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Enhanced performance of solid oxide electrolysis cells by integration with a partial oxidation reactor: Energy and exergy analyses

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ABSTRACT

Hydrogen production without carbon dioxide emission has received a large amount of attention recently. A solid oxide electrolysis cell (SOEC) can produce pure hydrogen and oxygen via a steam electrolysis reaction that does not emit greenhouse gases. Due to the high operating temperature of SOEC, an external heat source is required for operation, which also helps to improve SOEC performance and reduce operating electricity. The non-catalytic partial oxidation reaction (POX), which is a highly exothermic reaction, can be used as an external heat source and can be integrated with SOEC. Therefore, the aim of this work is to study the effect of operating parameters of non-catalytic POX (i.e., the oxygen to carbon ratio, operating temperature and pressure) on SOEC performance, including exergy analysis of the process. The study indicates that non-catalytic partial oxidation can enhance the hydrogen production rate and efficiency of the system. In terms of exergy analysis, the non-catalytic partial oxidation reactor is demonstrated to be the highest exergy destruction unit due to irreversible chemical reactions taking place, whereas SOEC is a low exergy destruction unit. This result indicates that the partial oxidation reactor should be improved and optimally designed to obtain a high energy and exergy system efficiency.

1. Introduction

Hydrogen is considered to be an important, clean energy carrier for the future since it can be used in fuel cells to generate electricity. However, conventional hydrogen production processes, such as reforming and gasification, emit carbon dioxide, which causes a global warming problem [1,2]. Electrolysis cells have received attention as a clean hydrogen technology because this technology can directly convert water to pure hydrogen and oxygen via an electrochemical reaction without carbon dioxide emission. Among the various types of electrolysis cells, the solid oxide electrolysis cell (SOEC) has received considerable attention because it has higher efficiency than other electrolysis cell types [3]. The SOEC is operated at high temperatures of approximately 1073–1273 K with thermal energy requirements. Ni et al. [4] studied the effects of electrode porosity, pore size and steam molar fraction on the SOEC performance. The results showed that increases in the electrode porosity, pore size and steam molar fraction can increase the SOEC performance. In addition, it was found that the electrical energy requirement was reduced at high operating temperatures (873–1273 K). This finding was similar to Udagawa's work [5] that the effect of intermediate temperatures on the SOEC performance was studied. Therefore, the use of thermal energy from external heat sources to supply the SOEC in high temperature operations is an attractive solution to reduce the requirement of electrical energy for SOEC operation [6]. As SOEC can produce pure oxygen, a combustion process that can provide thermal energy at a high temperature by using pure oxygen from SOEC has received attention [7,8].

The combustion process can be divided into two types: complete combustion and partial oxidation process (POX). Apart from heat, steam and carbon dioxide are produced in complete combustion. On the other hand, the partial oxidation process can produce carbon monoxide and hydrogen, which can be used as fuel in several processes. Therefore, the SOEC integrated with a partial oxidation system (SOEC-POX) can enhance the ability of hydrogen production and reduce the electrical requirement for SOEC operation [9].

To assess the SOEC-POX system performance and efficiency, energy and exergy analyses are used. The energy and exergy should be analyzed simultaneously to identify the sources of energy and exergy losses of the system by using the first law of

