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Performance evaluation of an energy recovery system for fuel reforming of PEM fuel cell power plants

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Abstract

This paper describes an energy recovery system that recovers waste thermal energy from a fuel cell stack and uses it for fuel reforming purposes. The energy recovery system includes a throttling valve, a heat exchanger, and a compressor, and is coupled with a coolant loop of the fuel cell stack. The feed stock of a fuel reformer, which is primarily a mixture of water and fuel, is vaporized in the heat exchanger and is compressed to a sufficiently high pressure before it is ducted into the fuel reformer. The performance of a fuel cell power plant equipped with the energy recovery system is evaluated. The results indicate that the power plant efficiency can be increased by more than 40% compared to that of a fuel cell power plant without the energy recovery system. Additionally, up to 90% of the waste heat generated in the fuel cell stack is recovered. As a result, the required heat dissipation capacity of the radiator that is used for cooling the fuel cell stack can be drastically reduced. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: PEM fuel cell; Energy recovery

1. Introduction

A fuel cell is a device that directly converts the chemical energy of reactants (a fuel and an oxidant) into low-voltage dc electricity. Many of the operational characteristics of fuel cell systems are superior to those of conventional power generation. Among several distinct types of fuel cells, the polymer electrolyte membrane or proton exchange membrane (PEM) fuel cell is most popular for transportation and portable applications. The PEM fuel cell could employ compressed hydrogen gas or methanol reformate as fuel. Other hydrocarbons, such as gasoline or diesel fuel could also be reformed to produce suitable reformate for the fuel cell. Although a fuel cell operating on pure hydrogen gas is considered to be the ultimate clean energy system, the difficulties associated with handling high-pressure compressed hydrogen gas and the lack of a hydrogen infrastructure would prevent the mass use of the fuel cell power plant in the foreseeable future. As a result, fuel cell power plants using reformate from methanol or from other hydrocarbons such as gasoline are actively under development. One of the drawbacks for reformate based fuel cell power plants is that a large amount of energy is needed for the fuel processing purpose. The total heat energy requirement for a reformer can be estimated by using the following relation (Edlund and Pledger [1])

$$\Delta H_{tot} = \Delta H_{rxn} + \Delta H_{vap} + \Delta H_{cp} + \Delta H_{loss}$$

where ΔH_{rxn} is the enthalpy of reforming reaction; ΔH_{vap} the enthalpy of vaporization of the liquid feedstock; ΔH_{cp} the enthalpy required to heat the vaporized feedstock to the reforming temperature; and ΔH_{loss} is the heat lost to the ambient which could be minimized with adequate insulation. It was estimated that heating value equivalent to that of about 20–30% of the hydrogen produced in the reformer is needed to provide a fuel stream with sufficient heating value to meet the heating requirement, ΔH_{tot}, of the reformer. This amount of heating value is usually provided through the combustion of remaining hydrogen/hydrocarbons in the exhaust gases from the fuel cell anode, burning the hydrogen/hydrocarbons in the byproduct stream of the reformer, or consumption of additional hydrocarbon fuel other than that being reformed in the reformer. It is evident that the energy input to the reformer must be reduced if the efficiency of a fuel cell power plant is to be increased.

Another problem generally associated with a PEM fuel cell power plant is the difficulty in dissipating the waste heat generated in the fuel cell stack. The voltage efficiency of a

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PEM fuel cell stack under normal operating condition is about 50–70% (Barbir et al. [2]). This means that 30–50% of the energy content of the hydrogen participating in the electrochemical reaction in the fuel cell stack will be dissipated into waste heat that must be removed from the fuel cell stack under steady state operating condition. Since a FEM fuel cell normally operates within a temperature range of 60–80 °C that is substantially lower than that of an internal combustion engine, a cooling system employing conventional radiators would require much more space and fan power for adequate heat removal from the fuel cell stack. In this paper, a unique energy recovery system is described and its performance is evaluated. The energy recovery system would substantially reduce the net energy input to the reformer and significantly increase the efficiency of a PEM fuel cell power plant. At the same time, the requirement for the heat dissipation capacity of the radiator is drastically reduced.

