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Performance Analysis of the Solid Oxide Fuel Cell and Oxyfuel Combustion Integrated System with Different Recycling Methods

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A solid oxide fuel cell (SOFC) has been regarded as the future power generation due to its high efficiency and environmental friendliness. In general, hydrogen used as a fuel in SOFC is produced from hydrocarbon fuel processing that releases carbon dioxide (CO_2). Thus, a SOFC power plant requires a CO_2-capture process. Among the various types of CO_2 separation, the oxyfuel combustion is an interesting approach due to its capability of total CO_2 capture with low energy consumption. In this study, the SOFC and oxyfuel combustion integrated system is investigated. To improve its performance, the integrated SOFC system with different recycling schemes: SOFC anode outlet stream (anode recycling) and water condensate stream (steam recycling), is proposed. Pameteric analysis of key design parameters in the SOFC system is performed by considering electricity and heat generation. The simulation results show that the SOFC system with anode recycling provides better electrical efficiency than that with steam recycling due to high utilization of fuel in SOFC and capability of integrating a fuel turbine in the SOFC system. For the SOFC with steam recycling, the fuel turbine cannot be implemented due to insufficient heat for preheating inlet streams.

1. Introduction

Fuel cell is an alternative, attractive power generation device because of its high electrical efficiency without mechanical loss caused by moving parts. Among the various types of fuel cells, a solid oxide fuel cell (SOFC) is interesting. It is operated at high temperatures and does not require expensive precious metal catalysts. For SOFC operation, hydrogen is used as a fuel. In general, the production of hydrogen involves carbon-based fuel processing that produces carbon dioxide (CO_2). CO_2 emissions from power plants are around 40 % of the world CO_2 emission and thus, a new design of power plant requires CO_2 capture processes, such as chemical looping process (Chen et al., 2015) and oxyfuel combustion (Petrakopoulou et al., 2014).

A SOFC and oxyfuel combustion integrated system is the most promising technology as CO_2 can be easily separated from exhaust gas by condensation, leading to a possibility of complete CO_2 capture. Park et al. (2011b) reported that such integrated system performed high electrical efficiency at 65.0 %, which gave higher efficiency than the SOFC and cycle gas turbine combined system with a liquid absorption process (53.8 %) (Pan et. al., 2014). In addition, the SOFC integrated with oxyfuel combustion provided better result than the SOFC-physical absorption integrated system in term of electrical efficiency (Park et al., 2011a). The oxyfuel combustion process, which uses oxygen from ion transport membrane (ITM), utilized energy less than the conventional CO_2 capture process. Franzoni et al. (2008) studied the performance of the high pressure SOFC-CO_2 capture integrated system and the results revealed that the SOFC and oxyfuel combustion was still preferred. Energy penalty of the oxyfuel combustion was 3.6 %, whereas the conventional process (amine absorption) was 17 %. In addition, the oxyfuel combustion gives higher performance in term of economic than the absorption process. The energy penalty of the oxyfuel combustion is near to its thermodynamic penalty, which is 2.14 %, whereas the thermodynamic penalty of the absorption process is 1.84% (Anantharaman et. al., 2013).

Regarding the fuel processing to produce hydrogen for SOFC, a steam reforming is widely used and it is generally operated at high steam to carbon (S/C) ratio; steam is added to a reformer higher than the

