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Energy, exergy and sensitivity analyses of a hybrid combined cooling, heating and power (CCHP) plant with molten carbonate fuel cell (MCFC) and Stirling engine

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A B S T R A C T

A hybrid combined cooling, heating and power (CCHP) system which consists of molten carbonate fuel cell (MCFC), Stirling engine and double effect LiBr/H_2O absorption chiller is introduced and analyzed. Molten carbonate fuel cell is the main power production source which its exhausted heat is used as heat source of the Stirling engine. Exhausted heat from the Stirling engine is used as heat source of the absorption chiller's generator. The produced power of the process is 6482 kW, also it provides 2137 kW heat duty and 1372 kW cold duty. Performance of the process is evaluated by energy and exergy analysis methods. Also sensitivity of the overall and electrical efficiencies to the fuel utilization factor, air flow rate to the burner, burner outlet temperature and oxidant flow rate are analyzed. Results of the energy analysis show that overall and electrical efficiencies are 71.71% and 42.28% respectively. Exergy analysis shows that molten carbonate fuel cell, Stirling engine and gas turbine have considerable efficiencies. Highest exergy destruction rate is related to the CH_4 and H_2 burners that mostly is because of the irreversible nature of the combustion.

1. Introduction

CCHP (combined cooling, heating and power) systems in addition to supplying power as a main product have the ability to produce process cooling and heating. So far many different configurations of CCHP systems have been proposed. A system based on co-firing of the natural gas and biomass gasification is proposed (Wang et al., 2015). Optimization of a biomass-fired cogeneration plant CHP/CCHP based on organic Rankine cycle for a network in Spain is investigated (Uris et al., 2015). Biomass gasification and co-gasification systems which have been used in the CHP processes are reviewed (Farzad et al., 2016). A solid oxide fuel cell CHP system is modeled and investigated (Pirkandi et al., 2012). Effect of temperature and pressure on the process power output are analyzed. The results show that overall efficiency of the system is about 73%. Alternatives for using transient renewable energy sources in CHP systems are studied (Andersen and Lund, 2007). The results show that large power stations can be replaced by small CHP systems. Also employing renewable energy sources decreases CO_2 emissions. A CHP system in olive processing industry is studied and analyzed (Celma et al., 2013). Installing of the CHP system in the process decreases energy demand (49%) and CO_2 emissions. Environmental evaluation of the CCHP systems based on the biomass combustion compared to the conventional systems is discussed (Maraver et al., 2013). Exergy analysis of a hybrid CCHP system with biomass gasification is considered (Wang et al., 2015). Biomass gasifier, heat pipe heat exchanger, internal combustion engine, absorption chiller/heater and domestic hot water heat exchanger are subsystems of this process. Biomass and coal co-firing CHP system is investigated by life cycle analysis method (Zuwała, 2012). The results show that CO_2 emission decreases by using biomass instead of coal. Modeling of a hybrid hydrogen/Air fuel cell is investigated (Mehrpooya and Daviran, 2013). Performance of a hybrid CCHP system which is fueled by COG (coke oven gas) is studied (Zhao et al., 2015). In this system LiBr/H_2O absorption refrigeration system (ARS) is used to provide the required refrigeration. A new generation of SOFC electrochemical power plant processes integrated with liquefied natural gas are proposed and analyzed (Mehrpooya, 2016). In this study absorption refrigeration systems are used as precooling cycle in the natural gas liquefaction

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Nomenclature

V	Real voltage of the cell (V)
LHV	Lower Heating Value (kJ/kg)
E_{Nerst}	Ideal voltage of the cell (V)
F	Faraday constant (C/mole)
R	Universal gas constant (J/mol.K)
N	Number of electrons
Z	Mole flow (mole/s)
J	Current density (mA/cm^2)
C	Coulomb
A	Ampere
N	Number of cells
A	Cell active area (cm^2)
K	Specific heat ratio
E	Effectiveness coefficient of regenerator
V	Volume of Stirling engine(m^3)
W	Electricity rate (kW)
Q	Heat transfer rate (kW)
M	Mass flow rate (kg/h)
X	Mole fraction
Ex	Exergy rate (kW)
I	Exergy destruction rate (kW)
U_f	Fuel utilization factor
R	Polarization resistance (Ω/m^2)
P	Partial pressure (atm)
E_{act}	Activation energy (kJ/kmol)

