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Recovery of cold energy from liquefied natural gas regasification: Applications beyond power cycles

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ABSTRACT

Liquefied natural gas releases large amounts of cold energy during the conventional regasification process. Currently, most studies have investigated the opportunities to utilize this waste cold for power cycles but few studies considered using this cold directly on other cold applications. In this paper, different cold recovery approaches are considered and compared depending on the energy carriers (i.e. electricity, liquid carbon dioxide, chilled water, liquid air/nitrogen and latent heat storage) used to support a few cold applications (i.e. air separation units, dry ice production, freezing and district cooling). Using different transportation methods, these energy carriers produced using the recovered cold as part or all of their energy input is coupled to these cold applications with different temperature requirements and located 5 km away from the regasification facilities. This paper investigates the change in overall exergy efficiency and carbon dioxide emissions throughout the whole process from energy carrier generation to their consumption in the cold applications when the cold applications are coupled to different alternative energy carriers, compared with the baseline case. With the availability of these alternative energy carriers, conventional cold applications can be modified to reduce their dependency on electricity and improve their performance. The baseline setup has an overall exergy efficiency of ≈13% while using electricity generated by waste cold assisted power cycles as energy carrier yields overall exergy efficiency of ≈13.2%. Using alternative energy carriers charged with recovered cold, such as liquid carbon dioxide/water, latent heat thermal storage and liquid nitrogen, yields lower overall exergy efficiencies of ≈9.7%, 11.5% and 10.2%, respectively which is largely due to the temperature mismatch and thus large amount of exergy destructions during the heat exchange process. For the carbon dioxide emissions analysis, the baseline setup yields carbon dioxide emissions of ≈22.3 kTPA. Using electricity generated with waste cold assisted power cycle yields improvement on carbon dioxide emissions of ≈18.3% while those using alternative energy carriers yield improvements on carbon dioxide emissions of ≈38.0%, ≈37.0% and ≈6.0%, respectively.

1. Introduction

Use of natural gas is expected to grow significantly over the next decades due to its abundance and relatively lower environmental impact when compared with oil and coal. Pipelines are usually employed to distribute natural gas from the production site to the consumers. However, it is shown that for long distance transport of natural gas, liquefied natural gas (LNG) is proven to be more cost effective and has higher flexibility [1]. During the liquefaction process, the volume of natural gas is reduced to 1/600th the original volume, with its temperature reduced to below −160 °C. LNG is normally regasified before distributed to end users, with about 860 kJ/kg of heat energy absorbed [2] or 370 kJ/kg of cold exergy released [3] in the process. Conventional LNG regasification involves direct heat exchange between the LNG and sea water or other heat sources, meaning that the cold energy is wasted alongside with large mechanical power required to drive the seawater pumps. With the projection of world LNG trade from about $1.53{\cdot}10^{11}$ tonnes in 2012 to about $3.70{\cdot}10^{11}$ tonnes in 2040[1] [4], the waste cold energy during the regasification process should be meaningfully reused and monetized by LNG plant operators.

Various processes to recover the LNG cold have been discussed and implemented in different countries, as reported in Table 1 [5–7]. As the

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[1] LNG density is assumed as 450kg/m^3 or 12.74kg/ft^3

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Nomenclature

Acronyms

ASU	Air separation unit
CC	Combustion chamber
COP	Coefficient of performance
CP	Compressor
EP	Expander
HPC	High pressure column
HRSG	Heat recovery steam generator
HX	Heat exchanger
JV	Joule-Thompson valve
LNG	Liquefied natural gas
LN_2	Liquid nitrogen
LO_2	Liquid oxygen
LPC	Low pressure column
MSHE	Multi stream heat exchanger
PCM	Phase change material
PP	Pump
SC	Separation column

Chemical symbols

CO_2	carbon dioxide

Greek symbols

η_{ex}	exergy efficiency [%]
η_{th}	thermal efficiency [%]
η_{net}	net efficiency [%]
ΔT	temperature difference [°C]
ρ	density [kg/m^3]

