NOx Emission Value - Study of On-board Measurement

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The on-board NOx monitoring method is one of the three ways for the periodical survey, which demonstrates compliance by means of the measurement of the NOx emission value on commercial operations. In this study, the NOx emission measurement, made on the same two-stroke engine, and with the same gas analyzer, was carried out on three occasions. That is a shop test, an sea trial and commercial operation. The effects of gas concentrations in UOB (universal oxygen balance) and UCB (universal carbon balance) method, compositions of the sampled fuel, stability of engine output power in operation, and the temperature and humidity correction factor $K_{hides}$ on the NOx emission value are discussed with regard to the derivation methods of the exhaust gas flow rate. The coefficient of humidity term, for the factor $K_{hides}$ should be larger than that of $K_{hides}$ as specified in the NOx technical code. This correlates the NOx emission values measured at sea trial and during in-service. The temperature and humidity should be measured in the engine room rather than in the steering house. The stability of the engine power can be evaluated alternatively by using the C.O.V. of the oxygen concentrations of the exhaust gas. The NOx emission values on an actual vessel do not agree to those at a test-bed due to the effect of the derived exhaust gas flow rate and the temperature of the intercooler outlet air.

1. Introduction

The NOx Technical Code(1) (NTC) on control of emission of Nitrogen Oxides, by the International Maritime Organization (IMO), defines the verification procedure of NOx emission value not only at an initial certification on a test-bed, but also at intermediate or periodical survey. With regard to the confirmation of compliance, there are three methods such as, (1) Engine parameter check method, (2) Simplified measurement method, (3) Direct measurement and monitoring method (hereinafter called monitoring method). Since the monitoring method is considered a practical method, enables to verify and certify based on measurement outcome during engine operation, a guideline for on-board NOx verification procedure(2) is defined. However, the on-board measurement has not been established, because the measurement result that exceeds an allowance of 15% (the use of RM-grade fuel) of the applicable NOx limit value is reported(3). That is, since the on-board measurement at sea changes simultaneously various factors, it has not rationally proved the measurement difference between on the test bed and during in-service.

In order to clarify the issue of on-board measurement, we investigated the exhaust gas measurement of the same marine 2-stroke diesel engine, using the same gas analyzer, in the shop test, sea trial and commercial operations. Also, in the commercial operation, a number of exhaust gas emission measurements was examined at the condition of the same fuel and the same output range.

This study shows, based on results of exhaust gas measurement on commercial operation, the calculation method of the exhaust gas mass flow, the influence of fuel composition to NOx emission value, the accuracy of engine load and the adjustment of temperature/humidity correction factor. Moreover, The difference of NOx emission value on the three occasions was discussed using the measured data.

2. Measurement Method

The type of vessel for the on-board measurement was a car-carrier with 62,190GT, 21,417DW, and accommodating 5,400 cars. The main engine specification is shown in Table 1. The measurement on board was performed during the operation, from Japan (Yokohama) to Singapore, for 9 days from November 22 to 29, 2005.

The concentrations of NOx, $O_2$ (MEXA-720, made by Horiba Corporation) and $CO_2$ (CGT-7000, made by Shimadzu...
Corporation) were measured using the Zirconia and NDIR analyzer, respectively. The data related to the engine performance was monitored using installed devices of the vessel. Measurement of atmospheric pressure, atmospheric temperature and relative humidity was performed at three points, i.e., engine room, garage deck and steering house.

