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Maximizing the Efficiency of a Heat Recovery Steam Generator for Solid Oxide Fuel Cell-Based Trigeneration Systems

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In this study, a complete strategy for the optimum design of a heat recovery steam generator (HRSG) is outlined. The performance of the heat recovery steam generator is examined by modelling a trigeneration system based on an ethanol-fuelled solid oxide fuel cell in Aspen Plus. To maximize the HRSG efficiency, the performance of the HRSG at different steam product specifications is investigated in terms of the exergy efficiency and exergy destruction. The result shows that to minimize exergy destruction in the HRSG, the temperature difference across the HRSG should be maintained at a minimum and superheated condition should be avoided. Heat recovery steam generator with double pressure levels shows the maximum efficiency when utilizing 10 - 30 % of recovered heat for cooling application and employing the remaining heat for heating devices at nearly saturated condition.

1. Introduction

Trigeneration technology, which involves the production of electricity, heat and cooling in single process, has been known to be an optimal solution for ultimate level of energy usage. Presently, a number of researchers strive to discover, develop and thoroughly understand its operation throughout the possible engines and thus, many of the scientific studies on this subject have been reported. A solid oxide fuel cell (SOFC)-based power system is regarded as a highly efficient and environmentally friendly process for trigeneration. Producing electricity on SOFCs offers more than 60 % efficiency over a wide range of primary fuels and power outputs (EG&G Technical Services, 2004). When the heat produced is also harnessed, the overall efficiency of the SOFC system in converting fuel to energy can be over 80 % (Thanomjit et al., 2012).

The SOFC-based trigeneration system can be physically decomposed into three sub-systems, i.e., power system (SOFC), heat recovery system (heat recovery steam generator, HRSG) and cooling system (absorption chiller). Due to its operation, the SOFC releases large amounts of thermal energy at relatively high temperatures (873 - 1,273 K). However, a commercially available absorption chiller rated between one to 1,000 refrigeration tons (one refrigeration ton is equal to 3.5168 kW) needs input steam at temperature of 423 K (Moné et al., 2001). Thus, a large temperature difference occurs between the two crucial elements in the system that strongly affects the overall system performance. The HRSG becomes a primary source of irreversibility and its comprehensive operation is needed to understand.

Generation of steam in HRSG is always associated with the use of exhaust heat from gas/steam turbines to create steam and deliver it to steam turbines which generate additional electricity. Franco and Giannini (2006) presented the optimum design of the HRSG at different levels of complexity with several operating parameters, geometrical details and technological elements. In case of HRSG failure, the steam cycle is shut down. Carazas et al. (2011) evaluated the reliability and availability of HRSGs and proposed the maintenance concepts. Kaviri et al. (2013) discussed in detail how the energy and exergy analyses of HRSGs in combined cycle power plant can be employed to evaluate the plant performance in environmental aspect. To date, the study on HRSG in the SOFC system is quite limited. Designing a HRSG to utilize a SOFC exhaust heat in the

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steam cycle in order to achieve optimum absorption chiller output is still a challenging problem for fuel cell-based trigeneration system.

The aim of this study is to design the HRSG for solid oxide fuel cell-based trigeneration system with respect to various key operating parameters, such as pressures, mass flow rates and temperature. Energy and exergy analyses are performed to optimize toward the maximum efficiency. The guideline of heat recovery assessment for the combined cooling, heating and power generation is provided.

2. Description of the Solid Oxide Fuel Cell-based Trigeneration Systems

Figure 1 shows a flowchart of the solid oxide fuel cell-based trigeneration system. It supplies energy in three forms: (1) electricity from the SOFC, (2) heat by recovering the SOFC exhaust gas in the form of steam and (3) chilled water by using the steam driven-absorption chiller.

