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Exergoenvironmental Analysis of Heat Recovery from Solid Oxide Fuel Cell System for Cooling Applications

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A recovery of high-quality by-product heat from a solid oxide fuel cell (SOFC) for steam production appears to be an interesting alternative to improve the SOFC performance. The produced steam can be used for chilled water generation via an absorption chiller. However, the main challenge in designing this combined cycle is the proper use of the SOFC exhaust gas in order to optimize the chilled water generation. Exergy analysis plays an important role in developing strategies and in providing guidelines for more effective use of exhaust heat in existing systems. In this study, a combined analysis of exergy and environmental impact (through greenhouse gas emissions) of the chilled water production process using the SOFC exhaust heat are performed under exergoenvironmental analysis. The study determines energy and exergy efficiencies, exergy destructions and CO_2 emissions as well as sustainability indexes (SI).

1. Introduction

Electricity is today's most important energy form in our whole way of life. Its production, conversion and use closely affect the environment and sustainable development. That is, globally, fossil fueled power stations are still major emitters of CO_2, and concern about these CO_2 emissions requires low carbon solutions. Currently, developing more efficient energy systems which can be driven by renewable resources is one of the most appealing solutions to overcome environmental issues. Solid oxide fuel cells (SOFCs) have been receiving intense attention to serve as a potentail option for power generation because they offer high electrical efficiency and nearly zero pollutant emission, depending on the fuel used. Moreover, SOFCs produce high quality by-product heat that can be recovered not only for heating by directly feeding to heat-demanding devices but also for cooling by driving an absorption chiller for potentially trigeneration applications.

Heat recovery from the SOFC exhaust gas for cooling applications faces a crucial challenge in process design. Thermodynamically, transferring heat through different temperatures, mixing of two or more different substances, occurring spontaneous chemical reactions and flowing of electric current in the system are all the main causes of irreversibility. The exhaust gas leaving the fuel cell under regular operating conditions has too high temperature to be used directly for an absorption cooling system. Developing strategies and providing guidelines for more effective use of exhaust heat for this combined cycle are needed.

Exergy analysis has become a very important tool for improving the efficiency of energy-resource usage, as it quantifies the locations, types and magnitudes of wastes and losses. As a multidisciplinary concept, exergy analysis can be applied via various techniques to assessing and improving the efficiency of processes, devices and systems. Combined Pinch and exergy analysis for the refrigeration system was studied by Raei (2011). The total site analysis (TSA) and exergy analysis are also subjects of interest in industrial clusters (Hackl and Harvey, 2012). Many previous studies have examined the feasibility of using absorption chillers based on SOFCs for trigeneration plants (Fong and Lee, 2014). Most of these studies have concluded that the SOFC trigeneration system is an attractive technology for energy generation in comparison to other

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technologies. However, the study on SOFCs fed by renewable fuels as a prime mover of the trigeneration plants through exergoenvironmental analysis is quite limited.

The aim of this study is focused on a combined analysis of exergy and environmental impacts of the chilled water production process using the SOFC exhaust heat. Ethanol is chosen to be a primary fuel in the SOFC system, because it is clean, affordable and low-carbon biofuel. The system is designed to determine energy and exergy efficiencies, exergy destructions and CO_2 emissions of each component in the system. A sustainability index (SI) evaluation is carried out and discussed.

2. System description

A schematic diagram of the ethanol fuelled-SOFC system integrated with an absorption cooling system is shown in Figure 1. The system is divided into four main sections: (1) an ethanol steam reformer to convert ethanol into H_2-rich gas via the steam reforming process, (2) the SOFC stack to generate electricity from the electrochemical reaction of hydrogen and oxygen, (3) heating units which comprised of an afterburner, an air pre-heater and a heat recovery steam generator (HRSG), and (4) cooling system; a double-effect LiBr/water absorption chiller, to produce chilled water for cooling applications.

2.1 Ethanol steam reformer

The ethanol steam reformer is a fuel processor to convert ethanol into hydrogen-rich gas by using steam as a reforming agent. It is performed at a temperature of 980 K and the steam-to-ethanol ratio is limited to 1.8 (Tippawan and Arpornwichanop, 2014). The equilibrium composition of the reforming products is determined by the minimization of a total Gibbs free energy. It is assumed that heat required for the reforming process is supplied by an anode exhaust gas and there are no heat losses to the surrounding. In these examinations, the mole fractions of hydrogen-rich gas from the ethanol steam reforming process are 0.60 H_2, 0.2 CO, 0.1 H_2O, 0.06 CO_2 and 0.04 CH_4.

