}I^2 + 1.2868{\cdot}10^{-4}{\cdot}I + 0.03908) - (P\text{-}Patm) / 2.75604 \quad (4)$$

$$\Delta V_{RH} = (-7.987{\cdot}10^{-8}{\cdot}RH^2 + 1.718{\cdot}10^{-5}{\cdot}RH - 4.766{\cdot}10^{-4}) \cdot I \quad (5)$$

The iterated value of current density has the unit of mA/cm^2.

The power per area or the power density (P_u) is

$$P_u = V{\cdot}I{\cdot}10^{-3} \quad (6)$$

To calculate the power in terms of Watts,

$$P = P_u{\cdot}N \quad (7)$$

where N is the active area per fuel cell multiplied by the number of cells.

The amount of hydrogen required for a PEM fuel cell to produce the targeted power output is calculated using the iterated value of current density,

$$n_{H2} = (I{\cdot}N)/2F \quad (8)$$

where F is Faraday's constant (^{o}C/kmol)

The range of current density is 0-850 mA/cm^2 [8].

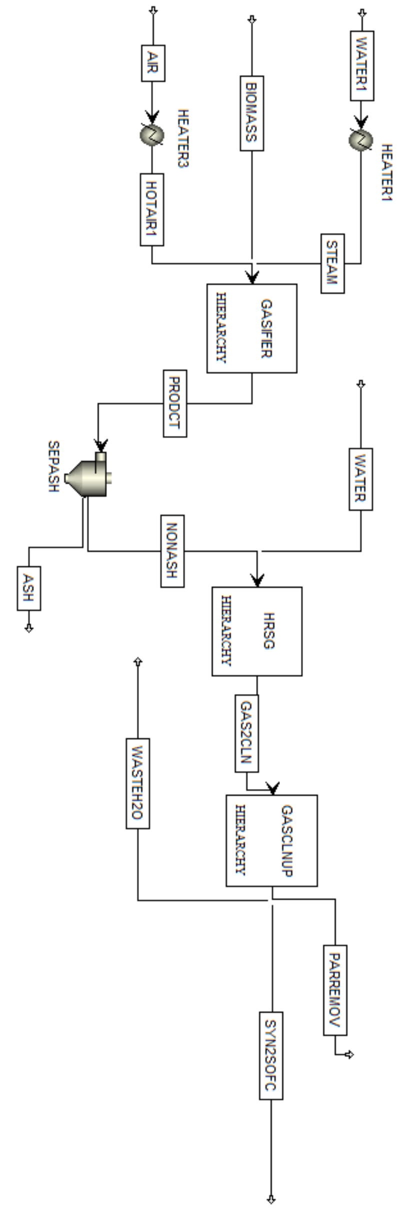

Fig. 2. Aspen simulation for biomass gasification process.

IV. Results

A. Optimal Operating Conditions of PEM Fuel Cell

PEM fuel cell optimization is needed in order to determine the amount of hydrogen input into the PEM fuel cell and the operating condition in terms of lowest amount of hydrogen input. This study focuses only on the power generation of 50 kW. The operating conditions that are optimized in this work are temperature, relative humidity and pressure.

The operating conditions for this PEM fuel cell model are based on Barelli's model [8] as shown in Table I.

TABLE I: RANGES OF OPERATING VARIABLES IN THE PEM FUEL CELL [8]

Variables	Ranges
Temperature (T)	80-120 °C
Pressure (P)	1 – 3 atm
Relative Humidity (%RH)	0 – 100 %

The effect of temperature on amount of hydrogen required for 50 kW power generations is shown in Fig. 3. The effect of increasing temperature causes an increase in the exchange current density, which decreases activation losses. Along with the exchange current density, the limit current density increases with the fuel cell operating temperature. With increasing limit current density, the mass transport is enhanced due to the increase of diffusivity [9], [10]. Therefore, as the temperature increases, the amount of hydrogen decreases, giving the best operating temperature at 120 ℃.

