Energy Conversion and Management 150 (2017) 678–692

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Energy, exergy and thermoeconomic analysis of a novel combined cooling and power system using low-temperature heat source and LNG cold energy recovery

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ARTICLE INFO

Keywords:
Cogeneration
LNG
Low-temperature heat source
Energy analysis
Exergy analysis
Exergoeconomic analysis

ABSTRACT

This paper deals with the energy, exergy, and economic analysis of a novel ammonia-water combined cooling and power cycle using waste heat as low-temperature heat source and LNG cold energy as thermal sink. For this purpose, thermodynamic modeling of the proposed system is presented and the performance of the cycle is investigated based on the following performance criteria: net power output, cooling output, first-law efficiency, second-law efficiency, and sum unit cost of the products (SUCPs) of the system. In this respect, the simulation revealed that the net power output, cooling output, first-law efficiency, second-law efficiency, and total SUCP of the system can be calculated 1379 kW, 1736 kW, 43.25%, 22.51%, and 133.7 $/GJ, respectively, showing a considerable enhancement through this integration. In addition, the irreversibility of each component and overall system are presented showing that heat exchanger 2 accounts for the highest exergy destruction among all components which is followed by the throttling valve 1. Moreover, a comprehensive parametric study is conducted to investigate the effects of considered key parameters, namely, vapor generator pressure, LNG turbine inlet pressure, evaporator temperature, condenser temperature, heat source temperature, and ammonia concentration on the performance criteria. It is observed that one can obtain a higher first-law efficiency at higher ammonia concentrations, heat source temperatures and LNG turbine inlet pressures or at lower condenser temperatures and vapor generator pressures, while a higher second-law efficiency can be obtained at lower ammonia concentrations, heat source temperatures and condenser temperatures or at higher vapor generator pressures, evaporator temperatures as well as LNG turbine inlet pressures.

1. Introduction

Liquefied natural gas (LNG) is natural gas (predominantly methane) which has been converted to liquid for transport or ease of storage. It is colorless, odorless, non-corrosive, and non-toxic. A higher reduction in volume compared to the compressed natural gas (CNG) makes LNG more cost-effective for long distance transportation where pipelines do not exist. This is because, the energy density of LNG is 2.4 times greater than that of CNG or 60% that of diesel fuel. In addition to regasification (process of converting LNG at -162 °C to natural gas at atmospheric temperature), many valuable byproducts can be produced using LNG cold energy such as extracting liquid oxygen and nitrogen gas from air [1]. However, due to abundant availability of natural gas, mature technology as well as its high acceptability in utilizing LNG without regasification in road and rail vehicles have made lesser demand for LNG regasification plants [2].

Throughout the last two decades, extraction of energy from power cycles using low-temperature heat sources as well as LNG cold energy as heat sink is highlighted by many researchers. As results of such studies, Lee and Han [3] used LNG as cold energy and waste heat from the conventional steam cycle to produce more power compared to the base cycle. They analyzed the proposed combined cycle based on the first- and second-laws of thermodynamics showing that the net produced power is nearly doubled compared to the conventional steam cycle. It is also concluded that the combined cycle made it possible to install CO_2 capture process on the power plant, too. In Rao et al. [4], a combined cycle utilizing low-temperature solar energy and LNG cold energy is proposed and compared the obtained performance criteria with that of the separated solar organic Rankine cycle (ORC) and LNG vapor system. The results demonstrated that, for the combined cycle, the solar collector and heat exchanger areas can be decreased by 82.2 and 31.7%, respectively. In addition, a regenerator was added to the proposed cycle leading to an enhancement in the energy and exergy efficiencies as well as solar collector area. Shi and Che [5] proposed a

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http://dx.doi.org/10.1016/j.enconman.2017.08.052
Received 17 May 2017; Received in revised form 17 August 2017; Accepted 18 August 2017

