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Energy management simulation in a PEM fuel cell system

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Abstract

In this research the simulation of an air independent PEM fuel cell propulsion system was taken into-consideration. The system consisted of a PEM fuel cell stack, metal hydride and liquid oxygen (LOX) tanks, and pre-heaters of oxygen and hydrogen gases which along with other heat exchangers cool the PEM fuel cell stack and use its wasted heat effectively in other sections. In this case study the operation of the whole system, inducing utilizing the wasted heat from the PEMFC have been simulated, and the effects of operating parameters such as PEMFC power, its operating temperature and cooling water mass flow rate were investigated and discussed.

1. Introduction

Due to the limitations of fossil energy sources and emissions of their products after burning, it is highly recommended to be replaced with new sources. Conventional power generation systems can be superseded by fuel cells, which change chemical energy directly to the electrical energy, due to their higher efficiency and much lower emission. Much research needs to be done to make fuel cell systems competitive with internal-combustion engines. The most common reasons limiting the use of fuel cells are their high cost and limited life time. In recent years, fuel cells are increasingly being used in various systems like space crafts and submarines [1]. There are many types, each with its own use. Among them, the Proton Exchange Membrane Fuel Cell (PEMFC) is the best having high efficiency and low operating temperature, which makes it especially useful for systems like submarines. The key parameters determining the power and efficiency of a PEMFC stack are managing the produced water, controlling the PEMFC's temperature, operating pressure, and

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mass flow rates of the reactants.

In 2001 Cownden et al. [2] introduced a PEM fuel cell system for transportation purposes in which all parts of the system were evaluated by the exergy analysis approach. In 2008 Corbo et al. evaluated a PEM fuel cell system of 20 KW power by testing automobile-like cycles [3]. Furthermore, Himanen et al. [4] designed a PEMFC that was an anode dead end and cathode free-breath, and evaluated its hydrogen pressure and moisture parameters. Haraldson et al. [5] mentioned the effect of providing oxygen or air and also heat management on the management of produced water. The effect of temperature and pressure on a PEMFC system was evaluated in another study [6]. Zhang et al. [7] did the same research but focused only on the different temperature conditions. Moreover, Shao et al. [8] investigated the effect of a new composite membrane in H_2/O_2 PEMFC under the operating conditions of 110°C, 1.36atm gas pressure, and 70% relative humidity for the sake of addressing the flooding problem.

In this research the system of a 64kW PEM fuel cell having different efficiencies has been taken under consideration, and it has been shown that energy management can help us to increase the efficiency of the system by pre-heating oxygen and hydrogen as well as cooling down the PEMFC stack.

2. Energy management approach

PEM fuel cells are not 100% efficient, and in addition to electrical energy some heat will also be produced. This is important because of the low operating temperature of the stack. This produced heat can either be transferred to the environment or used in other systems. Therefore, as the reactions of hydrogen desorption in metal hydride and vaporization of liquid oxygen in LOX are both endothermic, it would be wise to consume the waste heat of the fuel cell stack for such purposes. It could also be used for pre-heating the cold oxygen and hydrogen gases to reach a temperature close to stack operational temperature. This is called “energy management” in a PEM fuel cell system that concentrates on making the stack waste heat useful by consuming it in other sections that may need energy (heat) sources for their own purposes. This could lead to an increment in the whole efficiency of the system by gaining a part of the "thermal efficiency" of the PEM fuel cell, as well as avoiding the use of other energy sources for the sake of other sections’ energy demands. Moreover, this kind of energy management in PEM fuel cell systems could play an important role in solving the problem of excess produced heat in the stack.

It is the cooling water circuit of a PEM fuel cell system that undertakes the role of transferring the produced heat in stack to the other sections, so it must be designed according to the criteria of maximizing the thermal efficiency of the system. Focusing on the ability of the system to transfer wasted heat to a useful heat sink, Colella [9] designed four models for cooling water circuits and analyzed them to determine their operation toward the mentioned criteria. Besides those mentioned above, in another instance Cao [10] presented a novel fuel exchanger system that benefited from the excess produced heat of the stack and achieved an improvement of about 20% in the efficiency of the system and a decrement of about 70% in fuel usage (Fig. 1).