2. Description of the energy recovery system for fuel reforming

The energy recovery system conceived by Cao [3] is to recover a substantially large portion of the waste heat generated by the fuel cell stack and utilize it for fuel reforming purposes. Fig. 1 shows the diagram of a refromate/air PEM fuel cell power plant incorporating such an energy recovery system. Although the fuel cell power plant as illustrated in Fig. 1 uses methanol as fuel, it is also feasible for a fuel cell plant using other fuels to incorporate the energy recovery system (Cao [3]). The fuel cell power plant comprises a PEM fuel cell that includes at least an anode electrode, a cathode electrode, a proton exchange membrane (PEM) between the anode and cathode, and a cooler loop for removing the waste heat from the fuel cell stack. A water recovery unit recovers water from the cathode exhaust air stream and discharges it to a water tank. The

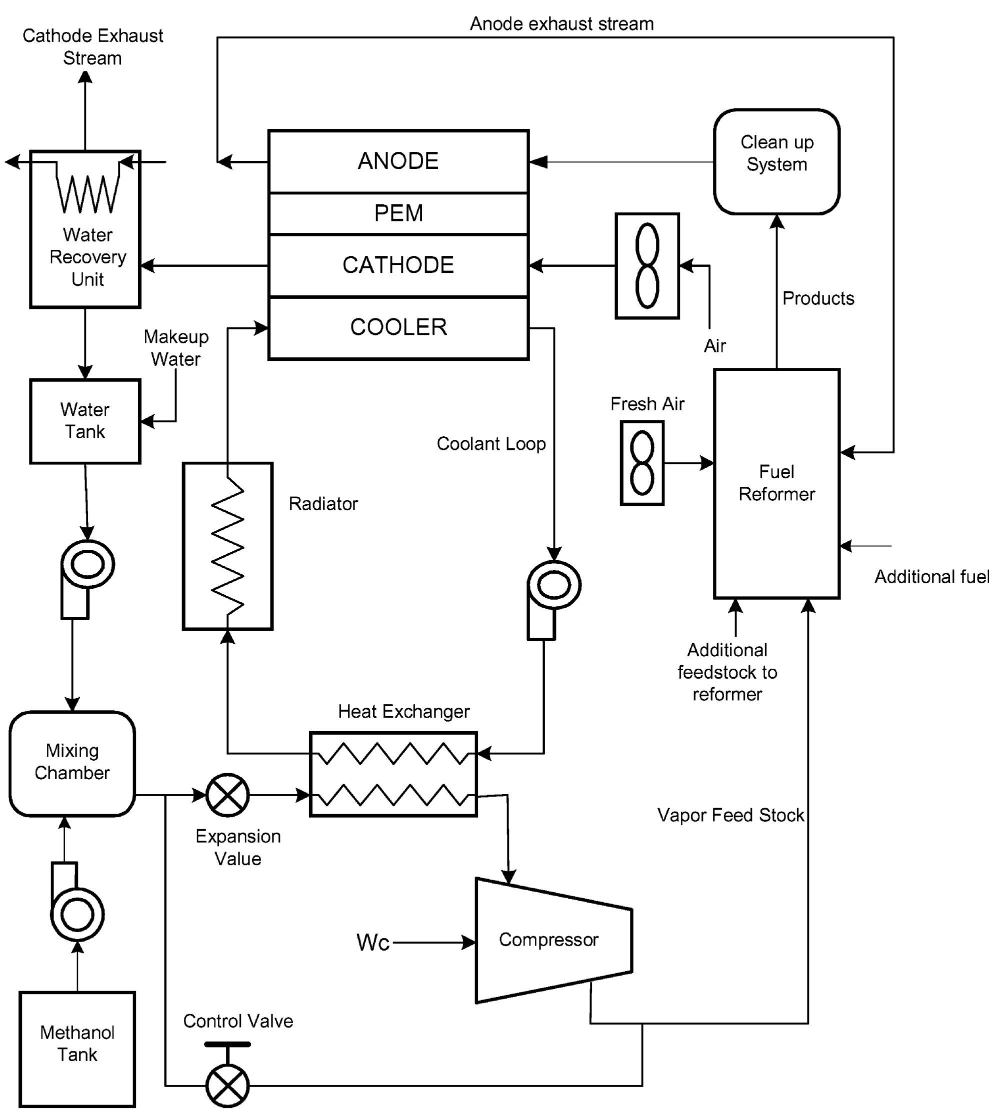

Fig. 1. Schematic of a fuel cell power plant incorporating the energy recovery system.

water tank could also receive water from a makeup-water source. The water is pumped into a mixing chamber and is mixed with the liquid methanol pumped from a methanol tank with an appropriate ratio. The ratio of water and methanol on a molar basis is generally greater than the stoichiometric ratio which is equal to one. After flowing through an expansion valve, the pressure of the water and methanol mixture is substantially reduced. The mixture with a reduced pressure enters a heat exchanger or evaporator and absorbs heat from the coolant of the fuel cell stack cooler. The pressure of the mixture is sufficiently low that it is substantially vaporized while absorbing heat from the coolant in the heat exchanger. The vapor mixture of water and methanol with a sufficient superheating emerges from the heat exchanger and enters a compressor where its pressure is raised to a sufficiently high level. Now, the water/methanol vapor mixture leaves the compressor and enters a fuel reformer as the vapor feedstock of the reformer. Additional thermal energy may be needed for reforming reaction. This is usually provided through a burner in the reformer that burns the hydrogen/hydrocarbons remaining in the anode exhaust stream as shown in the figure. The water/methanol vapor feed stock is converted in the reformer into a mixture of H_2 and CO_2 