ISSN 0209-2069

ZESZYTY NAUKOWE NR 66
WYŻSZEJ SZKOŁY MORSKIEJ
W SZCZECINIE

EXPLO-SHIP 2002

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Marine Engines NO_x Emission – On-board Verification Procedure Feasibility

Keywords: marine engines, exhaust emission, maintenance

In any program designed to reduce emissions from internal combustion engines, test procedures used for determining emission levels are as important as emissions standards that are implemented. Three duty cycles, designed by the ISO for marine diesel propulsion engines are employed. This paper discusses testing issues specific to marine engines and presents an example of such tests.

Emisja NO_x przez silniki okrętowe – możliwości weryfikacji w eksploatacji

Słowa kluczowe: silniki okrętowe, emisja spalin, eksploatacja

W każdym programie ukierunkowanym na redukcję emisji składników toksycznych spalin z silników tłokowych wykorzystuje się kontrolne procedury testowe, które są niezwykle istotne, tak jak ustanawiane ograniczenia emisji. Trzy cykle testowe sformułowane w normach ISO są przeznaczone dla okrętowych silników napędowych. Na podstawie podanego przykładu omówiono aspekty możliwości weryfikacji emisji NO_x w eksploatacji.

Introduction

Marine engines with a continuous rating are designed to maximize durability and fuel efficiency, which results in low operating costs. The E3 duty cycle is proposed to be used for measuring emissions from propulsion marine diesel engines operating on a propeller curve. Since most of the NO_x emissions from marine diesel engines come from commercial applications, the use the E3 cycle for all marine propulsion diesel engines operating on a propeller curve is acceptable. Using a single cycle to represent all propeller-curve marine diesel engines should reduce certification burdens for marine engines that are used.

Many larger propulsion marine engines do not operate on a propeller curve. These engines run at a constant speed and use a variable pitch propeller to control vessel speed. There is another class of propulsion engines that run at variable speed and use a variable pitch propeller. These engines are designed to operate near the power curve for the engine in order to maximize fuel efficiency. In general, these engines will operate at a constant speed except when maneuvering in port. The ISO does not have a test duty cycle specifically designed for these engines. In general, emission levels are sensitive to the duty cycle used to generate them. It seems that, if a marine engine is designed for low emissions on average over a low number of discrete test points, it may not necessarily operate with low emissions in-use [8]. This is due to a range of speed and load combinations that can occur on a vessel which do not necessarily lie in the test duty cycles. For instance, the test modes for the E3 cycle lie on an average propeller curve. However, a marine propulsion engine may never be fitted with an "average propeller." In addition, a light hull vessel may operate at lower torques than average, while the same engine operated on a heavy vessel with a deep displacement hull may operate at higher torques than average.

Ambient air conditions would likely have a significant effect on emissions from marine engines in use. Such ambient air conditions include temperature and humidity. To ensure real emissions control, the testing should include a wide range of ambient air conditions representative of real conditions. Ambient water temperature also may affect emissions due to its impact on engine and charge air cooling.

1. On-board NO_x emission verification procedures

Two methods are possible for the on-board survey depending on the conditions [2]:

- a performance parameter check method, which takes its origin in standard performance data listed in the record book,

- a component check method, which takes its origin in an opening-up inspection, but still requires performance data for the final adjustment of the engine, in order to obtain the specified engine performance.

Both methods require a brief engine performance and settings list from test bed – documentation from test-bed report. The list of necessary items includes:

- tables from the official test-bed report for particulars of engine, turbocharger, governor, auxiliary blower, air cooler and fuel valves (nozzle).
- tables of setting values of: exhaust cam lead angle, fuel cam lead angle and fuel cam lead lift, fuel pump shims and compression shims for piston rod – all for the individual cylinders.
- set of engine's performance data from all load tests.

1.1. On-board engine performance parameter check method

The parameter check can be performed using the manufacturer supplied, an easy detailed tool to calculate and present the expected NO_x emission [4]. The code should contain necessary engine parameters – Table 1. In some cases performance check provides standard performance data and dynamic cylinder pressure measurements (maximum compression and combustion pressures). According to the IMO-NO_x Technical Code, a record book is required to enter changes of components (through the defined IMO part numbers) or settings, and to document performance data collected to verify NO_x compliance for possible surveys.

