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Exhaust emissions reduction and fuel consumption from the LNG energy system depending on the ship operating modes

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ABSTRACT

In today's environment of increasing pressure to reduce fuel consumption and emissions of carbon dioxide (CO_2) and nitrogen oxides (NO_x), the LNG (Liquefied Natural Gas) transportation industry is growing in size and influence. In this context, further efforts are needed to improve the energy efficiency of LNG marine energy power plant.

The LNG vessels and their equipment considered in this study have different power consumption requirements depending on the vessel's mode of operation (loading/unloading, maneuvering, anchoring, at sea, etc.). For each ship mode, where the power plant requirements are the same, the specific fuel consumption (SFOC) and exhaust emissions, NO_x and CO_2, are compared with a different number of engines in the network to find the optimal number of engines in the network, considering both the safety aspect and the port requirements.

An analysis was performed showing the efficiency of the on-board power management system (PMS) in terms of manual load sharing between engines. A comprehensive analysis of the data and its comparison led to the conclusion that the manual distribution of power among the engines is the slightly better solution.

The obtained results show that further analysis of the number of engines for a given load with minimum fuel consumption and CO_2 and NO_x emissions is required.

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1 Introduction

The share of shipping emissions in global anthropogenic emissions has increased from 2.76% in 2012 to 2.89% in 2018 [1]. Although the shipping industry is only a small contributor to global anthropogenic CO_2 emissions today, it will face increasingly difficult global warming challenges in the future [2]. Most projections indicate that shipping volumes (and thus emissions) will increase in the foreseeable future [2].

Optimization techniques are needed to reduce fuel consumption and exhaust emissions from marine engines, as the global trend is toward environmental protection and exhaust emissions from ships are certainly taking their place [3]. The focus of this article is on the specific fuel oil consumption and the main pollutants CO_2 & NO_x and their reduction in the marine LNG energy power plant.

In the first part of the article, the marine LNG plant described in the article is introduced and the power management system is described. The power management system is a computerized system that automatically controls and monitors the operation of the main switchboard and generators. The results in this paper will show that the energy management system is not necessarily the optimal economic and environmental solution. There are already several works that address this situation, especially in some unforeseen situations where it is necessary to adjust the routes to avoid bad weather conditions, which can reduce the negative impact of high waves and strong winds on the ship's fuel consumption [4, 5]. Slow steaming can also drastically reduce fuel consumption: "Since the amount of cargo transported decreases linearly with speed, while the power demand of the engines depends approximately on the third power of speed, the advantage is obvious" [6,7]. In a previous research work, Stoumpos et al. [8] addressed the computational study of a large four-stroke dual-fuel marine engine to compare its performance and emissions in both diesel and gas modes using the commercial software GT-ISE. The derived results were analyzed to show the differences in engine performance and emissions in each mode. A similar method via parametric runs was used by Mavrelos and Teotokatos [9] to optimize the performance of large two-stroke marine engines with dual-fuel operation. Huaiyu Wang et al. [10] use the response surface methodology to optimize emissions and performance to determine the optimal parameters for engine tuning parameters. The model for predicting NO_x emissions from a large four-stroke marine dual-fuel engine is built using AVL-BOOST. Also, the model is further calibrated to calculate the power and emissions of the engine. Subsequently, the influences of boost pressure, compression ratio and intake valve timing on engine performance and emissions are analyzed. Baldi et al. [11] propose a generic method for modeling the power plant of an isolated system with mechanical, electrical, and thermal energy demands and for optimally load balancing the different components that can satisfy the demand. The optimization problem is presented in the form of a mixed integer linear programming problem (MINLP), where the number of running engines and/or boilers is represented by the integer variables, while their respective loads are represented by the non-integer variables. The individual components are modeled using a combination of first-principle models and polynomial regressions, making the system nonlinear. Pavlenko et al. [12] compare the life cycle greenhouse gas (GHG) emissions of LNG, marine gas oil, very low sulfur fuel oil, and heavy fuel oil when used in engines suitable for international shipping, including cruise ships. The analysis includes upstream emissions, combustion emissions, and unburned methane (methane slip), and they assess climate impacts using 100-year and 20-year global warming potentials. Lindstad et al. [13] investigate the conditions under which LNG can serve as a transition fuel in the decarbonization of maritime transport while ensuring the lowest possible incremental impact on global warming. The results show the importance of applying appropriate engine technologies to maximize GHG reductions, that applying the best engine technologies is not economically viable, and how regulations could be changed to reward the best engine technologies. Importantly, GHG reductions from LNG are limited even with the best engine technology (dual-fuel diesel engine).

