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Optimal design and economic analysis of a hybrid solid oxide fuel cell and parabolic solar dish collector, combined cooling, heating and power (CCHP) system used for a large commercial tower

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ABSTRACT

A combined system containing solid oxide fuel cell (SOFC), solar parabolic dish, double effect LiBr-H_2O absorption chiller system and organic Rankine cycle is modeled and analyzed to design a novel polygeneration system producing: electricity, space heating and cooling and domestic hot water, for a commercial tower in Tehran. The system also contains a number of auxiliary components required for the balance of the plant, such as: compressors, pumps, heat exchangers and etc. Developed electrochemical model of the fuel cell using the MATLAB software is validated with experimental results. Results indicate that electrical efficiency of the solid oxide fuel cell, electrical efficiency of the combined system and overall thermal efficiency of the system are 41.49%, 48.73% and 79.49% respectively. Investment cost for the cogeneration system is computed 3.470 million dollar. The simple payback period is obtained 4.43 years.

1. Introduction

In the past decade, many researchers' activities in the energy field have been concentrated on the improvement of new energy conversion systems that are able to reduce the consumption of fossil fuels [1–3]. Through this work, both high efficiency power plants and renewable energy sources are investigated. In the field of renewable energy, Iran possesses a lot of opportunities for future development due to a large amount solar energy incidents [4]. SOFCs have several benefits over other fuel cells, such as a high operating temperature range (800–1000°*C*), ability to use various fuels, kinds of electrolyte (ceramic) and ability to integrated with other auxiliary devices [5]. Because of their high operating temperature, SOFCs are one of the best future high efficiency decentralized technology. They can be easily integrated into polygeneration systems, when combined with absorption chillers the integrated system could result in a potential CO_2 reduction of about 45% [6]. Integrated natural gas liquefaction and SOFC power plants are investigated [7]. Based on the results overall thermal efficiency is about 80%.

Different heat sources such as waste heat, solar thermal, biomass and geothermal are used for supplying the required thermal energy of absorption refrigeration systems [8]. Such systems can be used for supplying the required refrigeration in the liquefied natural gas (LNG) processes. A single effect absorption refrigeration system used in LNG process is analyzed by advanced exergoeconomic method [9]. Lithium bromide-water and ammonia-water (NH_3-H_2O) are two conventional solutions of absorption chillers. LiBre-H_2O cycle is used in cases that the required refrigeration is above the freezing point of water while the NH_3-H_2O cycle is appropriate for temperatures below 0°*C* [10]. Double effect LiBre-H_2O absorption chiller system is a good option for integration with SOFC system. The overall efficiency in this kind of integrated system can get to 84% or even more in different conditions. An integrated SOFC and lithium bromide absorption heat pump process is presented [11]. In this work the electrical power of the SOFC is 110 kW. Optimization of a combined SOFC–gas turbine power plant is investigated [12]. A set of synthesis/design decision variable values are obtained, the capital cost of new design is significantly lower than that of the reference design. Optimal efficiency of the proposed plant is calculated 67.5%. The proposed model cost is 1.36

