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Notes and comments

Correcting injection pressure maladjustments to reduce NO_X emissions by marine diesel engines

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ABSTRACT

Emissions from the exhausts of marine diesel engines comprises several different gases including NO_X. These are currently regulated at the international level under Regulation 13 of ANNEX VI of MARPOL 73/78, but this regulation only applies to new engines and is based on bench tests, for only a single engine designated the "parent engine". Here, the need to take measurements from across their whole range and once in operation on board a vessel is examined. This would not only improve assessment of new equipment against the current regulation, but would also detect defects in the functioning of the engine.

1. Current situation

Marine diesel engines provide an efficient form of long-distance large-volume transport, but their emissions contribute significantly to the degradation of the natural environment. Despite technical advances that have lowered emissions per ton and kilometres transported, these engines continue to be a significant source of contaminant gases and contribute to the greenhouse effect. In Canada, for example, the emissions of NO_X originating from maritime transport account for 14% of the overall total emissions of this contaminant (Katsumi, 2004).

At the international level, emissions from marine engines are regulated under Regulation 13 of ANNEX VI of MARPOL 73/78. This standard sets an emissions limit as a function of the revolutions of the engine; the value (expressed in g/kW h) decreases the higher the speed. Once an engine is installed on board a vessel, any monitoring of its condition, if done at all, is limited to checking that any spare parts fitted are similar to those originally used in the engine. Because it is not known how the engine performs once in operation, there is no knowledge of its long-term emissions profile. There are operating parameters, however, that have a direct influence on the level of emissions that are produces, including the turbo feed pressure, air feed temperature, wear on nozzles, and maladjustments in the injection and injection pressures.

The generation of NO_X by a diesel engine is a complex process. Much of the knowledge acquired is obtained from direct measurements and from simplified studies of the flame. The thermal or Zeldovich mechanism is responsible for the majority of emissions of NO_X originating from a diesel engine when combustion temperatures exceed 2000 K. However, this high temperature is desirable to increase the engine's power output. The maximum value of the temperature and the approximation of the air/fuel ratio to the stoichiometric value of the mixture are important, but at temperatures below 1700 K their contribution is insignificant. Another mechanism known to influence the formation of NO compounds is the Fenimore mechanism – a very rapid process whereby gases are formed in the actual zone of combustion.

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Thus, generation of thermal NO gases is significant at temperatures higher than 2000 K. NO "immediates" will also be produced from fragments of fuel hydrocarbons with a change in the phase of combustion representing decreasing temperatures and, consequently, NO. Engines that burn heavy fuels require special attention because NO gases are also formed from the content of N in organic fuels, and such fuels contain a large amount of N.

When analysing regulations concerning contaminant emissions, it is important to understand the precise origin of these contaminants. The principal, but not exclusive, source of NO_X is the oxidation of atmospheric nitrogen at high temperatures produced in combustion; the higher the combustion temperature and the longer the time of residence at this temperature, the more NO_X will be formed. The amount of NO produced increases by a factor of 10 for each 100 K of increase of temperature (Goldsworthy, 2002).

The current measures by the manufacturers of marine diesel engines for controlling the levels of NO_X emissions are to set specific design parameters for engines (injection advance, compression ratio, mechanical injection, etc.). This paper looks at more dynamic approaches, changing totally in function of the operating conditions of the engine. As an example one can compare mechanical injection and electronic injection. Mechanical injection is adjusted when the engine is assembled, and is kept constant using the classic mechanisms of distribution gears and cams; in contrast, it is easy to manipulate electronic injection systems allowing and adjust as needed even with the engine operating. For example, with an electronically-controlled two stroke engine on the market, running at 75% of its maximum loading, changing from "Economy Mode" to "Special Emissions Mode", reduces the concentration of NO_X in the exhaust gases from 1150 ppm to 500 ppm (Sarvi et al., 2007), Thus, once the engine has been installed in the vessel, emissions are dependent on the mode of operations selected.