Engine test-bed measurements for NO_x, CO_2 and SFOC are presented and comparisons are made with respect to fuel type and engine load.

The objective of this article is to compare and analyze exhaust emissions and fuel oil consumption result for specific modes of operation of the ship, whether ship´s power management system is used or produced power onboard is randomly distributed.

In the second part of the article, the specific fuel oil consumption and exhaust emissions for different fuel types and operating modes of the ship are presented in tables to make the obtained data more descriptive and convenient to analyze.

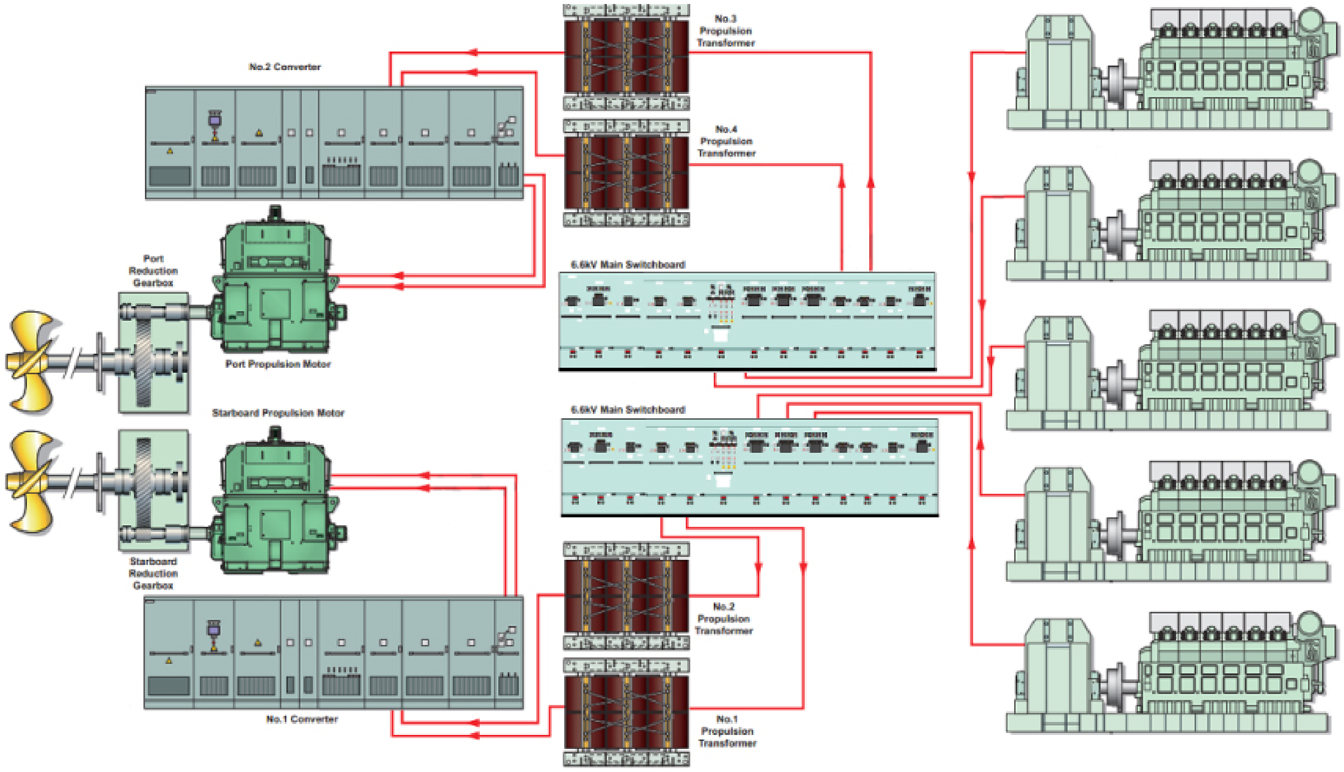

Figure 1 Simplified connection arrangement of diesel generators, main switchboards and propulsion systems [14]

Table 1 Auto-ignition temperatures of the various fuels

Fuel type	Diesel	Butane	Propane	Hydrogen	Methane
Auto-ignition temperature	220°C	400°C	470°C	500°C	600°C

Source: [9]

2 Dual fuel diesel engine plant overview

There are five main diesel generators aboard the ship. These are 8-cylinder in-line MAN8L51/60DF engines with an output of 8,000 kW.

