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Heat Integration of Solid Oxide Fuel Cell System

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Abstract. As solid oxide fuel cell (SOFC) has operating temperatures ranging between 973 K for intermediate temperature operation and 1273 K for high temperature operation, an advantage of the hot exhaust gas from SOFC can be used to drive a fuel processor for hydrogen production. In this study, the heat integration of a SOFC integrated with ethanol steam reformer, which is very highly endothermic reaction needed the large amount of energy supply, has been performed to improve the efficiency of SOFC system. In the conceptual design for heat integration, the pinch analysis is used. Under 1200 K of SOFC operating temperature and 973 K of reformer temperature, the hot exhaust gas leaving the SOFC is sufficient for heating requirements for the heat exchanger network and for the additional electricity generation from gas turbine. An energy integrated SOFC system presents a total electricity generation from SOFC and GT of 818 kW of which 386 kW is required for air compressor so an overall electricity production and efficiency are 432 kW and 35.0%, respectively.

Introduction

It has been distinguished that the processes of energy production need to be more efficient for a sustainable future. In addition, the severe problems of global warming, atmospheric pollution, rising energy cost and demand, and energy security in a decade ago have highlighted the need to develop power generation system for increasing efficiency and decreasing emissions. Therefore, there has been an increasing level of interest in developing fuel cell systems. It is recognized that fuel cells have attracted extensive interest as highly effective and environmentally acceptable systems since they can convert chemical energy to electrical energy and heat directly from fuels through electro-chemical reactions at electrodes. Among different types of fuel cells, a solid oxide fuel cell (SOFC) can offer the widest potential range of application and high system efficiency [1]. The SOFC is exceptionally interesting because of its very high operating temperature range between 973 and 1273 K that exhaust gas can be a heat source for the reforming process and their off-gases can be used to fire a secondary gas turbine to improve electrical efficiency. A SOFC power system mainly consisting of a fuel processor and a fuel cell generally demonstrates a lower overall efficiency because the additional energy is required to force the endothermic reforming reactions [2]. To improve the SOFC overall system efficiency, a heat integration is completed by using the pinch analysis.

Panopoulos et al. [3-4] performed the high temperature SOFC integrated with biomass gasification and focused on thermodynamic modeling and exergy analysis. Douvartzides et al. [5] reported the optimization of the overall ethanol-powered SOFC plant in terms of efficiency for generation of electrical power and exergy destruction due to irreversibility. The strategies of energy integration for SOFC systems combined with the Methylcyclohexane reactor were presented by Cresswell and Metcalfe [6]. Zhang et al. [7] also proposed various diverse integration strategies for SOFC energy systems. Srisiriwat et al. [8] presented SOFC integrated with different fuel processors fueled by ethanol that the efficiency of hydrogen production and SOFC power generation with various technologies of hydrogen production was compared. Although various works have been focused on the energy integration for SOFC system combined with many types of fuel resources to produce hydrogen-rich gas used as the fuel for the SOFC, the study on the energy integrated ethanol steam reformer and SOFC system is limited. In our previous work [9], the effects of steam reformer temperature and amount of water ratio on the efficiency of hydrogen production and SOFC operating conditions were presented.

In this paper, the heat integration of a combination of ethanol steam reformer and SOFC unit is performed by using the pinch design analysis in order to reduce the energy usage for SOFC system. The process description, the nominal parameters for an energy integrated SOFC system and the methodology of heat integration are presented as well.

