Potential energy recovery from LNG regasification in LNG-fueled ships

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Abstract. Recent regulatory initiatives regarding ships emissions raised the interest of maritime operators on cleaner fuels. The International Maritime Organization (IMO) with Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL) set strict limits on SO_x , NO_x and CO_2 emissions. Many studies have been carried out to increase engine efficiency based on waste heat recovery such as ORC or turbo-compounding. Using LNG as a fuel opens new opportunities in this prospect. In this study, an energy recovery from LNG regasification process, through a dedicated and optimized cycle, is investigated. The system is made of an open supercritical Rankine cycle performed before engine injection and exploiting LNG as a working fluid. Results showed the influence of the maximum temperature and pressure of the cycle on the system performance. A maximum power recovery up to 2.2% of main engine power was found.

1 Introduction

Nowadays, most of the vessels are fueled with Heavy Fuel Oil (HFO) for economic reasons. HFOs are cost effective, but they contain high levels of impurities, thus producing significant amounts of emissions such as nitrogen oxides (NO_x), sulphur oxides (SO_x), carbon dioxide (CO_2) and carbon monoxide (CO).

The general trend of global and local legislations is leaning towards tighter regulations and higher standards of compliance with tougher emission limitations. Many countries demanded actions to limit both air and sea emissions from the marine sector (i.e. Emission Control Areas, ECAs). The International Maritime Organization (IMO) with Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL) set strictly limits on SO_x and NO_x emissions from the ship engines. In April 2018, IMO's Marine Environment Protection Committee (MEPC) adopted an initial strategy for the reduction of greenhouse gas emissions from ships with the intent to reduce them rapidly [1].

These new targets are achieved by using complex and expensive emission control systems that retrofit HFO engines [2] or by adopting cleaner fuels such as Maritime Diesel Oil (MDO) or Liquified Natural Gas (LNG) [3]. By using LNG, not only SO_x and particulate matter emissions are reduced but also those of NO_x and CO_2. In addition, LNG price during the last

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years has been lower than MDO and HFO thus leading to an economic attractiveness of LNG as a marine fuel.

Many studies can be found in the literature that investigates the use of LNG as a fuel for ship propulsion [4-5]. Other authors analyzed the maritime traffic and made a statistical analysis that determined the benefits of using LNG [6]. Other authors focused on the technical and life cycle analysis of a propulsion system based on LNG and found an efficiency increase of 2% and an emission reduction of 80% for NO_x and 100% for SO_x [7].

About 50% of the total thermal energy of an internal combustion engine (ICE) is released to the ambient. One of the most studied technologies to increase propulsion system efficiency is the waste heat recovery (WHR) [8]. Waste heat can be used for several purposes such as refrigeration, desalination or power generation [9-14]. Regarding ICEs, there are different attractive sources of waste thermal energy that might be exploited: exhaust gases, cooling water, oil cooling and turbocharger intercooler [15].

In the case of LNG fueled ships, the recovery of cryogenic energy can play an important role in the efficiency increase of the generation system. In this study, an engine operating with LNG was considered. The traditional LNG regasification process, normally used to produce natural gas for engine use, was revised to produce additional power. In more detail, the process was arranged to operate as a supercritical Rankine cycle using natural gas as working fluid. A wide overview of available technologies for regasification in big onshore terminals are available in the literature [16] but only a few of them could be applied in engine applications.

2 Case study

The study has been carried out by considering a 12-cylinder marine engine (Wärtsilä 12V50DF) operating in Gas mode operation (Table 1) [17]. Wärtsilä engines of 50DF family can be run on either LNG, Light Fuel Oil (LFO) or HFO and are designed to provide the same output regardless of the fuel.

Table 1. Engine Specifications.