All engines have been designed to run on either boil-off gas from the cargo tanks (methane), marine diesel oil (MDO) and heavy fuel oil (HFO). Even though the two fuels have a slightly different calorific value, the engines can run equally well on either gas or MDO/HFO and can deliver the same maximum power output on either fuel. The engines can also be switched from one fuel to the other while still operating on load and without any interruption to the power supply. The MAN 8L51/60DF engines are used to drive direct coupled alternators that supply electricity to all the ship's systems including the main propulsion plant which uses electric motors to drive conventional propellers through a reduction gearbox. In gas mode the engines run as lean burn engines according to the Otto cycle. Ignition is initiated by injecting a small amount of diesel oil in the form of pilot fuel which provides a high energy ignition source for the main fuel gas charge in the cylinder. The 'micro-pilot' injection system uses less than 1% of nominal fuel amount [14]. In liquid fuel mode, the engines work just like a conventional diesel engine, utilizing a traditional 'jerk' type fuel injection system. Transfers between the two operating modes take place without interruption in the power supply. Controlling the fuel system in this way ensures that combustion remains within proper operating limits and that optimum performance of all cylinders is achieved as gas quality and ambient temperature vary.

Methane is the most common fuel gas for four-stroke DF engines. Compared to other liquid and gaseous fuels, methane is not as easy to ignite because it has a relatively high auto-ignition temperature of about 600 °C. Diesel oil, for example, has a much lower auto-ignition temperature, so it can be used to start combustion in a gas-air mixture, as used in dual-fuel engines. Table 1 shows the auto-ignition temperatures for different types of fuels. The main parameters of the engines considered are listed in Table 2.

Table 2 Specification of DF-8L 51/60 DF (100% load)

Engine parameters	Specifications
Cylinder No (-)	8
Cylinder diameter (mm)	510
Stroke (mm)	600
Compression ratio (-)	13.3
Speed (min^{-1})	514
Power (kW)	8000
Fire order (-)	1-4-7-6-8-5-2-3
Mean effective pressure (bar)	19
Ignition pressure (bar)	190

Source: Author

2.1 Power Distribution System

The main network consists of two 6.6 kV main switchboards. The number of generators connected to the main high voltage (HV) switchboard depends upon the electrical consumer load of the ship at the time. The generators can be manually run-up and connected to the main switchboard as required, but in normal operation, the Power Management System automatically controls the operation of the generators and major operational aspects of the main switchboard.

The panel interconnects provide both redundancy and continuity of supply in the event of a system failure. This means that the consumers on the port side can be supplied by the generators on the starboard side and vice versa. The configuration of the electrical network depends on the operating situation of the ship:

- normal seagoing 4 or 5 DGs (laden 5, ballast 4),
- maneuvering 2 DGs,
- cargo unloading 2 DGs,
- cargo loading 1 DG,
- port at idle 1 DG.

2.2 Power Management System (PMS)

The Power Management System is a computerized system that automatically controls and monitors the main switchboard and generator operation. The system is controlled by two redundant controllers located in the main switchboard room. The controllers are also connected to other control panel modules via a redundant Fault Tolerant Ethernet (FTE) network and to remote I/O panel modules at various locations via a redundant fiber optic network. The system includes the necessary generator control functions for system power management. All safety functions, such as shutdowns and alarms for the engines, are handled by the engine control system. Circuit breaker protection and control is provided in the control panels. The monitored electric power plant consists of the main switchboards and the five main diesel generators.

The PMS controls the starting, stopping, connecting, and load sharing of the main generators. The generators can be controlled from the Integrated Automation System (IAS) workstations. In the event of a control failure by the IAS, manual control can be provided on site from the control panels and engines. The IAS/PMS performs all the necessary functions to control the generators, governors and main circuit breakers. The following main functions are controlled by the PMS:

- automatic synchronizing,
- frequency control,
- automatic load sharing,
- load dependent start/stop,
- blackout automatic restart,
- start blocking of heavy consumers,
- generator stand-by selection.

2.2.1 Load Dependent Start/Stop of Generators

The PMS system monitors the number of generators connected to the system and the load demand of the consumers. The load dependent start/stop function is applied when the following conditions are met:

- load dependent start/stop functions are enabled on the PMS,
- generator remote is selected at the switchboard,
- the load dependent start/stop function is based on the percentage load (kW) of the connected generator(s),
- the load dependent stop is initiated if the load (kW) of the remaining generator(s) after stopping will be less than the specified value.