Zirconia (Zr) type NOx/O2 analyzer, which was used for on-board measurement, has an advantage of which enables to measure NOx and O2 by a sensor at the same time, under the wet condition. However, a zirconia sensor is not listed as a NOx concentration analyzer in NTC. In order to verify the accuracy, simultaneous measurement of Chemiluminescence detector (CLD) and Heated Chemiluminescence detector (HCLD) type NOx analyzer was verified for comparison on test bed. Table 2 shows three combinations of gas analyzer as Case 1~3. Figure 1 shows NOx concentration (wet) to each load and the ratio of NOx emission value to that in Case1. Case1 shows the measurement result under dry condition converted to under wet condition. Also, an oxygen balance method was used as an exhaust gas mass flow calculation method for NOx emission value. NOx concentration is the highest in Case1, the lowest in Case3. But the maximum concentration difference between Case3 and Case1 is 85 ppm, between Case3 and Case2 is 35 ppm. NOx emission value of Case2 and 3 show the difference of ±5 %, compared to Case1. The maximum difference between Case3 and Case2 is 0.9 g/kWh, difference between Case2 and Case1 is 0.9 g/kWh. Thereby, zirconia type NOx/O2 analyzer in Case3 was used in this measurement for the convenience as a measurement device, though each analyzer has the difference of the result by the measurement principle.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Engine specifications</th>
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<td>Engine cycle</td>
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<tr>
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<th>Table 2</th>
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<td>Case1</td>
<td>CLD (dry)</td>
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<tr>
<td>Case2</td>
<td>HCLD</td>
</tr>
<tr>
<td>Case3</td>
<td>Zr (Zirconiumdioxide sensor)</td>
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</table>

3. Measurement results and discussion

3.1 Measurement items relating to NOx emission

The NOx emission value in NTC is defined as

\[
\text{NOx [g/kWh]} = K_{\text{hde}} \times \text{NOx[ppm]} \times 10^4 \times \frac{G_{\text{exh,w}}[\text{kg/h}]}{\rho_{\text{exh}}[\text{kg/m}^3]} \times \frac{1}{W_b[\text{kW}]} \tag{1}
\]

where \(K_{\text{hde}}\) is temperature and humidity correction factor, 2053[\text{g/m}^3] is NOX density, \(G_{\text{exh,w}}\) is exhaust gas mass flow on wet basis, \(\rho_{\text{exh}}\) is exhaust gas density, and \(W_b\) is engine power output. The exhaust gas mass flow, power output and \(K_{\text{hde}}\) are discussed as follows.

3.1.1 Effect of calculation method and fuel component on exhaust gas flow
The calculation method for the exhaust gas flow is known as universal carbon method (UCB) and universal oxygen method (UOB). In order to compare those, CO2 and O2 concentration was measured on operation.

Since the fuel composition has influenced to exhaust gas flow calculation, fuel composition analysis was conducted. The fuel was sampled four times, putting off these date. Furthermore, two companies (No.1, No.2) performed the composition analysis for the same samples. Figure 2 shows the result of fuel analysis. Oxygen content is not shown here, as it was below the lowest value of measurement. Sulfur and nitrogen contents have little difference due to sampling date or analysis companies, except sulfur content on November 30. However, carbon content shows that there is a difference about 1 % according to sampling date and analysis companies, and it tends to decrease as the date passes. Hydrogen content shows the difference up to 0.5 % according to analysis companies.

The monitoring guideline has described the model fuel composition, which is approved as substitute fuel analysis. With this model fuel composition and two composition analysis results, Figure 3 shows the comparison of NOx emission calculated by UCB and UOB. Among three fuel composition, the case of No.2 composition has evaluated the maximum emission value. However, the fuel composition difference is not large. In addition, the exhaust gas flow hardly changes by the calculation
method. This result is the same as the report\(^{(4)}\) of comparison of exhaust gas flow calculation value with actual measurement value.

These four samplings show the fluctuation analysis of fuel composition in identical supplied fuel. Figure 4 shows the effect of fuel composition fluctuation to NOx emission. The horizontal axis shows the NOx emission calculated by analysis of fuel composition sampled in the closest time. The vertical axis shows the representing NOx emission value (NOx_first) calculated by analysis of fuel composition sampled first (11/22 in Figure 2). In both cases of UCB and UOB, the NOx emission calculated by representing value of fuel composition is large. The effect of fuel composition fluctuation is less than the difference by exhaust gas calculation method.

Figure 5 shows the exhaust gas flow at 70~80 % load. The exhaust gas flow does not have a large difference using any fuel composition or gas flow calculation method.

