



Assessment and optimization of a novel solar driven natural gas liquefaction based on cascade ORC integrated with linear Fresnel collectors



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ARTICLE INFO

Keywords:

Solar energy
Exergoeconomic
Exergoenvironment
NG liquefaction
cascade ORC
NSGA-II

ABSTRACT

A novel cascade organic Rankine cycle (ORC) configuration involving ejector refrigeration loops is introduced to produce liquefied natural gas (LNG) and power. Linear Fresnel solar collectors are utilized to supply the required energy of the system. Exergy, exergoeconomic and exergoenvironmental concepts are undertaken upon the concerned system during a year. A multi-objective optimization procedure based on a fast and elitist non-dominated sorting genetic algorithm (NSGA-II) is conducted and three decision makers, i.e. Shannon Entropy, LINMAP and TOPSIS methods are employed to find the ultimate optimum thermodynamic, economic and environmental impact performances from Pareto frontier obtained by NSGA-II with corresponding design variables of the system. As a result, the solar radiation increment affects the efficiencies negatively and the lowest total product cost and EI rates are obtained within 78.588 \$/h in May and 77.544 Pts/h in December, respectively. The optimum energy and exergy efficiencies are achieved respectively by about 7.3% and 12.6% in relation to the base point using Shannon Entropy decision maker. Moreover, the economic and EI performances of the system are improved respectively within 1.2% and 1.1% through the LINMAP method so that the highest reduction may be obtained for the cost and EI per unit exergies of LNG within 0.4200 \$/GJ and 7.36 Pts/GJ, respectively.

1. Introduction

Natural gas (NG) as the cleanest fossil fuel can be transported in either pipelines or in LNG carriers at pressures of 70–500 kPa and temperature around -150°C or lower [1]. The development of the liquefaction process will be addressed to provide the cost effective solution and an environmentally friendly for the NG transportation. Various LNG production processes have recently been reported in the literature. A single mixed refrigerant cycle [2], a nitrogen cycle [3] and two different open-loop cycles [4,5] were proposed for small-scale offshore liquefaction plants and the pre-cooled mixed refrigerant cycles and the dual mixed refrigerant cycle were suggested as the most efficient LNG processes for world-scale LNG plants.

On the other hand, the liquefaction process is a significant energy consumer, which requires 1188 kJ of energy to liquefy one-kilogram of NG [6]. This value depends on both NG liquefaction cycle and climatic site conditions.

Many efforts have been carried out on the analysis and enhancement of the energy consumption in the LNG plants. For example, the cryogenic turbine was used instead of the throttling valve used in NG liquefaction plants to produce power [7,8]. Lee et al. [9], Vaidyaraman

and Maranas [10] and Nogal et al. [11] optimized the mixed refrigeration cycles by improving the refrigerant compositions, mass flow rate, pressure levels and vaporizations. Shirazi and Mowla [12] optimized the energy consumption of a single stage mixed refrigerant cryogenic cycle with two compression stages which was selected for producing LNG. Mortazavi et al. [13] investigated the potential of various options to reduce the compressor power of the pre-cooled mixed refrigerant LNG plant by replacing conventional processes with expanders. Vatani et al. [14] proposed a novel integrated LNG and NG liquids production using two mixed refrigerant cycles and four multi stream heat exchangers to reduce the energy consumption. Pham et al. [15] added both a NG booster compressor and heavy refrigerant components into mixed refrigerant to reduce the compression requirement substantially in the proposed LNG processes. In order to avoid the formation of a liquid phase in the inlet streams of the compressors when adding heavy components, a separator was added. These two modifications affected synergistically the performance improvement of liquefaction cycles. Song et al. [16] optimized the unit energy consumption and the liquefaction rate of a single nitrogen expansion process with carbon dioxide pre-cooling by evolution theory.