If the load on any of the running generators reaches a value of 90% for a period of 15 seconds, a start command will be issued by the PMS to the first standby generator. When the load of the remaining power of the running generators drops to a value of 75% for a period of 900 seconds, a stop command is issued to a generator according to the priority position. The start/stop value settings can be adjusted to suit the ship's consumer load circumstances. In this paper, most frequent engine operation configurations are covered.

2.2.2 Heavy Consumer Start Blocking by PMS

To prevent overloading of the power plant, the PMS uses a start interlock for the large consumers such as ballast pumps, cargo pumps, deck spray pumps, and H/D & L/D compressors. When the PMS receives a start request from one of the above large consumers, the PMS checks to see if there is enough power generation capacity to allow a large electric motor to start. If the available power generation capacity exceeds the specified lockout limit, the PMS issues an available power signal and the motor start condition is activated. If the sufficient available capacity is not reached within a specified time period, the motor start command is timed and an alarm is activated.

3 Test bed measurement and results comparison

The LNG vessels and their equipment considered in this paper have different power consumption requirements depending on the vessel's mode of operation (loading/unloading, anchoring, maneuvering, etc.). Under these conditions, the ship power plant must be able to handle many combinations of energy demands with high efficiency. To determine the required number of engines in the grid, both the economic (fuel consumption) and environmental (exhaust emissions) efficiency of the engine should be considered.

For each of the above ship operating situations, the power management system fulfills its function, but based on author's experience with this type of marine LNG systems, in most cases power management system may not be necessarily the optimal economic and environmental solution in some cases.

Measurements for NO_x, CO_2 and SFOC from the engine test-bed are presented and comparisons are made in relation to the type of fuel and the engine load.

Test-bed – LNG Ship general characteristics:

- Length: 290 m.
- Breadth: 45.6 m.
- Design draft: 11.7 m.
- Speed service approx.: 19.5 knots.
- Cargo Tank capacity: 174,100 m^3.

Test-bed – Ship Engines general characteristics:

- Manufacturer: MAN B&W
- Type: 8L51/60DF
- Type: Four-stroke, in-line, dual fuel, turbocharged
- Rated power: 8,000 kW (MCR) on LNG, 8,000 kW (MCR) on MDO
- Speed: 514 min^{-1}
- Cylinder bore: 510 mm
- Piston stroke: 600 mm
- No. of cylinders: 8

Measurements on the test-bed were performed on two different types of ship propulsion fuel:

- MDO – Marine diesel oil and
- LNG – Liquefied natural gas

Comparisons on different fuel types of SFOC, NO_x and CO_2 at the following loads are shown graphically:

- 25% load (2000 kW)
- 50% load (4000 kW)
- 75% load (6000 kW)
- 85% load (6800 kW)
- 100% load (8000 kW)