2. Material and methods

Measurements are taken of emissions from medium-speed diesel engines, both on board and in bench trials. The instruments employed of the electrochemical cell type, the precision of which has been previously checked using chemiluminescence detection equipment (Emmersson NGA2000 CLD). In the bench trials, a series of tests were carried out on various medium-speed engines that meet the emissions standard of MARPOL 73/78, Regulation 13. The engines had the following characteristics: cylinder diameter: 210 mm, stroke: 290 mm, number of cylinders: 6/8, Nominal revolutions: 800/850 rpm, and brake power: 883 kW/956 kW/1030 kW. All the engines were manufactured in accordance with the engine family approval system, meaning they were not assessed in factory bench trials (checks were limited to comparing the components fitted to the engine with those fitted to the parent engine).

For measurement we used electrochemical cell technology and equipment from: BACHARACH, ECOLINE 6000, and TESTO 330-2. These instruments are not approved under the technical code of MARPOL 73/78, but the code does allow the use of other measuring instruments provided that they have been demonstrated to have accuracy similar to that of the approved instruments. Previous studies show the electrochemical cell equipment gives similar measurements to those obtained with the chemiluminescence detection (CLD) instruments approved under the technical code (Yanase et al, 1998; Martinez-Garcia et al., 2004; Bentz and Weaver, 1994).

The effect of the injection pressure on the emissions of NO_X was examined. Given that the process of injection employs pressure in the fuel system to induce the flow of fuel through the orifices of the injector, a high injection pressure produces a high flow of fuel to the outlet of the nozzle and a high exit speed of fuel from the nozzle. After the fuel has entered the combustion chamber, it is atomized by the collision of the turbulent jet of fuel with the air inside the combustion chamber; consequently, the greater the relative velocity between the air and the fuel, and the greater the density of the air, the more finely the fuel will be atomized.

In medium-speed diesel engines, the velocity of the air inside the combustion chamber is relatively slow because the air is only moved as a result of the inertia of its mass; the air tends to maintain the velocity at which it enters the cylinder due to the whirl or vortex effect. This effect is assisted by the movement of the piston; the degree of vortex is greater the closer the position of the piston is to the upper dead point. In these engines the nozzle is a determining factor in the efficiency with which the mixture is formed and the combustion takes place, due to the low speed of the air, and consequently the nozzle is a determining factor in the emissions of exhaust gases (Bosch, 2007). This is not examined here.

The tests concentrate exclusively on the injection pressure, because it is this that gets the fuel into the combustion chamber, and affects the maximum pressures and temperatures of combustion. Two types of measurement are taken:

- Emissions with the engine in the original conditions as supplied from the factory.
- Emissions with original nozzles not subject to wear from use, calibrated to an aperture pressure lower than the nominal pressure.

The usual operating condition of an injection system with the hours of use are replicated to see this affects emissions of NO_X. The tendency is for injection pressure to decrease with hours of use. The incidents that may take place in the system of injection include:

- Reduced aperture pressure of the injector nozzle.
- Wear of the injection nozzle.

- Wear of the piston, sleeve and delivery valves of the injection pump.
- Wear of the delivery valve, and retention of the injection pump.
- Maladjustment of the advance of the injection, i.e. advance or delay with respect to the optimum point (Gutiérrez et al., 2006).
- Wear of the injection cam, which will alter the profile of the cam and cause a drop in the injection pressure.

Maladjustment in the injection pressure can thus have serious effects on operating performance. Here we focus on emissions of NO_X, detecting them by periodically analysing emissions with portable equipment. The results refer to specific measurements (g/kWh) and to concentrations of emissions in the exhaust gases. For calculating the specific emissions mass balance and carbon balancing are used in accordance with Technical Code of Annex VI of MARPOL 73/78, which is similar to the ISO 8178-1:1996 (International Standards Organisation, 1996).

The mass balance establishes that the mass flow of exhaust gases equals the mass flow of suction air plus the mass flow of fuel. Thus knowing the composition of the fuel and the mass flow of fuel that enters the engine, and the composition of the exhaust gases (O_2, CO_2, CO, SO_X, NO_X, THC), a series of equilibrium equations can be established to determine the mass flows of the components of the exhaust gases. The density of smoke in the exhaust is also taken into account when calculating the mass flow, as well as the laboratory atmospheric factor (f_a), which is only applicable to a family of engines. According to the Technical Code of the IMO for engines with turbocharger, with or without suction air cooling, f_a is defined as

$$f_a = \left(\frac{99}{P_s}\right)^{0.7} \cdot \left(\frac{T_a}{298}\right)^{1.5} \tag{1}$$

where P_s is the atmospheric pressure in dry conditions [kPa], and T_a is the absolute temperature of the suction air [K]. According to the technical code [MARPOL Conference 73/78], for the validity of a test in bench trials to be recognised, the parameter f_a must be $0.98 \leqslant f_a \leqslant 1.02$. This is different from the ISO 8178-1 Standard that states that, when it is not possible for technical reasons to obtain these values, the atmospheric factor can be taken as between 0.93 and 1.07. In our test the atmospheric factor was in accordance with the ISO 8178 Standard, although for some of the tests it was within the values established in MARPOL's technical code.