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stoichiometric ratio of steam reforming and water gas shift reactions to prevent carbon deposition on catalyst surface (Braun, 2002). The common SOFC process uses a steam generation for the reforming process. To reduce energy consumption, an anode outlet stream of the SOFC at high temperatures can be used as a heat source for the reforming process and steam generation. This operational strategy is called anode recycling (AR). Many studies reported the improvement of the SOFC system efficient by using the anode recycling stream. Liso et al. (2011) showed that the implementation of AR could minimize the need for boiler to generate steam and reduce size of air equipment which lowers a capital cost. Furthermore, the overall efficiency of the SOFC system would be increased because of efficient energy usage. However, a higher CO_2 in the recycling stream causes the kinetic of the steam reforming reaction be lower (Peter et al., 2002).
In this study, the performance of a SOFC and oxyfuel combustion integrated system is investigated. The system with different operational strategies, i.e., anode recycling (AR) and steam recycling (SR), is studied. For the steam recycling method, water removed from CO_2-rich stream at the condensation stage of the oxyfuel combustion process is vaporized and recycled back to a pre-reformer. Energy production and demand of the proposed system is analyzed. Sensitivity analysis is performed to study effects of key operating parameters, e.g., steam to carbon ratio (s/c ratio), fuel utilization factor and SOFC temperature, on the system performance.

2. Model of SOFC-oxyfuel combustion integrated system

In this study, the SOFC and oxyfuel combustion integrated system is modelled in Aspen Plus simulator. The thermodynamic properties of components are predicted by Redlich–Kwong–Soave equation of state.

2.1 SOFC

SOFC model is developed based on the work by Zhang et al. (2005). The SOFC model consists of anode and cathode. The equilibrium reactor (RGibbs module) is used to explain the electrochemical reaction Eq(1), steam reforming reaction Eq(2) and water-gas shift reaction Eq(3) at the anode, whereas the gas separator represents the cathode of SOFC where oxygen is separated from air and sent to the anode.

$$2H_2 + O_2 \rightarrow 2H_2O \tag{1}$$

$$CH_4 + H_2O \rightarrow 3H_2 + CO \tag{2}$$

$$CO + H_2O \rightarrow H_2 + CO_2 \tag{3}$$

From the flowsheet of SOFC, stream data obtained are used to predict cell electrical characteristics using the electrochemical model proposed by Aguiar et al. (2004). This model is implemented in Aspen Plus flowsheet by using a Calculator Block tool. In addition, the Design Spec function is used to find air inlet stream flow rate for the SOFC operation at an adiabatic condition. To perform the simulation of SOFC, the oxygen transfer rate from the cathode to the anode is used to adjust a fuel utilization factor.

2.2 Oxyfuel combustion

Adiabatic catalytic combustor is applied to combust the remaining fuel from SOFC. The completed combustion reactions of hydrogen, methane and carbon monoxide are specified. Excess oxygen (2 %) is fed to the combustor and no pressure loss is assumed.

2.3 Pre-reformer

Pre-reformer is used for fuel preparation to SOFC. Changes in the pre-reformer are mostly explained by an equilibrium reactions (Liso et al., 2011). Thus, an equilibrium reactor is used and an adiabatic operation is assumed. The reactions occurred in the reformer are steam reforming Eq(2) and water-gas shift reaction Eq(3). Recycling stream flow rate is employed to adjust the steam-to-carbon feed ratio when considering the SOFC system with a recirculation.

2.4 Turbine and compressor

The isentropic models of turbine and compressor are used. Values of the isentropic efficiencies are listed in Table 1.
Figure 1 shows the schematic diagram of the SOFC and oxyfuel combustion integrated system. Methane is considered as fuel. The fuel is mixed with a recycling stream (Stream 37) before it is entered to Pre-reformer for hydrogen production via steam reforming and water gas shift reactions. The reformate stream (Stream 11) is supplied to the SOFC anode to produce power via electrochemical reaction. While air is mixed with SOFC cathode recycling stream (Stream 13) and fed to the SOFC cathode. The outlet stream from SOFC anode (Stream 21) is combusted with pure oxygen from the cryogenic air separation process

(Stream 20). Combustor temperature can be controlled by recycling its depleted stream (Stream 36), which is cooled down and split back to the combustor.

