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Energy and exergy analysis and optimal design of the hybrid molten carbonate fuel cell power plant and carbon dioxide capturing process

Javad Yazdanfar [a], Mehdi Mehrpooya [a,*], Hossein Yousefi [a], Ali Palizdar [b]

[a] Renewable Energies and Environmental Department, Faculty of New Science and Technologies, University of Tehran, Tehran, Iran
[b] School of Chemical Engineering, University College of Engineering, University of Tehran, P.O. Box: 11365-4563, Tehran, Iran

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ABSTRACT

A hybrid molten carbonate fuel cell power plant and carbon dioxide capturing process is investigated through the exergy and advanced exergy analysis. The results show that the greatest exergy destruction (181 MW) occurs in the combustion chamber. It is because of irreversibility of the chemical reactions in the combustion process. Also the lowest exergy efficiency is related to the fuel cell. Advanced exergy analysis shows that the most portion of the exergy destruction is avoidable (more than 65%). Optimal design of the process is done by adjusting the effective operating conditions for reducing the power consumption and carbon dioxide emission of the process. Results of the optimization shows that the power consumption in the compressors can be reduced up to 33%.

1. Introduction

Molten carbonate fuel cells (MCFC) produce power by a feed consists of carbon dioxide (CO_2) and oxygen. Also outlet stream from the anode electrode contains high percent of the carbon dioxide (40 volume%) which can result environmental problems. Nowadays, reducing the amount of CO_2 in the atmosphere is one of the most important challenges in different societies because of the air pollution and increasing the earth temperature. So designing a MCFC process with low CO_2 emission seems to be useful. A new process integrated to MCFC for separation and liquefaction of the anode outlet carbon dioxide is introduced [1]. In this process greenhouse gas emission is reduced and also a by-product is produced. Also it was concluded that in this process post-combustion capture offers higher availability in power generation [2]. There are several researches about the molten carbonate fuel cells. Specifications of a MCFC such as cell polarization, surface area, primary particle size, and crystallization index for nine particulate carbon samples derived from the fuel oil is reported [3]. Dynamics behavior of the MCFC systems operating in a load-following mode is investigated [4]. A 1 MW molten carbonate fuel cell system (MCFCS) pilot plant was developed and investigated [5]. In [6] research and development of molten carbonate fuel cells is studied. Rashidi et al. [7] investigated the performance of a combined industrial MCFC system, including a turbo expander, which was recently installed by Enbridge Inc. in Toronto, Canada. Sciacovelli and Verda [8] investigated sensitivity analysis applied to the multi-objective optimization of a MCFC hybrid plant. Operating pressure and temperature of the MCFC, turbine inlet temperature and fuel mass flow rate were considered as design variables. Also exergy analysis of a PEM fuel cell at variable operating conditions is carried out in [9]. Braun et al. [10] studied about performance improvement of a molten carbonate fuel cell power plant via exergy analysis. Rashidi et al. [11] also studied the energy and exergy analysis of a molten carbonate fuel cell hybrid system to determine the efficiencies, irreversibilities and performance of the system. The analysis includes the operation of each component of the system by mass, energy and exergy balance equations. More detail about the thermodynamic analysis and process specifications can be found in [12]. Energy and exergy analysis of a combined molten carbonate fuel cell and gas turbine system is investigated [13]. In the literature there is not a comprehensive study about exergy analysis and splitting the exergy destruction of the process introduced in [1].

In this paper, a new process is designed and analyzed by the exergy analysis method. Sensitivity analysis is carried out to investigate effect of the operating parameters on the exergy analysis indexes. Effective operating conditions are adjusted to reduce the power consumption of the compressors. Then an optimization problem is defined for finding the global optimum point. Optimization of the process is done by genetic algorithm in Matlab software.

* Corresponding author. Tel.: +98 21 61118564; fax: +98 21 88617087.
E-mail addresses: mehrpoya@ut.ac.ir, mehdiemp@gmail.com (M. Mehrpooya).