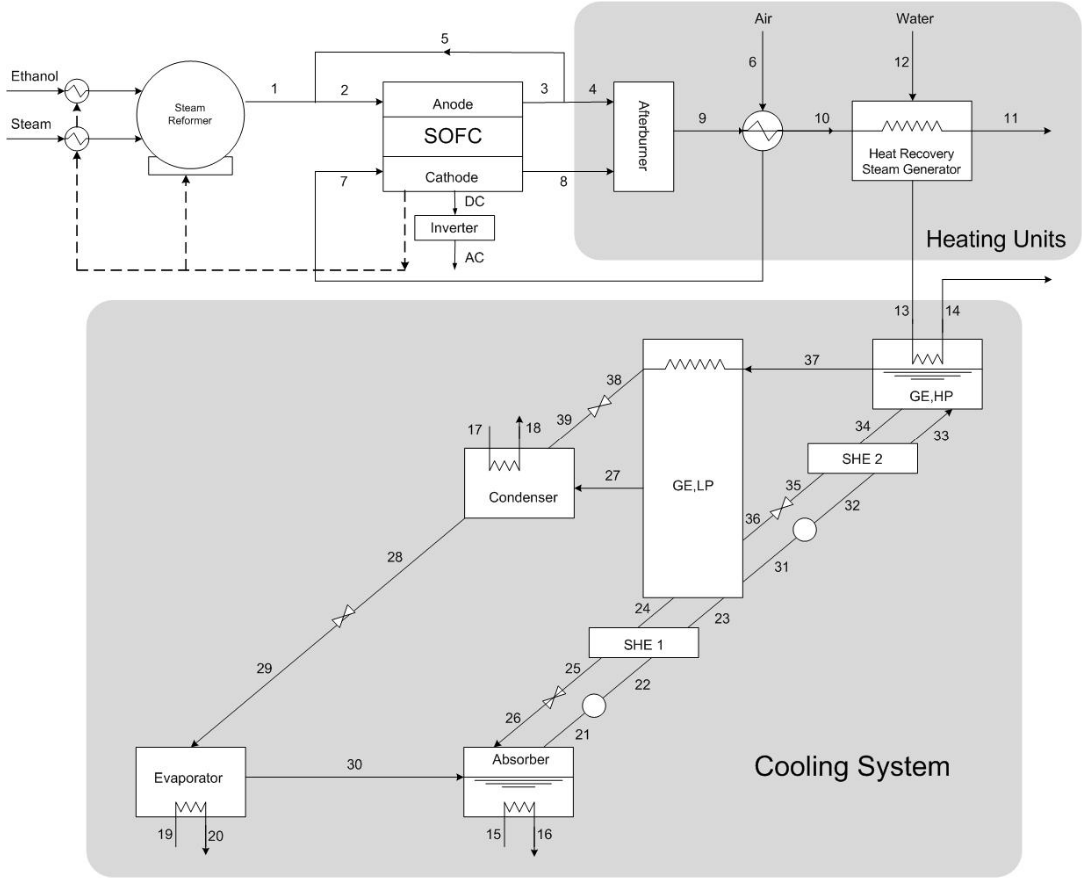

Figure 1: Schematic diagram of the ethanol-fuelled SOFC system integrated with a double-effect absorption cooling system

2.2 Solid oxide fuel cell (SOFC)

The SOFC is a power generator device that converts the chemical energy from ethanol reformate into electric power via an electrochemical reaction. The electricity generated by SOFC is direct current (DC), which is coverted to alternating current (AC) through an inverter. The electrochemical model of SOFC proposed by Aguiar et al. (2004) is used in this study. The internal reforming of CO and CH_4 can proceed inside the cell stack while the electrochemical reaction of hydrogen is only present. The recycling of the anode exhaust gas in this integrated SOFC system is considered to improve its performance.