According to the advantages of liquid fuel and environmental friendliness, ethanol can be chosen to be a primary fuel in fuel cell systems (Rossetti et al., 2015) by feeding hydrogen rich gas from ethanol steam reforming process (Tippawan and Arpornwichanop, 2014). The possible reactions in the ethanol-fuelled SOFC system are shown in Table 1. As a means of reducing the risk of misunderstanding, the electricity from SOFC is a mainly product. The maximizing efficiency of the HRSG is the consequence of using the heat from anode hot gas effectively. The SOFC modelled by using Aspen Plus simulator has been designed for 1 MW net power. The SOFC system is operated based on data given in Table 2. When the electrochemical reactions occur, the SOFC generates electricity and releases some heat as anode hot gas. Passing the HRSG, the hot gas transfers heat to the feed water, which is heated and converted into different kinds of steam: low pressure (LP), high pressure (HP) and superheated steam for cooling application, heating devices and entering the steam turbine to produce more electricity, respectively. For cooling application in the double-effect LiBr/water absorption chiller, the low pressure steam is set at 0.8 MPa, while the high pressure steam (7 MPa) is specified for heating and entering the steam turbine applications. To verify the models, validations of the SOFC model proposed by Aguiar et al. (2004) and the absorption chiller model developed by Herold et al. (1996) were performed by comparison with published data. For more information, the modelling details, assumptions and other parameters are given in our previous work (Tippawan et al., 2015a).

3. Design of the Heat Recovery Steam Generator

A preliminary design of the HRSG follows the system analysis based on 1 MW power output of SOFC, which releases exhaust gas with the mass flow rate of 924 kg/h at temperature of 1,073 K. Firstly, the maximum amount of energy that could be extracted from hot gas is calculated. Then, the heat recovery strategy is designed and five case studies for different products of steam are considered, as shown in Figure 2. Table 3 describes the steam product specification for each case study. Finally, the concept of energy analysis is applied to determine the energy requirement for each element of the HRSG as follows:

$$\dot{m}_{\mathrm{w,i}}(h_{\mathrm{w,out}} - h_{\mathrm{w,in}}) = \dot{m}_{\mathrm{g}}(h_{\mathrm{g,in}} - h_{\mathrm{g,out}}) \tag{1}$$

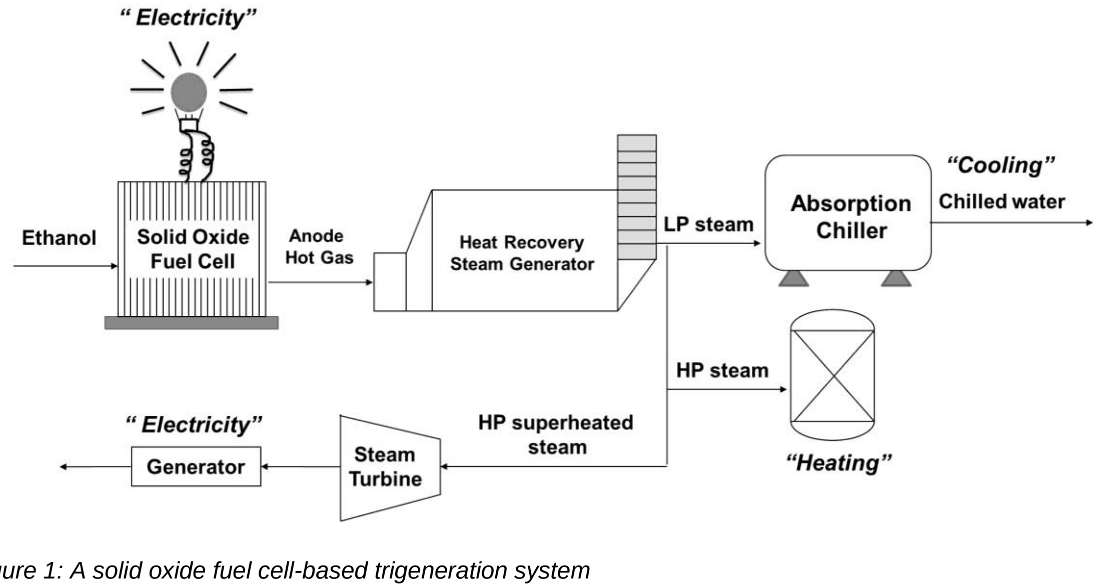

Figure 1: A solid oxide fuel cell-based trigeneration system

Table 1: Possible reactions in the ethanol-fuelled SOFC system (Tippawan and Arpornwichanop, 2016)