with a small amount of CO. A clean up system may be needed to reduce the CO content to an acceptable level before the dilute hydrogen stream is fed into the fuel cell stack to generate electricity. The advantage of the present energy recovery system is significant. The latent heat that is needed to vaporize the liquid water or liquid methanol feedstock would come from the waste heat from the fuel cell stack that could otherwise be dumped into the surrounding. Since the latent heat normally constitutes a large portion of the total reforming heat (sometimes higher than 50%), the fuel burned in the reformer burner would be substantially reduced and the efficiency of the fuel cell power plant could be significantly increased. On the other hand, since a huge amount of the waste heat from the stack is absorbed by the feedstock of the reformer, the heat dissipation load of the radiator following the heat exchanger can be drastically reduced, which substantially reduces the size of the radiator and power consumption of the cooling fan. Additionally, due to the nature of heat exchange occurring between the liquid coolant and two-phase water/methanol mixture in the heat exchanger, the size of the heat exchanger could be very small compared to that of a radiator. During the cold start of the fuel cell power plant when the waste heat is not available, the liquid feed stock could bypass the energy recovery system and directly flows into the fuel reformer, as shown in Fig. 1. One of the critical components of the present energy recovery system is the compressor. Due to a relatively small mass flow rate, a compact and less expensive centrifugal compressor may be used. Because of the limitation of the compression ratio, however, a PEM fuel cell power plant incorporating the present energy recovery system is to work preferably at a relatively low pressure compared to that of a power plant without incorporating the present energy recovery system. For some fuel cell power plants that require a higher operating pressure, multistage compression with intercooling may be needed to raise the feedstock to a required pressure and reduce the operating temperature of a compressor. Alternatively, the feed stock could be compressed to a relatively low pressure that is enough to overcome the resistance within the reformer. Additional compression could be done after the fuel reforming process.