The sampling probe was placed at a distance of 1.1 m because the regulation stipulates 0.5 m as a minimum, or three times the diameter of the exhaust pipe if this latter value is greater, as far as is feasible, although sufficiently close to the engine so that the minimum temperature of the exhaust gases is 343 K in the probe. Regarding the engines studied, the second condition is met; the diameter of the exhaust tube being approximately 350 mm meaning the minimum distance would have to be approximately 1050 mm. In any case, this is not a problem for concentrations of NO_X in the exhaust gases because it is not affected by the location of the probe (Yanase et al., 1998).

For measuring in bench trials, JUNKERS hydraulic test bench, Model BN12, calibrated prior to the trials, was employed. More than 600 medium-speed engines had been tested on the bench, and it is adequate for testing medium-speed engines. The measurement sequence shown in Fig. 1 was employed for the injection pressure: The equipment employed was an intrusive piezoelectric pressure transducer model PCB 108A02B, a SCB-68 terminal board and a laptop PC with data acquisition card PCMCIA 6062E.

Fig. 2 shows the sequence used to measure the combustion pressure in the chamber. The sequence of measurements is similar to that for injection pressure, except that the piezoelectric pressure transducer is of the PCB112B10 type. Due to this transducer's electrical characteristics, it is necessary to employ the in-line load amplifier model PCB422E, the output of which is applied as the input to the four-channel digitally-controlled PCB482A16 amplifier for systems with ICP transducers. In addition to these pressure transducers, the system requires two proximity transducers with their respective conditioner circuits. Type K thermocouples were employed for measuring temperatures, and DANFOSS pressure transmitters for measuring the turbocharger feed pressure.

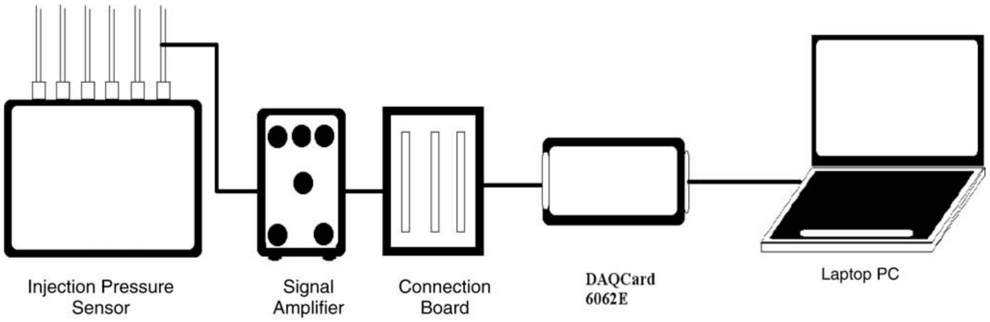


Fig. 1. Sequence of measurement for the injection pressure.

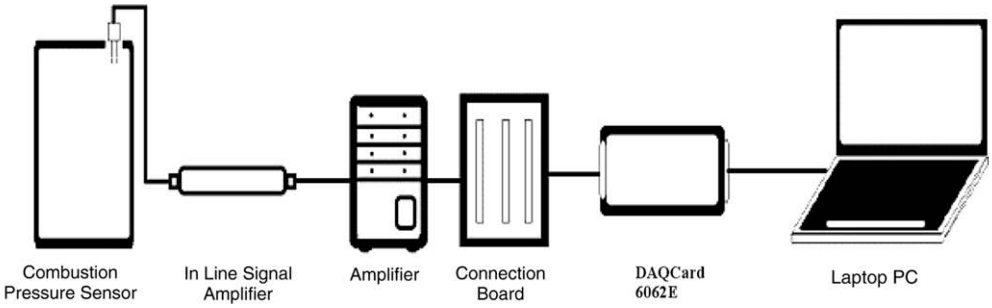


Fig. 2. Sequence of measurement for the combustion pressure.

