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# Thermodynamic analysis of a Brayton cycle and Rankine cycle arranged in series exploiting the cold exergy of LNG (liquefied natural gas)

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ABSTRACT

The LNG (liquefied natural gas) regasification process is a source of cold exergy capable of being exploited to improve the efficiency of energy conversion. This paper presents a novel power plant consisting of a combination of a CBC (closed Brayton cycle) with a SRC (steam Rankine cycle), arranged in series with regard to the power source, while exploiting the cold exergy available in the regasification process of LNG. The power plant is fuelled by a combustion system of natural gas where the flue gases firstly yield heat to the CBC, then to the SRC and finally to the combustion air by means of a heat recovery process.

The LNG cold exergy is exploited to cool the He used in the CBC to cryogenic temperatures at the compressor inlet as well as for generating electric power through direct expansion. The power plant is thermodynamically modelled and simulated using EES (Engineering Equation Solver). An energy and exergy analysis is carried out to evaluate the effect of some key parameters on the efficiency such as the temperature at the compressor inlet, the compression ratio, the temperature at the CBC turbine inlet and the LNG pressure during the regasification process. The outcome is a high efficiency power plant.



## 1. Introduction

LNG (liquefied natural gas) is produced by the cryogenic refrigeration of natural gas after the removal of the acid and water components. Throughout the world natural gas transportation is increasingly relying on liquefaction and conveyance through specialised tankers. For structural reasons LNG is shipped at basically atmospheric pressure at a temperature of about −165 °C [1]. A significant amount of energy is consumed to produce low temperature LNG. However, LNG must be regasified for normal use at the receiving site. At the receiving terminal a great amount of cold energy, about 800 kJ per kg/s of LNG, is released from the regasification process and is discarded into the sea water or another fluid which works as the heat source. Two conventional systems are used for the regasification of LNG: the Open Rack Vaporisers with sea water [2,3] and the Submerged Combustion Vaporisers [1,4], both under a significant amount of energy consumption. Due to rising energy prices and environmental restrictions, the need for energy recovery during regasification is evident. The recovery of cold energy is also of great interest because it has a relevant environmental impact, usually on the sea water around the regasification site. The cold energy of LNG can be recovered in several ways such as $CO_2$ capture technology [5], air separation [6], agro-food industry [7], etc. In recent years however, the most widely used application for exploiting the cold energy available in the LNG is that of improving the efficiency of the power plants, using LNG as a heat sink [1,8–11]. Studies such as those reflected in Refs. [12–16] show the improvement in the efficiency of organic Rankine cycles through the use of LNG vaporisation energy to condense the working fluid, rather than doing so conventionally with water or air. Although the organic Rankine cycles are a well known option for generating energy associated with LNG regasification, these systems are limited by the physical properties of the working fluid, which should be thermally stable at high temperatures and condensed at low temperatures without issues of freezing.

In the applications of LNG regasification using Brayton cycles [17–20], LNG is used to cool the gas to cryogenic temperatures at the compressor inlet. This achieves a decrease in the specific volume of gas and thereby reduces the compression work, implying an increase in the cycle's net power.

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**Nomenclature**

| | |
|---|---|
| $e$ | specific exergy (kJ/kg) |
| $\dot{E}_{fuel}$ | chemical exergy of the fuel (kW) |
| $\Delta\dot{G}_r$ | Gibbs free energy decrease rate (kW) |
| $h$ | specific enthalpy (kJ/kg) |
| $\bar{h}$ | specific enthalpy (kJ/kmol) |
| $\dot{I}$ | irreversibility (kW) |
| $\dot{m}$ | mass flow rate (kg/s) |
| $n_p$ | moles of combustion products |
| $n_r$ | moles of combustion reactants |
| $p$ | pressure (bar) |
| $\dot{Q}$ | heat transfer rate (kW) |
| $r$ | compressor pressure ratio |
| $T$ | temperature (°C) |
| $y$ | fraction of high steam extracted |
| $\dot{W}$ | power (kW) |
| $x$ | excess air ratio (%) |

