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Analysis of an integrated cryogenic air separation unit, oxy-combustion carbon dioxide power cycle and liquefied natural gas regasification process by exergoeconomic method

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ABSTRACT

Exergoeconomic and sensitivity analyses are performed on the integrated cryogenic air separation unit, oxy-combustion Carbon dioxide power cycle and liquefied natural gas regasification process. Exergy destruction, exergy efficiency, cost rate of exergy destruction, cost rate of capital investment and operating and maintenance, exergoeconomic factor and relative cost difference have been calculated for the major components of the process. The exergy efficiency of the process is around 67.1% and after mixers, tees, tank and expansion valves the multi-stream heat exchanger H-3 have the best exergy efficiency among all process components. Total exergy destruction rate of the process is 1.93×10^7 kW. Results of exergoeconomic analysis demonstrates that maximum exergy destruction and capital investment operating and maintenance cost rate are related to the multi-stream heat exchanger H-1 and pump P-1 with the values of 335,144 ($/h) and 12,838 ($/h), respectively. In the sensitivity analysis section the effects of the varying economic parameters, such as interest rate and plant life time are investigated on the trend of the capital investment operating and maintenance cost rate of the major components of the process and in another cases the effect of the gas turbine isentropic efficiency on the exergy and exergoeconomic parameters are studied.

1. Introduction

LNG (liquefied natural gas) is a substance with very low temperature (−163.15 °C) that should be vaporized and brought to a desired temperature and pressure before entering the pipeline network. In the conventional LNG vaporization terminals cold energy of LNG is released and wasted into the water or air without any recovering (about 0.2 kW h kg^{-1}). Cold energy is an expression for describing cryogenic exergy of LNG material stream. The utilization of the cold energy of LNG during vaporization processes can improve the economic and environmental aspects of these kinds of processes. Because of its very low temperature, LNG can be used in different applications such as desalination of seawater, deep freezing agro food industry facilities, space conditioning in the commercial and residential sector, low temperature power generation, manufacturing of dry ice, and rubber cryogenic grinding [1]. A novel integrated power plant using cold of LNG and solar energy is introduced and analyzed [2]. Also an integrated oxy-fuel power cycle, high temperature solar system and LNG cold recovery is introduced and analyzed. The results show that LNG flow rate is an important parameter which can affect the process efficiency. LNG cold energy is used in a combined chemical looping hydrogen production and power plant with carbon dioxide capture process [3]. In this study LNG cold energy is used as heat sink to improve the electrical efficiency of the power cycle. LNG cold energy is used in an oxy-fuel power cycle which a part of the required of it is supplied by a solar cycle [4]. The results show that LNG flow rate can affect the exergy efficiency and net electrical power of the process significantly. One of these applications is using cold energy of LNG as refrigeration source of cryogenic air separation processes [5]. Operating temperature of the air separation units (ASU) (−173 °C, −193 °C) is lower than the LNG, hence LNG cold energy can be used with high cold recovery efficiency compared to other methods [6]. The air separation units have high degree of power consumption and it is true fact that utilizing of LNG cold energy is leading to lower power consumption, but however integrating of air separation units with different types of power generation cycles can be very efficient. A novel air separation process based on cold energy of LNG integrated with coal gasification, transcritical CO_2 power cycle is investigated [7]. In these cycles usually the pure oxygen product of ASU is utilizing instead

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Nomenclature

c	cost per exergy unit ($/GJ)
$\dot{C}$	cost rate ($/h)
e	specific exergy (kJ/kg)
$\dot{E}$	exergy rate (kW)
G	Gibbs free energy (kJ)
h	specific enthalpy (kJ/kg)
H	annual working hour (h)
i	interest rate (%)
$\dot{m}$	mass flow rate (kg/s)
N	plant life time (year)
$\dot{Q}$	heat duty (kW)
r	relative cost difference (%)
s	specific entropy (kJ/kg °C)
T	temperature (K)
$\dot{W}$	power (kW)
x	mole fraction
Z	purchased equipment cost
$\dot{Z}$	capital investment and operating and maintenance cost rate ($/h)