Table 1

Input data for NO_x verification

Dane wejściowe do estymacji emisji NO_x

Engine Type	–
Ambient temperature	deg.C
Ambient pressure	mbar
Relative humidity of intake air	rel.%
Scavenging-air temperature	deg.C
Scavenging-air pressure	bar_{abs}
Sea-water temperature (or fixed central coolant temperature)	deg.C
Turbine back pressure	mmWC
Max. cylinder pressure	bar_{abs}
Max. compression pressure	bar_{abs}
Power	kW
Engine speed	r/min
Turbocharger speed	r/min
Fuel pump index	–
VIT index (if applicable)	–

All adjustments of settings, at least for the NO_x components, therefore, should be documented following repair or service. For spare part changes, a review of the record book would normally be sufficient. Although a standard performance check will discover changes in many NO_x components, if the NO_x sensitive dimension was changed, for example – the fuel nozzle is the most important component to affect the NO_x emission from an engine. Therefore, a nozzle should be inspected.

The parameter check method defined through the survey code accounts for the influence of certain parameters, through the cylinder pressure, adjustments of injection timing, VIT, compression shims and exhaust-valve timing, through the scavenging air temperature, a deteriorated scavenging air cooler performance, and through the back pressure, finally blocking up of the exhaust heat exchanger. To evaluate the NO_x compliance [1, 6], the following steps have to be performed:

- Estimation of the actual load condition through the power estimation charts. If the engine torque is available through torsion measurements on the shaft and verified in sea trials, this torque can be used as an alternative, or the load could be derived from the vessel engine room automation system.
- Evaluation of the performance influence on the ISO corrected NO_x values for each load condition – taking into account reference value and their tolerances given in Table 2.
- Calculation of the final average IMO-NO_x factor.

Table 2

Operating reference and tolerance values
Standardowe wartości parametrów i tolerancji

	Parameter	Reference Value *(at ISO ambient conditions)*				Tolerance *(at given engine power)*			
Engine parameters	Power – %	*100*	*75*	*50*	*25*	100	75	50	25
	Scavenging temperature – deg. C	*41*	*34*	*29*	*34*	+6	+3	+3	+3
	Cylinder maximum pressure – bar					+3/–3	+3/–3	+3/–3	+3/–3
	Exhaust back pressure – mm WC	*300*	*225*	*150*	*75*	max. 450	max. 340	max. 225	max. 115
Atmospheric conditions	Atmospheric pressure – mbar	1000							
	Ambient temperature – deg. C	25							
	Humidity – rel. %	30							
	Scavenging-air cooler sea-water inlet temperature – deg. C	25							
	Scavenging-air cooler inlet water temperature – deg. C	29	27	26	25				

1.2. Engine components check method

In order to verify the engine components and allowed settings, a check of the actual NOx emission sensitive components is necessary. Turbocharger, air cooler and auxiliary blower are verified through their nameplates. To verify the turbochargers internal parts (marked by the turbocharger manufacturer) dismantling is necessary.

However, to verify the setting values, a performance check has to be carried out using the on-board survey code. When specified performance data are obtained, the setting adjustments can be approved. The performance data to check the setting values for the survey can be based on the data from either before or after the opening-up inspection of the engine (one cylinder unit, usually requested). The engine shall always be assembled again using the last verified setting values. However, a check is always recommended after service or repair of the engine to prove continuing compliance. Performance data are obtained during the official test-bed test under survey conditions. The marking of the fuel nozzle should be inspected following the completion of the engine tests. And, if a cylinder is opened up for inspection after the test, verification by all marked components could be done.

2. Established correction factors affecting NO_x emission

Based on simultaneous measurements of NO_x emission and performance parameters from several different two-stroke engines, a special 'NO_x function' has been formulated to calculate NO_x as a function of specific engine parameters [4]. Together with the cycle simulation to predict dependent engine parameters (or simplified in the form of performance correction factors), the 'NO_x function' can be used to calculate the tolerances of the most common performance parameters.

