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Conventional and advanced exergoeconomic assessments of a new air separation unit integrated with a carbon dioxide electrical power cycle and a liquefied natural gas regasification unit

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ABSTRACT

In this study for the first time a new air separation unit with a carbon dioxide power cycle based on cold energy recovery of liquefied natural gas is investigated by conventional and advanced exergoeconomic analyses. With conventional exergy analysis, the source of irreversibility in the process can be determined, while with advanced exergy analysis, the real potential can be determined for improving the process operating performance as well as component interactions. The exergy destruction rate and total operating cost are divided into two catagories which are sub-parts of each other: endogenous/exogenous and unavoidable/avoidable. The exergy and exergoeconomic analyses indicate that the total process cost can be decreased by improving the performance and efficiencies of compressors and heat exchangers. This is because these types of process components have the largest and smallest exergoeconomic factor values, respectively. Results of the advanced exergy and exergoeconomic analyses demonstrate that, when considering the avoidable endogenous investment cost rate, compressors have priorities for modification. Also, based on the avoidable endogenous cost rate, one of the heat exchangers should be modified at first. The exergy destruction and investment cost rates in most of the process components are endogenous. A sensitivity analysis is performed to evaluate the effects of economic and thermodynamic parameters on the advanced exergoeconomic parameters. It is concluded that the configuration of the process components has a significant impact on their costs.

1. Introduction

To produce each ton of the liquefied natural gas (LNG) from natural gas (NG) 300 kWh of electrical power is needed [1]. Considering the temperature of the atmosphere is 20 °C, 240 kWh of cold energy (cooling) per ton of LNG is wasted during the regasification process [2]. Much work has been done on cold recovery from LNG [3]. This cold can be used in various types of processes. For the liquefaction of gases like carbon dioxide (CO_2) [4] and hydrogen [5], the LNG can be used as a heat sink in a subcritical Rankine-like cycle which uses a low-temperature solar electrical power cycle [4]. In this process, the working fluid of the cycle, CO_2, is captured in liquid state using the cold of LNG. The cold of LNG is used for pre-cooling in the hydrogen liquefaction process. This process has advantages including compression at ambient temperature and reduced specific electrical power consumption for liquefied hydrogen production [5]. In the air separation unit (ASU), the cold of LNG is used to pre-cool the inlet air stream [6]. In other uses, the cold of LNG is utilized for freeze drying in the food industry and for space conditioning [7]. The cold can also be used as a cold sink in various electrical power generation cycles. For instance, Lu et al. [8] propose a cascading Rankine electrical power cycle with direct expansion of LNG. Zhang et al. [9] propose a quasi-combined electrical power cycle consisting of a supercritical CO_2 Rankine-like cycle, a CO_2 Brayton cycle and a LNG regasification system. Wang et al. [10] thermodynamically model the Kalina cycle with an ammonia-water mixture as the working fluid and LNG as the heat sink. Deng et al. [11] propose a cogeneration power cycle which uses LNG cold and NG chemical energy as fuel for electrical and cooling power production.

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Nomenclature

A	area (m^2)
c	cost per unit exergy ($/GJ)
$\dot{C}$	cost rate ($/h)
$\dot{E}$	total exergy rate (kW)
e	specific flow exergy (kJ/kmol)
f	exergoeconomic factor (%)
h	specific enthalpy (kJ/kg)
H	annual working hours (h)
i	interest rate (%)
i_{eff}	average annual discount rate (cost of money) (%)
$\dot{I}$	irreversibility rate (kW)
$\dot{m}$	mass flow rate (kg/s)
N	plant life time (year)
P	pressure (bar)
PEC	purchase equipment cost ($)
$\dot{Q}$	heat energy rate (kW)
R	relative cost difference (%)
r_{FC}	fuel average nominal escalation rate (%)
r_P	pressure ratio (-)
r_{OMC}	annual escalation rate for operating and maintenance cost (%)
S	specific entropy (kJ/kg °C)
T	temperature (°C)
$\dot{W}$	electrical power rate (kW)
y	exergy destruction ratio (-)
$\dot{Z}$	investment cost rate ($/h)
Z	purchased equipment cost ($)

Greek letters

φ	maintenance factor
ε	exergy efficiency (%)
η	efficiency
τ	operating hours (h)

Superscripts

AV	avoidable
BL	book life
EN	endogenous
EX	exogenous
UN	unavoidable

Subscripts

A	air
ch	chemical
D	destruction
E	exit
F	fuel
g	gas
i	inlet, stream *i*
is	isentropic
k	component k
L	levelized
min	minimum
o	other
P	product
ph	physical
Q	heat
t	total
W	work

Abbreviations

ASU	air separation unit
C	compressor
CC	carrying chargers
CI	capital investment
CRF	capital recovery factor
D	diameter
E	heater
F	separator
fc	fixed cost
HE	heat exchanger
HP	horsepower
GT	gas turbine
L	length
LMTD	logarithmic mean temperature difference
LNG	liquefied natural gas
min	minimum
MTA	minimum temperature approach
NG	natural gas
NGL	natural gas liquid
OMC	operating and maintenance cost
ORC	Organic Rankine cycle
P	pump
ROI	return on investment
SW	sea water
T	tower
TE	turboexpander
TCR	total capital recovery
TRR	total revenue requirement
uc	unit cost
V	expansion valve
W	weight

Also, LNG can be utilized as a working fluid, with electrical power generated by the expansion of evaporating LNG [12].

Integrating LNG regasification with another process requiring refrigeration at a temperature lower than LNG can also be a suitable way to exploit the cold of LNG. One the most widely used examples is an ASU. Air separation generally can be categorized as cryogenic or non-cryogenic; the latter type of processes include membrane separation [13], adsorption [14] and chemical looping [15]. The polymeric membrane for gas separation includes of two solution and diffusion mechanisms. The porous polymer structures consists of pores of different sizes. The gaseous molecules can pass through the pores (solubility mechanism), and move from one cavity to the other (diffusion mechanism) [16]. In the adsorption process, the air passes through a zeolitic material bed. In this case, the nitrogen molecules are more strongly adsorbed than oxygen or argon molecules. So, the nitrogen molecules are retained and an oxygen-rich stream exits the zeolite bed [14]. The chemical looping approach for air separation is based on the cyclic oxidation and reduction of a metallic oxide as a means of separating oxygen molecules from air [15].

Cryogenic distillation is currently done using two cryogenic distillation columns at different pressures, and is one of the conventional methods for large-scale production of pure oxygen and nitrogen [17]. In this type of ASU, two columns at high and low levels of operating pressure act as a condenser and a reboiler where much energy is saved [18]. The temperature of a cryogenic ASU is lower than that of LNG [19]. A cryogenic ASU permits cold recovery from LNG in a relatively