Overview of SOFC system

The process flow diagram for a steam reformer (SR) integrated with solid oxide fuel cell (SOFC) fueled by ethanol to generate electricity and waste heat is demonstrated in Fig. 1. The system is composted of pumping devices, including liquid pumps and air compressor, heat exchangers, steam reformer and SOFC unit. Ethanol mixed with water is preheated before entering the SR at which the high energy for the endothermic reaction is added. The hydrogen-rich gas is produced in the SR and then fed into the anode side SOFC and air is compressed and preheated before entering the cathode side to produce the direct current power and hot exhaust gas from SOFC (stream *a*). Inside the fuel cell, the SOFC reactions that take place at anode and cathode to generate both of the electricity and heat can be described as:

Anode: $H_2 + O^{2-}$ $H_2O + 2e^-$

Cathode: $\frac{1}{2}O_2 + 2e^-$ O^{2-}

Overall: $H_2 + \frac{1}{2}O_2$ H_2O (1)

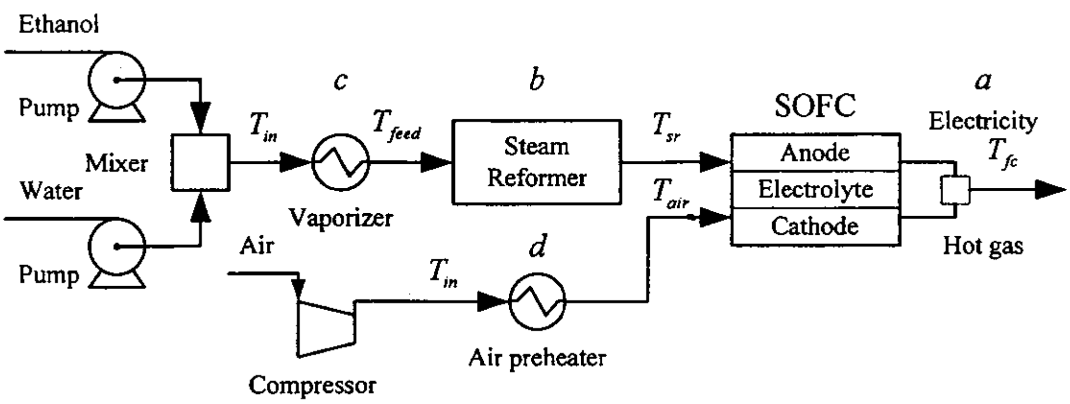

Fig. 1 Process flow diagram for SOFC system.

Heat Integration

A key component of the overall system efficiency is the energy integration [6] that the waste heat from the fuel cell can be used to drive the fuel processors, which is steam reformer (SR) in this study. Table 1 shows the hot and cold streams and the supply and target temperatures of each stream under SOFC operating temperature of 1200 K at which an adiabatic operation of the SOFC is assumed. Due to the exothermic reaction of SOFC, the excess air fed into SOFC of 74.9 mol/s is supplied to obtain the adiabatic SOFC that the total air in feed of 89.2 mol/s is used. However, the excess air necessitated in the SOFC operation depends on the SOFC operating temperature. Table 2 shows nominal parameters for the energy integrated SOFC system.

There is one hot stream from the SOFC exhaust gas (stream *a*) which must be cooled so the hot stream can be exchanged with cold streams to supply heat for SR (stream *b*), vaporizer (stream *c*) and air preheater (stream *d*) with the heat load of 477, 554 and 1281 kW, respectively, when the well insulated heat exchanger system is assumed so the heat loss can be neglected. However, the small amount of heat load of liquid pumps compared with other units can be negligible.

Table 1 Hot and cold streams

Stream	Description	Hot/Cold	Supply Temp. (K)	Target Temp. (K)
a	Fuel cell exhaust	Hot	1200	318
b	Steam Reformer	Cold	473	973
c	Vaporizer	Cold	298	473
d	Air preheater	Cold	298	773

Table 2 Nominal parameters for SR integrated SOFC system

Ethanol molar flowrate	1.0 mol/s	SOFC temp.	1200 K
Water molar flowrate	10.0 mol/s	Cell Voltage	0.64 V
Air molar flowrate	89.2 mol/s	Current	1037.5 A
H_2O:EtOH ratio	10	Cell Power	664 KW
Cathode gas of (%) O_2/N_2	21/79	Stack pressure	1.01 bar
Anode gas (%) $H_2/CO_2/CO/H_2O$	35.9/9.3/4.0/50.8	Air utilization	0.16
Outlet gas of SOFC (%) $H_2O/CO_2/O_2/N_2$	12.8/2.6/15.4/69.2	Fuel utilization	0.90