### 3.1.2 Stability of engine load

With regard to the stability of engine load, the monitoring guideline instructs to measure for more than 10 minutes, at sampling rate higher than 1Hz, and C.O.V. should be below 5 %. In this study, the gas concentration was measured at 1Hz, while the sampling rate of shaft power was 0.1Hz due to the device capacity.

Figure 6 shows an example of time series of engine power, NOx, and \(O_2\) concentration. (a) shows the result in steady operation (average engine power 11275 kW, C.O.V. 2.23 %), and (b) shows the result in transient operation (average engine power 4720 kW, C.O.V. 10.3 %). At the steady operation, the measurement data does not have data exceeding ±5 % of the average value. At transient operation, some data shows engine power exceeded ±10% of the average value. \(O_2\) concentration has a high following capability against engine power change. On the other hand, NOx concentration does not have such a following capability as \(O_2\) concentration.

Figure 7 shows the relation between C.O.V. of engine power and C.O.V. of oxygen concentration. C.O.V. of engine power is below about 3 % at steady operation. There is a linear relation between C.O.V. of engine power and C.O.V. of oxygen concentration. Because C.O.V. of engine power of 5 % is required according to the monitoring guideline, it is necessary for C.O.V. of \(O_2\) concentration within 1.25 %.

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**Fig. 6 Engine power and gas concentrations**
3.1.3 The change of the temperature and humidity correction factor

Many researchers investigated the temperature and humidity correction factor. NTC defines the correction factor, $K_{H_{\text{dies}}}$ used for diesel engines with intercooler (I/C), in following formula:

$$\frac{1}{K_{H_{\text{dies}}}} = 1 - 0.012(H_a - 10.71) - 0.00275(T_a - 298)$$

$$+ 0.00285(T_{s_{\text{c-ref}}} - T_{sc})$$

(2)

where $H_a$ is the absolute humidity of the intake air [g/kg], $T_a$ is the air temperature [K], $T_{sc}$ is the temperature of intercooled air [K], and $T_{s_{\text{c-ref}}}$ is the intercooled air reference temperature. Figure 8 shows the temporal change of the temperature and humidity correction factor, $K_{H_{\text{dies}}}$, during operation. As the ship left for Singapore from Japan, $K_{H_{\text{dies}}}$ gradually becomes larger. $K_{H_{\text{dies}}}$ in engine room, garage deck, and steering house are different values, and the outcome in engine room is the smallest.

Atmospheric factor, $f_a$, shows as following formula, in case of turbocharged diesel engine:

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

(3)

where $P_s$ is dry atmospheric pressure [kPa]. Figure 8 shows $f_a$ calculated by atmospheric data in engine room, which was in effective range, 0.96~1.06.

Figure 9 shows the relation between $K_{H_{\text{dies}}}$ used the temperature and humidity measured in engine room and steering house and NOx concentration. $K_{H_{\text{dies}}}$ used by the measurement in steering house, and the fluctuation are large, compared to the one in engine room. The position of temperature and humidity measurement is important, and the measurement in engine room is necessary. Figure 10 shows the relation between corrected NOx concentration, multiplied by $K_{H_{\text{dies}}}$ and $K_{H_{\text{dies}}}$ by the symbol ▼. The corrected NOx concentration remains the fluctuation of over 100 ppm, with the tilt to the temperature and humidity correction factor. As with the reference (5), we conducted a multiple regression analysis to find $K_{H_{\text{dies}}}$ suitable to this engine by this measurement results. Table 2 shows $H_a$, $T_a$, $T_{sc}$ factor, and Figure 10 shows the re-corrected result by the symbol ○. The NOx correction value is maintained constant, 1230 ppm, regardless of atmospheric conditions. The correction factor ($K_{H_{\text{dies}}}$) has about 1.5 times for the humidity and one third for the temperature, compared with the correction factor by IMO.

