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Thermodynamic analysis of integrated LNG regasification process configurations

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ABSTRACT

Effective utilization of liquefied natural gas (LNG) cold energy during its regasification in both renewable and nonrenewable processes is discussed and analyzed. Conventional and non-conventional thermodynamic cycles, are described and categorized. Expressions for exergy and energy efficiencies are developed to facilitate evaluation of the processes. Finally suggestions for improving the efficiency of such systems are developed and the technical advantages and challenges are pointed out. The obtained results indicate that, among the considered cycles, the highest energy and exergy efficiencies are about 86.3% and 80.0% respectively; which is related to the combined cycles. Conversely the lowest energy and exergy efficiencies occur in other application of LNG cold energy cycles (i.e., production of hydrogen by a solar aid liquefied natural gas hybrid CO_2 cycle) and Rankine cycle (i.e., CO_2 transcritical geothermal power generation cycle) with the values of 7.39% and 7.95%; respectively.

Contents

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Nomenclature

e	Specific flow exergy (kJ/kg)
$\dot{E}_x$	Exergy rate (kW)
$\dot{W}$	Work transfer rate (kW)
$\dot{m}$	Mass flow rate (kg/s)
h	Specific enthalpy (kJ/kg)
T	Temperature (°C)
p	Pressure (bar)
s	Specific entropy (kJ/kg K)
g	Gravitational constant (m/s^2)
v	Speed (m/s)
x	Mole fraction (-)
R	Gas constant (J/ K mol)

Greek letters

η	Efficiency

Subscripts

i	Inlet
i	Component
sh	Shaft
F	Fuel
th	Thermal
ex	Exergy
CMB	Combustion
mix	Mixture

Reference state

p	Potential
L	Lost
tot	Total
mec	Mechanical

Subscripts

alt	Alternator
RG	Regasification plant
ov	Overall
chem	Chemical
ph	Physical
el	Electrical
k	Kinetic

Abbreviations

LNG	Liquefied Natural Gas
CAES	Compressed air energy storage
CC	Combined cycle
CD	Condenser
C-i	Compressor
Exp	Expander
E-i	Exchanger
GT-i	Gas turbine
G-i	Generator
RO	Reverse Osmosis
LCC	Life cycle cost
ORV	Open rack vaporizer
WF	Working Fluid
CCPP	Combined cycle power plant
LHV	Lower Heating Value
NG	Natural Gas
PEM	Proton exchange membrane
IEA	International Energy Agency
ORC	Organic Rankine cycle
BOG	Boil Off Gas
ANG	Adsorbed Natural Gas
CAS	Cryogenic air separation
ASU	Air separation unit
HRSG HX-i	Heat Recovery Steam Generator Heat exchanger
CHP	Combined heat and power
CES	Cryogenic energy storage
FSRU	Floating storage & regasification unit
ODP	Ozone depletion potential
GWP	Global warming potential
RC TK	Rankine cycle Tank
BC	Brayton cycle
SOFC	Solid oxide fuel cell
GT P-i	Gas turbine Pump
V-i	Valve

1. Introduction

With the current growing rate of energy consumption and environmental issues, it is necessary to find energy resources that can be utilized with higher efficiency. Renewable energies are good resources to reduce the greenhouse gas effects [1]. To overcome this issue and reducing emission of greenhouse gases many attempts have been done to utilize the exhaust waste heat from the flue gases [2]. Cold energy recovery of liquefied natural gas (LNG) decreases the required refrigeration and causes energy saving in the process [3]. LNG is transported by ship to the receiving terminal at atmospheric pressure and temperature of about 110 K [4]. Natural gas liquefaction process consume a considerable amount of energy, approximately 500 kW/h electric energy per ton of LNG, at about −161 °C, which contains a significant amount of the cold energy [5]. The required power for natural gas liquefaction process changes between 0.45 and 0.55 kWh/kg [6]. The proximity of these values shows that improving the liquefaction process performance is almost difficult and limited. In the conventional supply chain of natural gas, LNG after production is loaded into the especial insulated tanks and after arriving to destination, it is pressurized to suitable pressure for transportation via pipeline and then is vaporized to reach the ambient temperature.

During the last two decades, regasification systems have not been improved considerably, and 1.5% of LNG energy is consumed through the vaporization [7]. In order to increasing LNG cold energy recovery, various types of regasification processes have been investigated [8–10]. Vaporization systems usually use air or sea water as the heat sources and therefore cold energy of LNG is wasted [11,12]. In order to overcome this issue, LNG regasification can be integrated with other types of processes [13]. For instance, electrical power cycle and other applications [14,15]. In power generation cycles, the obtained cold energy through the regasification can be utilized as a heat sink [5,16]. Also, for other applications the LNG cold energy has been utilized to provide the required cold energy, like cryogenic air separation unit [17,18] and seawater desalination [19]. For generation of 240 kWh of electrical power near one ton of LNG is consumed [20]. Before the gasification, it is better to increase pressure of the LNG to the required pressure for transportation or various usages of the produced natural gas. Because if regasification is carried out at low pressure, the produced natural gas pressure must be increased by a compressor which its required power is much more than the pump [21]. Outlet natural gas pressure in LNG vaporization terminals depends on the downstream process (Table 1) [22].

Temperature difference between the LNG and ambient air (or sea water) is about 182 K. So there is considerable cold energy source which can be recovered by two basic methods: using the cold energy directly and electrical power generation. Direct cold energy