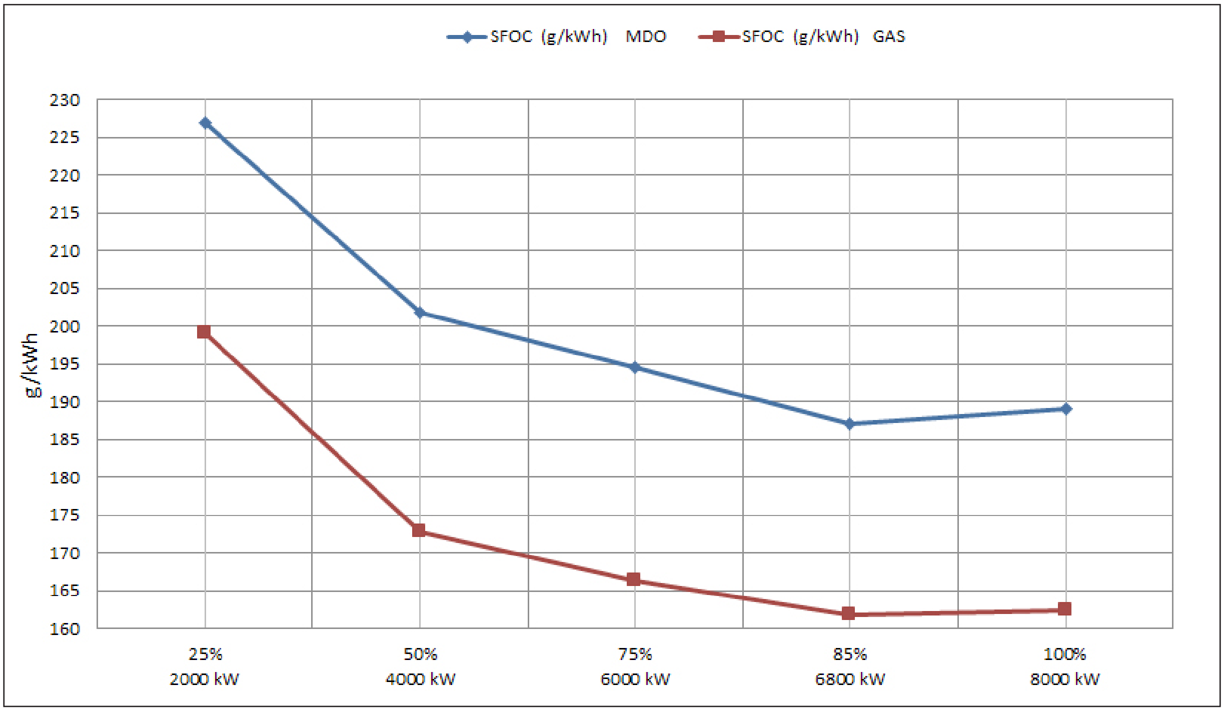

Figure 2 Test-bed SFOC – Comparison of two fuel types at different loads

Source: Author

Figure 2 shows the SFOC, expressed in g/kWh at different engine loads and for two different fuel types (MDO and LNG). To facilitate the comparison of the units of measurement with other fuels, the LNG consumption was recalculated and the final value expressed in g/kWh. For the calculation, the gas density and net calorific value data were taken from the LNG specification, as shown below:

- Standard density of the gas – 0.7740 kg/m^3
- NCV (Net Calorific Value) natural gas (volume) – 37874 kJ/m^3
- Gas temperature at the engine inlet – 21°C

It can be observed that the SFOC is higher for both fuel types at lower engine loads and gradually decreases in parallel with the increase in engine load. The downward trend continues up to an engine load of 85%, and thereafter it can be seen that SFOC increases slightly with engine load. At 100% engine load, it is found to increase from 187.1 g/kWh to 189.1 g/kWh for MDO, while it increases from 161.9 g/kWh to 162.4 g/kWh for LNG fuel.

When engine is running on LNG, that the specific fuel consumption is significantly lower than the MDO at all engine loads, which is due to the different calorific value of these two fuels. The lower calorific value of LNG is 48 MJ / kg which is higher than that of MDO, whose calorific value is 42.7 MJ / kg. [8]

Figure 3 shows the CO$_2$ emissions (expressed in %) of the test-bed at different engine loads and consumption of two fuel types (MDO and LNG). It can be seen that the CO$_2$ content of both fuels is similar regardless of engine load.

Table 3 Volumetric Density (VD) and Low Calorific Value (LCV) for different fuel types

Fuel Type	VD Kg/m^3	LCV MJ/kg
LNG	450	48
HFO	991	40.2
MDO	900	42.7

Source: [8]

The test-bed results show only a slight decrease in CO$_2$ content compared to the initial engine load (25%) and the maximum load (100%):

- MDO from 5.59% to 5.51% CO$_2$,
- LNG from 4.93 to 4.46% CO$_2$.

It can also be observed that the CO$_2$ content is consistently slightly lower in all operating modes when the engine is running on LNG than with the MDO.

Since the amount of CO$_2$ emitted is directly proportional to the amount of fuel consumed and energy efficiency, a reduction in CO$_2$ emissions can be achieved by reducing SFOC [17].

Figure 4 shows the NO$_x$ emissions (ppm) measured on a test-bed, at different engine loads and consumption of two different fuel types (MDO and LNG).