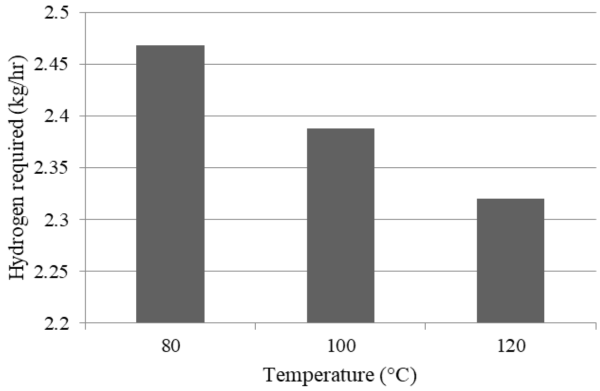

Fig. 3. Hydrogen required for a PEM fuel cell 50kW at different temperatures when P = 3atm and RH = 100**%.**

The effect of operating pressure on the amount of hydrogen input into the PEM fuel cell with 50 kW power capacity is shown on Fig. 4. It is clearly seen that lower pressure requires the highest amount of hydrogen. As the pressure is increased, voltage and power density also increase. Therefore, increasing pressure results in an improved cell performance in either the anode or the cathode side. Increasing pressure, the mass transfer resistance of the cell is decreased. When the fuel cell is working under pressure, the effective active area in the electrochemical reactions would be increased since the oxygen and hydrogen are forced to pass these areas [11].

Fig. 5 illustrates the relationship between operating relative humidity (%RH) and the amount of hydrogen needed to be input for a 50 kW PEM fuel cell. The results shown that the hydrogen required for %RH values are slightly different. When relative humidity increased, both voltage and power density are higher. Increasing relative humidity leads to decreasing partial pressure of both oxygen and hydrogen; thereby increasing the overall cell voltage of the fuel cell. When the relative humidity is set at a higher value, the charge transfer coefficient is lower associated with the fuel cell reaction kinetics. Moreover, the mass transfer resistance increases with decreasing relative humidity [12].

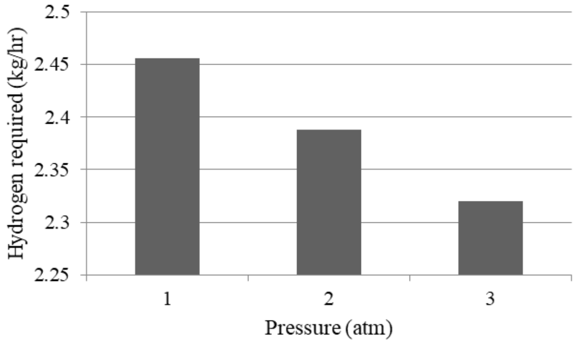

Fig. 4. Hydrogen required for a PEM fuel cell 50kW at different pressures when T = 120 ℃ and RH = 100**%.**

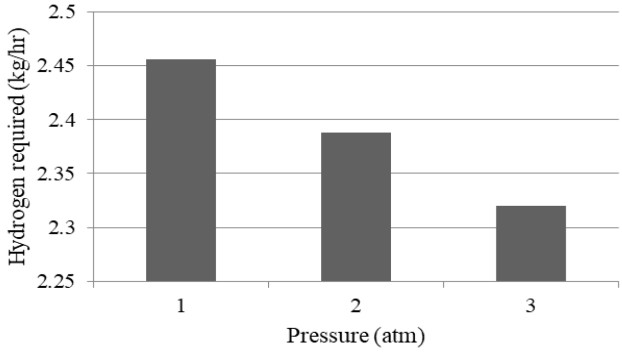

Fig. 5. Hydrogen required for a PEM fuel cell operating at different relative humidity T = 120 ℃, P = 3atm.

B. Optimal Operating Conditions of Biomass Gasification Process

The biomass gasification process is investigated through the Aspen Plus process simulation. Rice straw is used as biomass feedstock and rice straw compositions are referenced by [13]. The important variables affecting the gasification outputs are studied. The variables mentioned are temperature of gasifier, air-to-biomass ratio, and steam-to-biomass ratio as shown in Table II. The gasifier is operated under the atmospheric pressure as the gasifier pressure has no effect on the gas composition after undergoing the process.

TABLE II: RANGES OF OPERATING VARIABLES IN THE GASIFICATION PROCESS [13], [14]

Variables	Ranges
Gasification Temperature	800-1200 °C
Steam / Biomass ratio	0.6 – 2.0
Air / Biomass Ratio	2.0 – 4.0

The results of the amount of hydrogen produced at specific temperature, from 800 ℃ to 1200 ℃ shown in Fig. 6. As a result, the amount of hydrogen produced decreases when the gasifier temperature increases because when the temperature of gasifier is increased, the reverse reaction of water-gas shift ($CO_2 + H_2 \leftrightarrow CO + H_2O$) is strengthened. So, the amount of hydrogen in the reaction is reduced. Therefore, the maximum amount of hydrogen output for syngas can be produced at the gasifier temperature of 800 ℃.