Parameter	Value
Engine output @514rpm [kW]	11700
Exhaust gas flow at full load [kg/s]	19.0
Temperature after turbocharger [°C]	382
Gas consumption at full load [kg/h]	1722
Minimum gas pressure to engine [bar]	5.92
Gas temperature to the engine [°C]	0-60

In the proposed arrangement (Figure 1), LNG from a tank (Type A tank, @ 1.1 barA and -160 °C) was pumped at high pressure by a cryogenic pump and then sent to two heat exchangers for gasification. In the first heat exchanger (EX1), natural gas is warmed up to -15°C. This cooling power may be recovered for cooling purposes. In the second heat exchanger (EX2), the natural gas is heated up by an intermediate heat transfer fluid and then sent to the high-pressure turbine. The turbine inlet temperature is a function of the heat source recovered (seawater, engine jacket water, thermal cascades or engine exhaust gas). After the turbine, if the temperature of natural gas is below -15°C, additional cooling power may be provided to the system (EX3). Afterwards, natural gas is heated up in another heat exchanger (EX4) and then expanded in a low-pressure turbine. After this turbine, depending on the temperature, the fluid may still provide some useful energy for cooling (EX5). Before the injection into the engine, the gas temperature is regulated in a seawater heat exchanger (EX6).
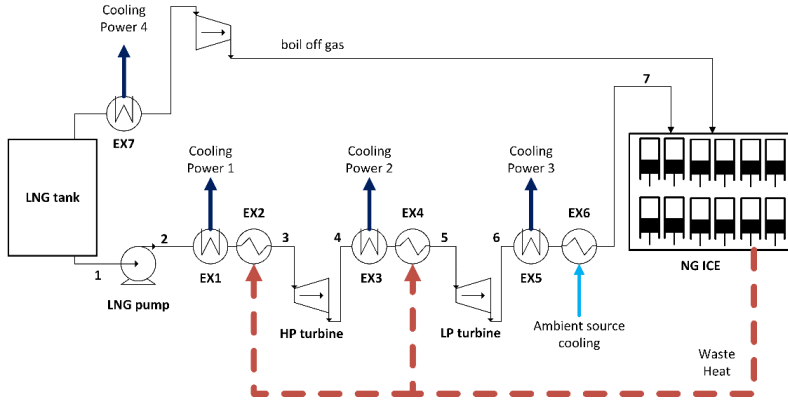
Fig. 1. Proposed system, layout

Boil-off gas (BOG), from the fuel tank was warmed up in the heat exchanger EX7 (energy may be recovered for cooling), sent to a compressor and injected. The performance of this arrangement was simulated in a wide range of maximum cycle pressure (from 50 to 300 bar) and temperature (from 20°C to 250°C) corresponding to different system complexities and waste heat thermal sources.

3 Methodology

A VBA model based on CoolProp equation of state for LNG thermo-physical properties was developed to analyze the performance of the system. For the sake of simplicity, LNG composition was considered as 100% of methane. The amount of BOG depends on the volume of the cryogenic tank and was estimated by linearly extrapolating data reported in [16] by considering a tank volume of 490 m^3 (Eq. 1).

$$\dot{m}_{BOG} = 7.42 \cdot 10^{-6} \cdot V_{tank} + 0.025 \qquad (1)$$

where $\dot{m}_{BOG}$ is the BOG mass flow rate in kg/s and V_{tank} is the tank volume in m^3. The power requested by the BOG compressor was estimated as:

$$\dot{W}_{BOG} = \frac{\dot{m}_{BOG} \cdot \Delta h_{is,c}}{\eta_{is,c}} \qquad (2)$$

where $\dot{m}_{BOG}$ is the BOG mass flow rate, $\Delta h_{is,c}$ is the isentropic enthalpy variation and $\eta_{is,c}$ is the isentropic efficiency of the BOG compressor, assumed as 70%. The pumping power requested by the cryogenic pump was estimated as:

$$\dot{W}_{p} = \frac{\dot{m}_{LNG} \cdot \Delta P}{\rho \cdot \eta_{is,p}} \qquad (3)$$