3.Governing equations of the model

According to the produced heat, operating temperature and the cooling water temperature the mass flow rate of the cooling water will be calculated as [11]:

$$\dot{m}_{water} = \frac{\dot{Q}_{45\%}}{C_p\left(T_{water} - T_{water_{1''}}\right)} \qquad (1)$$

Also, for calculation of mass flow rates and outlet temperatures of heat exchangers and evaporator, we have [11]:

$$\dot{Q} = \dot{m}_1 C_1 \Delta T_1 = \dot{m}_2 C_2 \Delta T_2 \qquad (2)$$

The necessary oxygen can be determined via [11]:

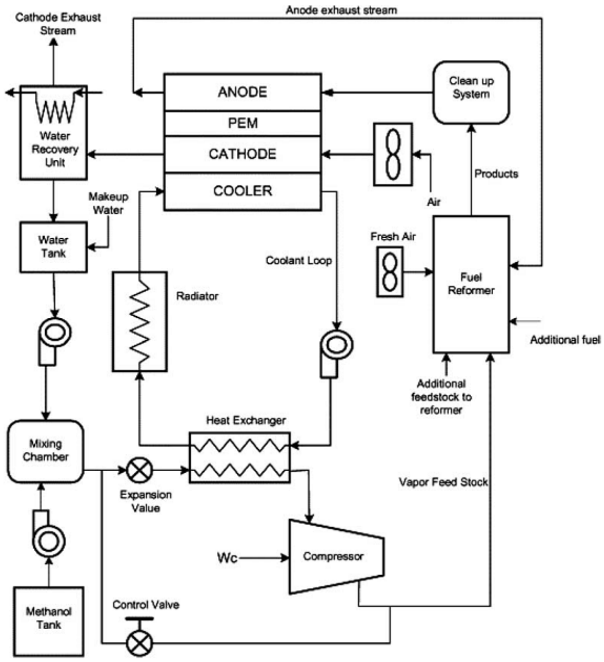

Fig. 1. Fuel exchanger system introduced by Cao [10].

$$\dot{m}_{O_2} = 8.29\times10^{-8} S.R_{o_2} \frac{P_{PEM}}{V_c} \quad (3)$$

where S.R is the stoichiometric coefficient.

Then the mass flow rate of water needed to cool the PEMFC can be calculated by [11]:

$$CWF = \frac{Q_w}{C_w\left(T_{pem} - T_{in}\right)} \quad (4)$$

where CWF is the cooling water flow rate and is measured as kg/s.

The produced water mass flow rate can also be obtained utilizing Eq. (5) [11]:

$$W_p = 934\times10^{-8} \frac{P_{PEM}}{V_c} \quad (5)$$

where W_p is the produced water mass flow rate and is measured as kg/s.

4. Model description

Nowadays, modeling and simulation are the best support for experimental efforts resulting in less time and cost. Most simulations can be categorized in two major classes' namely whole system simulations and detailed equipment simulations [12].

A whole system simulation was used in this research in order to see how varying the operating parameters of each piece of equipment affects the whole system. The ASPEN HYSYS Package, used by most professional companies as well as many academic studies, was employed to perform the simulation in this research [13]. The schematic of the 64kW PEMFC system simulated by ASPEN HYSYS is depicted in Fig. 2.

5. Results and discussion

In the following the results of the simulation of a 64kW PEMFC system with constant operating pressure and temperature are presented. The stoichiometric coefficient was 1.01 for both cathode and anode. This low value is due to the dead-end mode operation of the system.

In Fig. 3, the dependency of the cooling water mass flow rate in relation with the PEMFC operating temperature has been shown. It can be seen that in at constant efficiency an increase of operating temperature caused the decrease of the cooling water mass flow rate.