3. Evaluation of the performance of a FEM fuel cell power plant incorporating the energy recovery system

In the foregoing section, the function of the energy recovery system is described. However, the benefit of employing the energy recovery system must be quantitatively evaluated to justify the deployment of the system. For this purpose, a PEM fuel cell power plant as shown in Fig. 1 is considered. A sample evaluation is first performed based on a set of given conditions although these conditions can be relaxed in later systematic calculation. The fuel cell stack is assumed to have an electrochemical efficiency of 65% based on the higher heating value of hydrogen (122,885.0 kJ/kmol H_2). It should be noted that this efficiency is for the amount of hydrogen that participates in the electrochemical reaction within the fuel cell stack. The products at the outlet of the reformer is assumed to be at a temperature of 150 °C with the remaining water in a vapor condition and the CO content is ignored during the calculation of the thermal energy requirement. For the reduction of CO content in the products during the steam reforming process, excess water is normally used for the steam reform of methanol. In the present calculation, percent theoretical water, which is defined as the actual molar water–methanol ratio divided by the stoichiometric water–methanol ratio, is taken to be 1.5. The liquid water/methanol mixture is assumed to be throttled to a pressure of 0.2 bar through the expansion valve as shown in Fig. 1, and the vapor water/methanol is assumed to be at 60 °C at the outlet of the heat exchanger. Based on the theory of binary solutions, the vapor of water/methanol mixture at this temperature is slightly superheated (Stoecker [4]). It is also implied that the fuel cell stack is working at a temperature of above 60 °C, preferably at about 70 °C, to facilitate the heat transfer between the stack coolant and the water–methanol mixture. The evaluation of the compressor work input is based on the assumption of ideal water–methanol vapor mixture to simplify the calculation procedure (Moran and Shapiro [5]), and the vapor mixture is compressed to a pressure of 3 bar. Other assumptions involve the neglect of parasitic loads and sensible heat absorbed by the feedstock in the heat exchanger.

The evaluation gets started by first considering a fuel cell power plant without incorporating the present energy recovery system for the purpose of comparison. In this case, a control volume that encloses the reformer is depicted in Fig. 2 with various flow streams labeled at the boundary of

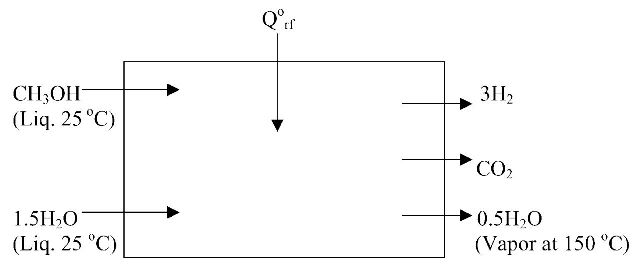

Fig. 2. Energy balance for a control volume enclosing the feedstock in the fuel reformer of a base fuel cell power plant.

the control volume. At the steady state, the net thermal energy input to the reformer can be calculated by the following relations

$$CH_3OH + 1.5H_2O = 3H_2 + CO_2 + 0.5H_2O$$

$$\begin{aligned} Q^0_{rf} &= \sum_P n_e(\bar{h}^0_f + \Delta\bar{h}) - \sum_R n_i(\bar{h}^0_f + \Delta\bar{h}) \\ &= 3(3632) + 1(-393520 + 4938) \\ &\quad + 0.5(-241820 + 4239) \\ &\quad - (-238810 - (1.5)(285830)) \\ &= 171078.5\,\text{kJ/3 kmol of H}_2 \end{aligned}$$

As above, all the evaluation that follows will be based on the 3 kmol of H_2. To provide the required heat input to the reformer, a portion of the 3 kmol of H_2 must be burned in the reformer burner without participating in the electrochemical reaction in the fuel cell stack. This portion of H_2 can be conveniently calculated using the higher heating value of H_2, HHV.