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Nomenclature

B_g	permeability (m^2)
d_a	thickness of anode (m)
d_c	thickness of cathode (m)
$D_{H_2-H_2O}$	molecular diffusion
$D^{eff}_{H_2O}$	effective diffusion coefficient of steam ($m^2\ s^{-1}$)
$D_{H_2O,k}$	Knudsen diffusion
E^0	standard potential (V)
$E_{act,i}$	activation energy at cathode and anode ($J\ mol^{-1}\ K^{-1}$)
ex_{ch}	specific chemical exergy ($J\ mol^{-1}$)
$ex_{ch,i}$	standard chemical exergy of species *i* ($J\ mol^{-1}$)
$\dot{E}x_d$	exergy destruction (W)
ex_i	specific exergy ($J\ mol^{-1}$)
ex_{ph}	specific physical exergy ($J\ mol^{-1}$)
$\dot{E}x_Q$	exergy of thermal energy (W)
$\dot{E}x_W$	exergy of work (W)
F	Faraday's constant (96,485 $C\ mol^{-1}$)
h_i	enthalpy of species *i* at general state ($J\ mol^{-1}$)
$h_{i,0}$	enthalpy of species *i* at reference environment state ($J\ mol^{-1}$)
J	current density ($A\ m^{-2}$)
$J_{0,a}$	exchange current density at anode ($A\ m^{-2}$)
$J_{0,c}$	exchange current density at cathode ($A\ m^{-2}$)
L	thickness of electrolyte (m)
LHV_{in}	lower heating value of inlet ($kJ\ kmol^{-1}$)
LHV_{out}	lower heating value of outlet ($kJ\ kmol^{-1}$)
LHV_{H_2}	lower heating value of hydrogen ($kJ\ mol^{-1}$)
M_{H_2}	molecular weight of hydrogen
M_{H_2O}	molecular weight of steam
n_e	number of electron for electrochemical reaction (2 electron)
n_p	electrode porosity
N_{cell}	number of cells
$\dot{N}_{CH_4 in}$	molar flow rate of inlet methane ($kmol\ h^{-1}$)
$\dot{N}_{H_2,out}$	outlet molar flow rate of hydrogen ($kmol\ h^{-1}$)
$\dot{N}_{H_2 produced}$	molar flow rate of produced hydrogen ($kmol\ h^{-1}$)
$\dot{N}_{H_2O,in}$	molar flow rate of steam ($kmol\ h^{-1}$)
$\dot{N}_{in}$	molar flow rate of inlet ($kmol\ h^{-1}$)
$\dot{N}_{out}$	molar flow rate of outlet ($kmol\ h^{-1}$)
P	operating pressure of SOEC (atm)
p_{H_2}	partial pressure of hydrogen ($N\ m^{-2}$)
p_{H_2O}	partial pressure of steam ($N\ m^{-2}$)
p_{O_2}	partial pressure of oxygen ($N\ m^{-2}$)
Q	heat of the system (W)
Q_{cell}	thermal energy input rate of SOEC (W)
Q_{out}	heat rate of the reaction ($kJ\ h^{-1}$)
Q_{ovp}	heat of overpotential (W)
r	average electrode pore radius (m)
R	gas constant (8.314 $J\ mol^{-1}\ K^{-1}$)
s_i	entropy of species *i* at general state ($J\ mol^{-1}\ K^{-1}$)
$s_{i,0}$	entropy of species *i* at reference environment state ($J\ mol^{-1}\ K^{-1}$)
T	operating temperature (K)
T^*	dimensionless temperature
T_0	reference temperature (298.15 K)
U_f	utilization factor
W	electrical work (W)
W_{comp}	used energy for compressor (W)
W_{SOEC}	power of SOEC (W)
W_{SG}	used energy for steam generator (W)
y_i	composition of species *i*

Greek symbol

σ_{H_2}	collision diameter of hydrogen (m)
σ_{H_2O}	collision diameter of steam (m)
α	charge transfer coefficient
γ_i	pre-exponential factor at cathode and anode ($A\ m^{-2}$)
$\frac{\varepsilon_{H_2}}{\kappa}$	Lennard-Jones Potentials of hydrogen
$\frac{\varepsilon_{H_2O}}{\kappa}$	Lennard-Jones Potentials of steam
$\eta_{act,a}$	anode activation overpotential (V)
$\eta_{act,c}$	cathode activation overpotential (V)
$\eta_{con,a}$	anode concentration overpotential (V)
$\eta_{con,c}$	cathode concentration overpotential (V)
η_{en}	energy efficiency
η_{ex}	exergy efficiency
η_{ohm}	ohmic overpotential (V)
μ	dynamic viscosity ($kg\ m^{-1}\ s^{-1}$)
ξ	electrode tortuosity
Ω_D	dimensionless diffusion collision integral

thermodynamics and the second law of thermodynamics, respectively. Energy analysis is used to determine the energy requirement in forms of matter streams, heat and work; however, it cannot identify the real thermodynamic inefficiencies associated with the energy conversion system. In contrast, exergy analysis is a powerful tool that can be applied to a wide range of processes. It can be used to identify the location, quantity and quality of irreversible losses, as well as inefficient energy usage [10]. For this reason, there are currently many studies on energy and exergy analyses of the irreversible process. Ni et al. [11] conducted energy and exergy analyses of a proton exchange membrane electrolyzer plant to examine the effect of operating parameters on the performance and efficiency of the plant. Albrecht et al. [12] conducted exergy analysis of the partial oxidation of natural gas for a gas turbine plant. The result of this research showed that the most exergy loss occurred in the partial oxidation reactor (9.57%) and the air separation unit (6.21%). However, an exergy analysis of SOEC integrated with a partial oxidation system has not been reported yet.

The objective of this work is to study the SOEC integrated with a non-catalytic POX system in order to reduce the electrical energy and increase the SOEC system efficiency. The effects of the oxygen to carbon ratio, operating temperature, and pressure on the hydrogen yield and the efficiency of the POX reactor, as well as on the overpotentials and efficiency of the integrated SOEC system performance, are analyzed. In addition, energy and exergy analyses are applied to evaluate the performance of the SOEC-POX system, as well as the quality of energy usage within the system. The exergy destruction and efficiency of each unit of the SOEC-POX system are investigated to identify which unit should be improved.

2. Process description

2.1. Solid oxide electrolysis cell

A solid oxide electrolysis cell (SOEC) is an electrochemical device for hydrogen production via the electrochemical reaction of steam at high operating temperatures. The mechanism of SOEC operation is shown in Fig. 1(a). Fig. 1(b) presents the energy consumption in terms of electrical and thermal energies in water electrolysis. The steam is fed to a cathode channel where the electrochemical reaction takes place. The steam splits into a hydrogen molecule and an oxygen ion. Afterwards, the hydrogen is transported out of the cathode channel, while the oxygen ion