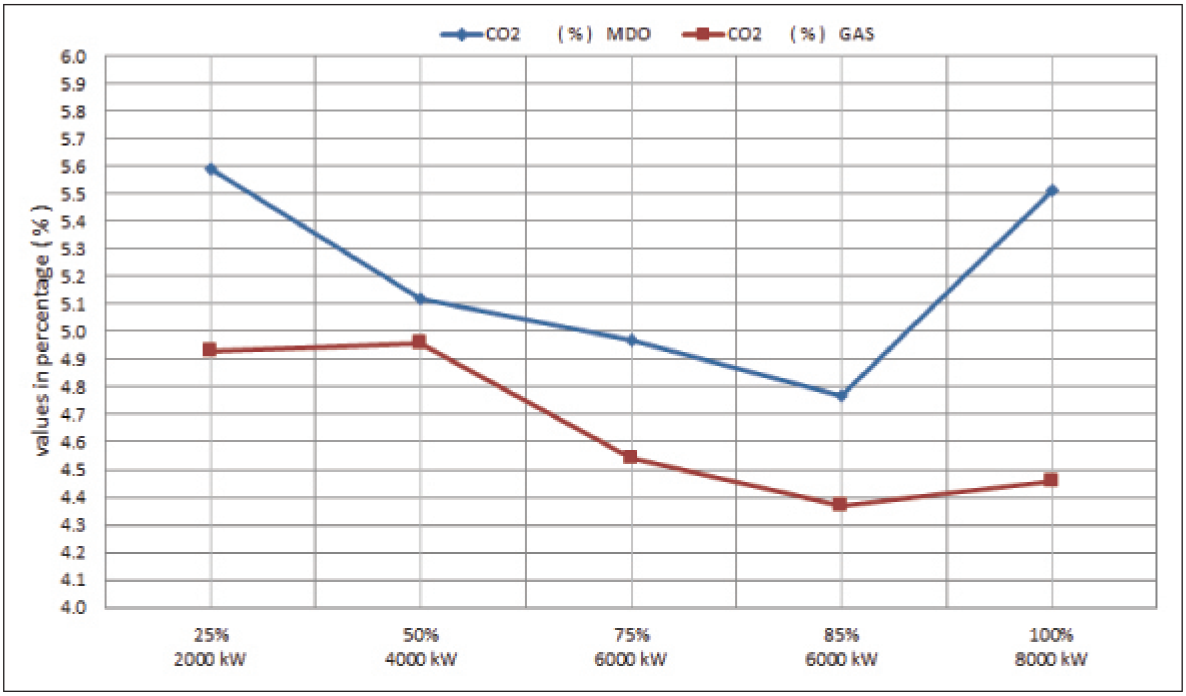

Figure 3 Test-bed comparisons of CO_2 emissions on two types of fuel and different loads.