2.3 Heating units

In general, the SOFC cannot electrochemically utilize 100% of the fuel. The residual fuel and the excess air are combusted in an afterburner to obtain extra useful heat at high temperatures. The equilibrium composition of the combustion process is determined by a stoichiometric approach. The hot flue gas from the afterburner flows through an air pre-heater to exchange the heat for air preheating in the heat exchanger and then passes the HRSG, where it transfers the heat to the feed water, which is heated and converted into a superheated steam which is used to drive a double-effect absorption chiller.

2.4 Cooling system

The key components of the cooling system are an evaporator, an absorber, a low pressure generator (GE,LP), a high pressure generator (GE,HP), a condenser, two solution heat exchangers (SHE), a pump and throttling valves, as shown in Figure 1. The heat in superheated steam from HRSG is supplied to an absorption chiller to generate chilled water. Simulation of a double-effect absorption chiller is based on the model developed by Herold et al. (1996). The chilled water return temperature is set at 285 K, but the chilled water supply temperature is varied according to the amount and performance of heat recovery.

3. Modelling and assessment

3.1 Energy and exergy analyses

The first and second laws of thermodynamics are applied to each component in the integrated system. Considering each component as a control volume under the steady-state condition, the conservation of energy balance equation around the components of the system in Figure 1 can be written as follows:

$$\dot{Q}_{\mathrm{cv}} - \dot{W}_{\mathrm{cv}} = \sum_{\mathrm{out}} \dot{n}_{\mathrm{i}} h_{\mathrm{i}} - \sum_{\mathrm{in}} \dot{n}_{\mathrm{i}} h_{\mathrm{i}} \qquad (1)$$

where $\dot{n}_{\mathrm{i}}$ and h_{i} represent the molar flow rate and specific molar enthalpy, respectively, of the flow stream into and out of each component in the system.

Unlike energy, exergy is not conserved. Exergy is defined as the maximum work that can be extracted from a system interacting with a reference environment (Dincer and Rosen, 2013). Exergy destruction is an important parameter in an exergy analysis. It is formulated as the lost of potential work due to its irreversibility. The exergy destruction rate of a control volume at a steady state is defined as

$$\dot{E}x_{\mathrm{d}} = \sum \left(1 - \frac{T_0}{T}\right) \dot{Q}_{\mathrm{cv}} - \dot{W}_{\mathrm{cv}} + \sum_{\mathrm{in}} \dot{n}_{\mathrm{i}} ex_{\mathrm{i}} - \sum_{\mathrm{out}} \dot{n}_{\mathrm{i}} ex_{\mathrm{i}} \qquad (2)$$

where ex_{i} is the specific molar flow exergy for each component of the inlet and outlet flow streams. The subscript i is the property value at state i, and the subscript 0 is the value of a property at the surroundings. This exergy can be defined by neglecting the kinetic and potential energy changes as follows:

$$ex_{\mathrm{i}} = (h_{\mathrm{i}} - h_0) - T_0 (s_{\mathrm{i}} - s_0) + ex_{\mathrm{ch}} \qquad (3)$$

The specific chemical exergy (ex_{ch}) of different species in a gas mixture is defined as:

$$ex_{\mathrm{ch}} = \sum y_{\mathrm{i}} \cdot ex_{\mathrm{ch,i}} + RT_0 \sum y_{\mathrm{i}} \cdot \ln y_{\mathrm{i}} \qquad (4)$$

where $ex_{\mathrm{ch,i}}$ is the specific molar chemical exergy of the flow streams and y_{i} is the molar fraction of the gas species i in the gas mixture. The standard molar chemical exergies of relevant substances are reported by

Kotas (1995). The enthalpy and entropy for each gaseous component are calculated using thermophysical property functions in the EES (Engineering Equation Solver) as a function of the temperature and/or pressure. The equations used to calculate the energy and exergy efficiencies for the trigeneration system can be expressed as follows:

$$\eta_{\mathrm{tri}} = \frac{\dot{W}_{\mathrm{SOFC}} + \dot{Q}_{\mathrm{h}} + \dot{Q}_{\mathrm{c}}}{\dot{Q}_{\mathrm{fuel,\ in}}} \tag{5}$$

$$\psi_{\mathrm{tri}} = \frac{\dot{W}_{\mathrm{SOFC}} + \dot{E}x_{\mathrm{h}} + \dot{E}x_{\mathrm{c}}}{\dot{E}x_{\mathrm{fuel,in}}} \tag{6}$$

where $\dot{Q}$ and $\dot{E}x$ are the energy and exergy rates, respectively, the subscripts h and c indicate the heating and cooling, respectively and $\dot{W}_{\mathrm{SOFC}}$ is the output power of SOFC.