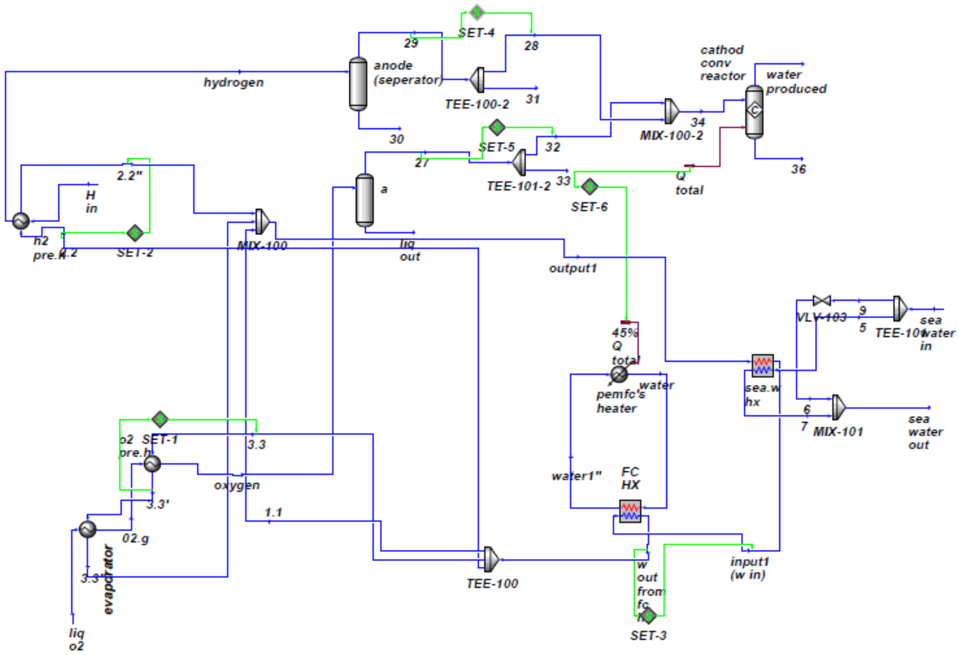

Fig. 2. PEMFC system designed and simulated in ASPEN HYSYS

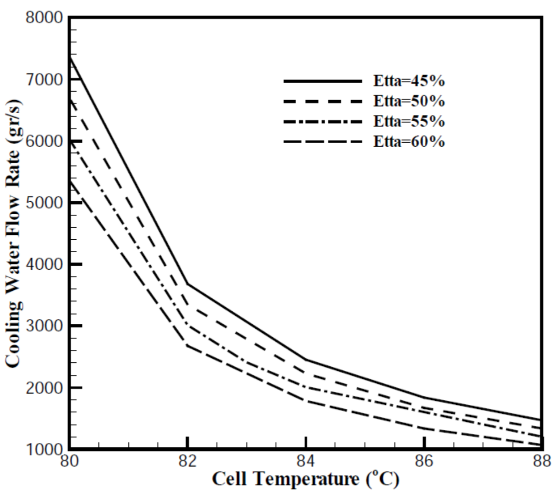

Fig. 3. Cooling water mass flow according to cell temperature.

According to Eq. (2) at a constant generated heat and cooling water temperature, increasing the outlet temperature of the cooling water should decrease the mass flow rate in order to keep the Q constant.

It can also be seen that at a specific cooling water temperature and PEMFC operating temperature, the case having higher efficiency needs less mass flow rate to be cooled. This can be explained by the more efficient the system is the less heat it will lose, and therefore, needless cooling water mass flow rate.

In the next step the relationship between the oxygen and the cooling water mass flow rates in η=55% and different stoichiometry's were examined, and the results are shown in Fig. 4. It can be seen that when the oxygen mass flow rate increased the heat produced in the reactor (PEMFC) increased, meaning that the PEMFC lost more heat to cool itself. Accordingly, the PEMFC operating temperature needed to be kept constant at 80°C and the cooling water temperature at 78°C, so the cooling water mass flow rate should be more than the previous case. The effect of the stoichiometry was shown when increasing the stoichiometric coefficient caused the water mass flow rate needed to cool the PEMFC to decrease. The fact is when the stoichiometric coefficient increases, the system will purge more oxygen and hydrogen before getting into the reactor. This means the inlet oxygen and hydrogen mass flow rate would be less than the previous case where the stoichiometry was smaller making the reactor produce less heat, and less produced heat means less heat to lose and as a result less water needed to cool the PEMFC.