$$\begin{aligned} (H_2)_{burner} &= Q^0_{rf}/\text{HHV} \\ &= 171078.5/122885 \\ &= 1.39\,\text{kmol of H}_2 \end{aligned}$$

As a result, the efficiency of the power plant can be calculated based on the previously mentioned stack electrochemical efficiency of 65%.

$$\eta_0 = \frac{(3 - 1.39)(0.65)}{3} \approx 35\%$$

Now, the fuel cell power plant employing the energy recovery system is considered. The compressor work is first evaluated by assuming that the compressor has an isentropic efficiency of 80%. The temperature at the outlet of the compressor, $T_{out,s}$, for the isentropic compression can be evaluated by the following relations (Moran and Shapiro [5])

$$\begin{aligned} \Delta\bar{s} &= y_w\Delta\bar{s}_w + y_{Me}\Delta\bar{s}_{Me} = y_w\left[\bar{c}_{p,w}\ln\left(\frac{T_{out,s}}{T_{in}}\right) - \bar{R}\ln\left(\frac{P_{out}}{P_{in}}\right)\right] \\ &\quad + y_{Me}\left[\bar{c}_{p,Me}\ln\left(\frac{T_{out,s}}{T_{in}}\right) - \bar{R}\ln\left(\frac{P_{out}}{P_{in}}\right)\right] \\ &= (y_w\bar{c}_{p,w} + y_{Me}\bar{c}_{p,Me})\ln\left(\frac{T_{out,s}}{T_{in}}\right) \\ &\quad - (y_w + y_{Me})\bar{R}\ln\left(\frac{P_{out}}{P_{in}}\right) = 0 \end{aligned}$$

$$\begin{aligned} T_{out,s} &= T_{in}\exp\left[\frac{y_w + y_{Me}}{y_w\bar{c}_{p,w} + y_{Me}\bar{c}_{p,Me}}\bar{R}\ln\frac{p_{out}}{p_{in}}\right] \\ &= (333.15)\exp\left[\frac{0.6 + 0.4}{(0.6)(33.7) + (0.4)(44.96)} \times (8.3145)\ln\frac{3}{0.2}\right] = 600.4\,\text{K} = 327\,^\circ\text{C} \end{aligned}$$

where y_w and y_{Me} are mole fractions of water and methanol in the mixture, receptively. The isentropic work can be calculated based on the following relation:

$$\begin{aligned} W_{c,s} &= (n_w\bar{c}_{p,w} + n_{Me}\bar{c}_{p,Me})(T_{out,s} - T_{in}) \\ &= [(1.5)(33.7) + (1)(44.96)](327.5 - 60) = 25546\,\text{kJ} \end{aligned}$$

After the isentropic work is obtained, the compressor work can be evaluated using the compressor isentropic efficiency

$$W_c = W_{c,s}/\eta_{comp} = 25546/0.8 = 31932.8\,\text{kJ/3 kmol of H}_2$$

The total latent heat absorbed by the feed stock in the heat exchanger from the stack coolant through the vaporization of water and methanol is

$$\begin{aligned} Q_L &= n_wM_wh_{fg,w} + n_{Me}M_{Me}h_{fg,Me} \\ &= (1.5)(18)(2358.5) + (1)(32)(1105) = 99039.5\,\text{kJ} \end{aligned}$$

where M_w, $h_{fg,w}$, M_{Me}, and $h_{fg,Me}$ are the water molecular weight, water latent heat of vaporization, methanol molecular weight, and methanol latent heat of vaporization, respectively. Consider a control volume as shown in Fig. 3, which encloses the feed stock from the inlet of the heat exchanger to the outlet of the fuel reformer, the net thermal energy input to the reformer is evaluated as follows

$$\begin{aligned} Q^0_{rf} &= \left[\sum_P n_e(\bar{h}^0_f + \Delta\bar{h}) - \sum_R n_e(\bar{h}^0_f + \Delta\bar{h})\right] - (Q_L + W_c) \\ &= Q^0_{rf} - (Q_L + W) = 171078.5 - (99039.5 + 31932.8) \\ &= 40106.2\,\text{kJ} \end{aligned}$$