3.2 Exergoenvironmental analysis

Energy conversion processes should be designed by reducing an environmental impact, resulting in the improved process performance. Because CO_2 emission is a significant issue, a reduction in this green house gas in the afterburner of the SOFC system can lead to the improvement of the cycle. The normalized CO_2 emissions of the trigeneration system can be expressed as follows:

$$Emi(\mathrm{CO_2}, \mathrm{tri}) = \frac{\dot{m}_{\mathrm{CO_2}}}{(\dot{W}_{\mathrm{SOFC}} + \dot{Q}_{\mathrm{h}} + \dot{Q}_{\mathrm{c}})} \tag{5}$$

To improve environmental sustainability, a sustainability index SI is used here to relate the exergy with environmental impact as:

$$SI = \frac{1}{D_{\mathrm{P}}} \tag{6}$$

where D_{P} is the depletion number, which is defined as the exergy destruction/input exergy. This relation demonstrates how reducing a system's environmental impact can be achieved by reducing its exergy destruction (Dincer and Naterer, 2010).

4. Results and discussion

The process equipment data and model, as mentioned in the previous section, are used to determine the energy and exergy efficiencies and exergy destruction rate, and to estimate the environmental impacts for the trigeneration system. The analyses in the effect of current density and SOFC temperatures are shown in Figures 2-5. Figure 2 shows that increasing the current density causes a decrease in the efficiencies, but an increase in the exergy destructions. Given the constant fuel utilization, an increase of current density means an increase of the ethanol fuel flow fed into the system. This leads to the higher inputs of the system and higher exergy destruction. However, the sustainability index decreases with increased current density as shown in Figure 3. It implies that the destruction of exergy mainly dominates the increase of exergy from input. Figure 3 also shows that increasing current density increases CO_2 emission due to the increase of the mass flow rate injected from the afterburner. On the other hand, increasing the SOFC temperature enhances the efficiencies and the exergy destruction decreases as presented in Figure 4. This is attributed to the fact that the increase of temperature promotes the electrochemical reaction in the SOFC stack to generate more electrical power. The optimum values of the SOFC temperature are shown in Figures 4-5. At the optimum temperature, a decrease in the exergy destruction of SOFC is higher than an increase in the exergy destruction of afterburner. Consequently, the total exergy destruction is minimized and sustainability index reaches the maximum value. The exergy destruction in system components is shown in Figure 6. The highest exergy destruction occurs in the afterburner mainly due to the irreversibilities associated with the combustion reaction and the large temperature difference between the gases entering the afterburner and the flame temperature. Significant exergy destruction can also be noticed in the SOFC, HRSG and the air pre-heater. To provide environmental insights, Figure 7 shows that the trigeneration system (including cooling application) has less CO_2 emission than the SOFC and the combined-heat and power cycles, providing a significant motivation for the use of heat from SOFC for cooling application as well. It is also observed that the present trigeneration system provides higher power output, compared to other types of conventional power plants.

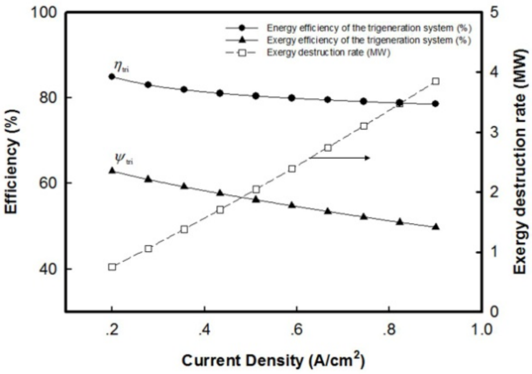

Figure 2: Effect of current density on the energy and exergy efficiencies and the total exergy destruction rate of the trigeneration system

