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The exploitation of the physical exergy of liquid natural gas by closed power thermodynamic cycles. An overview

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ABSTRACT

The world trade in LNG (liquefied natural gas) has tripled in the last 15 years and the forecasts are for its further rapid expansion. Although the cryogenic exergy of the LNG could be used in many industrial processes, it is recognized also as a source for power cycles.

When using the low temperature capacity of LNG for power production, several thermodynamic cycles can be considered. This paper reports the state-of-the art of the most relevant solutions based on conventional and non-conventional thermodynamic closed cycles. Moreover, a novel metrics framework, suitable for a fairer comparison among the energy recovery performances of the different technologies is proposed. According to the defined indicators the compounds plants with gas turbine and closed Brayton cycles perform really better, with an almost full use of LNG available cold temperature and a fuel consumption with an efficiency better than that of the current combined cycles. The Rankine cycles with organic working fluids (pure fluids or non-azeotropic mixtures) using seawater or heat available at low temperature (for instance at 150 °C) also perform in a very satisfactory way. Real gas Brayton cycles and carbon dioxide condensation cycles work with very good thermal efficiency also at relatively low maximum temperatures (300 ÷ 600 °C) and could have peculiar applications.

1. Introduction

The consumption of LNG (Liquified Natural Gas) has been growing steadily around the world for years. In 2012, Japan alone consumed 37% of the total LNG commercialised. According to many analysts [1], recent years have seen a further revolution in production, distribution and consumption of LNG; since 2013, the United States has no longer been the major importer of gas and petroleum, but has been replaced by China, but, on the contrary, is likely to be one of the leading exporters of LNG, thanks to the technological exploitation of shale gas. Consumption of LNG is expected to rise sharply in the Far East (China, Japan, South Korea), whilst Indonesia, which used to be an exporter, has now become an importer of LNG. Several Asian companies have plans to create LNG export terminals in Canada, across the Pacific from Asia (on the coast of British Columbia). The government of the United States has recently approved the construction of four export terminals for the liquefaction and distribution of LNG. Australia, one of the major producers of gas in the world, is increasing its output capacity. Although estimates for shale gas in the U.S. are still rather imprecise, [2, p. 88], the fact still remains that it will be widely available for the coming decades and the fast-developing nations will ensure high consumption levels of LNG.

Among the earliest regasification plants built in the world we have that of Panigallia in the Gulf of La Spezia (Porto Venere, Italy), operating since 1971, and that of Barcelona (Spain), in operation since 1970, [3, p. 29]. Today, just in Japan, there are around thirty import terminals with regasification.

The vaporisation of LNG can be accompanied by numerous technological uses of its cold exergy capacity: in the Senbouku 1 terminal of the Osaka Gas Co., for example, 100% of the cold exergy of the LNG during its regasification is used for petrochemical processes of separation and refrigeration, for the separation and liquefaction of air, the liquefaction of carbon dioxide, air-conditioning and the spray cooling of intake air of a gas turbine during the summer, [4]. Another typical use for the cold exergy of LNG in the import terminals is the recovery of the Boil-off gas (BOG re-liquefaction).

One interesting use of the cold exergy of LNG is in the production of electricity, using closed thermodynamic cycles and the LNG

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Nomenclature

Symbols, acronyms and subscripts

$\dot{E}$	exergy rate, W
h	specific enthalpy, J/*kg*
$LMTD_G$	log mean temperature difference in the regasification heat exchanger, °C
$\dot{m}$	mass flow rate, kg/*s*
$MITA_G$	minimum temperature difference in the regasification heat exchanger, °C
P	pressure, bar
r_C	compression ratio
SPP	specific power performance parameter, *MW*/*kg*/*s* of LNG
SPP*	"net" specific power performance parameter, *MW*/*kg*/*s* of LNG (equation (5))
T	temperature, K or °C
T_C	condensation temperature, K or °C
$T_{C,HP}$	high pressure condensation temperature, K or °C
$T_{C,LP}$	low pressure condensation temperature, K or °C
T_{cr}	temperature at the critical point, K or °C
T_E	evaporation temperature, K or °C
T_r	reduced temperature ($=T/T_{cr}$)
T_0	ambient temperature, K or °C
$\dot{W}$	electric or mechanical power, W
$\dot{W}_{available}$	available electric or mechanical power available, W
$\dot{W}^*$	"net" electric or mechanical power (equation (3)), W
η	cycle thermal efficiency
η_{II}	exergy efficiency
$\eta_{II,ref}$	reference exergy efficiency
η^*_{II}	"net" exergy efficiency (equation (4))
x	molar fraction
ASU	air separation unit
GT	gas turbine
GWP	global warming potential
HRSG	heat recovery steam generator
in	at inlet conditions
out	at outlet conditions
LHV	lower heating value
LNG	liquefied natural gas
NG	natural gas
1,2…	representative points in a thermodynamic cycle

as a low temperature heat reservoir. One of the first publications to describe this specific application was the article by G. Angelino in 1977, [5].