2.1. Correction to ISO ambient conditions

The measured data have also been used to formulate an equation to correct emissions at the given ambient conditions to the specified ISO ambient conditions in order to compare emission values at the same conditions [1] [5].

$$\text{CorrNO}_x(H_a, T_a, p_{amb}) = \frac{1}{1 + C1 \cdot (H_a - 10.71) + C2 \cdot (T_a - 298.15) + C3 \cdot (p_{amb} - 1000)}$$

where: H_a – water content in scavenging air (g_{H2O}/kg_{dryair}),

T_a – ambient-air temperature (K),

p_{amb} – ambient air pressure (mbar),
$C1$ to $C3$ – coefficients dependent on engine load (given in Table 3).

Table 3

ISO ambient conditions correction coefficients
Współczynniki korekcyjne dla warunków otoczenia według ISO

Engine load – %	$C1$	$C2$	$C3$
100	–0.00994	0.00144	–0.00007
75, 50, 25	–0.00505	0.00145	–0.00011

H_a can be calculated in the following way:

$$H_a^* = \frac{6.220 \cdot R_a \cdot p_a}{p_b - p_a \cdot R_a \cdot 10^{-2}}$$

$$H_{sc} = \frac{6.220 \cdot p_{sc} \cdot 100}{p_c - p_{sc}}$$

If $H^*_a \geq H_{sc}$ then $H_a = H_{sc}$ else $H_a = H^*_a$

where: H^*_a – water content at ambient air condition (g_{H2O}/kg_{dryair}),
R_a – relative humidity of intake air (%),
p_a – saturation vapour pressure at ambient air condition (kPa),
p_b – total barometric pressure (kPa),
H_{sc} – water content at scavenging air condition (g_{H2O}/kg_{dryair}),
p_c – scavenging-air pressure (kPa),
p_{sc} – saturation vapour pressure at scavenging-air condition (kPa).

The saturation vapour pressure is only a function of temperature and can be calculated in the following way:

$$p = 1.013 \cdot e^{19.008 - \frac{5325.35}{T}}$$

where: T – temperature (K).

2.2. Correction to reference performance conditions

The NO_x function has been used to derive a simplified method to calculate the variation in the ISO corrected NO_x value as a function of maximum cylinder pressure, scavenging-air temperature and turbine back pressure [7]. The relative changes are shown in Table 4 at the four specific cycle point of load conditions. However, the simplified method will predict slightly higher NO_x emissions than the NO_x function.

Table 4

Relative changes in NO_x for P_{max}, T_{scav} and $P_{turb.back}$

Względne wartości zmian emisji NO_x dla zmian P_{max}, T_{scav} and $P_{turb.back}$

Power (%)	ΔNO_x, P_{max} [1) (gNO$_x$/kWh pr. bar)	ΔNO_x, T_{scav} [2) (gNO$_x$/kWh pr. Deg. C)	ΔNO_x, $P_{turb.back}$ [3) (gNO$_x$/kWh pr. mm WC)
100	0.1816	0.0224	0.0004
75	0.1760	0.0209	0.0006
50	0.1760	0.0209	0.0006
25	0.1760	0.0209	0.0006

1) Relative increase in NO_x value (corrected to ISO ambient conditions) resulting from a one bar increase in the cylinder maximum pressure.
2) Relative increase in NO_x value (corrected to ISO ambient conditions) resulting from a one degree increase in the scavenging-air temperature.
3) Relative increase in NO_x value (corrected to ISO ambient conditions) resulting from a one mm WC increase in the turbine back pressure.

The ISO corrected NO_x value at the maximum tolerances is calculated using the equation for the average weighted NO_x emission (IMO NO_x) given in the 'IMO-NO_x Technical Code':

$$\text{IMO NO}_x = \frac{\sum_{i=1}^{i=n} \text{Specific emission}_i \cdot \text{Power}_i \cdot \text{WF}_i}{\sum_{i=1}^{i=n} \text{Power}_i \cdot WF_i}$$

where: $n = 4$ represents the four engine load points of the E3/E2 cycle.

