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High efficiency power plant with liquefied natural gas cold energy utilization

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ABSTRACT

This article proposes a novel power plant comprising a closed Brayton cycle (CBC) and a Rankine cycle (RC) coupled in series with respect to the flue gases instead of a conventional combined cycle, where the cold energy of the LNG is used to cool the CBC compressor suction. The research study focuses on finding working fluids best suited to the proposed CBC–RC plant and on achieving high efficiency. The proposed working fluids that fulfil the requirements for the CBC are He, N_2 and for the RC are CO_2, ammonia, ethanol or water. An analysis of the power plant using different working fluids is carried out and it is ascertained that the best efficiency conditions for the CBC are achieved with He and CO_2 for the RC. As a result, a thermal efficiency of 67·60%, an overall efficiency of 55·13% and a specific power of 2·465 MW/(kg s^{-1} LNG) is achieved.

1. Introduction

The objective of this study is to determine the efficiency of a power plant consisting of a closed Brayton cycle (CBC) and a Rankine cycle (RC), innovatively arranged in series, in relation to the power source whilst exploiting the cold energy generated in the regasification process of liquefied natural gas (LNG). The power plant features, as an energy source, a natural gas (NG) flue system where the gases firstly yield heat to the CBC and then to the RC. The CBC can use N_2 or He as the working fluid and the RC can either be organic or not.

The combination of efficiently power conversion and the regasification of LNG have been under study in recent years [1–5], due to rising fuel prices and environmental restrictions. In power plants, LNG is used complementary as a heat sink to decrease the minimum cycle temperature and thereby increase Carnot efficiency.

Studies such as those reflected in Refs. [6–9] show the improvement in the efficiency of organic Rankine cycles (ORCs) by using the LNG vaporisation energy to condense the working fluid, rather than doing it conventionally with water or air. Although the ORCs 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. It is for these reasons that ORCs often tend to use low thermal quality heat such as in a waste incineration plant [9].

CBCs are an alternative to ORCs for taking advantage of the cold energy from the LNG [10–13]. In these types of cycles 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.

By using N_2 or He as the working fluid (WF), temperatures of around 1000 °C can be reached. Both N_2 as well He are stable at very high temperatures. According to Ref. [14], N_2 has a range of application of between −210 and 1726 °C and He of −271 to 1225 °C.

Closed loop gas turbines using of He as the working fluid, are very common for generating electricity in nuclear plants. McDonald [15] has been carrying out a study of the evolution of this type of turbine since the early 40's to date. One of the major advances has been the increase the turbine inlet temperature (TIT). At the beginning it was of around 600 °C whereas nowadays can reach 1000 °C with the use of turbine blade cooling and high temperature alloys such as titanium, zirconium and molybdenum.

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List of symbols

h	specific enthalpy, kJ kg^{-1}
$\bar{h}$	specific enthalpy, kJ kmol^{-1}
HX	heat exchanger
$\dot{m}$	mass flow rate, kg s^{-1}
n_p	moles of combustion products
n_r	moles of combustion reactants
p	pressure, bar
q	specific heat, kJ kg^{-1}
r	compressor pressure ratio
T	temperature, °C
w	specific work, kJ kg^{-1}
x	excess air ratio, %
y	fraction of steam extracted
β	air–fuel ratio
η	thermal efficiency
η_{ov}	overall efficiency
η_{mec}	mechanical efficiency
η_{alt}	alternator efficiency
η_{comb}	combustion efficiency

Subscripts

bl	blower
f	fuel
g	flue gas
i	inlet
o	outlet

In the power plant proposed in this paper, comprising a CBC and an RC arranged in series with respect to the combustion gases, it is achieved to unify in one single plant the advantages offered by the high temperature of the CBC's working fluid as well as its refrigeration to cryogenic temperatures at the compressor suction, with the cooling energy of the LNG. With an RC, (organic or not), the system's overall efficiency is improved to make the most of the energy available in the flue gases.

The present paper is organised as follows: the first section describes and analyses the CBC, obtaining as a result a higher thermal efficiency but low overall efficiency. Next, the proposed CBC–RC power plant is analysed for different working fluids: N_2 and He in the case of CBC; and water, ammonia, ethane, and CO_2 for the RC, followed by a discussion of results and finally concluding with the outcomes of the conducted study.

2. High temperature CBC and using LNG as a heat sink

In conventional closed cycle gas turbine plants, the maximum ratio between the maximum and minimum temperature is of around 3·4 [16]. However, for the proposed high TIT using LNG as a heat sink, the ratio reaches 8·3, which implies a significant decrease of the compression work and a significant increase in efficiency.

The flue gases generated in a combustion chamber are used as an energy source. The temperature of the gases is controlled by the air–fuel ratio and is set at 1300 °C.

Fig. 1 shows a schematic of a regenerative CBC power plant with two turbine stages and a NG based combustion system. The plant data are displayed in Table 1.

2.1. CBC efficiency

In any power plant a distinction must be made between the thermal efficiency of the thermodynamic cycle and the overall efficiency of the plant. The thermal efficiency is defined as the ratio of the net power output to the heat input which is computed according to the following expressions:

Specific net work:

$$w_{net-CBC} = h_3 - h_4 + h_5 - h_6 - (h_2 - h_1) \tag{1}$$

Heat input:

$$q_{i-CBC} = h_3 - h_8 + h_5 - h_4 \tag{2}$$

Energy balance in the regenerator:

$$h_6 - h_7 = h_8 - h_2 \tag{3}$$

In accordance with the T-s diagram shown in Fig. 1(b) and in order to satisfy the first and second law of thermodynamics, it must be fulfilled that $T_8 < T_6$ and $T_7 > T_2$. As a result of these restrictions, it is of interest to establish a compromise between heat transfer flow and the size of the regenerator. For this, a temperature difference $(T_7 - T_2)$ of 10 °C is set to enable an adequate heat flow transfer. Thus, regenerator effectiveness is defined by:

$$\varepsilon = \frac{h_8 - h_2}{q_{max}} \tag{4}$$

where maximum transferred heat exchange is given by the following expression:

$$q_{max} = h_6 - h_7 \; assuming \; T_7 = T_2$$

Energy balance of the LNG heat exchanger: