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Thermoeconomic and environmental assessments of a combined cycle for the small scale LNG cold utilization

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HIGHLIGHTS

- A combined cycle is proposed for the LNG cold energy applications.
- An exergy-cost matrix is produced for the proposed combined cycle.
- 7% higher power generation was provided in the combined cycle.
- Emission reduction is observed as 7.8% at the pressure ratio of 3.64.
- The levelized product cost is 25% higher in the proposed combined cycle.

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ABSTRACT

Liquefied natural gas (LNG) cold utilized micro-cogeneration systems can be used as a part of small scale LNG regasification processes. The study proposes a LNG cold utilized micro-cogeneration system which combines a Stirling engine and a micro gas turbine. The combined system is compared to a conventional micro-cogeneration system the point of thermodynamic, environmental and thermoeconomic views. Parametric studies are conducted in the ranges of 288.15–313.15 K for the ambient air temperature and 3–4 for the compressor pressure ratio, respectively. Thermodynamic efficiencies and power generation rates are studied in thermodynamic analyses while carbon dioxide emission rates and the relevant emission reductions are observed in environmental analyses. An original exergy-cost matrix is produced for the combined system and thermoeconomic comparison is performed between the combined system and the conventional micro-cogeneration system. It is found that the combined system provides 7.8% higher power generation rates whereas it has 1% and 2.4% higher energetic and exergetic efficiencies, respectively at the actual pressure ratio of the micro gas turbine. Emission reductions are observed as 3.9%, 7.8% or 8% at individual pressure ratio of 3, 3.64 or 4. The unit fuel costs are calculated for the system components and it is deduced that the combined system has higher unit fuel costs at the lower pressure ratios. It is found that the single system has roundly 25% less levelized product cost than the combined system at the actual pressure ratio. A simple graphic-based thermoeconomic optimization study demonstrates that the minimum relative cost differences are at different locations for the combined cycle.

1. Introduction

Liquefied natural gas (LNG) is one of the ways for the natural gas transportation and it is non-corrosive, non-toxic cryogenic liquid (162 °C) [1,2] at the atmospheric conditions. It is the only feasible, mature and commercial natural gas transportation method for the distances for roundly 3500 km and above from the producing country to the consuming country [1]. Japan, South Korea, Taiwan, UK, Turkey and Spain are some of these consumer countries and areas which have giant LNG imports according to International Gas Union data [3]. The LNG trade has four main steps which are: (i) exploration and production, (ii) liquefaction, (iii) transportation, and (iv) regasification. The cost of the LNG trade depends on the cost performances of these steps, and the regasification step is the most crucial step on the LNG cost chain for the consumer

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Nomenclature

c	unit cost, \$/kJ
C	cost, \$
e	specific exergy, kJ/kmol
ER	emission reduction, %
$\dot{E}$	exergy, kJ/s
f	exergoeconomic factor, %
F	fuel flow rate of microturbine, kJ/s
$\bar{h}$	specific enthalpy, kJ/kmol
$\dot{H}$	energy, kJ/s
L	heat loss ratio from combustion chamber, %
LHV	lower heating value, kJ/kg
M	molar mass, kg/kmol
$\dot{m}$	mass flow rate, kg/s
$\dot{n}$	molar flow rate, kmol/s
p	pressure, bar
r	relative cost difference, %
RV	reversibility factor
$\bar{R}$	universal gas constant, kJ/kmol K
$\bar{s}$	specific entropy, kJ/kmol K
PEC	purchased equipment cost, \$
T	temperature, K
$\dot{W}$	work, kJ/s
$\dot{Q}$	heat, kJ/s
x	molar fraction
y	exergy ratio, %

Greek letters

β	power to heat ratio
γ	constant for polytropic state
$\bar{\lambda}$	fuel-air ratio
ζ	ratio of cold gas inlet to hot gas inlet
ϵ	effectiveness
η	energetic efficiency
ε	exergetic efficiency
ς	carbon dioxide emission rate
τ	annual operation time, h
ω	heat exchanger effectiveness

Superscripts

a	air
CH	chemical exergy
M	mechanical component of physical exergy
T	thermal component of physical exergy
p	product
PH	physical exergy

Subscripts

0	dead state
a	air
abs	absolute
C	compressor
CL	combustion loss
CC	combustion chamber
D	destruction
GT	gas turbine
gen	generated
HE	heat exchanger
f	fuel
L	loss
mec, st	mechanical for Stirling engine
$O\&M$	operation and maintenance
p	product
pcy	polytropic
REC	recuperator
ref	reference state
tab	tabular source
th	thermal energy

Abbreviations

CHE	Cold Heat Exchanger
HHE	Hot Heat Exchanger
LNG	Liquefied Natural Gas
MCHP	Micro Combined Heat and Power
NIST	National Institute of Standards and Technology
ORC	Organic Rankine Cycle
US	United States
PCM	Phase Change Material
TES	Thermal Energy Storage

countries due to its high operation costs which corresponds 15–25% of the total LNG trade cost. To decrease operation costs and increase thermal efficiencies of the LNG regasification processes, LNG cold utilization systems have been used for many years. LNG cold utilization is a way to use the LNG cryogenic energy in some facilities such as power generation [4–6], separation technology [7], carbon dioxide (CO_2) capture [8], waste treatment [9], food storage [10], and desalination [11].

LNG cold utilization systems have been widely used in power generation sector from past to present. In Japan, there are 14 LNG cryogenic power plants which have been operated according to Rankine and/or direct expansion cycle principles [1,12]. Besides these principles, Brayton cycles were designed in many studies for LNG cold utilization purposes. Basic theoretical background and some of the crucial studies of the Rankine, Brayton and direct expansion based LNG cold utilization systems were presented in the review of Gomez et al. [12]. Stirling engines were also proposed for LNG cold utilization studies by Oshima et al. [13], Dong et al. [14], and Szczygiel et al. [15]. All these cycles can be operated as single cycles in LNG cold utilization systems but it is also possible to integrate them into each other.

One of the pioneer combined cycle study for the LNG cold utilization was conducted by Angelino [16] in the second half of 1970s. Various combined cycle configurations were studied and four different inert organic gases were investigated as working fluids. In 1990s, Najjar and Zaamout [17], Wong [18], Chiesa [19] and Hisazumi et al. [20] contributed to LNG cold utilization studies by designing various combined cycles. Najjar and Zaamout [17] used propane in an organic Rankine cycle (ORC) and the ORC was combined with the Brayton and direct expansion cycles which could totally produce 2000 MW power. Freon was firstly used by Hisazumi et al. [20] in the combined LNG cold utilization systems that had 240 MW capacity. Shi and his colleagues performed various studies on the combined LNG cold utilization systems [21–23]. Two different novel designs were proposed. In the first novel cycle [21], a heat recovery steam generator combined with Brayton and steam cycles. In addition, the LNG direct expansion cycle was also combined with those two cycles. Parametric studies were conducted by using various inlet and outlet temperatures of the direct expansion turbine, inlet temperature of the gas turbine and condenser pressure of the steam cycle. In the second novel design [23], application of inlet air cooling and intercooling processes