where $\dot{m}_{LNG}$ is the LNG mass flow rate, ΔP is the pressure difference between the highest system pressure (point 2) and the tank, ρ is LNG density and $\eta_{is,p}$ is the isentropic efficiency of the pump, assumed as 70%. The same temperature in 3 and 5 was assumed in the analysis. Turbines power was evaluated as:

$$\dot{W}_{t} = \dot{m}_{LNG} \cdot \Delta h_{is,t} \cdot \eta_{is,t} \qquad (4)$$

where $\Delta h_{is,t}$ is the isentropic enthalpy drop and $\eta_{is,t}$ is the isentropic efficiency of the turbines, assumed as 80%. The net power output takes into account the contributions of all devices and can be calculated as:

$$\dot{W}_{NET} = \dot{W}_{t,HP} + \dot{W}_{t,LP} - \dot{W}_p - \dot{W}_{BOG} \tag{5}$$

where $\dot{W}_{t,HP}$ and $\dot{W}_{t,LP}$ are respectively the power output of the high-pressure and low-pressure turbine. The cooling capacity was estimated by considering the warming up of LNG or cold natural gas after the expansions and BOG up to a temperature of -15°C. A pneumatic coefficient of 0.98 was considered for each heat exchanger to take into account pressure drops.

4 Results

For a fixed total mass flow rate of LNG (with constant BOG), representing the engine consumption at full load, a sensitivity analysis to find the condition in which the net output power of the proposed system is maximized has been carried out. In Figure 2, the optimal pressure ratio of the two turbines, for several maximum pressure and temperature, is reported.
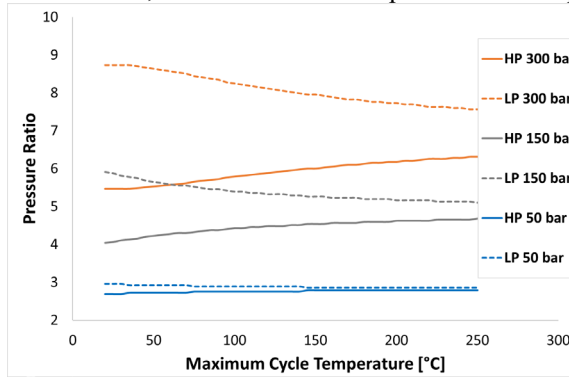

**Fig. 2.** Optimal pressure ratio for some combinations of maximum pressure and temperatures.

Figure 2 shows that there is a great difference between the HP and LP turbine pressure ratios, especially when the cycle pressure is high and the turbine inlet temperature is low. This behavior depends on the thermo-physical properties of methane, which are far from those of an ideal gas in these conditions. When the pressure decreases (e.g. when the maximum cycle pressure is 50 bar) the pressure ratio of HP and LP turbines are similar and almost insensitive to maximum cycle temperature ($\beta_{HP}=\beta_{LP}=\sqrt{\beta_{TOT}}$). For higher pressures (e.g. 150 bar and 300 bar) the influence of real gas properties leads to higher pressure ratio of LP turbine when the maximum temperature decreases.

In Figure 3, the net power output for three cycle maximum pressures is reported. It is worth to notice that the influence of pressure is negligible on power output when maximum cycle temperature is low (50 °C). In this case, a value of pressure that maximized the system power output exists. By increasing the temperature of the cycle, the pressure has a large influence on the system power output, up to about 100-120 bar of maximum cycle pressure, and then its benefic effect is sharply reduced. The reduction in cycle power output with a pressure increase, especially at high temperature, is due to the increase of pump power absorption.

