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Cost and economic potential analysis of a cascading power cycle with liquefied natural gas regasification

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ABSTRACT

Cost analyses and advanced exergoeconomic analyses are applied to a cascading power cycle with liquefied natural gas regasification. These analyses provide information about the causes of irreversibilities and determine the amount of avoidable irreversibility of the process. The results show that in all components except one of the gas turbines, most of the irreversibility is due to the endogenous exergy destruction. It also indicates that most of the exergy destruction except in combustion chamber is unavoidable, but that there is still a large potential to improve the performance of the system. In terms of avoidable endogenous exergy destruction cost rate, the analysis indicates that combustion chamber and one of the gas turbines should be modified first, because their avoidable endogenous exergy destruction cost rates are higher than those of other components. The cost of exergy destruction and investment in most of the process components are endogenous. So interactions among the components in these processes are not strong. The investment costs of the heat exchangers, one of the compressors, gas turbines and pumps are unavoidable due to technological and economic limits while other process equipment have potentials for improvement. Also based on the avoidable endogenous/exogenous part, three strategies are suggested to improve the performance of the components by reducing exergy destruction costs in the process components. The exergy efficiency and total exergy destruction rate of the process are about 59.4% and 159,600 kW, respectively.

1. Introduction

In recent years, natural gas (NG) has become known as a relatively clean fuel source, compared to other fossil fuels, with high conversion efficiency via combustion [1]. The transportation of liquefied natural gas (LNG) over long distances is often an economic approach for transporting NG [2]. The annual use of LNG is growing at 10% within the next ten years, and the demand is expected to reach 500 million tons per year by 2030 globally [3]. The International Energy Agency forecasts that the world's natural gas liquefaction capacity will increase by about five times by 2030 [4].

The regasification of LNG to complete the supply chain is carried out at LNG terminals. In the typical LNG regasification terminal, heat from the environment or waste heat is utilized [5]. The LNG regasification cost is a small fraction of the LNG supply chain cost [6]. But, LNG at a temperature of 110 K contains a significant exergetic potential of 370 kJ/kg·s [7]. This cold exergy is attributable to sensible and latent heat. Various methods have been developed for utilization of the LNG cold energy [8]. For instance, this cold energy can be utilized in air separation and liquefaction to pre-cool the air feed stream which leads to energy savings [9], for agro-food transformation and conservation as well as for some loops in the cold chain in food industries [10], sea water desalination by using the ice bucket on flake ice makers [11], and in other industrial processes such as waste incinerator which is integrated with ammonia closed Rankine cycle and an LNG open Rankine cycle [12] or for capturing CO_2 in the exhaust gas discharged from magnesite processing [13]. Also, the cold energy from LNG regasification can be efficiently used as a heat sink in the electrical power conversion processes [14], and in the same way utilized in the co-production of hydrogen and electricity through integrating biomass gasification, chemical looping combustion, and electrical power generation with CO_2 capture [15].

Various types of integrated thermodynamic cycles with LNG regasification for power generation have been proposed. For instance, in

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Nomenclature

A	heat transfer area (m^2)
C	cost per unit exergy ($/GJ)
$\dot{C}$	cost rate ($/h)
E	specific flow exergy (kJ/mol)
e^0	standard chemical exergy (kJ/mol)
$\dot{E}_x$	total exergy rate (kW)
Ƒ	exergoeconomic factor (%)
G	Gibbs free energy (kJ/mol)
H	specific enthalpy (kJ/kg)
H	annual working hours (h)
i	interest rate (%)
$\dot{m}$	mass flow rate (kg/s)
N	plant life time (year)
P	pressure (kPa)
$\dot{Q}$	heat transfer rate (kW)
r	relative cost difference (%)
r_P	pressure ratio
S	specific entropy (kJ/kg °C)
T	temperature (K)
$\dot{W}$	electrical power rate (kW)
x	mole fraction (–)
y	exergy destruction ratio (–)
$\dot{Z}$	investment cost rate ($/h)
Z	purchased equipment cost ($)

Greek letters

φ	maintenance factor
ε	exergy efficiency (%)
λ	air to fuel ratio in CC (–)

Superscripts

AV	avoidable
CI	capital investment
EN	endogenous
EX	exogenous
OM	operation and maintenance
UN	unavoidable

Subscripts

0	standard
a	ambient
A	air
bs	boundary surface
CH	chemical
D	destruction
e	exit
F	fuel
g	gas
i	input
is	isentropic
k	component k
L	LNG, lost
min	minimum
o	output
P	product
PH	physical
Q	heat
R	rankine
tot	total
W	work

Abbreviations

C	compressor
CC	combustion chamber
CRF	capital recovery factor
fc	fixed cost
H	heat exchanger
G	generator
GT	gas turbine
LMTD	logarithmic mean temperature difference
LNG	liquefied natural gas
M	mixer
min	minimum
MTA	minimum temperature approach
NG	natural gas
ORC	organic Rankine cycle
P	pump
T	tee
uc	unit cost

Rankine cycle power plants the cold exergy of LNG has been utilized to cool and condense the working fluid to a temperature below ambient [16]. The cold exergy of LNG regasification has been used in Brayton cycles to decrease the compressor inlet air stream temperature [17]. Some researchers propose integrating Brayton and Rankine cycles with respect to the heat source for recovering cold exergy [8]. In order to analyze the performance of each of these cycles, an exergoeconomic technique based on the second law of thermodynamics was developed [18]. In this study, the waste heat from a supercritical Brayton cycle is used in either a transcritical CO_2 cycle or an ORC. The results show that the total unit product cost of the Brayton and ORC cycles is slightly lower than those for the Brayton and transcritical CO_2 cycles. The exergoeconomic analysis considers the exergy and cost of production in processes [19]. By using exergoeconomic analysis for all of the process material and energy streams, the cost of each is determined. [20]. This provides a reasonable approach for price allocation and thermodynamic performance evaluation of the processes in a system. Several processes have been studied from this point of view. Ozdil et al. [21] proposed a specific exergy costing method for the exergoeconomic analysis of an industrial organic Rankine cycle (ORC), and showed that better ORC exergoeconomic performance is obtained when the evaporator inlet is in the saturated liquid phase. Zare et al. [22] performed an exergoeconomic analyses of three ORC configurations of binary geothermal power plants. The analyses included profitability evaluations based on the total capital investment and payback period of the cycles. Hassoun et al. [23] carried out an exergoeconomic analysis of a new ORC-based multigeneration system which uses solar energy as a prime energy source. The cycle meets the demands of a net zero energy building in Lebanon. The cost of the overall system is determined with exergoeconomic analysis to be 118×10^3 $ for the year 2013. Note that all monetary values listed in the paper are in US dollars. Khaljani et al. [24] present an exergoeconomic analysis of a combined heat and power cycle consisting of a gas turbine (GT), an ORC and a single-pressure heat recovery steam generator (HRSG). The exergoeconomic factor for the cycle is about 10.6%, indicating that the exergy destruction cost rate exceeds the capital investment cost rate. Exergoeconomic analysis