THE EMISSION AND COMBUSTION CHARACTERISTICS OF MARINE DIESEL ENGINE WITH EXTREME THROTTLED OF AIR OR EXHAUST DUCTS


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Abstract. Presented paper shows the results of the laboratory tests on the relationship between the extreme throttling of both air intake duct and exhaust gas duct and gaseous emission from the marine engine. The object of research is a laboratory, 4-stroke, DI diesel engine, operated at loads from 50 kW to 250 kW at a constant speed equal to 750 rpm. During the laboratory tests the thermodynamic and exhaust gas emission characteristics of the engine were measured with technical condition recognized as "working properly" and with simulated throttling of both air intake duct and exhaust gas duct. Air intake duct throttling by 60% causes visible changes at both gas temperature and pressure behind the intercooler. The study results show significant changes of NOx and CO_2 emission for considered air intake duct throttling. The best indicator of exhaust gas duct throttling among considered thermodynamic parameters of the engine is mean in-cylinder pressure. In the case of measuring the composition of exhaust gas, the throttling of the exhaust gas duct causes visible changes in CO_2 and NOx emission. The conclusion is that the results of measurements of the composition of the exhaust gas may contain valuable diagnostic information about the technical condition of air intake and exhaust gas duct of the marine engine.

Keywords: marine engine, throttling, emission, combustion, malfunction

INTRODUCTION

In classic technical solution of a ship engine room, a few diesel engines are installed. One or more engines are installed as a main propulsion. There are usually low speed, two-stroke diesel engines operating with fixed pitch propeller (Carlton, 2012), or medium speed, 4-stroke diesel engines, operating at a constant speed with variable pitch propeller. Moreover, there are at least 3 or more power generators in the ship engine room. The power generator usually contains medium speed, 4-stroke diesel engine, operating at a constant speed. Other solutions are rarely used, e.g. solutions based on a gas or steam turbine or electric motor with power generators. Marine internal combustion engines are usually turbocharged diesel engines with direct fuel injections into cylinders. Fuel delivery system of such engine consists of mechanically controlled Bosh type fuel pump and injectors with multi-hole nozzle type (Heywood, 1988). The first Common Rail system in marine, medium speed, 4-stroke diesel engine was installed in 2001. It should be noted that engine producers still offer marine diesel engines with mechanically controlled fuel systems (IMO, 2013). Constructions of such were intensively studied in XX century. Unfortunately, most of the publications were focused on aspects related to improving the energy efficiency. Less attention was paid to the reduction of toxic compounds emission. It should be noted that mentioned studies were conducted for small engines. Construction of marine diesel engines is different in comparison to on road operated engines. Most important differences are: large dimensions of the engine cylinders (typically 10-30 dm^3 volume per cylinder), low the engine speed, usually not exceeded 1000 rpm, extended stroke, usually longest than bore, high air boost pressure, greater than the exhaust gas pressure for all the engine load conditions, start of combustion process before piston top dead canter position, combustion process settings for maximum efficiency at maximum the engine load, lack of the exhaust gas recirculation system and the engine operation at constant speed or according to the characteristic of the ship propeller.

Mentioned differences between small diesel engines and marine diesel engines cause large changes in both the thermodynamic parameters and the exhaust gas composition of the engine. (Sarvi et al., 2008), present large work, concerning emission characteristics of the large-scale medium-speed diesel engine with parameters similar to marine engine parameters. According to presented results increase of the engine load at constant speed cause decrease of the nitric oxides (NOx) emission. Mentioned results are opposite to NOx emission characteristic for small engine (Agarwal, 2011). It should be noted that decrease of the engine speed causes increase of the NOx emission (Sarvi et al., 2008, Sarvi et al., 2010). It's high probability that the emission characteristics of other exhaust gas components of the marine diesel engine are different also.

Combustion process in the engine cylinders causes changes in the air-fuel mixture according to rotation of the crankshaft, the engine load and speed, and the technical condition of the engine components and systems. Solid particles present in the air and soot from the exhaust gas can cause damage to the turbine blades, the exhaust gas duct and other components of the engine charging system. This may cause the exhaust gas duct and air delivery system throttling and changes in parameters of the combustion process. The effect of these may change of the composition of the exhaust gas also. It should be noted that air and exhaust gas flow, not laminar usually, significantly influences on the combustion process and exhaust gas composition (Applied Energy 2011). Moreover the exhaust duct may be extreme throttled by construction elements of the ship engine room i.e. utilizing boiler or particulate filter (Buonoa et all. 2012, Lin, 2002). Keeping in mind presented differences between constructions of small and large marine diesel engines, the influence of the throttling of both the air and the exhaust duct may cause different effects in exhaust characteristics.