Ethanol steam reforming
$C_2H_5OH \leftrightarrow CH_3CHO + H_2$
$C_2H_5OH \leftrightarrow C_2H_4 + H_2O$
$CH_3CHO \leftrightarrow CH_4 + CO$
$CH_4 + H_2O \leftrightarrow CO + 3H_2$
$CO + H_2O \leftrightarrow CO_2 + H_2$
$C_2H_4 \leftrightarrow [polymers] \leftrightarrow 2C + 2H_2$
$2CO \leftrightarrow CO_2 + C$
$CO + H_2 \leftrightarrow H_2O + C$
$CO_2 + 2H_2 \leftrightarrow 2H_2O + C$
SOFC electrochemical reactions
$0.5O_2 + 2e^- \rightarrow O^{2-}$
$H_2 + O^{2-} \rightarrow H_2O + 2e^-$
$H_2 + 0.5O_2 \rightarrow H_2O$

Table 2: Simulation data for the SOFC system

SOFC materials and thickness	
Anode	Ni-YSZ 500 µm
Cathode	$La_{1-x}Sr_xMnO_3$ 50 µm
Electrolyte	YSZ 20 µm
SOFC operating conditions	
Power output	1 MW
Operating temperature	1,073 K
Operating pressure	1 atm
Fuel utilization	70 %
SOFC anode hot gas compositions (mole fraction)	
H_2O	0.5157
CO_2	0.2196
CO	0.0745
H_2	0.1902

4. Maximizing the Efficiency of a Heat Recovery Steam Generator

When the same amount of energy is supplied to HRSGs for producing steam in each case study and no heat loss to surroundings is also assumed, the energy analysis cannot sufficiently explain the way energy is used and provide no information about the usefulness of this recovered heat. Exergy analysis can overcome the limitation of this energy analysis by providing the meaningful efficiencies and the true magnitudes loss of the energy in term of the exergy destruction (Tippawan et al., 2015b).

When applying the exergy balance, the exergy destruction can be explained as:

$$\dot{E}x_{\mathrm{D}} = \sum_{\mathrm{in}} \dot{E}x_{\mathrm{i}} - \sum_{\mathrm{out}} \dot{E}x_{\mathrm{i}} \tag{2}$$

where $\dot{E}x_{\mathrm{i}}$ is the exergy of each stream in the system that can be calculated as follows:

$$\dot{E}x_{\mathrm{i}} = (h_{\mathrm{i}} - h_0) - T_0(s_{\mathrm{i}} - s_0) \tag{3}$$

To determine the maximum efficiency of HRSG, the exergy efficiency is used and defined as the product exergy output divided by the exergy input as follows:

$$\eta_{\mathrm{Ex}}(\%) = \left(\sum_{\mathrm{out}} \dot{E}x_{\mathrm{i}} \Big/ \sum_{\mathrm{in}} \dot{E}x_{\mathrm{i}} \right) \times 100 \tag{4}$$