Table 1: Operating conditions and simulation data

Parameters	Value	Unit	References
Methane inlet flow rate	36	kmol/h	
Number of SOFC cells	74,000		(Rokni, 2010)
SOFC pressure	8	bar	
SOFC temperature difference	150	°C	(Liese and Gemme, 2005)
Pre-reformer inlet temperature	700	°C	(Liso et al., 2011)
Oxygen excess	2	%	
Maximum turbine inlet temperature	1,300	°C	(Rokni, 2010, Zhang et al., 2008)
Fuel turbine efficiency	0.89		(Rokni, 2010, Zhang et al., 2008)
Air turbine efficiency	0.90		(Rokni, 2010, Zhang et al., 2008)
Compressor efficiency	0.88		(Rokni, 2010, Zhang et al., 2008)
Pump efficiency	0.85		(Rokni, 2010, Zhang et al., 2008)
Mechanical efficiency	0.95		(Rokni, 2010, Zhang et al., 2008)
Maximum turbine inlet temperature	1,300	°C	(Rokni, 2010, Zhang et al., 2008)
Number of CO_2 compression stages	5		
CO_2 compression outlet temperature	30	°C	
CO_2 compression isentropic efficiency	0.8		
CO_2 compression mechanical efficiency	0.9		
Temperature difference of cold side and hot side	20	°C	
AC/DC invertor & Generator	93	%	(Park et al., 2011a)
Power usage for oxygen production	924	kJ/kg	(Kansha et al., 2011)