Nomenclature

Symbols

A	area (m^2))
c	cost per exergy unit ($ GJ^{-1})
$\dot{C}$	cost rate ($ yr^{-1})
CRF	capital recovery factor
$\bar{e}$	standard chemical exergy (kJ/kg)
$\dot{E}$	exergy rate (kW)
h	specific enthalpy (kJ kg^{-1})
I	exergy destruction rate (kW)
i_r	interest rate
LMTD	logarithmic mean temperature difference (K)
LNG	liquified natural gas
LTHS	low-temperature heat source
$\dot{m}$	mass flow rate (kg s^{-1})
N	annual number of hours (h)
n	components expected life
$\dot{n}$	molar flow rate (mol s^{-1})
P	pressure (bar)
Q	heat transfer (kJ)
$\dot{Q}$	heat transfer rate (kW)
$\bar{R}$	universal gases constant (J kg^{-1} K^{-1})
S	specific entropy (kJ kg^{-1} K^{-1})
SUCP	sum unit cost of the product
T	temperature (K)
TTDHS	heat source terminal temperature differential (K)
TV	throttling valve
U	overall heat transfer coefficient (kW m^{-2} K^{-1})
w	weighting coefficient
$\dot{W}$	power (kW)
X_B/X	ammonia mass fraction of basic solution (%)
Z	investment cost of components ($)
$\dot{Z}$	investment cost rate of components ($ yr^{-1})
y_i	molar concentration

Greek symbols

η_I	first-law efficiency (%)
η_{II}	second-law efficiency (%)
ψ	Exergy
ϕ_r	maintenance factor

Subscripts and superscripts

ABS	absorber
CH	chemical
CI	capital investment
COND	condenser
CV	control volume
D	destruction
EVA	evaporator
fu	fuel
gen	generation
HS	heat source
HX	heat exchanger
in	inlet
is	isentropic
i	ith component
k	kth component
LNG	liquified natural gas
min	minimum
MIX	mixer
NET	net value
OM	operating & maintenance
out	outlet
pp	pinch point
pr	product
PUM	pump
q	heating
R	reference
REG	regenerator
s	constant entropy
SEP	separator
TOT	total value
TUR	turbine
TV	throttling valve
VG	vapor generator
w	work
1, 2, …	cycle locations
0	dead state

combined power system recovered by low-temperature waste heat and cold energy of liquefied natural gas using ammonia-water mixture Rankine cycle. They reported energy and exergy efficiencies of 33% and 48%, respectively. They also carried out a comprehensive parametric study showing that a peak point is observed for net the power output as the LNG turbine inlet pressure increases. Moreover, it was concluded that increasing of the LNG turbine outlet pressure can increase the exergy efficiency while decrease the net power output. Mosaffa et al. [6] analyzed four organic Rankine cycles using geothermal energy as low-temperature heat source (LTHS) and LNG cold energy as a thermal sink. Energy, exergy, and exergoeconomic analysis of the proposed cycles were conducted and a comprehensive parametric study was carried out by this group. It is shown, regenerative-based system reveals the highest thermal efficiency, while system by an internal heat exchanger (IHE) results the highest exergy efficiency. However, from economic viewpoint, dual-fluid power system was resulted in a higher total cost rate, nevertheless, it is shown that this cycle can be the best case for maximum power production purposes. Morosuk and Tsatsaronis [7] proposed a combination of the open- and closed-cycle gas turbine systems with combustion of natural gas as the heat source and regasification of LNG as the heat sink. In their study, some novel concepts were proposed for this purpose and the results were compared with each other from thermodynamic, thermoeconomic, and ecological viewpoints. It is demonstrated that the energy and exergy efficiencies are increased from 68% to 86% and 52.6% to 54.3%, respectively, compared to the base case. However, the capital investment cost was approximately fixed for all cases. Lee [8] used a cascade Rankine cycle to recover the cold energy consumed in the liquefaction process of LNG which is disposed by the heat exchanger in the regasification process. They used two working fluids of ethane and propane in the cascade cycle. It is shown that ethane-propane utilization could result in the highest output power in their proposed cycle. Meanwhile, Chen et al. [9] proposed a gas and steam mixture cycle (GSMC) to improve power output efficiency, peak shaving, energy storage and CO_2 capture. They concluded that the output power efficiency of LNG and equivalent net efficiency can be up to 49.2% and 46.4%, respectively. These performance criteria can be even increased by increasing of the turbine inlet temperature at constant turbine inlet pressure. Shi et al. [10] used inlet air cooling and inter-cooling in a conventional power system to improve its performance. Their analysis demonstrated that the net electrical efficiency and overall output power can be improved up to 2.8% and 76.8 kW compared to the conventional system. In addition, they found that the proposed system shows a good off-design performance compared to the basic system.