Using the weight factor (WF), the power (in kW) and the specific NO_x emission (in g/kWh) for the four load points, the equation can also be written as:

$$IMONO_x = 0.2909 \cdot NO_x(100\%) + 0.5455 \cdot NO_x(75\%) + 0.1091 \cdot NO_x(50\%) + 0.0545 \cdot NO_x(25\%)$$

However, for the above equation to be valid, the load points of the E3/E2 cycle must correspond exactly to 100, 75, 50 and 25% of MCR. The extent of the verification depends on the type of engine certification. On the test bed all the four E3/E2 load points are requested (100%, 75%, 50% and 25% loads). Whereas on board only the 75% load is requested, plus in case of an engine with VIT also one load point above the VIT break point (from 85 to 100% loads). This will ensure the verification of the engine performance status and not be too burdensome on the ship.

Since the verification method is based on 'real' performance data for the four ISO-cycle load conditions, the actual load points are attached a certain tolerance. In cases where a specific load point is missing (due to weather or sea conditions, or other circumstances), it is recommended to use a 'similarity' approximation to evaluate the missing load-point NO_x value:

- The ratio between estimated NO_x and measured test-bed NO_x at the two closest load points is averaged.
- The NO_x estimate for the missing load point is calculated by multiplying the measured test-bed NO_x with the averaged ratio from above.

This approximated 'missing' load-point NO_x value can now be used together with the remaining cycle values to estimate the average-cycle NO_x value needed to verify the compliance. The power is usually derived from torque and speed. If the torque is difficult to measure directly, the engine manufacturer's diagrams can be used to estimate the brake power.

The correction for cooling-water temperature depends on the actual cooling system. On board either a sea-water or a central cooling-water system can be used. In the former, the scavenging-air temperature is tied to the sea-water temperature, whereas in the latter the scavenging-air temperature depends on the temperature setting strategy for the central-cooling system.

Finally, on a test bed, the setting on the cooling-water temperature in most cases is independent of the sea-water temperature, and the cooling-water temperature shall not be used for correction. As the usual variations in turbine back pressure have been shown only to have a minor influence on the NO_x emission and the measurement of the turbine back pressure, they could be omitted during a NO_x compliance verification [7].

3. A method to check NO_x compliance – verification cases

The discussed load points and cooling conditions lead to the following cases:

1. Engine without VIT – the actual NO_x compliance is estimated from performance data at 75% load only, assuming that the $NO_{x(test\ bed\ 75\%)}/NO_{x(estimated\ 75\%)}$ ratio is identical for the ratio of the remaining load points.
2. Engine with VIT – the actual NOx compliance assuming the 25 to 75% load points contribute as those without VIT, based on the 75% performance data. The 100% load point contribution is estimated from the actual performance at the measured load, adjusting the NO_x (test bed 100%) for the same P_{max} difference as the measured load, but for a T_{Scav} and $P_{turb.back}$ reflecting the 100% load:

$$T_{Scav(100\%)} = T_{Scav(meas.load\%)} + \frac{(100 - meas.load\%) \cdot (T_{Scav.ref.(100\%)} - T_{Scav.ref.(75\%)})}{25}$$

$$P_{turb.back(100\%)} = P_{turb.back(meas.load\%)} + \frac{(100 - meas.load\%) \cdot (P_{turb.back.ref(100\%)} - P_{turb.back.ref(75\%)})}{25}$$

4. NO_x emission verification examples

The NO_x emission can be estimated at different performance conditions using the following calculation method:

1) by means of measuring the maximum pressure, scavenging-air temperature, turbine back pressure and ambient conditions at the required load points given in Table 5;
2) derivation of the equivalent relative change in NO_x emission (g/kWh) presented in Table 6, based on the actual performance in step 1 and reference conditions.