In the energy integration, it can be found that there is no pinch temperature for the energy integrated SOFC system when an energy integration using the pinch analysis was investigated at ΔT_{min} of 20 K as shown in Table 3 that shows the specific problems remaining pinch free called threshold problems. In this case, the heat integration design can be started from the non-utility end, using the pinch design rules [10]. It can be observed that for the high temperature SOFC, the usable heat of hot stream leaving SOFC unit was much enough to drive the integrated SR with SOFC unit. The additional electricity generated by heat recovery gas turbine (GT), placed in the SOFC system to reduce the cold utility of 628.68 kW for removing heat, can supply for the compressor and other electrical devices in SOFC systems as shown in Fig. 2.

Table 3 Hot and cold utility at ΔT_{min} = 20 K for SOFC system

Boundary Temp. (K)	Stream and Temperature (K) Cold Stream		Hot Stream		Deficit (-) Surplus(+) (kW)	Accumulated Heat (kW) Input	Output
1190		1180	1200				
					-691.38	0	691.38
983		973	993				
					-476.00	691.38	1167.38
783		773	793				
					-96.00	1167.38	1071.38
483		473	493				
					442.75	1071.38	628.63
308		298	318				

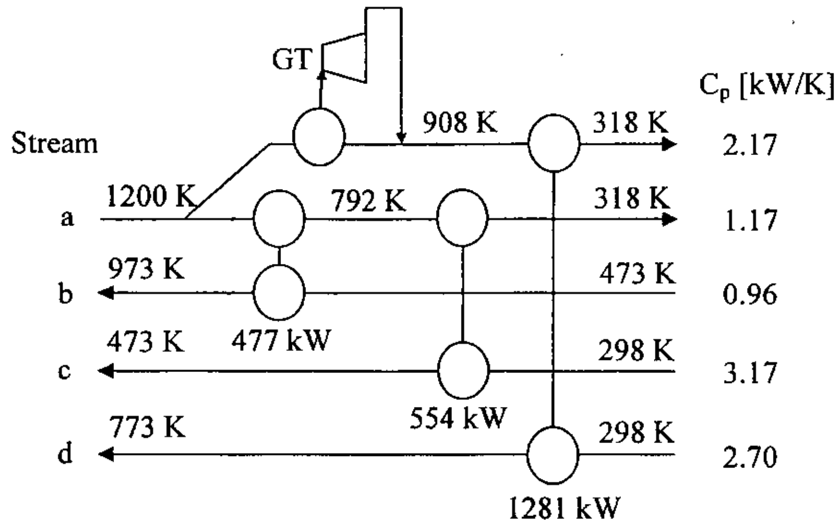

Fig. 2 Stream match and placement of gas turbine.

The outlet stream of SOFC unit is recycled through the HEN in order to provide energy to the integrated SOFC system. As illustrated in Fig. 3, the hot stream leaving the SOFC unit is split into two streams by the splitter that the value of splitter fraction of 0.35 can be calculated as the mass flowrate in the hot stream a divided by the total mass flowrate of the SOFC exhaust stream. The spite hot stream a_1 must be enough to supply heat for both the SR and the vaporizer of ethanol solution. The high temperature exhaust of the remaining split hot stream a_2 can be used to generate the additional electricity using GT. As the high quality of the high temperature steam production is practicable, the hot stream a_2 is initially fed into heat recovery unit. The hot exhaust gas leaving the heat recovery unit is then supplied for the air preheater.

The molar flowrate and temperatures around the flowsheet are also summarized in Fig. 3. They show a total electricity generation of 818 kW while 386 kW is required for air compressor. Therefore, an overall electricity production and efficiency of the energy integrated SOFC system are 432 kW and 35.0%, respectively.