The amount H_2 that needs to be burned in the reformer burner to provide Q_{rf} is

$$(H_2)_{burner} = Q_{rf}/\text{HHV} = 40106.2/122885 = 0.326\,\text{kmol H}_2$$

If this amount of H_2 is to be provided through the H_2 remaining in the exhaust product stream at the outlet of the fuel cell stack, the excess H_2 at the inlet of the stack would be about 11%, which is generally acceptable for a PEM fuel cell stack design.

The efficiency of the PEM power plant incorporating the energy recovery system can thus be evaluated

$$\begin{aligned} \eta &= \frac{(3 - 0.326)(0.65) - W_c/\text{HHV}}{3} \\ &= \frac{(3 - 0.326)(0.65) - 0.26}{3} = 49.3\% \end{aligned}$$

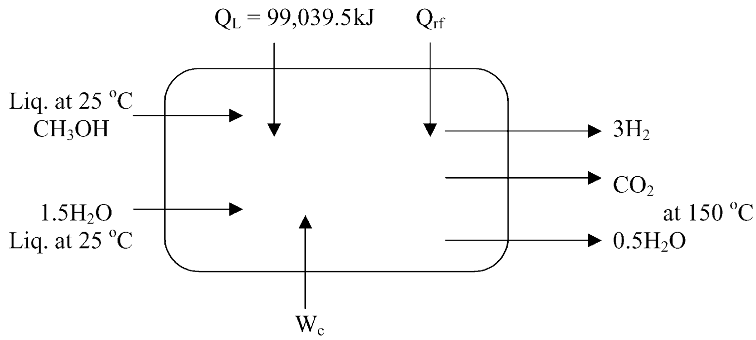

Fig. 3. Energy balance for a control volume enclosing the feedstock between the inlet of the heat exchanger and the outlet of the fuel reformer of a fuel cell power plant with the energy recovery system.

Compared to the PEM fuel cell power plant without the energy recovery system, the power plant efficiency is increased by

$$\phi = \frac{\eta - \eta_0}{\eta_0} \approx 40\%$$

The waste heat generated in the fuel cell stack is

$$Q_{stack} = (3 - 0.326)(1 - 0.65)(122885) = 115008\,\text{kJ}$$

The percentage of the waste heat that is recovered for the fuel reforming process is

$$Q_{recovery}/Q_{stack} \approx 99039.5/115008 = 86\%.$$

This means that the capacity of the radiator following the heat exchanger could be reduced by more than 86%. As a result, the size of the radiator and the power consumption of the cooling fan could be drastically reduced.

Systematic calculations are then undertaken for the evaluation of the performance of the energy recovery system as shown in Fig. 1. The parameters that are varied in the present calculations are the feedstock temperature at the inlet of the compressor, T_{in}, which is directly related to the operating temperature of a fuel cell stack, feed stock pressure at the outlet of the compressor, p_{out}, which is directly related to the reforming pressure and the operating pressure of the fuel stack, and the percent theoretical water, ϕ, which is defined as the actual molar water–methanol ratio divided by the stoichiometric water–methanol ratio, and is directly related to the excess water used during the reforming process. As mentioned earlier, if the inlet pressure of the feed stock is taken to be the saturated water vapor pressure corresponding to the feedstock temperature, the feedstock would be maintained at a superheated condition. The above assumption will be made throughout the following calculations. Other assumptions as indicated before for the above sample calculation would also apply for the following calculation.