In the last step, we tried to show that the relationship between the inlet oxygen mass flow rate and the power

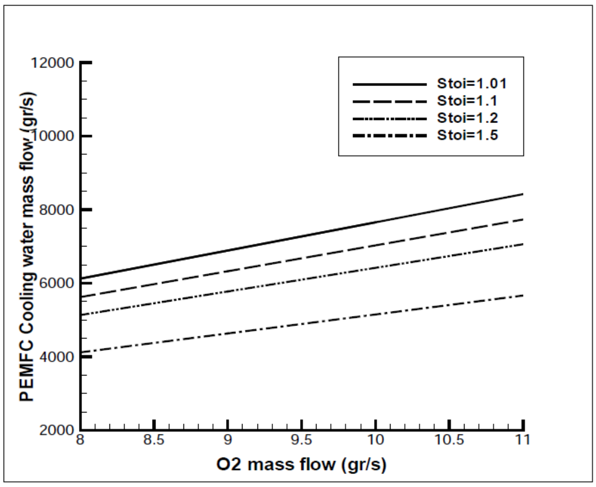

Fig. 4. Cooling water mass according to O_2 mass in different stoichiometries.

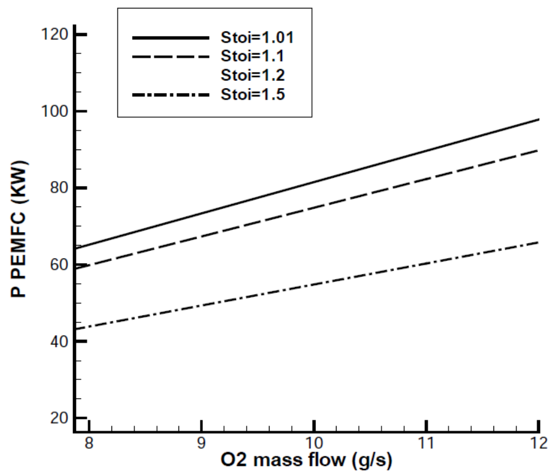

Fig. 5. Inlet O_2 mass flow and the power produced in PEMFC, η=55%.

produced in the PEMFC. Fig. 5 has been derived in a specific and constant pressure and temperature of inlet Hydrogen and Oxygen and with η=55%. As shown in Fig. 5, the PEMFC's power increased as the oxygen flow rate increased. This can be interpreted as follows: keeping the stoichiometric coefficient constant and increasing the reactants flow rates will results in an increment in the produced heat in the reactor (PEMFC) and of course produced power. Then the effect of the stoichiometric coefficient was shown, and it was seen that at a high stoichiometric coefficient with a constant oxygen mass flow rate, the purged mass will be higher than a case with a lower stoichiometric coefficient, and as a result these purged gases played the role of heat sinks with greater capacities of heat to remove.

6. Conclusion

In this paper the effect of different parameters of a 64kW PEMFC system have been taken into consideration. In the first step, after analyzing the relationship between the stack operating temperature and the water mass flow rate needed for cooling it in four cases having different efficiencies, it was concluded that increasing the stack operation temperature according to the constant heat lost by the reactor (PEMFC) decreased the cooling water mass flow rate. In the next step, this case was evaluated in order to show the relationship between the cooling water and the inlet oxygen mass flow rates in four cases having different stoichiometric coefficients. Then the basic relationship between the inlet Oxygen mass flow rate and the power produced in a reactor (PEMFC) at different stoichiometric coefficients was shown. The results showed that increasing the stoichiometric coefficient decreased the power because the amount of the purged oxygen and hydrogen increased.

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