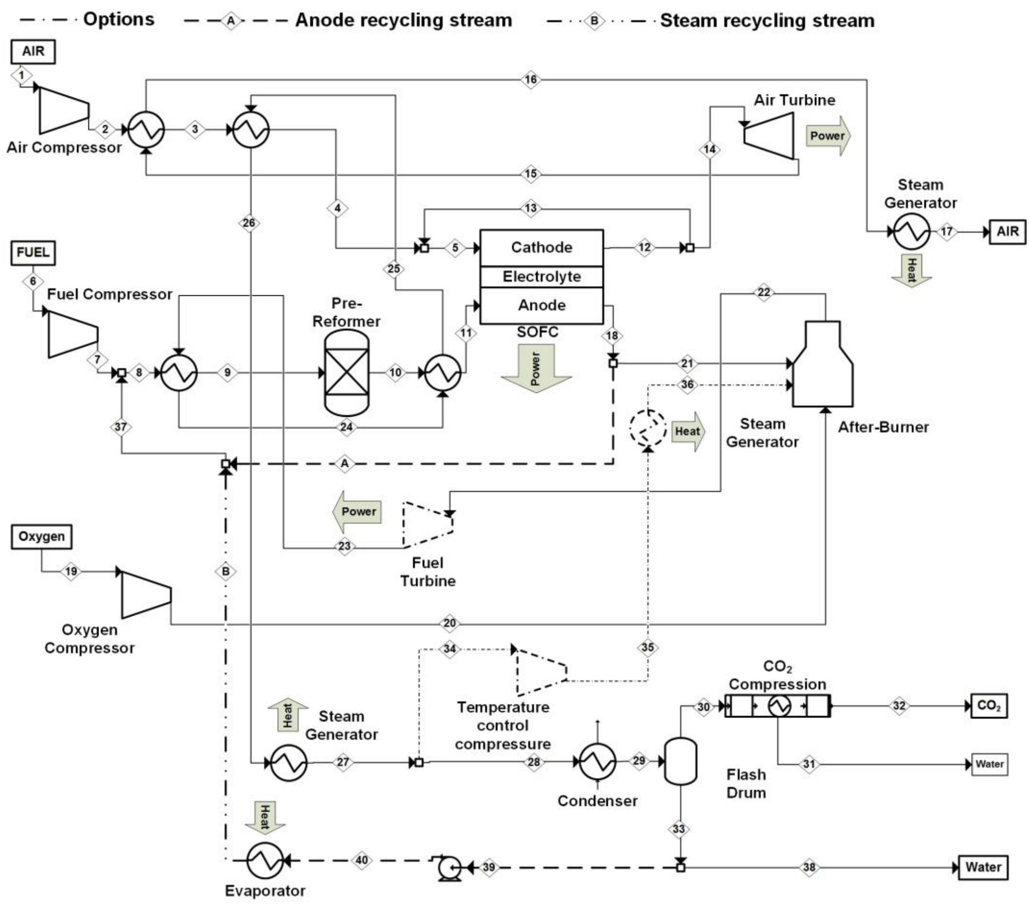

Figure 1: Process description

Regarding the oxyfuel combustion process, exhaust stream (Stream 22) can generate additional power by using a fuel turbine. SOFC cathode outlet stream (Stream 14) can also produce power via air turbine. High temperature streams from the preheating section (Stream 16 and Stream 26) have potential to deliver high pressure saturated stream (60 bar). To purify and liquefy CO_2 stream, 5 stages multi-compressor is implemented. In this study, two recycling methods are considered: Anode recycling stream (Stream A) and Steam recycling stream (Stream B).

It is noted that the dash lines represent optional operation which may or may not happen due to stream conditions. For example, in this study, the after-burner temperature is controlled below 1,300 °C by its exhaust stream (Stream 36). When the combustion temperature does not reach its constraint (1,300 °C), Streams 34-36 will be not considered.

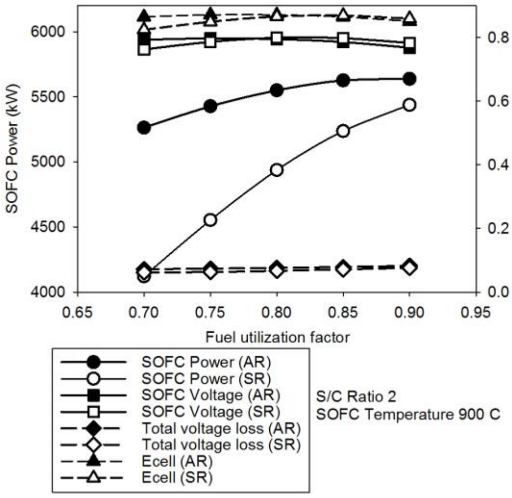

Figure 2: Effect of fuel utilization factor on SOFC

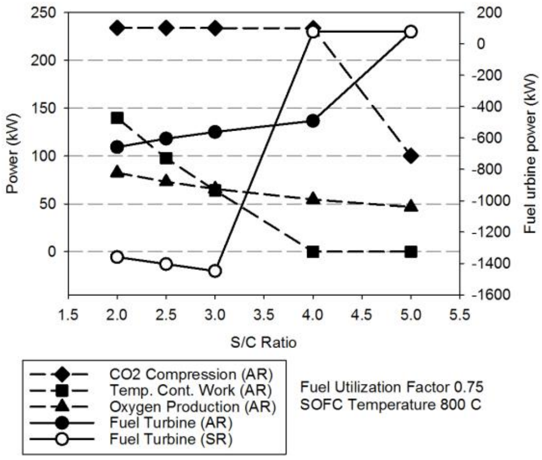

Figure 3: Effect of S/C ratio on auxiliary power.

3. Result and discussion

3.1 Effect of SOFC utilization factor on SOFC performance

Effect of utilization factor on SOFC power and voltage is presented by Figure 2. SOFC power increases with increasing utilization factor. Utilization factor means a fraction of fuel that is utilized by SOFC. Therefore, higher utilization of fuel leads to increasing SOFC power. The SOFC with AR gives higher power than that with SR as the remaining fuel at the anode is recycled to the fuel cell. However, for AR case, the utilization factor has less effect on the system power at its high value because the flow rate of the remaining fuel is low. For the system with SR, it can be seen that the power directly increases with the fuel utilization factor.