The paper presents the results of experimental and studies on the effects of extreme throttling the cross section area of both the engine exhaust gas duct and the engine air intake duct on the parameters of the combustion processes and exhaust gas composition of the marine diesel engine.

LABORATORY STAND

The chosen object of research is 3-cylinder, four-stroke, turbocharged, laboratory engine. The engine is loaded by a generator, electrically connected to the water resistance. During tests the engine was fuelled by diesel oil and operated at a constant speed of 750 rpm. The fuelling system of the engine consists of the mechanically controlled Bosh type fuel pumps connected to injectors with multi-hole type nozzles. The engine load and speed, parameters of the turbocharger, systems of cooling, fuelling, lubricating, and air exchange were measured. The composition of the exhaust gas was also recorded using electrochemical gas analyser with infrared carbon dioxide sensor. Pressure, temperature and humidity of air were recorded by laboratory equipment also. The precisions and ranges of measurement equipment are presented in Table 1.

Table 1.
Precisions and ranges of measurement equipment.

Parameter	Range	Precision Values
Environment Air Temperature	0 – 60°C	±0.5°C
Environment Air Humidity	0 – 90%	±2.0%
Exhaust gas temperature	0 – 650°C	±1.35%
Carbon Oxide CO	0 – 10000 ppm	±5.0%
Sulfur Dioxide SO_2	0 – 5000 ppm	±5.0%
Nitric Oxide NO	0 – 3000 ppm	±5.0%
Nitric Dioxide NO_2	0 – 500 ppm	±5.0%
Carbon Dioxide CO_2	0 – 50%	±0.5%
Oxygen O_2	0 – 25%	0.8%
Liquid temperatures	0 – 100°C	±0.35%
Liquid pressures	0 – 4 bar	±0.3%
Combustion Pressure	0 – 200 bar	±0.5%
Fuel Consumption [kg/h]	–	±2.8%
Electric power [kW]	–	±0.5%

All mentioned results were recorded with a sampling time of 1 second. Combustion pressure was also collected with resolution of 0.5 degree of engine shaft angle. The scheme of the laboratory stand is presented in (Kowalski, 2016) and the engine parameters are presented in Table 2.

Table 2.
Parameters of the engine.

Parameter	Value	Unit
Max. electric power	250	kW
Rotational speed	750	rpm
Cylinders number	3	–
Bore	250	mm
Stroke	300	mm
Compression ratio	12.7	–

The experimental study consists of 4 stages of 3 observations with simulations of different malfunctions of both air intake duct and exhaust gas manifold. During each start of the observation, the engine was loaded to maximum load equal 250 kW, and, after stabilizing the temperature of the exhaust gas behind the turbine, the engine operating parameters were recorded for 3 to 5 minutes. After this, the load of the engine was decreased by 10 kW and, after stabilizing the temperature of the exhaust gas behind the turbine, the engine operating parameters were recorded again. The observation was continued with loads up to 50 kW. Stages of experiment were set as follows:

- first stage during the operation of the engine assumed as “working properly”,
- second stage during the operation of the engine with cross section area of air intake duct limited by 60% (extreme throttling),
- third stage during the operation of the engine with throttled cross section area of the exhaust gas duct by the barrier angle mounted in the exhaust gas duct behind the turbine changed by 21 degrees,
- fourth stage during the operation of the engine with extreme throttled cross section area of the exhaust gas duct by mentioned barrier angle changed by 71 degrees.

Schemes of throttling methods of both the exhaust gas duct and the air intake duct are presented in Fig. 1. The air intake duct throttling simulation consisted of inserting throttling flanges to the air intake duct in front of the compressor.