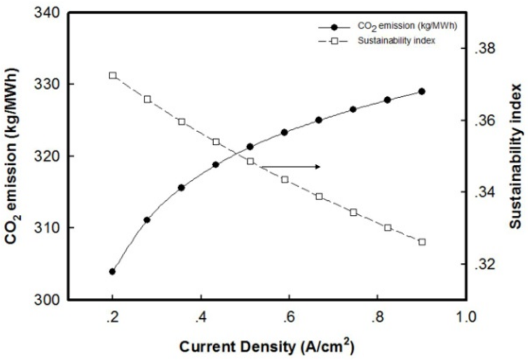

Figure 3: Effect of current density on CO_2 emission and sustainability index

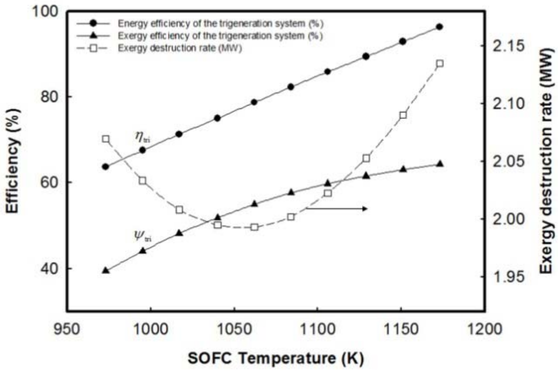

Figure 4: Effect of SOFC temperature on the energy and exergy efficiencies and the total exergy destruction rate of the trigeneration system

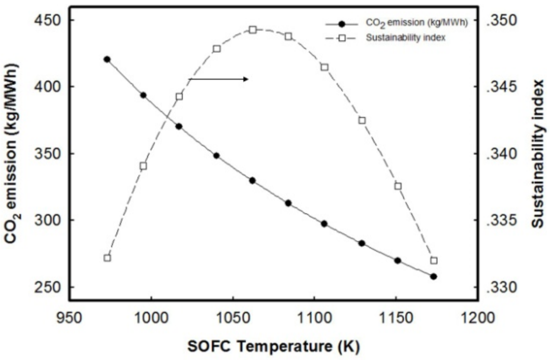

Figure 5: Effect of SOFC temperature on CO_2 emission and sustainability index

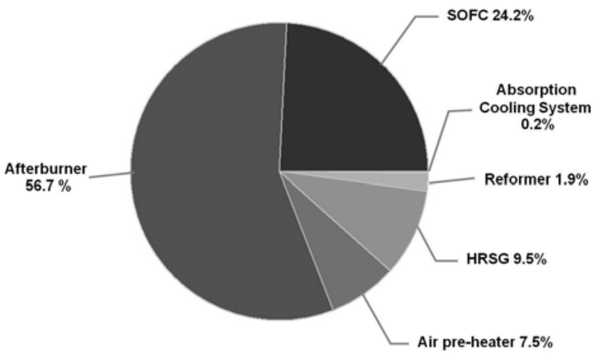

Figure 6: Exergy destruction in the system components

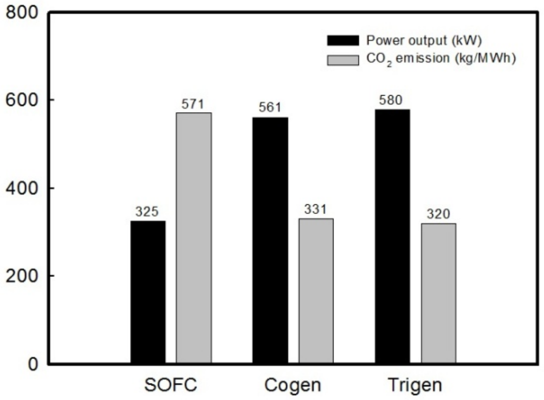

Figure 7: Comparison of CO_2 emission and power output of different types of plants

5. Conclusions

An exergoenvironmental analysis of solid oxide fuel cell systems for heating, cooling and electricity generation has been performed to provide useful insights in terms of heat recovery and environmental aspects. The results show that system efficiencies, exergy destructions, the amount of CO_2 emission and sustainability index are notably affected by operating current density and SOFC temperature. The afterburner and SOFC are the two main components with the high exergy destruction while the use of absorption chillers offers effective heat recovery with the lowest exergy destruction of the whole system. In addition, chilled water generation from absorption chillers in the trigeneration system is one of the best heat recovery strategies that exhibit lesser CO_2 emissions than other types of conventional power plants.

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