Source: Author

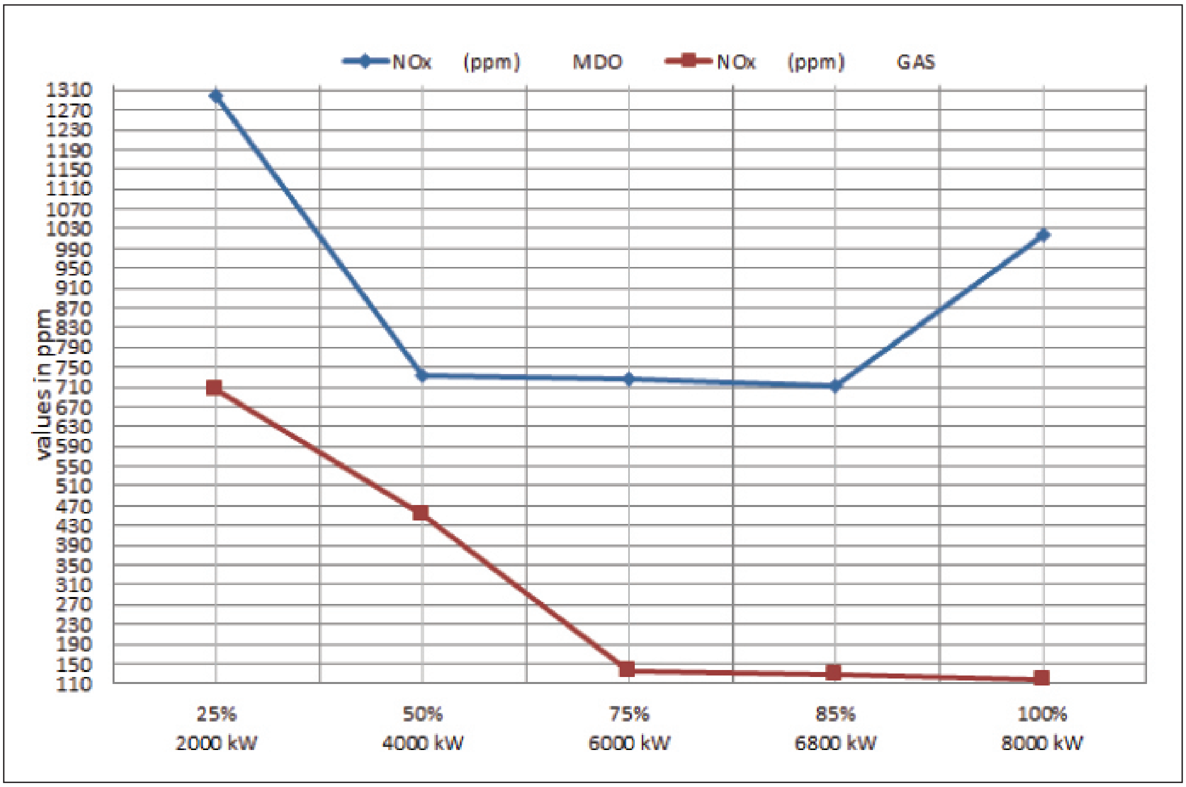

Figure 4 Test-bed comparisons of NO_x emissions on two types of fuel and different loads

Source: Author

There are significant differences when the engine is running on LNG. NO_x emissions are significantly lower than when the engine is operated on liquid fuel (MDO).

The test-bed results show that NO_x emissions are higher at lower engine loads and that they decrease at higher engine loads for both fuels (MDO and LNG).

For engines consuming LNG as fuel, a constant decrease in NO_x emissions is observed in relation to the increase in engine load to diesel. A constant decrease in NO_x emissions is seen up to an engine load of 85%, after which NO_x emissions increase slightly at 100% engine load. This trend of NO_x emissions from the test-bed can be explained by the fact that the formation of NO_x in a diesel engine depends on the combination of high temperatures, the availability of oxygen and nitrogen, and the duration of combustion. Since the formation of NOx is strongly dependent on the combustion temperature, the rate of formation in the exhaust gases increases at higher temperatures. [15, 16]

3.1 Engine's load comparation table on two different fuel types

Test-bed SFOC and NO_x results for specific engine load points are selected from the graphs above. Specific load points and engine operating configurations/options are assumed to correspond to the most common vessel operating modes: at sea, maneuvering, and in port. Each mode of operation is assigned an equivalent power output, and a total of two engine operating configurations are considered:

- Configuration 1 – fewer engines operating at higher load:
  - 4000 kW – (1 motor at 50% load),
  - 12000 kW – (2 motors at 75% load).
- Configuration 2 – more motors operating at lower load:
  - 4000 kW – (2 motors at 25% load),
  - 12000 kW – (3 motors at 50% load).

The results presented in Table 4 serve to highlight the differences between two observed engine configurations at two different fuel types and the same load. The table consists of two sections showing the results for different fuel types.

In both sections, the lower values are considered as reference values. It is noticeable that the increase of SFOC and NO_x in the last column is expressed as a percentage for both fuel types, clearly indicating that the first configuration with less online engines offers more economic and environmental benefits.

Table 5 gives an example of a typical load in ship operation (17700 kW) associated with equivalent power, and considers two engine operating configurations. The first configuration is engine load sharing according to the power management system, where the load is automatically distributed evenly among the number of engines in the network without considering the optimal engine operating point, fuel consumption and exhaust emissions. In the second option/configuration, the power management sys-

Table 4 Results of engine load configurations on two different fuel types

GAS						
POWER (kW)	**Engines on load / % of MCR**	**SFOC (g/kWh)**	**Total cons. MT/day**	**NO_x (ppm)**	**Difference in %**	
					MT/day	**NO_x**
4000	1 / 50%	172.9	21.4	452	/	/
	2 / 25%	2*199.1	24.6	1409.2	14.9	211.7
12000	2 / 75%	2*166.5	61.9	268.8	/	/
	3 / 50%	3*172.9	64.2	1356.3	3.7	404.5
MDO						
4000	1 / 50%	201.9	23.3	733.9	/	/
	2 / 25%	2*226.9	26.2	2599.2	12.4	254.1
12000	2 / 75%	2*194.6	67.5	1449	/	/
	3 / 50%	3*201.9	70.0	2201.7	3.7	51.9

Source: Author

Table 5 Different engine load distribution

LOAD	Configuration	SFOC (g/kWh)		Consumption MT/day		NO_x (ppm)	
		GAS	**MDO**	**GAS**	**MDO**	**GAS**	**MDO**
17700 kW	3 engines equally sharing load (3 x 5900kW)	3*166.5	3*194.6	92.93	101.28	403.2	2173.5
	3 engines adjusted load (2x6800kW / 1x4100kW)	2*162.5 1*172.9	2*188.2 1*201.9	89.92	97.3	710.1	2157.9