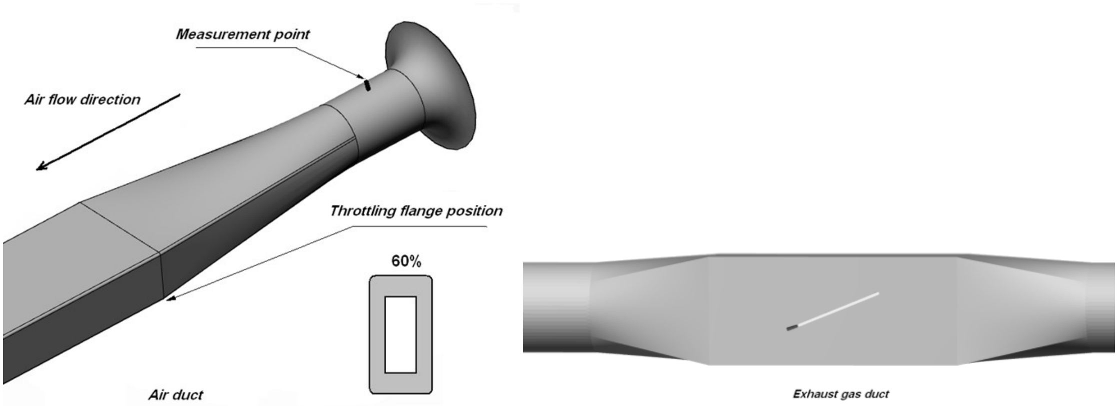

Fig. 1. Scheme of air intake duct throttling and exhaust gas duct throttling.

Left side of Fig. 2 presents dependences between the position angle of the exhaust gas duct barrier and the exhaust gas flow. Presented results are obtained by CFD model of exhaust gas duct prepared on AVL Fire package. Mentioned CFD model is presented in (Kowalski, 2013). According to presented results the throttling of exhaust gas duct by angle changing of barrier plate by 21 and 71 degrees cause mean decrease of exhaust gas flow by 27% and 86% respectively.

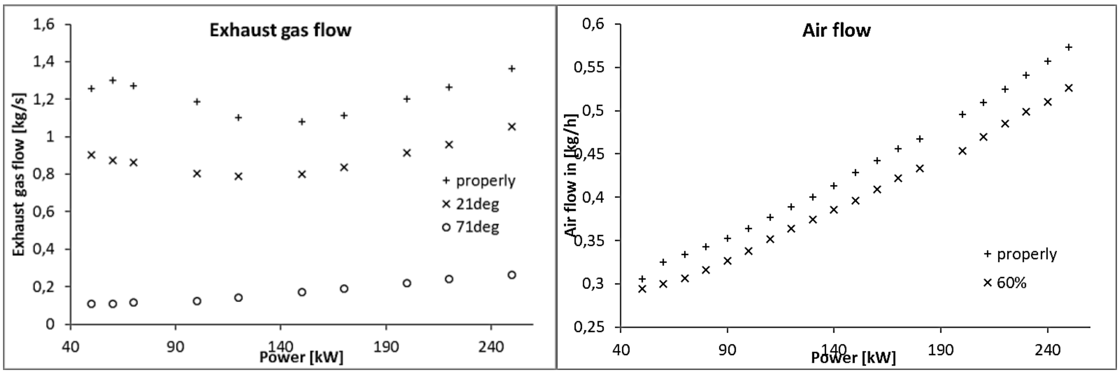

Fig. 2. Changes of air and exhaust gas flow.

The right side of Fig. 2 presents the result of air duct throttling on air flow. Results are obtained by direct measurement of air flow by Venturi orifice (measurement point is presented in Fig. 1). According to presented results the throttling of air intake duct by limitation of cross section area by 60% causes mean decrease of air flow by 7.5%.

RESULTS AND DISCUSSION

The throttling of the air inlet or the exhaust gas duct outlet changes the flow characteristic throughout the engine. Figures 3 and 4 present average changes of measured and calculated parameters of the engine with simulated malfunctions in relation to parameters of the operation of the engine recognized as "working properly". "X" symbols represent extreme air duct throttling, "+" symbols represent low exhaust gas throttling and circles represent extreme exhaust duct throttling.

Presented results are average values for individual engine loads and all mentioned observations. Emission characteristics are obtained by laboratory measurements and calculations according to ISO 8178 regulations.

