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Optimal design of solid oxide fuel cell, ammonia-water single effect absorption cycle and Rankine steam cycle hybrid system

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HIGHLIGHTS

- A combined system containing a solid oxide fuel cell is introduced and analyzed.
- In this process electricity-heat and cooling are produced simultaneously.
- Energy and exergy analyses along with economic factors are done.

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ABSTRACT

A combined system containing solid oxide fuel cell-gas turbine power plant, Rankine steam cycle and ammonia-water absorption refrigeration system is introduced and analyzed. In this process, power, heat and cooling are produced. Energy and exergy analyses along with the economic factors are used to distinguish optimum operating point of the system. The developed electrochemical model of the fuel cell is validated with experimental results. Thermodynamic package and main parameters of the absorption refrigeration system are validated. The power output of the system is 500 kW. An optimization problem is defined in order to finding the optimal operating point. Decision variables are current density, temperature of the exhaust gases from the boiler, steam turbine pressure (high and medium), generator temperature and consumed cooling water. Results indicate that electrical efficiency of the combined system is 62.4% (LHV). Produced refrigeration (at −10 °C) and heat recovery are 101 kW and 22.1 kW respectively. Investment cost for the combined system (without absorption cycle) is about 2917$ kW^{-1}.
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1. Introduction

In many industrial processes, such as food and chemical industries both electrical power and refrigeration (at low temperatures) are required [1]. Combined cooling heat and power systems have developed in residential and commercial sections. Solid oxide fuel cell (SOFC) and absorption refrigeration systems have been considered and analyzed as cogenerations systems. High efficiency, low emissions, no moving parts, reliability, low maintenance and fuel flexibility are advantages of using solid oxide fuel cells systems [2–5]. Also high operating temperature of the SOFCs causes they are used in cogeneration power plants [6,7]. Absorption refrigeration systems can work with various heat sources such as waste heat, solar thermal, geothermal and biomass [8]. Generally absorption cycles can be used with two conventional solutions: lithium bromide-water and ammonia-water. Lithium bromide-water cycle is limited to temperatures above the freezing point of water whereas the ammonia-water cycle is favorable for temperatures below 0 °C [2]. So for sub-zero refrigeration, ammonia—-water absorption refrigeration system is a good option that can be integrated with SOFC system. A new CCHP system whose main fuel is methane is proposed [9]. Overall energy conversion efficiency of this system can exceed 80% under the given conditions. Different concepts/strategies for SOFC-based integrated systems which are based on direct/indirect thermal coupling and fuel coupling schemes are studied [2]. Integration of SOFC and a double-effect lithium bromide-water absorption is investigated [10]. This hybrid system can achieve a total efficiency of 84% or more in different modes. In addition electrical efficiency has a maximum

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Nomenclature

A	Area, m^2
A_{cell}	Active area of each cell, cm^2
A_s	Specific area, m^{-1}
C	Cost of equipment ($)
CF	Capacity factor
COE	Cost of electricity, $ $kWhr^{-1}$
D_i^{eff}	Effective diffusion coefficient of species i, $cm^2\ s^{-1}$
Dij	Binary diffusion coefficient between gas species i and j, $cm^2\ s^{-1}$
$D_{i,K}$	Knudsen diffusion coefficient of species i, $cm^2\ s^{-1}$
$D_{i,M}$	Diffusivity of species i in gas mixture, $cm^2\ s^{-1}$
d_{pore}	Average pore diameter, cm
E_{thermo}	Thermodynamic voltage, V
E_{act}	Activation energy of anode or cathode, j mol^{-1}
Ex	Exergy, kW
Ex^Q	Exergy associated with heat transfer, kW
$Ex_{ch,m}$	Chemical exergy of mixture, kW
$Ex_{o,i}$	Standard molar chemical exergy, kW
F	Faraday constant, 96488.5C mol^{-1}
h	Specific enthalpy at real condition, kW
h_0	Specific enthalpy at environmental condition, kW
I	Exergy loss, kW
I	Interest rate
J	Current density, A cm^{-2}
j_0	Exchange Current density, A cm^{-2}
INDEX	Chemical engineering index
LHV	Lower Heating value of fuel, kj kg^{-1}
M_i	Molecular weight of species i
M_{ij}	Average molecular weight species i and j
m_s	Mass flow rate of strong solution, kg hr^{-1}
m_r	Mass flow rate of refrigerant, kg hr^{-1}
m_{fuel}	Mass flow rate of fuel, kg s^{-1}
N_{cells}	Number of cells
n	Number of years
n_e	Moles number of electron transferred
n_i	Moles rate of species i, mol s^{-1}
P	Total Pressure, bar
P_i	Partial pressure of species i, bar
P_o	Standard Pressure, 1atm
P_i^*	Reaction site partial pressure of species i, bar
P_i^0	Bulk partial pressure of species i, bar
R	Gas constant,8.314 $jmol^{-1}K^{-1}$,83.14cm^3 bar $mol^{-1}\ K^{-1}$
R_{H2}	Electrochemical reaction rate of H_2, mol $cm^{-2}\ s^{-1}$
R_r	Reforming reaction rate, mol $m^{-3}\ s^{-1}$
R_s	Shift reaction rate, mol $m^{-3}\ s^{-1}$
S	Specific entropy at real condition, kW K^{-1}
S_0	Specific enthalpy at environmental condition, kW K^{-1}
S/C	Steam to Carbone ratio
T	Temperature, K
T_{ap}	Approach temperature, °C
T_0	Standard Temperature, 298 K
TIC	Total investment cost, $
TPC	Total production cost, $ $year^{-1}$
U_{fuel}	Fuel utilization coefficient
V	Voltage of single cell, V
W	Work or electric power, kW

Greek letters

ΔEx	exergy change, kW
ΔG	Gibbs free energy change, kj mol^{-1}
ΔH	Heat of reaction, kj mol^{-1}
A	Transfer Coefficient, 0.5
γ	Pre-exponential factor of anode or cathode, A cm^{-2}
γ_i	Activity coefficient of i-th component
δ	Thickness, cm
ε	Porosity
η_{act}	Activation loss, V
η_{conc}	Concentration loss, V
η_{elec}	Electrical efficiency
$\eta_{elec(final)}$	Final electrical efficiency
η_{Ex}	Second law efficiency
$\eta_{net\ overal}$	Net overall efficiency
η_{Overal}	Overall efficiency
η_{ohmic}	Ohmic loss, V
τ	Tortuosity
σ	Ionic or electronic conductivity, $\Omega^{-1}\ cm^{-1}$
$\tilde{\sigma}_{ij}$	collision diameter of species i and j, nm
Ω_D	Collision diffusion integral
φ	Efficiency defect of combined system equipment
ψ	Rational efficiency

Subscripts

a	absorber
ABC	Absorption Cycle
AC	Electrical power output with conversion to Alternating Current
act	activation
AGR	Anode Gas Recycle
an	anode
c	condenser
cat	cathode
ch	chemical
comp	vapor compression cycle
con	power consumption
CS	Carbon Steel
cw	cooling water
e	evaporator, electron
elec	electrical efficiency
equi,ABC	equivalent power for absorption chiller
fuel	fuel inlet to system
g	generator
HHV	Higher Heating Value of fuel
in	inlet
k	kinetic
out	outlet
p	potential
ph	physical
real	real condition
SC	Steam Cycle
SS	Stainless steel
ST	Steam Turbine

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