Fig. 4 shows the power plant efficiency with the energy recovery system, η, at different reforming pressures, p_{out}, as a function of compressor inlet temperature, T_{in}. As can be seen from the figure, the power plant efficiency is maintained at about 50%, varying slightly with the variation of p_{out} and T_{in}. A more important gage that would be used to justify the use of the present energy recovery system is the improvement of the plant efficiency over that of a base power plant, η_0, without the energy recovery system. Fig. 5 illustrates the variation of $(\eta - \eta_0)/\eta_0$ with T_{in} at different p_{out}. In most cases, the improvement of the power plant efficiency is maintained at about 40% and is also insensitive to the change of T_{in} and p_{out}. The results from Figs. 4 and 5

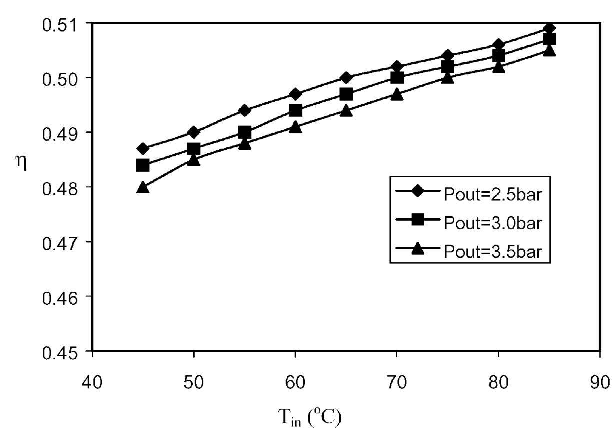

Fig. 4. Variation of the fuel cell power plant efficiency with T_{in} and p_{out}.

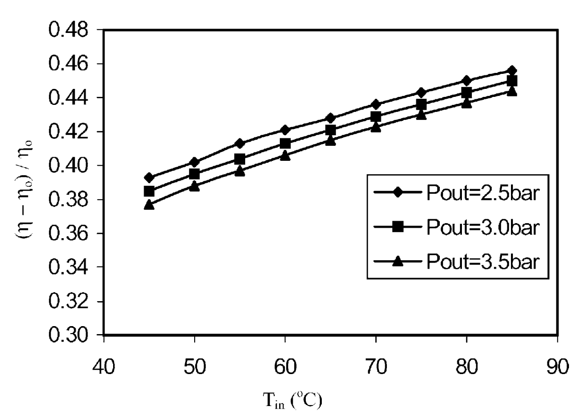

Fig. 5. Improvement of fuel cell power plant efficiency with different T_{in} and p_{out}.

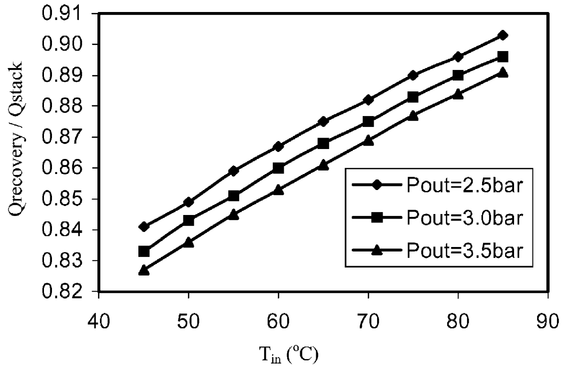

Fig. 6. The ratio of waste heat recovery with different T_{in} and p_{out}.

indicate that the energy recovery system could substantially improve the power plant efficiency and work at a fairly large range of fuel cell stack working temperatures. It should be pointed out, however, at an even higher compression ratio, which is dictated by a smaller T_{in} and a higher p_{out}, the compressor outlet temperature could reach a substantially high lever. In this case, as mentioned earlier, a multistage compression with intercooling system may be needed. As discussed in the earlier sections, additional benefit of the present energy recovery system is the substantial reduction of the waste heat that needs to be dissipated by the radiator. Fig. 6 shows the ratio of the waste heat recovered by the energy recovery system to the total waste heat energy generated by the fuel cell stack as a function of T_{in} and p_{out}. As can be seen from the figure, more than 90% of the waste heat could be recovered. As a result, the needed heat dissipation capacity of a radiator could be reduced by more than 90%, and the size of the radiator and the associated fan power consumption could be drastically reduced. Finally, Figs. 7 and 8 illustrate the influence of percent theoretical water, ϕ, on the improvement of the power plant efficiency at $T_{in} = 60$ °C and $p_{out} = 3.0$ bar, as well as on the energy recovery ratio. The results indicate that with a higher percent theoretical water, the efficiency improvement is more pronounced. However, even at a low percent theoretical water, $\phi = 1.1$, the improvement is still above 30%. Fig. 8 shows