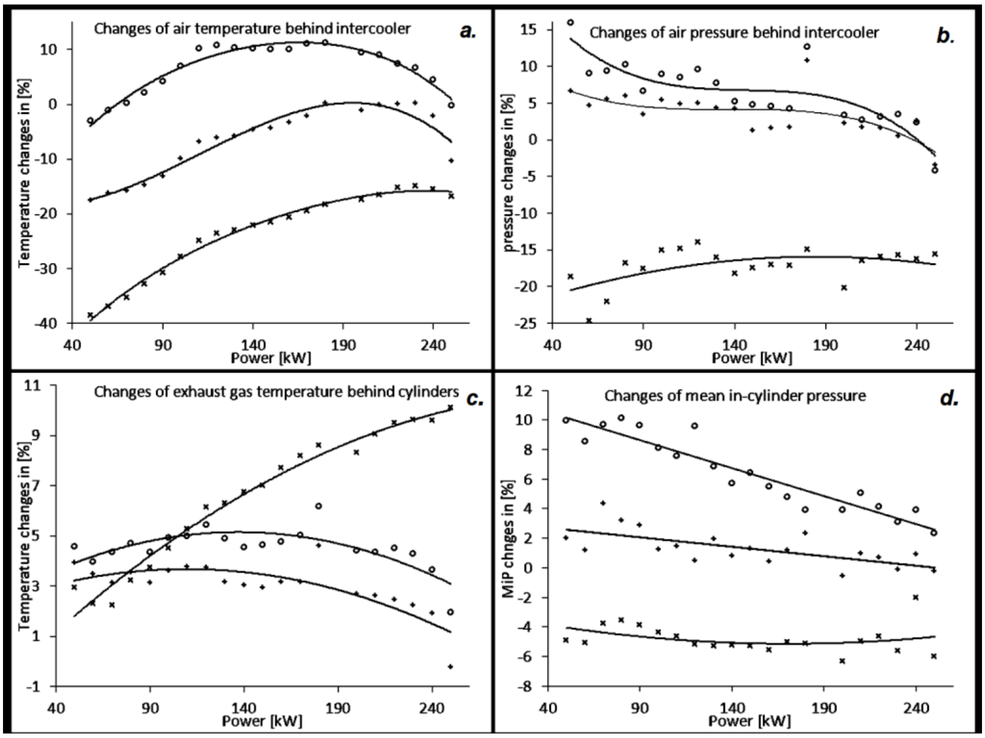

Fig. 3. Parameters related to combustion process in engine cylinders.

Extreme throttling of the air intake duct

Extreme throttling of air intake duct reduces pressure and temperature of the charging air. Fig. 3a and Fig. 3b show the decrease of temperature and the pressure of air, measured behind the intercooler. According to presented results, the changing of air pressure is clearly visible in a low load condition of the engine. The decreasing of air temperature, is the best indicator of extreme throttling of the intake air duct among considered thermodynamic parameters of the engine. This temperature decreases in average by 20% to 40%. The consequence of this is a reduction of the amount of air supplied to the engine. Fig.4a shows changes of air-fuel excess ratio. Air-fuel excess ratio decreases during the air intake duct extreme throttling. Decreasing the amount of air delivered to the engine cylinders causes the combustion process of a rich mixture. This situation promotes the extension of the combustion process in time, which results the decrease of the mean in-cylinder pressure (MIP). Fig. 3d presents changes of the MIP. Extreme throttling causes significant decrease of pressure in the engine cylinders. The rich mixture combustion causes the increase of the exhaust temperature behind the cylinders, presented in Fig. 3c (especially at high loads) and the temperature of the exhaust gas behind the turbine. Relative small throttling of the air intake duct results no significant changes of the temperature behind the cylinders (result no presented).

