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Conceptual design and energy analysis of novel integrated liquefied natural gas and fuel cell electrochemical power plant processes

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ABSTRACT

A novel hybrid combined cooling, heating, fuel cell-steam turbine power plant integrated with a liquefied natural gas process is introduced and analyzed. Precooling vapor compression refrigeration cycle of the liquefaction process is replaced by an absorption refrigeration system which the required hot utility of the cycle, is supplied by the power plant. Results show that the absorption refrigeration systems can be successfully replaced by precooling compression refrigeration cycles in the liquefaction processes. Also applying the absorption refrigeration system, decreases the required power in the process. Hybrid fuel cell power plants can be used for supplying the required power and heat duty in the designed liquefaction process. An integrated solid oxide fuel cell steam turbine power plant is designed and analyzed. The results show that the electrical and overall energy efficiency of the power plant is high. Also SOFC-ST system can provide the required heat duty in the absorption refrigeration system.

1. Introduction

Supplying the required refrigeration in the cryogenic processes is one of the most important concerns in design and operation of them. Vapor compression refrigeration cycle is the most conventional method for reaching to the cryogenics temperatures less than −150 °C. As temperature decreases, colder refrigerants (like: ethane, methane and nitrogen) will be required and for refrigerants cooler than the propane, cascade cycles should be applied. In the other hand as number of the cycles increases, overall required power and consequently the required fuel for supplying the required energy increases. In such situation there are some methods which can be used to decrease the required power. The processes used for natural gas liquefaction are of the most important and low temperature ones that need high rate of cryogenic refrigeration. Refrigeration systems used in LNG processes are categorized [1]. They are divided into three categories: single stage, multi stage and cascade. Five of the most conventional LNG processes are investigated by energy and exergy analysis methods [2,3]. High value of the required power in the refrigeration cycle compressors is the most important point which can be investigated for improving the liquefaction efficiency. Also in some cases integration of the liquefaction process with the upstream processes like hydrocarbon recovery process is proposed to decrease the overall required refrigeration [4–6]. A new parameter for evaluating the degree of integration in cryogenic liquid recovery processes is introduced and analyzed [7]. Optimization of the process based on the operating variables is investigated [8–11]. Nitrogen based processes are analyzed for efficiency optimization by compression energy minimization [8]. Propane precooled mixed refrigerant (C3MR) and dual mixed refrigerant (DMR) processes are investigated by thermodynamic and economic optimization. Total power consumption, total investment cost (TCI), total annualized cost (TAC) and total capital cost of the main components are considered as objective functions. In recent years several different modifications has been done on the refrigeration system process configuration and operating condition in order to decrease the initial costs and required power [12–15]. Natural gas liquefaction process performance is assessed by ratio of the consumed power to the produced LNG (kWh kg^{-1}LNG) which is called specific power consumption (SPC). Researches on the process configurations and operating condition are done to decrease the SPC. This parameter varies from 0.2 to 0.6 for various liquefactions processes. For industrial processes this value is about 0.3. Decreasing the SPC to

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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
ARS	absorption refrigeration system
AC	air cooler
ARC	absorption refrigeration cycle
AR	absorption refrigeration
CB-i	cold box
CO-i	air cooler
Con-i	condenser
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, 96488.5 °C mol^{-1}
ST-i	steam turbine
H-i	heater
HE-i	heat exchanger
h	specific enthalpy at real condition, kW
h_0	specific enthalpy at environmental condition, kW
I	exergy loss, kW
J	current density, A cm^{-2}
j_0	exchange current density, A cm^{-2}
K	absorption coefficient (kPa)$^{-1}$
k	reaction rate constant (kmole kg cat s^{-1})(kPa)
LHV	lower heating value of fuel, kJ kg^{-1}
MR	mixed refrigerant
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_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, 1 atm
p_1^*	reaction site partial pressure of species i, bar
p_1^0	bulk partial pressure of species i, bar
P-i	pump
R	gas constant, 8.314 j mol^{-1} K^{-1}, 83.14 cm^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}
Re	Reboiler
S	specific entropy at real condition, kW K^{-1}
T-i	tower
S_0	specific enthalpy at environmental condition, kW K^{-1}
S/C	steam to carbon ratio
SPC	specific power consumption
T	temperature, K
P	pump
T_0	standard temperature, 298 K
U_{fuel}	fuel utilization coefficient
V	voltage of single cell, V
V-i	valve
W	work or electric power, kW
U	overall heat transfer coefficient (kJ °C^{-1}hr^{-1})

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, Ω^{-1} cm^{-1}
$\tilde{\sigma}_{ij}$	collision diameter of species i and j, nm
Ω_D	collision diffusion integral

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
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