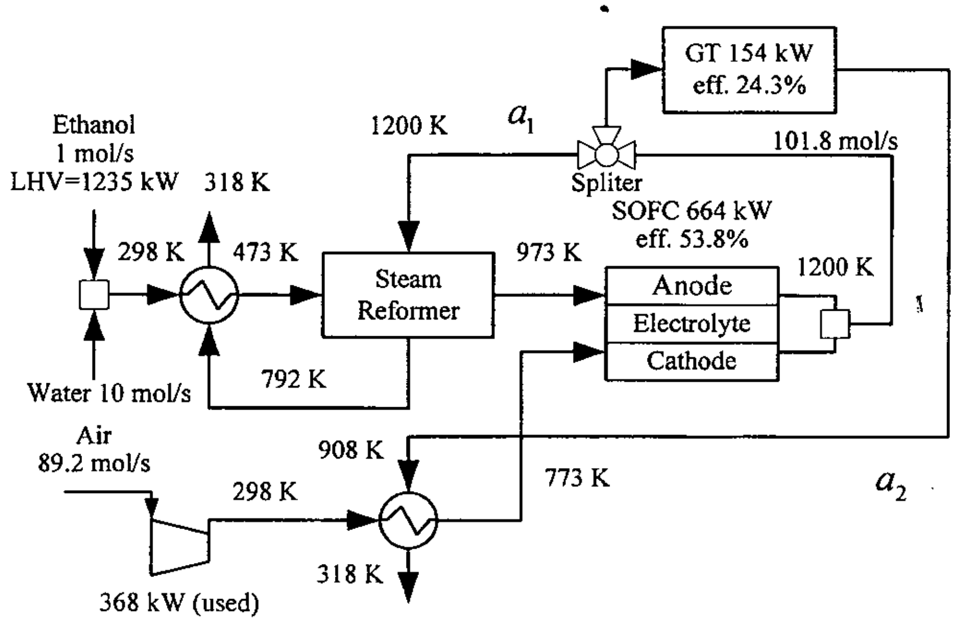

Fig. 3 Heat integration for SOFC system.

Conclusion

The heat integration of solid oxide fuel cell (SOFC) system under 1200 K of SOFC operating temperature and 973 K of steam reformer (SR) temperature was carried out by using the pinch analysis. The high operating temperature of the SOFC gives an important advantage compared to low temperature fuel cells. The waste heat is needed to reject at a much higher temperature and that is an advantage if the waste heat is to be utilized for heating the other units so the waste heat can be turned into useful energy. In this study, one hot exhaust stream leaving SOFC is enough for driving the SR being very highly endothermic in the nature needed the large amount of energy supply and for heating requirements for the heat exchanger network and for the additional electricity generation from gas turbine. A total electricity generation from SOFC and GT is 818 kW of which 386 kW is required for air compressor. Consequently, the energy integration can achieve an overall electricity production and efficiency of 432 kW and 35.0%, respectively.

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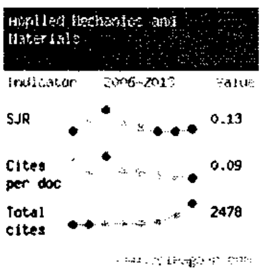

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Indicators	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
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Total Documents	-	-	-	-	-	-	-	64	44	233	298	2.022	7.752	19.420	29.233
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Total References	-	-	-	-	-	-	-	757	440	1.888	2.273	17.038	63.057	158.660	243.968
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Cited Docs.	-	-	-	-	-	-	-	11	14	41	53	81	238	768	1.927
Uncited Docs.	-	-	-	-	-	-	-	55	116	133	288	494	2.315	9.304	27.267
% International Collaboration	-	-	-	-	-	-	-	18,75	15,91	11,59	3,69	2,03	3,22	2,51	2,49