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Nomenclature

A	Area, m^2
A_{cell}	Active area of each cell, cm^2
A_s	Specific area, m^{-1}
AC	air cooler
D_i^{eff}	effective diffusion coefficient of species i, $cm^2\ s^{-1}$
D_{ij}	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}
F	Faraday constant, 96488.5 °C mol^{-1}
HE-i	heat exchanger
J	current density, A cm^{-2}
J_0	exchange current density, A cm^{-2}
M_i	Molecular weight of species i
M_{ij}	Average molecular weight species i and j
m_{fuel}	Mass flow rate of fuel
N_{cell}	Number of cells
n_e	Moles number of electron transferred
P	Total Pressure
P_i	Partial pressure of species i
P_o	Standard Pressure, 1 atm
P_i^*	Reaction site partial pressure of species i
P_i^0	Bulk partial pressure of species i
P-1	Pump
R	Gas constant,8.314 $jmol^{-1}\ K^{-1}$
T	Temperature, °C
T_0	Standard Temperature, 298 K
U_{fuel}	Fuel utilization coefficient
V	Voltage of single cell
W	Work or electric power, kW
ΔG	Gibbs free energy change, kj mol^{-1}
A_a	aperture area of dish concentrator m^2
A_c	entrance aperture area of receiver m^2
A_w	cavity internal area of receiver m^2
C	geometric concentration ratio
D	diameter of the cavity
Gr_l	Grashof number based on length L
g	gravitational acceleration, 9.807 m/s^2
H	height of the cavity, m
L	characteristic dimension of cavity, m
I	direct normal insolation per unit of collector area W/m^2
Q_{lk}	conductive heat loss from receiver, W
Q_l	heat losses from the receiver to the surroundings, W
Q_{lc}	convective heat loss through the receiver aperture, W
K	thermal conductivity of the ambient air, W/m K
Q_{lo}	optical loss from the collector, W
Q_{lr}	radiative heat loss through the receiver aperture, W
Q_r	radiant solar energy falling on the receiver, W
Q_s	solar energy incident on the dish concentrator aperture, W
N	maximum possible sunshine during day
H	daily global solar radiation
$\overline{n}$	monthly mean daily sunshine duration
G_{on}	extraterrestrial radiation
G_{sc}	solar constant 1367 W/m^2
n	day of the year
Q_u	useful energy collected, W
T_a	ambient temperature, K
T_w	average operating wall temperature in the cavity, K
λ	land factor of un-shading
ρ	dish reflectance
$\tau\alpha$	transmittance–absorptance product
γ	intercept factor of receiver
θ	angle of incidence, degree
Nu_l	Nusselt number based on length L
h_c	convective heat transfer coefficient, W/m^2 K
η_c	solar collector thermal efficiency
η_0	optical efficiency
η_r	receiver thermal efficiency
ε_{eff}	effective infrared emittance of cavity
ε_c	cavity surface emittance
I_d	hourly diffuse solar radiation
β	volumetric expansion coefficient of the ambient air, K^{-1}
ϕ_1	tilt angle of cavity, radian
φ	local geographic latitude
δ	solar declination
ω_s	sunset hour angle
ω	hour angle in degrees for time
K_t	clearness index of a day
H_d	daily diffuse solar radiation
S_f	solar fraction
Q_u	useful energy collected, W
ν	kinematic viscosity of the ambient air, m^2/s

million dollar. A total energy system combining a SOFC and an exhaust gas driven absorption chiller is investigated to supply power, cooling and heating simultaneously [13]. Operating pressure is 1 bar, anode inlet gas composition is 89% H_2 and 11% H_2O and operating temperature is 1000 °C. A cogeneration plant based on SOFC and ORC is investigated [14]. Net electrical power of the system is ranged from about 400 kW to 540 kW. A hybrid fuel cell system and carbon dioxide super critical power cycle is investigated [15]. The results show that the net electrical efficiency is about 66%. An integrated trigeneration system combining a SOFC and a double effect LiBre-H2O absorption chiller is discussed [16]. In this work fuel pressure and SOFC cathode inlet temperature are 1.01 bar and 780 °C respectively. Economic analysis of a hybrid fuel cell generator and absorption chillers system is investigated [17]. Economic analysis of two systems (the vapor compression system and vapor absorption system) for different cooling capacities between 200 and 800 kW investigated. Results illustrate that the proposed system saves 4% of total cost through using the cogeneration system. Energy and exergy analysis of a hybrid molten carbonate fuel cell power plant and carbon dioxide capturing process is presented [18]. In this work the biggest exergy dissipation between the components is in the combustion chamber (181 MW). Consequences of optimization illustrate that power consumption in the compressors is declined by about 33%. A cogeneration system containing SOFC-GT, NH_3-H_2O absorption refrigeration system and Rankine steam cycle is introduced and analyzed [19]. The voltage is 0.784 V and the current density is 0.4 A/cm^2. The net power and optimum electrical efficiency (LHV) are computed 500 kW and 62.4% respectively. The performance of three different SOFC combined systems with zero-CO_2 emission are analyzed [20]. In this