Greek letters

H	Efficiency
T	Ratio of cold and hot heat Sources temperatures
Γ	Activity coefficient
Ψ	Rational efficiency
Φ	Component efficiency

Subscripts

Act	Activation
Conc	Concentration
Thermo	Thermodynamically
Mech	Mechanical
In	Inlet
H	Hot heat source
Elec	Electrical
Equi	Equivalent
ABC	Absorption cycle
Con	Consumed
Comp	Compression
Ph	Physical
Ch	Chemical
K	Kinetic
P	Potential
0	Dead state
I	i-th component
Out	Outlet

Abbreviations

CCHP	combined cooling, heating and power
MCFC	molten carbonate fuel cell
GT	gas turbine
ICE	internal combustion engine
SOFC	solid oxide fuel cell
COG	coke oven gas
HRSG	heat recovery steam generator
ORC	organic Rankine cycle
GA	genetic algorithm
LNG	liquefied natural gas
CHP	combined heating and power
GMDH	group method of data handling
DC	direct current
AC	alternative current
COP	coefficient of performance
EPC	exergetic performance coefficient

process. The required heat duty in the ARS is supplied from the SOFC exhaust heat. A new process configuration for liquefaction of natural gas, using a single effect ARS as the precooling cycle is introduced and investigated (Mehrpooya et al., 2016d). The required heat duty in this process is supplied by the exhaust heat from the gas turbines outlet. Evaluation of CCHP systems with energy storage units at different locations is investigated (Jiang et al., 2016a). In this work it is shown that how the electrical demand is satisfied which have distinct effect on the output of the plant. The energy mismatch issue between CCHP systems and their users, as well as the multiple effects of energy storage units (ESUs) on CCHP systems is investigated (Jiang et al., 2016b). An integrated system which includes coal gasification, air separation process and trans-critical CO_2 power cycle is introduced and analyzed (Mehrpooya et al., 2017a). Using high temperature fuel cell systems such as SOFC and MCFC, improves the electrical efficiency of the hybrid power plants. Molten carbonate fuel cells (MCFC) produce power with carbon dioxide (CO_2) and oxygen as the input feed. Also outlet stream from the anode electrode contains high percent of carbon dioxide (40% volume). The exergy and advanced exergy analysis of a hybrid molten carbonate fuel cell power plant is investigated (Yazdanfar et al., 2015). The results show that the greatest exergy destruction occurs in the combustion chamber. Also the optimal design of the process is done by adjusting the effective operating conditions. A new hybrid IGCC (Integrated Gasification Combined Cycle), CO_2 capturing and MCFC system is investigated (Duan et al., 2015). Hybrid gas-steam combined cycle power plant with MCFC for CO_2 capturing is analyzed (Carapellucci and Giordano, 2014). MCFC is used for high efficiency CO_2 capture from natural gas combined systems (Campanari and Chiesa, 2013). A hybrid chemical looping hydrogen production, power cycle and CO_2 capture is investigated (Mehrpooya et al., 2017b). The results show that Thermal efficiency of the process is 57.3%. A novel integrated MCFC, gas turbine and organic Rankine power cycle is proposed (Haghighat Mamaghani et al., 2015). This hybrid system is investigated by energy, exergy, economic and environmental analysis methods. The results show that overall exergy efficiency of the system is 59.4%. An integrated a MCFC and supercritical CO_2 Brayton cycle process is introduced and analyzed (Mehrpooya et al., 2016a). The results show that the net overall thermal efficiency (LHV basis) is about 78%.

Modeling and optimization of the hybrid solid oxide fuel cell-gas turbine power plants are investigated (Mehrpooya et al., 2014a). A 2-D model of the SOFC considering co- and counter-flow configurations is developed and analyzed. Optimization of CCHP SOFC, ammonia-water single effect absorption cycle and