3.2 Effect of steam to carbon ratio (s/c ratio) on auxiliary power and heat of system

Figure 3 shows the effect of s/c ratio on the auxiliary power of other units in the SOFC system, such as fuel turbine, oxygen production unit by cryogenic air separation and compression. The positive and negative values mean the demand and generation of power, respectively. In addition, energy work used to compress low temperature gas stream to the After-burner for controlling the inlet temperature not exceed than 1,300 °C is shown in the figure. It is noted that most results given are for the SOFC system with AR. For the SOFC with SR, the fuel turbine power is only given as other results are similar to the SOFC with AR.

As can be seen from Figure 3, the power obtained from a fuel turbine is significant to the SOFC system. For the SOFC with AR, an increase in the s/c ratio makes fuel turbine recover less power. Because the portion of the remaining fuel from anode-off gas is recycled to the SOFC, less energy is obtained from the After-burner and fuel turbine. Moreover, a heat recovery from the fuel stream (Stream 26) is reduced. However, the fuel turbine power of the SOFC with SR shows an opposite trend. The power obtained from the fuel turbine in the SOFC with SR is significantly higher than that with AR because the anode gas is totally sent to the After-burner. The increased s/c ratio increases the flow rate of fuel to the fuel turbine and thus, the fuel turbine power.

3.3 Effect of SOFC temperature on system efficiencies

Effect of SOFC temperatures on system efficiencies is shown in Figure 4. The electrical efficiency of the SOFC with AR and SR shows similar trend at temperatures 800-900 °C. Operating the SOFC at higher temperatures reduces the total voltage losses. The fuel turbine power is also increased because of higher energy gas stream obtained from the combustor. However, the total power of the SOFC with steam recycling seems to be decreased at the SOFC temperature of 1,000 °C because the fuel turbine is disabled at this condition. Although the fuel turbine in the SOFC with AR is not implemented at the SOFC temperature of 900 °C, the electrical efficiency of the system is higher than that run at temperature of 800 °C. This is caused by a reduction of the voltage loss at high temperature operation. Regarding the overall system efficiency, an increase in the SOFC temperature has a positive effect. The overall efficiency of the SOFC wit SR is lower than that with AR due to a slight heat production, which is mainly utilized for vaporizing steam. Therefore, it can be concluded that, SR case can increases SOFC efficiency by cancelling effect of impurity, however, overall efficiency of AR case is superior than SR case in term of system consideration.

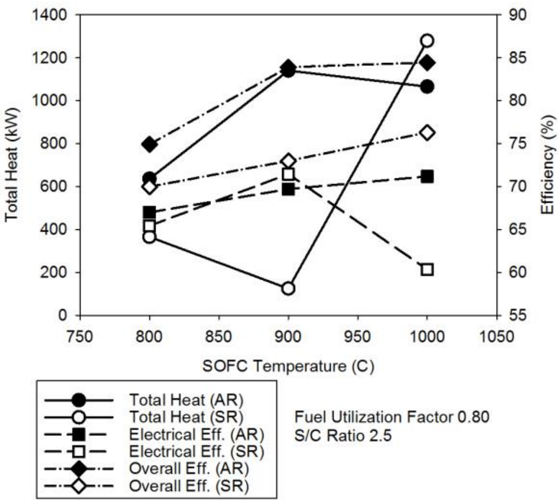

Figure 4 Effect of SOFC temperature on system efficiencies

4. Conclusions

In this study, a solid oxide fuel cell (SOFC) and oxyfuel combustion integrated system is proposed. Two different recycling methods: anode recycling (AR) and steam recycling (SR), are considered. Effects of important operating parameters, e.g., steam to carbon ratio (s/c), utilization factor and SOFC temperature, on system performance are presented. The result shows that although the fuel turbine power obtained from the SOFC with AR is lower than that with SR, the SOFC with AR shows better efficiency due to high SOFC power. The SOFC with SR is highly sensitive to the s/c ratio and SOFC temperature.

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