Table 5

Input engine and ambient parameters

Wejściowe parametry silnika i otoczenia

Load (%)	Power ($\%_{nom}$)	T_{amb} (deg. C)	P_{amb} (mbar)	R_a (rel. %)	T_{Scav} (deg. C)	P_{Scav} (bar_{abs})	P_{back} (mmWC)	P_{max} (bar_{abs})
100	100.1	18.1	998	30	33	3.60	140	149.8
75	75.1	19.5	999	30	25	2.81	75	125.5
50	50.0	19.0	999	30	24	1.89	25	96.2
25	25.9	18.0	998	30	24	1.35	2	70.5

Table 6

Calculation of expected NO_x 'at site' performance and ISO ambient condition

Obliczenie współczynnika emisji NO_x w eksploatacji, do warunków ISO

Power (%)	Shopping Test ISO-NO_x (g/kWh)	Measur. max. pressure (bar_{abs})	Relative change in NO_x (g/kWh)	Meassur. scav. air temp. (deg.C)	Relative change in NO_x (g/kWh)	Measur. turb. back pressure (mmWC)	Relative change in NO_x (g/kWh)	Expected site ISO-NO_x (g/kWh)
100	15.3	149.8	–0.221	33	–0.179	140	–0.064	14.42
75	17.1	125.5	–1.320	25	–0.188	75	–0.075	16.49
50	16.2	96.2	–0.846	24	–0.105	25	–0.045	15.08
25	14.3	70.5	0.095	24	–0.209	2	–0.020	13.02
	16.4	E2 cycle NO_x emission factor value						15.54

Conclusions

As described above, the correction is performed using simplified NO_x function that has been formulated by the engine manufacturer to calculate NO_x as a function of specific engine parameters based on the parameter sensitivity tests [4]. Next, the NO_x function is used to derive an easy method to calculate the variation in the ISO corrected NO_x value as a function of maximum cylinder pressure, scavenging-air temperature and turbine back pressure. Rough examination of the verification results (Fig. 1) shows that some operating factors would result in weighted exhaust emissions discrepancy.

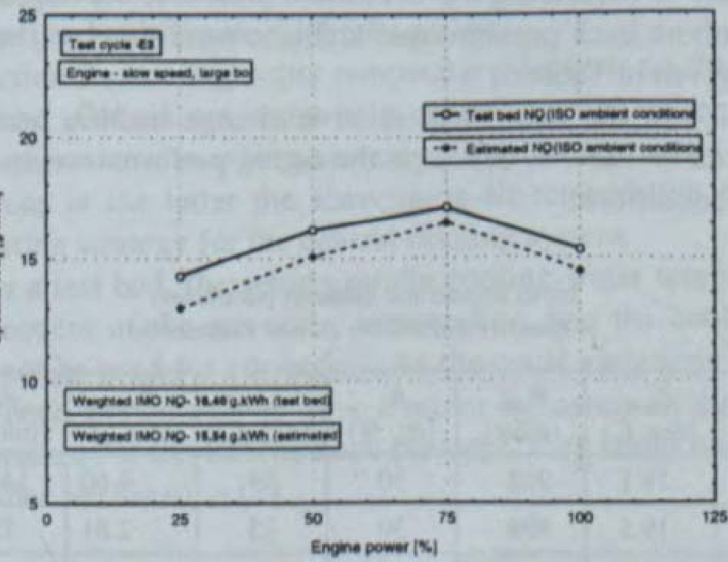

Fig. 1. Comparison of NO_x emission test bed and estimated factors

Rys. 1. Porównanie wartości współczynników emisji NO_x – ze stanowiska i estymowanego

Aside from the duty cycle, there are a few other aspects of marine diesel engine testing that need to be considered. Because marine engines are an integral part of a vessel, in-use testing to be performed on the vessel would be the best option. There are several portable sampling systems on the market that, if used carefully, can give fairly accurate results. When this is the case, it may be more appropriate to test the engine aboard the vessel. For vessels, there should be enough space to bring a portable sampler aboard, similar to those used for stationary source testing. Engine speed can be monitored directly, but load may have to be determined indirectly. For constant speed engines, it should be relatively easy to set the engine to the points specified in the duty cycles.

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