Greek letters

η	efficiency (%)
ε	exergetic efficiency (%)
φ	maintenance factor

Subscripts

°	dead state
ch	chemical
D	destruction
F	fuel
In	input
K	kth component
Out	output
P	product
Ph	physical
Tot	total

Superscripts

°	standard condition
CL	capital
OM	operating & maintenance

Abbreviations

LNG	liquefied natural gas
ASU	air separation unit
IGCC	integrated gasification combined cycle
ORC	organic Rankine cycle
SPECO	specific exergy costing
SOFC	solid oxide fuel cell
CCHP	combined cooling, heating and power
NG	natural gas
LHV	lower heating value
CRF	capital recovery factor

of air in combustion chamber component of power generation cycle and it is leading to very high efficient combustion process. These power generation cycles are known as "oxy-combustion" or "oxy-fuel" power plants. In recent years different configurations of air separation units integrated with oxy-combustion power plants are introduced. Fu et al. [8] proposed an advanced cryogenic air separation process integrated with oxy-combustion power cycle based on self-heat recuperation technology and in contrast with conventional two distillation columns air separation unit, they used one column type. The results of this process showed that power consumption would be reduced by 20.2% compared to other similar processes. In another work a comparative thermodynamic, economic and risk analysis of integrated cryogenic and hybrid air separation unit with oxy-combustion power plant was investigated [9] and similarly, another configurations of hybrid air separation units are introduced by Burdyny and Struchtrup [10] and compared with each other. The thermo-economic analysis of the oxy-type supercritical power plant integrated with the cryogenic air separation unit was proposed by Janusz-Szymanska and Dryjańska [11] and possibilities of improving were investigated. One of the most common integrated ASU-oxy-combustion units is the IGCC (integrated gasification combined cycle) plants. In this type of cycles the output pure oxygen of ASU section enters the component which name is "gasifier" and burning with coal, the output flue gases are leading to the gas turbine for power generation intention. Coal is one of the convenient fossil fuels in the matter of price but its environmental impacts always have been high. Fortunately integrating of these cycles with CO_2 capturing units have solved this problem [12]. According to the concept of integrating ASU cycles with oxy-combustion power plants, the application of transcritical CO_2 power cycles can be considered [13]. Carbon dioxide power cycles already have been used in different configurations of recent researches. An integrated molten carbonate fuel cell-supercritical carbon dioxide is introduced and analyzed [14]. In this study a Brayton cycle is used to recover heat from the catalytic burner exhaust gas.

A novel hybrid three reactor chemical looping, and fuel cell power plant cycle is introduced and analyzed [15]. Carbon dioxide is produced in one of these reactors. In one of these studies a transcritical CO_2 power cycle which utilizes geothermal wells as its heat source and LNG cold energy as its heat sink, was studied [16]. In this very particular configuration chilled water and power generation in natural gas turbine, were the alternative products and for further examination also exergoeconomic and multi-objective optimization had been considered. Vélez et al. [17] exclusively investigated the low temperature heat sources and specially CO_2 transcritical working fluid for power generation and their results showed that this type of power cycles, integrated or non-integrated with other cycles would be one of the next generation of power production cycles. CO_2 power cycles also are integrated with solar energy sources [18]. In Al-Sulaiman and Atif [19] research study, a thermodynamic comparison of five supercritical carbon dioxide Brayton cycles integrated with a solar power tower was studied. In this work the heliostat solar field was optimized for better optical performance and then configured with the supercritical CO_2 Brayton cycles. In Xia et al. [20] research study a solar-powered transcritical CO_2 power cycle has been employed for reverse osmosis desalination of sea water and in this very particular work, LNG cold energy was used as heat sink of the power cycle process and in the following, LNG is vaporized and employed in natural gas turbine in order to producing power. Mahmoudi and Ghavimi [21] was proposed an integrated molten carbonate fuel cell (MCFC) – supercritical CO_2 – organic Rankine cycle (ORC) and LNG cold energy as heat sink of the whole process and considered it in the aspects of thermoeconomic and multi-objective optimization.