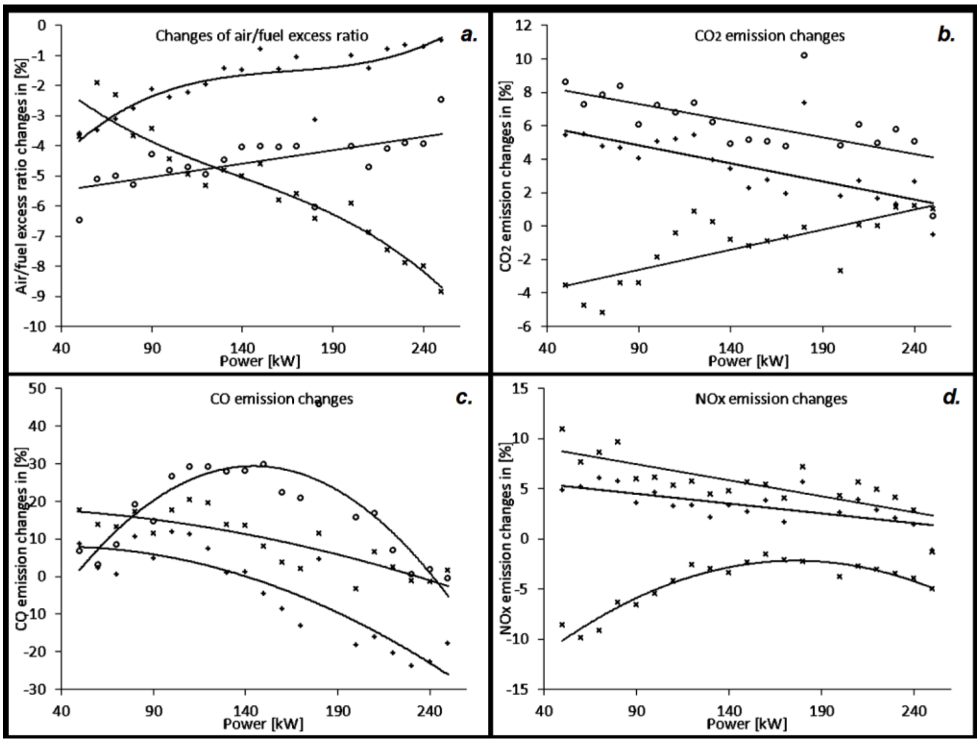

Fig. 4. Exhaust gas composition.

Throttled cross section area of the air intake duct reduces the amount of air delivered to the cylinders of the engine and result of this is the increase of the fuel consumption. It’s clearly visible in the emission values. The effect of changes of the fuel consumption is indirectly visible in Fig. 4b and Fig. 4c (changes in carbon compounds emission). According to dependences presented in Fig.4b, extreme throttling of the air duct causes the decrease of the CO_2 emission at a low load engine and the increase mentioned emission in high loads of the engine. It means that at low loads the amount of air delivered to cylinders is enough to proper combustion. This trend is opposite to observed in on-road engines. It should be noted, that marine engines are regulated for maximum efficiency at maximum the engine load. Fig. 4d shows dependences between a corrected nitric oxides emission (as a sum of NO and NO_2 emission) and the load of the engine. The nitric oxides (NOx) emission depends not only on parameters of the working engine but on parameters of the air surrounding the engine. Mentioned parameters are temperature, pressure and humidity of air. According to ISO 8178 rules standard parameters of air for nitric oxides measuring are; pressure – 101.3 kPa, temperature – 25°C and humidity – 10.71 gH_2O/kg of air.

According to mentioned standards, all emissions of nitric oxides from diesel engines measured in other air conditions must be corrected to standard parameters by using the correction formula. The dependencies from Fig. 4d show that extreme throttling of the air intake duct reduces the NOx emission level. Qualitatively similar results are presented in (Transport Res. D-Tr. E, 2011). Possible explanation of this phenomenon is reduction of the oxygen quantity in engine cylinders and the decrease of the exhaust gas flow rate.

Throttling of the exhaust gas duct

Throttling of the exhaust gas duct slightly increases the exhaust gas temperature behind the cylinders (Fig. 3c). Accordingly, pressure of the exhaust gas and the speed of turbocharger increase also (not presented in figures). It results in the change of the air pressure at low loads engine conditions. Fig. 3b shows visible changes of the air pressure only at partial engine loads. The exhaust duct throttling causes the increase of the MIP, significant especially for low loads of the engine. This is the effect of growth of the fuel consumption (not presented in figures). Low throttling of the exhaust gas duct causes average increase of the fuel consumption by 3.7%, and 8.2% for extreme throttling of the exhaust duct.

Fig. 4a presents changes of the air/fuel excess ratio. The increase of exhaust gas duct throttling decreases presented coefficient. It means that, although the air pressure behind the intercooler increases (Fig. 3b), the air temperature behind the intercooler decreases (Fig. 3a) and the quantity of air delivered to the engine decreases. Simultaneously with this phenomena, the quantity of delivered fuel increases. It means that the quantity of air delivered to cylinders increases, but the fuel consumption increases also. The effect of this is combustion of the richer mixtures in the cylinders. The confirmation of this state is the decrease of the air-fuel excess ratio. As mentioned earlier, during throttling of the exhaust gas duct, the richer mixture is combusted in engine cylinders. This phenomenon takes effect in deteriorations in the combustion process and changes in the CO emissions. Fig. 4c shows dependences between the CO emission and the load of the engine and the throttling of the exhaust gas duct. The exhaust gas duct throttling causes the increase of the CO emission at low load engine condition. Maximum load of the engine decreases mentioned emission, but only during engine operation with low throttling of the exhaust gas duct. It means that the efficiency of the combustion process is changed with the load of the engine (Heywood, 1988), and level of throttling. It’s interesting that extreme throttling of the exhaust duct causes change of the dependence between CO emission changes and the engine load. The maximum increase of CO emission during extreme throttling is at medium load, meanwhile for low throttling maximum CO is in low load of the engine.