Source: Author

Table 6 Overall result differences

LOAD	Configuration	Consumption difference in percentage (%)		Difference in percentage (%) NO_x	
		GAS	MDO	GAS	MDO
17700 kW	3 engines equally sharing load (3 x 5900 kW)	3.34%	4.09%	-43.2%	0.72%
	3 engines adjusted load (2x6800kW / 1x4100 kW)	/	/	/	/

Source: Author

tem is ignored, and the load is manually adjusted between the engines, so that the loads of the engines are manually adjusted to the optimal operating point (85% of MCR) and the remaining load is taken by an engine that would operate at a lower load.

For the specific load considered in Table 5 and for both fuel types, it is noticeable that the second option, where the load is manually adjusted between engines, is a better option in terms of fuel consumption. The results show that the daily fuel consumption, expressed in MT/day, is lower for both fuel types than for the first option, in which the load is distributed evenly among the engines according to the power management system.

Regarding NO_x emissions when MDO is used, the results in the table also show that the second option is better, in which the engine load is manually adjusted to the optimal operating point (85% of MCR) and the rest of the load is taken by an engine operating at a lower load. In this case, NO_x emissions are slightly lower than in the case where the load is evenly distributed among the engines, and it can be concluded that this option is also better from an environmental point of view.

When the engines are operated with LNG, it is noticeable that the situation is different and that the NO_x emissions are significantly higher in the second option, where the power is distributed manually among the engines.

Table 6 shows the difference of the results in percent. The lower values are considered as reference values. It can be seen that the fuel consumption (MT/day) for both fuel types at this specific load is 3.34% higher when the engines use LNG and 4.09% higher when the engines use MDO, which clearly indicates that the second configuration, where the load is manually adjusted between the engines, is economically more beneficial than the first configuration, where the load is evenly distributed among the engines according to the power management system.

It can be seen that the NO_x emissions in the first configuration are 0.72% higher when the engine uses MDO, and it can be concluded that the second option is also better from an environmental point of view. However, if the engine uses LNG, the situation is different according to the data in the test table. Then the NO_x emissions are 43.2% lower in the first option, where the load is distributed evenly among the engines, than in the second option, where the power is distributed manually, and it can be concluded that in this case the first option is better from an environmental point of view.

4 Conclusion

Apart from the commercial aspects, the main argument for LNG as a marine fuel and for replacing conventional fuels HFO and MDO with LNG is the significant reduction in air pollution, both for NO_x emissions and for the greenhouse gas CO_2, when the lower SFOC is taken into account.

The results show that the daily fuel consumption for both fuel types (MDO and LNG) is lower when the load is manually distributed among the engines than when the load is evenly distributed among the engines according to the power management system. Over a 24-hour period, given an example of a typical ship load in sailing mode (17700 kW) associated with an equivalent power output, and considering two engine operating configurations, fuel consumption decreases by 4.09% when the engine is running on MDO and by 3.34% when running on LNG. Considering the high daily fuel consumption of this type of vessel, it is concluded that the fuel savings will be significant on an annual basis.

Regarding NO_x emissions, the results during MDO operation show that the emissions are lower when the load is manually distributed among the engines than when the load is evenly distributed among the engines according to the power management system.

In the option where the engines consume LNG, this relationship changes and the results show that NO_x emissions are 43.2% lower when the load is distributed evenly among the engines with the power management system, and therefore is the better option from an environmental point of view.

For each of the functions of the power management system described above, we can conclude that the PMS itself performs its function, but based on the results obtained in this paper, the power management system may not be the optimal economic and environmental solution under normal operating conditions, as well as in some special situations such as rough seas, long maneuvers, and staying in a port for several days when using multiple engines with low loads.

As the results of the study show, the load of the engines should be optimized on a daily basis. Sometimes it is necessary to manually distribute the load among the engines to achieve the best results in terms of fuel consumption, NO_x and CO_2 emissions.

There is no reliable algorithm on board that determines the number of engines and distributes their load according to the required workload in certain modes of the ship, taking into account fuel consumption and exhaust emissions. The proposal for further research is to analyze the benefits of using a mathematical optimization model to optimize the power systems in search of energy efficiency improvement on an LNG ship.

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