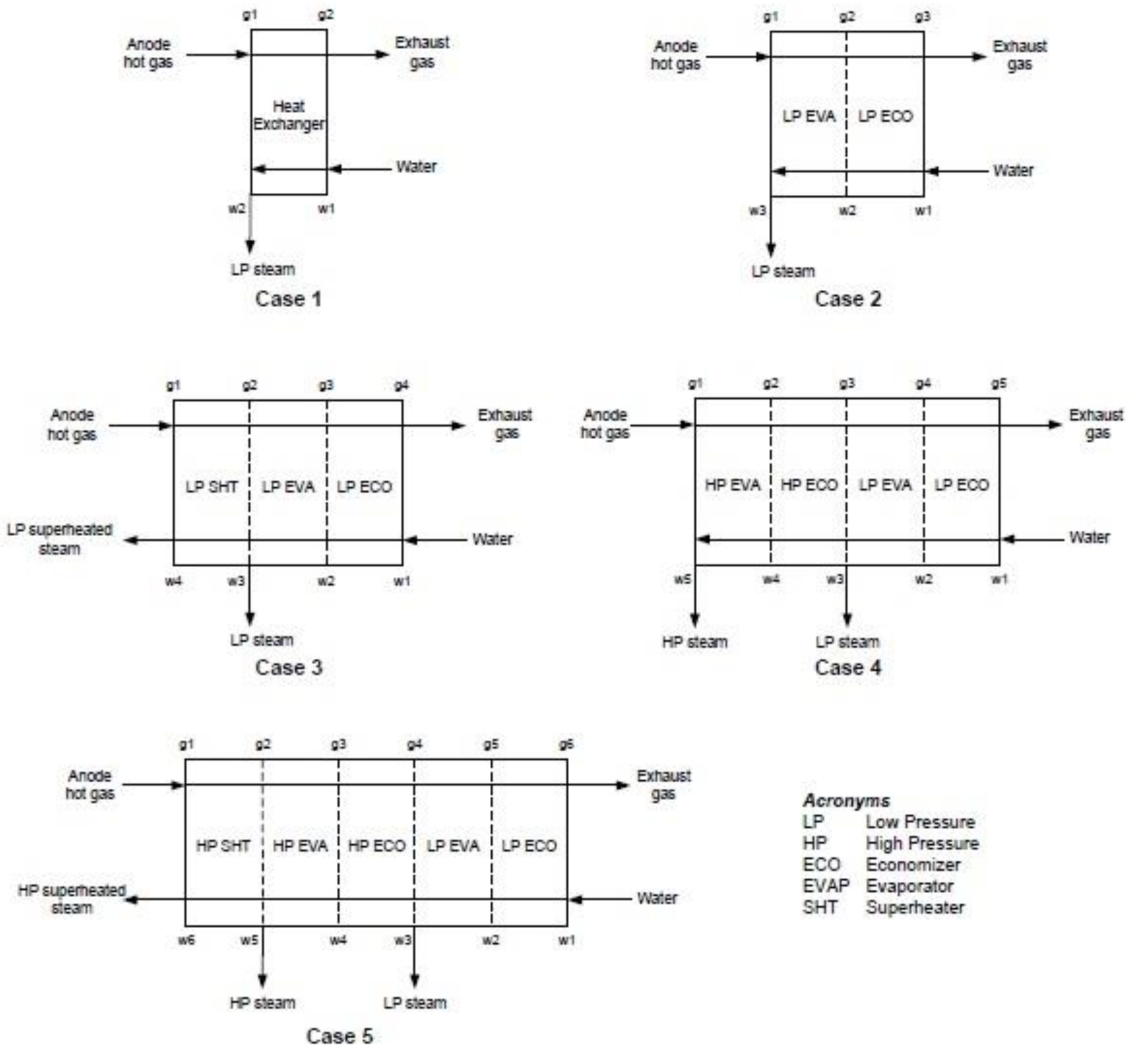

Figure 2: Schematic diagrams of the heat recovery steam generator in each case study.

Table 3: Specification of the steam produced from the heat recovery steam generator in each case study.