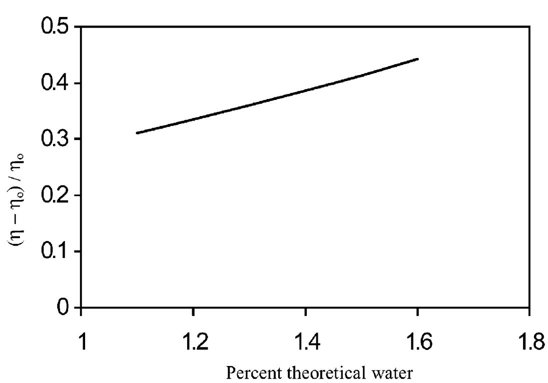

Fig. 7. Variation of the improvement of power plant efficiency with the percent theoretical water.

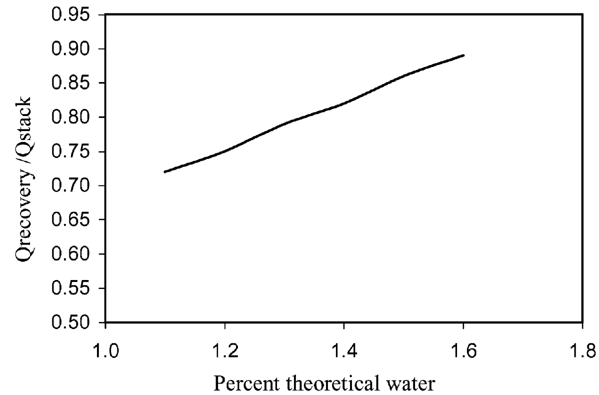

Fig. 8. Variation of the ratio of the waste heat recovery with the percent theoretical water.

the influence of the percent theoretical water on the ratio of the waste heat recovered by the energy recovery system to the total waste heat energy generated by the fuel cell stack. As illustrated, even at a low percent theoretical water, more than 70% of the waste heat is recovered by the energy recovery system.

The foregoing descriptions and evaluations are all based upon a fuel cell power plant using methanol as fuel. The energy recovery system described in this paper, however, can also be employed for a fuel cell power plant using other hydrocarbon fuels such as gasoline or ethanol as fuel. The primary objective of the present energy recovery system is to provide thermal energy for steam reforming through the waste heat recovery from the fuel cell stack. It is believed that the present energy recovery system could be found useful whenever a large amount of steam is needed for a fuel cell power plant working at a relatively low temperature. It also serves as an effective means to cool the fuel cell stack.

4. Conclusions

A fuel cell power plant employing an energy recovery system, which recovers waste thermal energy from the fuel cell stack and uses it for fuel steam reforming, is described. A systematic evaluation for the performance of a fuel cell power plant using methanol as fuel is undertaken. The results indicate that the power plant efficiency can be increased by more than 40% compared to that of a base power plant without the energy recovery system. In addition, up to 90% of the waste heat generated by the fuel cell stack is recovered, which would drastically reduce the size of the radiator and the associated fan power consumption. The results also indicate that the performance of the fuel cell power plant is relatively insensitive to the operating temperature and pressure of the fuel cell stack. The excess water used for the steam reforming would have a significant effect on the performance. However, even with a low excess water, the improvement on the power plant efficiency is still more than 30%.

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