Roman symbols

A	heat transfer area [m^2]
D	pipe diameter [m]
e	specific exergy [kJ/kg]
E_C	chemical exergy [kJ/kg]
E_D	exergy destroyed [kJ/kg]
E_{IN}	inlet exergy [kJ/kg]
E_L	exergy loss as waste stream [kJ kg^{-1}]
E_M	exergy contained in material stream [kJ kg^{-1}]
E_P	physical exergy [kJ kg^{-1}]
E_R	exergy recovered [kJ kg^{-1}]
f	friction factor [–]
h	specific enthalpy [kJ kg^{-1}]
H	convective heat transfer coefficient [–]
k	thermal conductivity [W m^{-1} °C^{-1}]
L	length of pipe [m]
$\dot{m}$	mass flow rate [kg s^{-1}]
R	thermal resistance [°C W^{-1}]
s	specific entropy [kJ kg^{-1} °C^{-1}]s
V	velocity of working fluid [m s^{-1}]
$\dot{W}$	power [W]

Subscripts

ASU	air separation unit
BCC	baseline combined cycle
CC	combustion chamber
CP	compressor
cond	conduction
conv	convection
CW	chilled water
DF	deep freezing
DI	dry ice production
EP	expander
HX	heat exchanger
in	inlet
ins	insulation
JV	Joule-Thompson valve
LAPC	LNG assisted power cycle
LCO_2	liquid carbon dioxide
misc	miscellaneous
NG	natural gas
out	outlet
PP	pump
TN	thermal network
TS	thermal storage
0	reference condition

world's largest importer of LNG, Japan demonstrates a large variety of LNG cold recovery technologies in use. Between 20 and 30% of LNG cold energy is utilized in Japan [6], with Osaka Gas Co. becoming the first plant in Japan to achieve 100% utilization of LNG cold energy by cascading cold applications with different temperature requirements for cold exchange with the LNG to be regasified [8]. South Korea as the world's second largest importer of LNG has also utilized LNG cold for air separation and cryogenic comminution [9].

Table 1
Processes and countries where LNG cold energy recovery has been implemented [5–7].

Process	Temperature range (°C)	Country
Air separation	−191 to −130	China, France, Japan, South Korea
Electricity generation	−160 to 0	Japan
Hydrocarbon liquefaction	−120 to −60	Japan
Cryogenic comminution	−110 to −60	Japan, South Korea
Liquid CO_2/dry ice	−60	Japan
Refrigeration/cold storage	−30 to 0	Japan, South Korea
Seawater desalination	−10 to 10	United States
Gas turbine inlet air cooling	0–10	India, Japan

Several research studies discuss utilizing the LNG cold energy to improve efficiencies of different power cycles by reducing the compressor inlet temperature in Brayton Cycles or reducing the working fluid condensation temperature in Rankine Cycles or Kalina Cycles [3]. In addition, direct expansion cycle of regasified LNG through a turbine is also used to harvest the mechanical exergy contained in LNG. Table 2 reports some of the power cycles which utilize LNG cold energy to improve thermal and exergy efficiency [10–36], with thermal and exergy efficiencies tabulated as η_{th} and η_{ex}, respectively.

With correct choice of working fluid for the power cycles, LNG cold can be utilized at different temperature ranges well below ambient temperature. By decreasing the condensation temperature of the working fluid between ≈ -50 °C and ≈ -120 °C (as reported in [20–22,25,33] in Table 2), efficiencies between ≈12% and ≈34% can be achieved even with low to medium temperature heat sources, such as seawater, solar power or industrial waste heat. Rankine cycles with carbon dioxide (CO_2) as working fluid [26,28,30,31] can undergo a larger change of temperature when compared to organic working fluids and this allows a high-temperature heat source, such as combustion heat to be used. As a result, the process achieves higher thermal