3. Bench testing

The purpose of this test was to compare the effect on the emissions of NO_X of the drop in aperture pressure that occurs over the course of the engine's operating hours. We focus on the effect of the reduction of pressure on the emissions of NO_X, and the possibility of detecting this effect by analysing the exhaust gases. The nominal aperture pressure in the injectors of the engines tested is 35 MPa. From field experience of these engines, about 2000 h of use normally elapses before the injectors need to be repaired and reconditioned, these are found to have an aperture pressure reduced to around 30–31 MPa. During the life of the nozzles, some 4000–5000 h, it is normal to find no significant variations in the geometry of the nozzle (i.e. in the shape and diameter of the orifices). As a result of this, no significant increase of the flow occurs due to the ageing of the nozzle, and the structure of the jet is hardly affected at all by this reduction of aperture pressure over this period of use of the nozzle (Karlsson and Chomiak, 1995).

In addition, the wear in the nozzle orifices will cause the maximum pressure reached in the injection to diminish over time; therefore a reduction of the nozzle aperture pressure causes this aperture pressure to be reached sooner, and causes the needle to lift from its seat sooner, thus advancing the entry of fuel into the combustion chamber. The advancing of the injection produces an input of fuel when the pressure and temperature in the combustion chamber are lower; this retards the start of the combustion and increases the quantity of fuel that enters during the time of retard; this fuel is then burned very rapidly in the premixing combustion phase. This will produce an increase of pressure and temperature, resulting in the formation of more NO_X (Yanase et al., 1998; Al-Sened and Karimi, 2001) The injection starts with at a low pressure, which initially produces fuel droplets of larger diameter; these need more time to evaporate and begin the process of auto-ignition (Fig. 3).

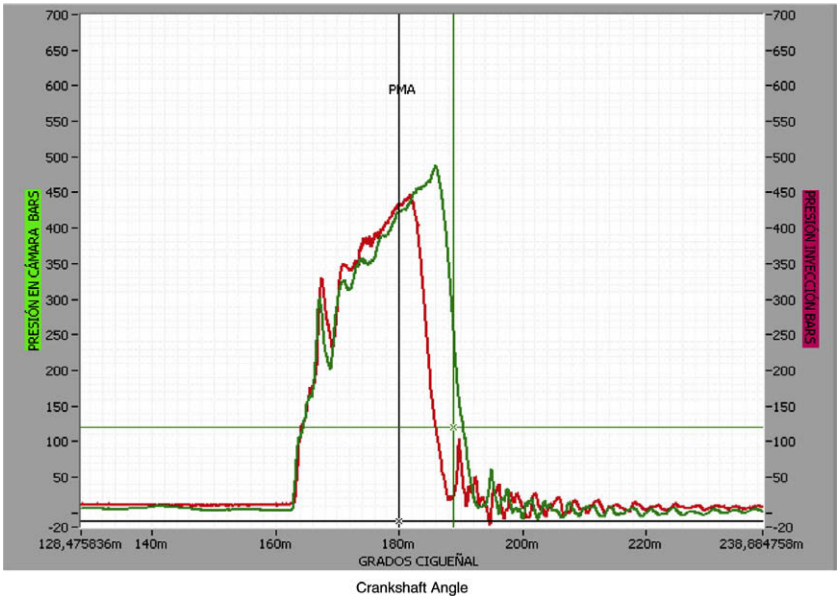
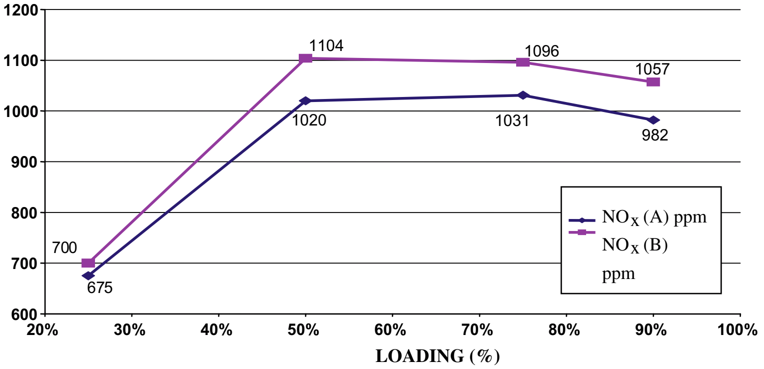


Fig. 3. Injection pressure in fuel pipe to injector.