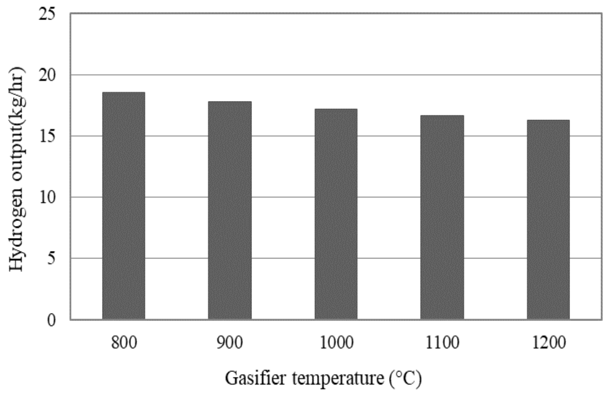

Fig. 6. Effect of gasifier temperature on hydrogen output.

The effect of air to biomass ratio is shown in Fig. 7. It was found that there is no significant difference in the hydrogen output content when the air to biomass ratios are changed. So, it is preferable to select the minimal ratio of air to biomass as it consumes fewer amounts of resources.

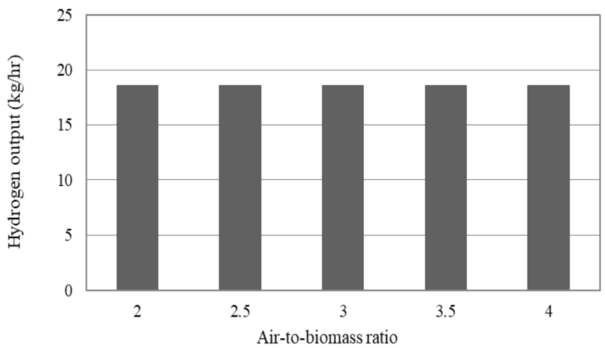

Fig. 7. Effect of air to biomass ratio on hydrogen output.

Fig. 8 illustrates the trend of hydrogen output when the steam-to-biomass ratios are increased. The results shown that there is a slight increase on the hydrogen production in the syngas as the steam-to-biomass ratio is increased. According to the water gas reaction ($C + H_2O \leftrightarrow H_2 + CO$) water gas shift reaction ($CO + H_2O \leftrightarrow CO_2 + H_2$) and steam reforming ($CH_4 + H_2O \leftrightarrow CO + 3H_2$) [15]. Therefore, the maximum amount of hydrogen output for syngas can be produced at the steam-to-biomass ratio of 2.0.

C. Minimum Biomass Required for 50kW

After obtaining the optimal conditions for operating the biomass gasification in order to produce the highest amount of hydrogen, these conditions are applied to find the amount of biomass required to feed into the process to generate power output of 50 kW.

The amount of hydrogen can be obtained from the PEM fuel cell model by iterating the process of the model resulting in which the hydrogen requirement of 2.320 kg/hr. This amount is used to track back the amount of biomass feed under the optimal conditions of biomass gasification process. Table III shows the biomass needed to generate power of 50 kW is 27.641 kg/hr while the feed rate of air and steam are 410.64 kg/hr, 410.64 kg/hr, respectively. In other words, the amount of rice straw required to the gasification process is 663.39 kg/day or 236.57 tons annually to generate 50 kW of electricity.

TABLE III: OPTIMAL BIOMASS FEED RATE AND HYDROGEN AMOUNT FOR 50KW OF POWER

Optimal Results	
Hydrogen Amount	2.320 kg/hr
Biomass Feed Rate	27.641 kg/hr

V. CONCLUSION

The objectives of this study are to determine the amount of biomass feed (rice straw) to biomass gasification and the hydrogen input to the PEM fuel cell where the operating conditions are optimized to produce power output of 50 kW. For the PEM fuel cell part, the PEM mathematical models are calculated to determine the amount of hydrogen input. For the biomass gasification part, the process is investigated through the Aspen Plus simulation. The results reveal that the optimal operating conditions for the PEM fuel cell are 120 ℃, 3 atm and 100%RH, and the amount of hydrogen required for PEM fuel cell is 2.320 kg/hr. In additions, the optimal operating conditions of biomass gasification are 800 ℃ gasifier temperature, 2.0 air to biomass ratio and 2.0 steam to biomass ratio. Moreover, the optimal amount of biomass feed is 27.641 kg/hr to generate 50 kW of power from the PEM fuel cell. Thus, this study can be used as the basis for the operation of biomass gasification with PEM fuel cell power generation system.

ACKNOWLEDGMENT

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

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