*Subscripts*

| | |
|---|---|
| comb | combustion |
| g | flue gas |

*Greek letters*

| | |
|---|---|
| $\beta$ | air-fuel ratio (kg air/kg fuel) |
| $\eta$ | thermal efficiency |
| $\eta_{alt}$ | alternator efficiency |
| $\eta_{comb}$ | combustion efficiency |
| $\eta_{ex}$ | exergy efficiency |
| $\eta_{mec}$ | mechanical efficiency |
| $\eta_{ov}$ | overall efficiency |

*Abbreviations*

| | |
|---|---|
| APH | air preheater |
| C | compressor |
| CBC | closed Brayton cycle |
| EX | expander |
| HP | high pressure |
| HT | helium turbine |
| HX | heat exchanger |
| LHV | lower heating value |
| LP | low pressure |
| LNG | liquefied natural gas |
| NG | natural gas |
| SPP | specific power performance (MW/(kg/s LNG)) |
| SRC | steam Rankine cycle |
| ST | steam turbine |

Other authors propose combined cycle-based strategies. For example, Xiaojun Shi et al. [21,22] propose the integration of a thermal power system for a conventional combined cycle power plant in order to exploit the energy from the LNG and improving the overall efficiency of the cycle. The authors of references [23–26] propose different power plant configurations that employ the combination of open gas cycles and closed Brayton cycles wherein the LNG is used as the closed Brayton cycle heat sink.

The objective of this research study is to determine the efficiency of a novel power plant. The novelty of the power plant lies in its configuration, which consists of a CBC (closed Brayton cycle) and a SRC (steam Rankine cycle) arranged in series with respect to the power source, while exploiting the cold exergy available in the regasification process of LNG. The authors have made an exhaustive search for works related to power plants that exploit the LNG exergy during its regasification process and did not find any papers addressing power plants with the same characteristics.

The power plant is characterised for featuring, as a power source, a natural gas fuelled combustion system where the flue gases first yield heat to the CBC and then to the SRC. LNG exergy recovery is performed through two different methods:

- Cooling the CBC working fluid to cryogenic temperatures at the compressor inlet.
- Through direct expansion in an expander to generate power.

The proposed power plant is analysed and optimised, based on the first and second laws, to use the cold exergy which is released during regasification. The methodology used in this work is divided into the following steps: power plant description, energy, exergy and combustion analysis, case study, discussion of results and conclusions.

## 2. Description of the proposed power plant

The diagram shown in Fig. 1 illustrates the novel power plant structure which integrates power generation and recovery of the exergy available in the LNG during the regasification process through a CBC and SRC as shown in the $T$–$s$ diagrams in Fig. 2. The power plant consists of four systems, as described below:

- LNG regasification system: state points 1–4. LNG at −165 °C and 1.3 bar enters the pump to be compressed, passes through the HX1 heat exchanger where it is regasified and superheated by the Brayton cycle working fluid, and then is finally expanded to NG distribution pressure. The NG supplying pressure depends on the characteristics of the of the gas consumers. References [24,25] establish this pressure at 80 bar (point 4).
- CBC: state points 5–12. The CBC is regenerative with two turbine stages and uses He as the working fluid, due to its good properties for transferring heat owing to its high specific heat [27] and its ability to generate power at both high and low temperatures [26,28]. He absorbs heat from the flue gases through the HX3 and HX4 heat exchangers and rejects the heat after having developed work in the two turbines, through the HX2 regenerator and HX1 LNG regasifier. The TIT (turbine inlet temperature) is set at 1000 °C and the He temperature at the compressor inlet at −144 °C, which is the minimum value to be found in literature according to the data obtained from Ref. [24].

Fig. 2(a) shows the $T$–$s$ diagram of the CBC, where process 5–6 represents He compression, 6-7 depicts the heat absorption corresponding to regeneration (6–12) and to heat yielded by the flue gases in HX3 (12-7). In process 7–8, the He expands in the high pressure turbine and in 8–9 is reheated in HX4, to later expand again in the low-pressure turbine, at stage 9–10. At the exit from here, the He still maintains a high temperature, allowing regeneration during process 10–11 in HX2. To close the cycle, the He is cooled at stage 11-5 before entry to the compressor along LNG regasification in HX1.

- SRC: state points 13–28. A Rankine steam is chosen with two pressure levels and intermediate reheating whose $T$–$s$ diagram is illustrated in Fig. 2(b). Steam at high temperature and