The use of a thermodynamic cycle can also be accompanied by the expansion of high pressure LNG in a turbine, before sending out to the distribution network.

We shall discuss below the most representative thermodynamic cycles that have the potential for power generation from the regasification of LNG.

2. The characteristics of the LNG as a heat sink

All calculations were made using the Aspen-Plus v7.3 program, while the thermodynamic properties of the various fluids were estimated by the Peng–Robinson equation of state, [6].

The Peng–Robinson equation of state, a cubic equation, although relatively simple, is widely used in the oil industry and the results for natural gas are more than satisfactory for the purposes we have set here (see, for example, [7–9]). The same equation was also used for all the compounds considered as working fluids in the thermodynamic cycles we analysed.

The temperature and pressure of the reference environment were assumed to be 15 °C and 1.01325 bar, respectively.

Fig. 1a reports the limit curve for LNG with three isobars, derived from calculation using the chosen equation of state. The standard composition of the LNG was that in Ref. [13] and it is shown in Fig. 1a. The supercritical isobar at 80 bar is the pressure at which the regasification of the LNG is assumed to take place in the numerical examples worked out in the following.

Fig. 1a represents some supercritical and subcritical isobars of natural gas in the Temperature-Entropy thermodynamic diagram. Assuming the molar composition given in Figure, the subcritical isobars show a considerable temperature glide. Resorting then to thermodynamic cycles for the exploitation of the "cold" exergy of LNG, this fact makes the problem of regasification of LNG at subcritical or supercritical pressures basically the same. Nevertheless, in the next, among the cited systems, there are also examples of subcritical regasification of LNG (assumed often by various Authors as pure methane).

Fig. 1b reports the heating curve for the liquid LNG at the pressure of 80 bar, from a temperature of −160 °C (liquefaction temperature at room pressure), to the room temperature. The physical exergy ($\dot{E}_{LNG,in} - \dot{E}_{NG,out}$) available from just the regasification is about 348 *kJ*/*kg*.

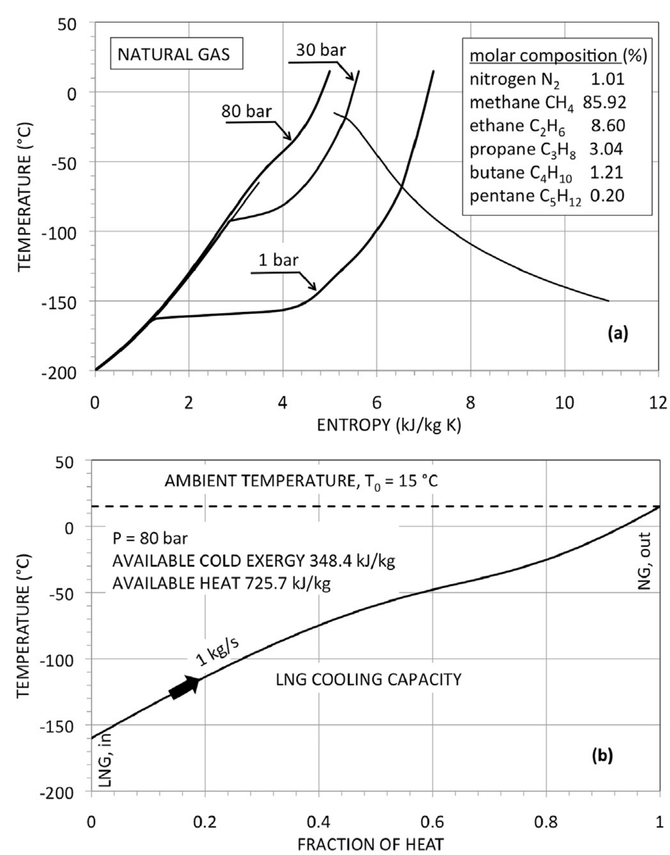

Fig. 1. **a** Thermodynamic properties of LNG. Three isobars and the saturated vapour and liquid curves in the T-S plane. **b** Thermodynamic properties of LNG. The cooling capacity of supercritical LNG in relation to an ambient temperature of 15 °C.