Case study	Description
1	Low pressure steam production at 0.8 MPa
2	Low pressure steam production at 0.8 MPa with separated evaporator
3	Low pressure and superheated steam production at 0.8 MPa
4	Low pressure (0.8 MPa) and high pressure (7 MPa) steam production
5	Low pressure (0.8 MPa), high pressure (7 MPa) and superheated steam production at 7 MPa

5. Results and Discussion

Useful heat from SOFC exhaust gas can be recovered to produce steam with different specifications for various applications. The exergy efficiency and exergy destruction for each case study are shown in Figure 3(a)-(b). The results show that when the recovered heat is totally used for cooling application, the HRSG with Case 1 configuration for LP steam production has the maximum efficiency and shows the lowest exergy destruction. However, in this case, a two-phase heat exchanger with large heat transfer area is required. By using separated evaporator (Case 2), the size of the heat exchanger become smaller and the HRSG efficiencies of both the Case 1 and 2 are close. When steam with LP for cooling and with other specifications for heating is considered (Cases 3-5), the efficiencies of the HRSG decreases. The exergy analysis of the steam production at various product ratios (the amount of steam for heating and that for cooling) for Cases 3-5 is examined as shown in Figure 4(a)-(d). The results indicate that when producing more steam for heating applications, the exergy efficiency of the HRSG increases whereas its exergy destruction decreases. Increasing pressure to produce HP steam is better than increasing temperature for superheated steam production (Figure 4(a) and (b)). This is because the steam near saturated temperature has higher quality of energy than that at superheated temperature. For this reason, the HRSG efficiency of Case 5 where HP superheated steam is produced (Figure 4 (c)-(d)) is not high as that of Case 4. In general, a superheated steam has the extremely high temperature that causes high entropy generation and the energy degradation.

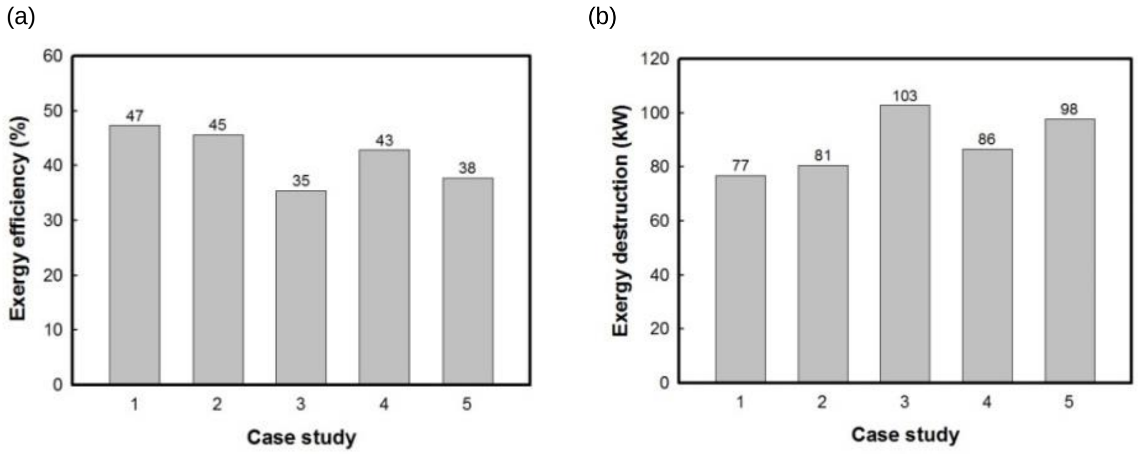

Figure 3: (a) Exergy efficiency and (b) exergy destruction for each case study of the heat recovery steam generator.