Increasing the dose of fuel delivered to the combustion process increases CO_2 emission (Heywood, 1988). Decreasing of the engine load and increasing of exhaust gas duct throttling increase the CO_2 emission from the engine. According to presented on Fig. 4b dependences, the low exhaust gas duct throttling increases the level of carbon dioxide emission in average by 3% in all considered loads of the engine. More visible effects appear in the extreme throttling conditions. The high throttling of the exhaust gas duct causes the increase of the CO_2 emission level in average by 7%. Obtained results are compatible with fuel consumption changes.

Fig.4d presents the dependence of the exhaust gas duct throttling on the NOx emission changes. According to presented dependences, throttling of the exhaust gas duct increases NOx emission for all considered loads of the engine. For low throttling, the average increase of the NOx emission is 2.7%, and for the extreme throttling the NOx emission increases in average by 6.7%.

CONCLUSIONS

The paper presents the results of laboratory tests carried out on the four-stroke diesel engine for marine applications. The study consisted of determining the impact of extreme throttling of both the air intake duct and the exhaust gas duct on the engine operating parameters including the composition of the exhaust gas.

Obtained results allow concluding that the extreme throttling of the air intake duct throttling at both gas temperature and the pressure behind the intercooler. The study results show the decrease of both NOx and CO_2 emission and the increase of CO emission. Presented results are significant visible at low load of the engine.

The best indicator of the exhaust gas duct throttling among considered thermodynamic parameters of the engine is MIP. The MIP increases with the increase of the exhaust gas duct throttling due to the increase of fuel consumption and amount of air delivered to the cylinders.

Presented results show, that the extreme exhaust gas duct throttling causes visible changes in CO_2 and NOx emission.

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REFERENCES

Agarwal, D. Singh, S.K. Agarwal, A.K. (2011). Effect of Exhaust Gas Recirculation (EGR) on performance, emissions, deposits and durability of a constant speed compression ignition engine, Applied Energy, 88, pp. 2900-2907.

Buonoa, D. Senatorea, A. Pratib, M.V. (2012). Particulate filter behaviour of a Diesel engine fueled with biodiesel, Applied Thermal Engineering, 49, pp. 147-153.

Carlton J.(2012). Marine Propellers and Propulsion Third Ed. Elsevier Ltd.

Chalet, D. Mahe, A. Migaud, J. Hetet, J.-F. (2011). A frequency modelling of the pressure waves in the inlet manifold of internal combustion engine, Applied Energy, 88, pp. 2988-2994.

Heywood J.B. (1988). Internal Combustion Engine Fundamentals, McGraw-Hill.

IMO, (2013). Marine Engine IMO Tier II Programme.

Kowalski, J. (2013). The model of the exhaust gas duct flow of the marine 4-stroke diesel engine. Journal of Polish CIMAC, 8(1), pp. 59-66.

Kowalski, J. (2016). An experimental study of emission and combustion Characteristics of marine diesel engine with fuel Injector malfunctions, Polish Maritime Research, 23(1), pp. 77-84.

Lin, C.-Y. (2002), Reduction of particulate matter and gaseous emission from marine diesel engines using a catalyzed particulate filter, Ocean Engineering, 29, pp. 1327-1341.

Sarvi, A. and Zevenhoven, R. (2010) Large-scale diesel engine emission control parameters, Energy, 35, pp. 1139-1145.

Sarvi, A. Fogelholm, C.J. Zevenhoven, R. (2008). Emissions from large-scale medium-speed diesel engines: 1. Influence of engine operation mode and turbocharger, Fuel processing technology, 89, pp. 510-519.

Sarvi, A. Fogelholm, C.J. Zevenhoven, R. (2008). Emissions from large-scale medium-speed diesel engines: 2. Influence of fuel type and operating mode, Fuel processing technology, 89, pp. 520-527.

Uriondo, Z. Grados, C. Clemente, M. Gutiérrez, J.M. Martín, L. (2011). Effects of charged air temperature and pressure on NOx emissions of marine medium speed engines, Transportation Research Part D: Transport and Environment, 16(4), pp. 288-295.

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