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Optimal design and integration of a cryogenic Air Separation Unit (ASU) with Liquefied Natural Gas (LNG) as heat sink, thermodynamic and economic analyses

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ABSTRACT

LNG regasification terminals are the final destination of LNG carriers. This is where the liquefied natural gas is returned to the gaseous state and fed into transmission and distribution grids. While regasification process, cryogenic LNG has a great potential for cold energy recovery. This cold energy can be used in various applications such as power generation, material freezing and sea water desalination. In this study, we used the mentioned cold energy for cryogenic air separation unit to improve the performance of this cycle. Some of the most important results of this integration are 8.04% reduction in the amount of power requirement and also 17.05% reduction in initial capital cost of ASU plant. In this paper, the required LNG flow rate for applied integration was 24.43% of ASU cycle generated oxygen flow rate. Annualized cost of system was chosen as an economic approach. A year reduction of system period of return in relation to the before integration of ASU cycle with LNG, was the most important economic result of this integration. Sensitivity analysis was done on the system economic parameters (electrical energy, oxygen and nitrogen price). The results show that the considered integration will have a more positive impact on the system period of return in higher prices of electrical energy and also in lower prices of oxygen in the market.

1. Introduction

The components presented in air (Nitrogen, Oxygen, Argon etc.) are very often practical components in chemical technology. Large quantities of high-purity air products are used in several industries, including the steel, chemical, semiconductor, aeronautical, refining, food processing, and medical industries.

The largest markets for oxygen are in primary metals production, chemicals, gasification, clay, glass, concrete products, petroleum refineries and welding. The use of medical oxygen is an increasing market. Gaseous nitrogen is used in chemical and petroleum industries and it is also used extensively by the electronics and metals industries for its inert properties. Argon, the third major component of air, finds uses as an inert material primarily in welding, steelmaking, heat treating, and in the manufacturing processes for electronics [1].

Oxygen is usually obtained from air separation technologies. Different types of air separation technologies have been developed: Cryogenic air separation, Membrane air separation, Separation by adsorption and others. Different technologies are applicable for different requirements on amount and purity of the products [1].

The cryogenic distillation is used when high purity of the products is needed. The cryogenic systems can fractionate air in a distillation process carried out at temperature of about −160 °C by exploiting different liquefaction temperatures of O_2 and N_2. They may deliver large oxygen flow rate (over 3000 ton O_2 per day in a single line) with purity close to 100% and, among all the air separation technologies, they are the most cost-effective and the most efficient in terms of energy consumption per unit of product when high flow rates of oxygen are requested [1].

Natural gas is a kind of clean and efficient energy resource. In contrast to other resources, such as coal and gasoline, natural gas has higher combustion heat and produces much less pollution. The disadvantage is that it is in a gaseous state under ambient temperature and pressure, so it must be usually liquefied to LNG for long distance transportation and storage. Natural gas has to be pretreated to remove acid substances, water and other impurities

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Nomenclature

B	Bottom product of distillation column, kg/s
C	Cost, US$
CC	Capital cost, US$
C_P	Specific heat in constant pressure, kJ/kgK
C_{Tray}	Tray price
C_{Ve}	Vessel price
D	Distillated product of distillation column, kg/s
D_C	Column diameter, m
F	Vapor or liquid feed in column, kg/s
f	Annual inflation rate
F_M	Material factor
f_q	Quantity factor
H	Enthalpy, kJ
ΔH	Enthalpy change, kJ
i	Annual real interest rate
j	Nominal interest rate
K	Equilibrium constant
L	Liquid flow, kg/s
L_t	Plate spacing, m
$\dot{m}$	Mass flow rate, kg/s
N_{act}	Actual number of trays
NC	Number of component
NT	Number of tray
P	Pressure, kPa
Q	Transferred heat, kJ
R	Universal gas constant, J/mol K
RR	Reflux ratio
T	Temperature, K
ΔT	Temperature difference, K
$\hat{U}_V$	Maximum allowable vapor velocity, m/s
V	Vapor flow, kg/s
V_W	Maximum vapor rate, kg/s
$\dot{W}$	Power, kW
x	Liquid fraction
y	Vapor fraction
ope	Operating cost
ref	Reference
rep	Replacement cost
s	Supply
Y_{proj}	Project lifetime, Year
Y_{rep}	Component replacement time

Abbreviation

AB	Annual benefit
ACS	Annualized cost of system
ASU	Air separation unit
AV	Additive value
CRF	Capital recovery factor
HRSG	Heat recovery steam generator
LCOP	Levelized cost of product
LNG	Liquefied natural gas
NAB	Net annual benefit
NPV	Net present value
OFC	Operating flow cost
PC	Prime cost
POR	Period of return
PSA	Pressure swing adsorption
ROR	Rate of return
SFF	Sinking fund factor
SOPC	Summation of product cost

Greek letter

η	Efficiency
ρ	Density, kg/m^3

Subscript

a	Air
acap	Annualized capital cost
amain	Annualized maintenance cost
aope	Annualized operating cost
arep	Annualized replacement cost
c	Cold stream
cap	Capital cost
con	Condenser
dc	Discharge
h	Hot stream
main	Maintenance cost
min	Minimum
suc	Suction

and liquefied at a low temperature before transported in a liquid state, either by ships or vehicles [2,3].

LNG is a low temperature multicomponent liquid mixture. Its main component is methane, whose concentration is usually above 80% in the mixture. It also contains nitrogen, ethane, propane, normal butane and isobutane, normal pentane and isopentane. Feed natural gas is liquefied at cryogenic liquefaction units, and then is transported and stored at ambient pressure and corresponding saturated temperature of about −162 °C. At the users end, LNG will be gasified again to be supplied as natural gas at ambient temperature [2,4].

LNG production process may consume a considerable amount of energy, while the cold availability, also known as cold energy, has been stored in LNG. At a receiving terminal, LNG needs to be evaporated into gas at environmental temperature before being fed into the gas distribution system. Many ways of LNG cold energy utilization, such as power generation, material freezing, seawater desalination, fresh and frozen food production and intake air cooling have been developed in the past few decades [3,4]. Several researchers have proposed processes for industrial oxygen production and Liquefied Natural Gas (LNG) and the applications of its cold energy. G. Angelino et al. [5] considered a carbon dioxide power cycle using liquid natural gas as heat sink and concluded that Conventional power cycle, both Rankine and Brayton, can be adapted to the exploitation of the LNG thermal exergy with conversion efficiencies in the range of 50–54%. L.V. van der Ham et al. [6] evaluated two process designs of a cryogenic ASU using exergy analysis. They differed in the number of distillation columns that were used; either two or three. Addition of the third column reduced the exergy destruction in the distillation section with 31%. G. Tsatsaronis et al. [7] evaluated a novel system for generating electricity and vaporizing liquefied natural gas using advanced exergy analysis. The analysis included splitting the exergy destruction within each component into its unavoidable, avoidable, endogenous and exogenous parts. The results of the advanced exergetic analysis were confirmed through a sensitively analysis. H. Tan et al. [4] proposed an experimental study on liquid/solid phase change for cold energy storage of