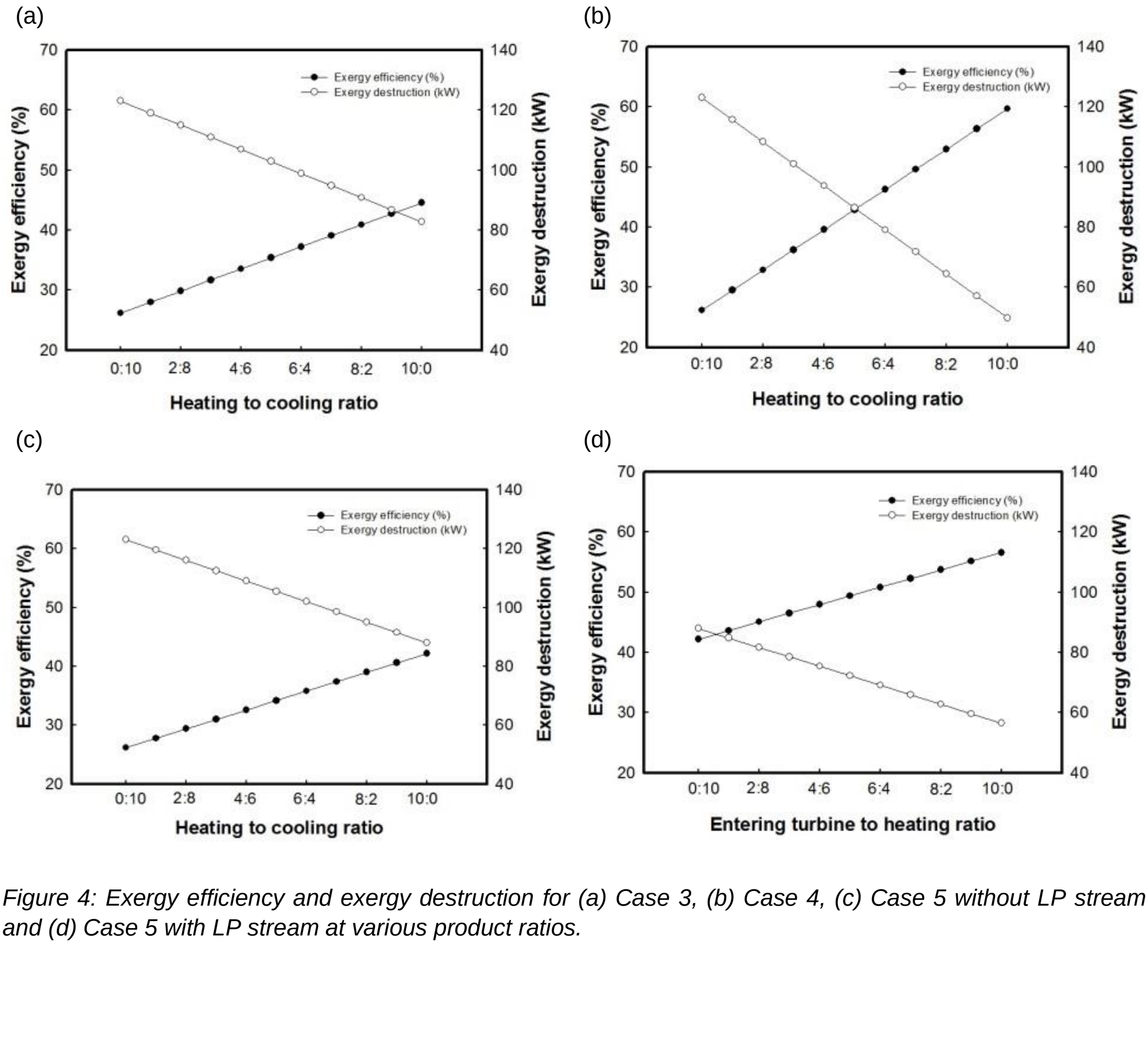

Figure 4: Exergy efficiency and exergy destruction for (a) Case 3, (b) Case 4, (c) Case 5 without LP stream and (d) Case 5 with LP stream at various product ratios.

6. Conclusions

In this study, the use of a heat recovery steam generator (HRSG) for a solid oxide fuel cell-based trigeneration system is investigated. The best strategy of using the HRSG in the solid oxide fuel cell system is found that utilization of the exhaust heat from the fuel cell to generate LP steam for cooling application (10-30 %) and to produce HP steam for heating application (70-90 %) provides the maximum efficiency. A dual-pressure HRSG with two economizers (LP and HP) and two evaporators (LP and HP) is recommended.

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