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Nomenclature

I	irreversibility (kW)
e	specific flow exergy (kJ/kg mole)
Ex	exergy (kW)
$\dot{E}$	exergy flow (kW)
S	entropy (kJ/kg mole °C)
$\dot{m}$	flow rate (kg mole/s)
Q	heat duty (kW)
W	work transfer rate (kW)
m	number of cold streams
n	number of hot streams

Greek letters

ε	exergy efficiency
Δ	gradient

Subscripts

i	inlet
i	component
o	outlet
sh	shaft
a	air
c	cold
h	hot
k	kth component
D	destruction
P	production
F	fuel
L	loss
tot	total
others	other components

Superscripts

ΔP	pressure component
ΔT	thermal component
AV	avoidable
UN	unavoidable
EN	endogenous
EX	exogenous

Abbreviations

C	compressor
E	multi stream heat exchanger
P	pump
V	expansion valve
D	flash drum
AC	air cooler
MIX	mixer
MCFC	molten carbonate fuel cell

2. Process description

Fig. 1 shows the process flow diagram of the hybrid system. This process has four main parts:

1. Combustion of the natural gas in the combustion chamber.
2. Electrochemical reactions in the fuel cell.
3. Cooling high temperature outlet streams from the fuel cell by water cycle.
4. Separation and liquefaction of the outlet CO_2 gas from the anode.

2.1. Combustion

Inlet natural gas, stream 7, is divided into two parts. A portion of it enters E2 heat exchanger and its temperature increases up to 156 °C. Outlet streams from E2, stream 8, is mixed with a recycled gas from CO_2 separation part, stream 15, and enters combustion chamber as fuel. In the chamber, natural gas hydrocarbons burn completely and produce water and CO_2. The required air is supplied by stream 1 which its pressure is increased to the 23.3 bar by C-1 compressor. Outlet flue gas from the combustion chamber follows to the T-1 turbine which a portion of the power of the process is produced in this device.

2.2. Fuel cell and electrochemical reactions

Combustion chamber outlet enters the gas turbine and its outlet follows to the fuel cell cathode. In the cathode below electrochemical reaction occurs [14]:

$$CO_2 + 0.5O_2 + 2e^- \rightarrow CO_3^{2-} \tag{1}$$

Another part of the inlet gas to the process is mixed with the generated steam in the cooling section and after the temperature adjustment in E-1 heat exchanger, stream 10, enters the fuel cell anode. At this section hydrocarbons react with steam and produce CO and hydrogen. Then hydrogen and CO convert to CO_2 and water by means of (2) and (3) reactions [14]:

$$H_2 + CO_3^{2-} \rightarrow CO_2 + H_2O + 2e^- \tag{2}$$

$$CO + CO_3^{2-} \rightarrow 2CO_2 + 2e^- \tag{3}$$

2.3. Cooling high temperature outlet streams from the fuel cell

In this part, high temperature outlet streams from the anode and cathode enter a multi-stream heat exchanger and are cooled by a water flow at 32 °C. This heat exchanger works as the evaporator of the cooling cycle. Outlet steam from HRSG is expanded at T-2 and a fraction of it, stream 20, is sent to E-1 for adjusting the temperature of the anode inlet stream. Another fraction, steam 21, is used in E-2 heat exchanger and then leaves the process. Remained steam is rejected to the water cycle. Anode outlet, stream 11, after passing through HRSG follows to a cooler and its water is separated in a flash drum. Then it is compressed in C-3 compressor and enters the CO_2 separation section through stream 13.

2.4. Cooling and CO_2 capturing

CO_2 separation process is added to the main process of mechanical energy production for two reasons. The major reason is to reduce harmful environmental effects of large amounts of CO_2 production in the fuel cell. So based on this process the CO_2 dispersion reaches to zero. On the other hand, the produced CO_2 in the process can be used as a part of feed of the fuel cell. In this section outlet stream from the anode is separated and liquefied. Inlet feed contains CO_2, CO, H_2, H_2O and N_2. After drying and water separation, CO_2 can be separated based on the boiling point difference. After separation of the CO_2, stream 14 which includes other above said components is sent to the main process and enters