Table 1
Results of tests based on the MARPOL technical code.

8 Cylinders	1036 kW at 800 rpm		Measurements of NO_X – Assay E2		
Loading [%]	100	75	50	25	Result
NO_X [gr/kWh] [A]	9.44	9.72	9.88	9.56	9.67
NO_X [gr/kWh] [B]	10.96	9.61	10.25	9.80	10.00
Difference	13.88%	−1.21%	3.59%	2.49%	3.38%
weighting factors	0.2	0.5	0.15	0.15	
IMO Limit	9.42				
Loading [%]	25	50	75	90	
NO_X (A) [ppm]	675	1020	1031	982	
NO_X (B) [ppm]	700	1104	1096	1057	
P_{max} [A] [MPa]	6.2	9.1	12.5	15.3	
P_{max} [B] [MPa]	6.6	10.1	12.6	15.4	
Maximum combustion pressure					
TH (A) °C	307.43	380.6	378.95	370.35	
TH (B) °C	290.38	362.93	358.53	346.88	
Temperature of exhaust gases at the outlet of the turbocharger					
CO (A) [ppm]	100.5	57	40.5	37.5	
CO (B) [ppm]	109.5	48.5	37	32.75	

Note: (A) Normal conditions; (B) measurements made with new nozzles and reduced aperture pressure.



NO_X(A): Emissions from new engine
NO_X (B): Emissions from new engine with injection pressure reduced from 35MPa to 31,5

Fig. 4. Emissions of NO_X against loading, with nominal pressure and reduced injection pressure.

The test performed corresponds to the type E2 according to the Technical Code of Annex VI of MARPOL 73/78, in which the revolutions of the engine are held constant and the loading applied to the engine is varied. The increase of NO_X concentrations in exhaust gases is possible to see in Fig. 4 and the specific emissions calculated according IMO Technical Code are possible to see in Table 1. There is a difference between concentrations and specific emissions and the changes due to different nozzle opening pressures; but the increased emission level due to lower opening pressure is clear in both ways of measuring the emissions. In the case of the specific emissions [gr/kWh], the change of fuel consumption has a direct effect in the calculation of exhaust mass flow rate which consequently changes the NO_X mass flow rate. Therefore, the concentration level will give a partial information of the emissions and more data are required to get any conclusion (fuel consumption, oxygen concentration in exhaust gases, engine output).

4. Conclusions

Emissions of NO_X increase when the nominal aperture pressure is reduced, to simulate a normal period of operation. There is a very small increase in the maximum combustion pressures that may be due to the small advance of the injection that occurs when the injection pressure is reduced, but this is unlikely to be appreciable in field conditions where it is very difficult to replicate the same loading conditions as during bench trials or in the initial delivery trials of the engines.

The emissions of CO hardly vary and the exhaust gas temperature shows little change, whether measured after leaving the turbocompressor or the cylinders, and no clear trend is shown. There are no noticeable differences in fuel consumption.

However, the results obtained from the measurements of NO_X emissions can lead to erroneous interpretations, depending on the unit in which they are expressed. When the emissions are in g/kWh, it can be seen that the values obtained are inversely proportional to the power developed, but this does not occur when this value is expressed in units of volumetric concentration (ppm). In addition, the volumetric concentrations depend directly on the mode of tests – they are much higher as the revolutions diminish, when the test is conducted corresponding to the demand of the propeller for power (Mode E3).

From the operational perspective, it could be deduced that a lower aperture pressure does not produce significant variations in the operating characteristics of the engine; however, this should not mislead one into thinking that the engine's hours of operation could be prolonged, because the aperture pressure will diminish progressively during operation, and more markedly with longer time of operation. The situation could be reached in which the needle of the injector does not seal the nozzle properly in its seat against the strong pressures of the combustion chamber, and gets contaminated with fuel. Furthermore, if the aperture pressure is low, reflex injections can occur in response to the pressure waves after the injection has finished, as well as leaking from the nozzle. All this is very prejudicial to the engine, and even puts at risk the engine's physical integrity.

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