Ali et al. [17] used a metaheuristic vortex search algorithm to

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Nomenclature

A_p	collector aperture area, m ²
A_r	receiver area, m ²
$\dot{B}$	environmental impact rate associated with an exergy stream, Pt/s
B	mirror length, m
b	specific environmental impact per unit of exergy, Pts/J
C	concentration ratio
$\dot{C}$	cost rate associated with an exergy stream, \$/s
c	cost per unit of exergy, \$/J
C_p	specific heat of fluid, kJ/kg·K
D	diameter, m
$\dot{E}_x$	total exergy rate, kW
ex	specific exergy, kJ/kg
f_b	exergoenvironmental factor
f_c	exergoeconomic factor
G_B	beam radiation falling on the horizontal surface, W/m ²
h	specific enthalpy, kJ/kg
i	interest rate, %
K	thermal conductivity, W/m·K
L	receiver length, m
$\dot{m}$	mass of fluid flow rate, kg/s
N	system life, year
P	pressure, kPa
$\dot{Q}$	heat transfer rate, kW
q'	heat transfer rate per unit of collector length, kW/m
r	shading factor
r_b	relative environmental impact difference
r_c	relative cost difference
Re	Reynolds number
s	specific entropy, kJ/kg·K
S	absorbed solar heat, W/m ²
S_n	distance between mirror elements, m
t	time, s
T	temperature, K
U	overall heat transfer coefficient, W/m ² ·K
V	volume, m ³
w	mirror width, m
$\dot{W}$	power rate, W
$\dot{Y}$	component-related environmental impact rate, Pt/s
Z	cost associated with investment expenditures, \$
$\dot{Z}$	cost rate associated with investment expenditures, \$/s

Abbreviation

CHE	cascade heat exchanger
CON	condenser
CRF	capital recovery factor
EI	environmental impact
EJC	ejector
EVP	evaporator
HHE	high temperature heat exchanger
LFC	linear Fresnel solar collector
LHE	low temperature heat exchanger

LNG	liquefied natural gas
NG	nature gas
ORC	organic Rankine cycle
P	pump
PRC	precooler
REG	regenerator
TST	thermal storage tank
TUR	turbine
TV	throttling valve

Subscript

0	dead state
<i>a</i>	air
D	destruction
En	energy
Ex	exergy
F	fuel
<i>g</i>	glass cover
<i>i</i>	inner
<i>in</i>	input
<i>inlet</i>	inlet
<i>k</i>	kth component
<i>L</i>	loss
<i>load</i>	load
<i>o</i>	outer
<i>oil</i>	Therminol-PV1
<i>outlet</i>	outlet
<i>P</i>	product
<i>r</i>	receiver
<i>u</i>	useful
<i>w</i>	wind

Superscript

<i>ch</i>	chemical
<i>M</i>	mechanical
<i>ph</i>	physical
<i>T</i>	thermal
<i>tot</i>	total

Greek letter

α	absorptivity
γ	refeectivity
ε	emissivity of the surface
λ	convection heat transfer coefficient, W/m ² ·K
ρ	density, kg/m ³
σ	Stefan–Boltzman constant, 5.6697×10^{-8} W/m ² ·K ⁴
τ	transitivity
η	efficiency, %
θ_n	tilt angle, °
φ	maintenance factor

optimize a single mixed refrigerant natural gas liquefaction process. The optimal operating conditions found by the vortex search algorithm significantly reduced the required energy of the single mixed refrigerant process and improved the coefficient of performance in comparison with the base case.

Reversed-Brayton cycle are turbine-based processes recommended to liquefy the natural gas with advantages of simpler design and operating costs [18,19]. Chang et al. [20] performed a thermodynamic

study on reversed-Brayton cycle to liquefy methane in a distributed scale by considering the real properties of refrigerant, the heat transfer coefficients, and the heat exchanger performance with phase change process. Chang et al. [21] thermodynamically studied four different modified cycles for the peak-shaving LNG processes or off-shore plants and precooling was considered to enhance the efficiency.

Besides, organic Rankine cycles (ORCs) apply the low boiling point organic fluids to produce power from the low grade heat resources such

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