The back-work ratio (Figure 4 left), i.e. the ratio between the pump absorption and the net power output of the cycle is a parameter that allows the estimation of the impact of pump absorption on cycle performance [19].
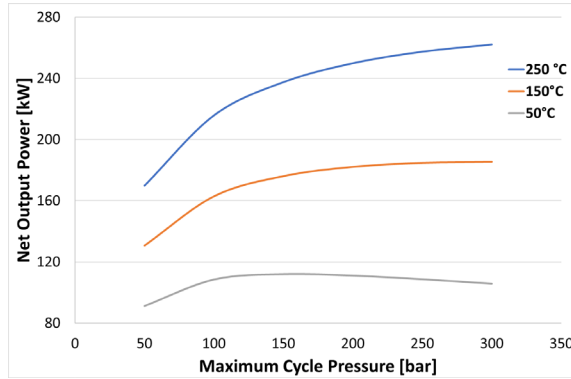
Fig. 3. Net output Power as a function of maximum pressure for 3 maximum temperatures.

The back-work ratio is very high when the cycle temperature is low and pressure is high. As an example, when the pressure is 300 bar and the maximum cycle temperature is 20 °C, the pump consumes about 58% of the net power produced. This value decreases by increasing the maximum cycle temperature and reducing the maximum pressure. As a summary, in Figure 4 right, the Net Output Power output and the available Cooling Power are reported for all the simulated cases.
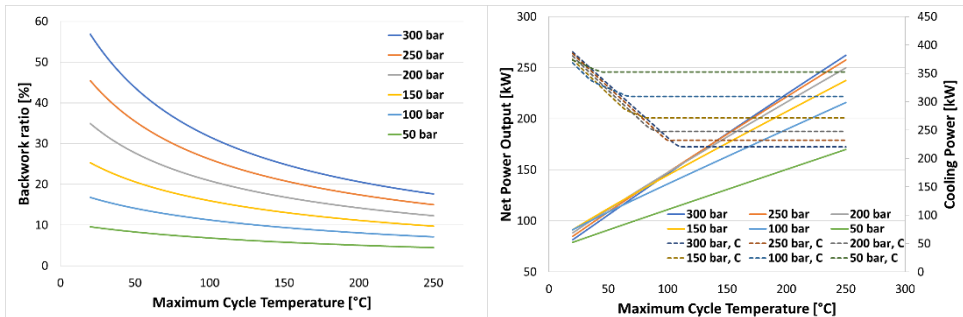
Fig. 4. Net Power and Cooling Power Output, all cases.

Due to the strong influence of pumping absorption, only small benefits in terms of net power output are achieved by increasing the maximum pressure over 150 bar and only if the maximum temperature is above 100°C. Beyond 200 bar the gain in power output, even at the highest temperature, is minimal. As a summary, the maximum gain in power output is in the range between 0.7 and 2.2% of the engine power output, by varying the maximum cycle temperature from 20 °C to 250 °C. Maximum cooling powers are plotted with dashed lines in Figure 4, right. These values are the cooling power achievable if four different cooling circuits are employed (equal to the number of possible cooling extractions). The horizontal portion of the trends is the contribution of the cooling power 1 and 4 in Figure 1. By increasing the pressure, the cooling power decreases because of the contribution of the pump (point 2 in Figure 1). Cooling power 2 and 3 are highly affected by the maximum cycle temperature and becomes null when the cycle maximum temperature increases.

5 Conclusions

This study is focused on thermodynamic analysis of a dual pressure direct expansion cycle of LNG before injection in an internal combustion engine for naval purposes. Such system

might operate also as a bottoming unit of other WHR systems. In more detail, the process was arranged to operate as a supercritical Rankine cycle using natural gas as working fluid. Simulations have been carried out for different maximum cycle pressure and temperature (50-300 bar and 20-250 °C) to optimize the expansion ratio and maximize the power output. Results showed that up to 262 kW could be recovered (2.2% of main engine power) by using only a portion of the total waste heat. The influence of the maximum cycle pressure turned out to be small in comparison to that of the maximum cycle temperature: an increase of the pressure above 150 bar leads to small benefits and only for temperatures above 100 °C. The proposed system allows the recovery of free cooling power for onboard demand, such as air condition, food conservation or even for additional engine enhancement (intake air cooling). Economic and technical issues, also concerning current regulatory framework, will be carefully analyzed in future developments.

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