Fig. 7 Relation of C.O.V. of engine power and O₂ concentration
3.2 Comparison of on-board measurement with measurement on the test bed

Figure 11 shows the results of NOx emission value, in the shop test, sea trial and in-service conditions. All concentration measurement were used with the same measurement device (Zr), and the exhaust gas flow was calculated by UOB. As known, nitrogen content in fuel being transformed to NOx, nitrogen content in fuel is 0.19 % in DM grade fuel on the shop test, 0.15, 0.2 % in DM, RM grade fuel at the sea trial, 0.42~0.47 % in the in-service conditions. The result in the case of in-service condition shows about 2 g/kWh smaller than the result in the case of the shop test and the sea trial. This difference is relatively large, compared with NOx emission standard deviation, 0.37 g/kWh, at 70~80 % load in service. Figure 12 shows the change on each measurement data of NOx in the shop test, the sea trial and in-service conditions at 70~80 % load. NOx emission value is calculated by multiplying corrected NOx concentration (KHdies x NOx[ppm]) with exhaust gas flow [kg/kWh]. Temperature/humidity corrected NOx concentration using DM, RM grade fuel (◇, ○) at sea trial is about 4 % smaller than the average of in-service data. In contrast, the exhaust gas flow per engine power is larger for about 22 %. Thereby, NOx emission at the sea trial is larger for about 18 % than the result of in-service condition. The difference of exhaust gas flow influences the difference of turbocharger engine speed ω [rpm], and the sea trial condition is about 10 % larger than in-service condition. In the result in shop test (◆), since temperature/humidity correction NOx concentration is about 6 % larger than in-service condition, and exhaust gas flow is about 12 % larger, NOx emission value is larger than the value of in-service condition as well as the sea trial condition. This measurement in the in-service condition shows the measurement for air and exhaust gas flow has not been examined in the same condition as in the shop test and the sea trial.

![Figure 8: Temporal change of humidity correction factor](image1)

![Figure 9: Influence of measurement position of atmospheric condition on gas concentration](image2)

![Figure 10: Effect of correction factor on temperature and humidity](image3)

### Table 2 Coefficients of KHdies

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<tr>
<th></th>
<th>Ha</th>
<th>Ta</th>
<th>Tsc</th>
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<td>KHdies IMO</td>
<td>-0.012</td>
<td>-0.00275</td>
<td>0.00285</td>
</tr>
<tr>
<td>KHdies 2</td>
<td>-0.0175</td>
<td>-0.000911</td>
<td>0.00804</td>
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</table>
While the temperature/humidity corrected NOx concentration in the shop test has demonstrated higher than those in other conditions, Figure 13 shows the relation between $K_{K diagnosis_2}$ and the factor for $K_{K diagnosis}$. Since $K_{K diagnosis_2}$ is calculated by $H_a$, $T_a$, $T_{sc}$ in service, the temperature and humidity in service have been distributed against $K_{K diagnosis_2}$ with good linearity. In contrast, the values on the shop test deviates from this relation. $K_{K diagnosis_2}$ is calculated from the result that obtained in the range of $H_a$: 4~20g/kg, $T_a$: 27~39 deg., $T_{sc}$: 51~53 deg.. Because the value on the shop test is outside this range, $K_{K diagnosis_2}$ cannot correct properly. Figure 13 shows NOx 13. NOx 13 is defined by the following formula:

$$\text{NOx}_{13}[\text{ppm}] = K_{K diagnosis} \times \text{NOx}[\text{ppm}] \times \frac{O_{2_{as}} - 0.13}{O_{2_{as}} - O_{2_{exh}}} \quad (4)$$
where $O_{2\text{,exh}}$ and $O_{2\text{,sur}}$ are the concentration of oxygen in the exhaust gas and atmospheric concentration of oxygen (wet condition), respectively. While the result of NOx13 on the shop test is not on the straight line, the result on the sea trial has matched to the line by the result in the commercial operation. NOx 13 in Figure 13, which has tilt toward $K_{Hdies_{2},2}$, has not eliminated the temperature/humidity influence, because the temperature/humidity correction factor has been performed only to NOx concentration, and the change of oxygen concentration has not corrected. Tsc is greatly different, either in the case on the test bed or on board. This difference is attributed to coolant temperature of air cooler, and this is one of the causes of the difference between the shop test measurement and the on-board measurement.

4. Conclusions

In order to clarify the issue at on-board NOx emission measurement, the exhaust gas measurement of the same 2-stroke engine, using the same gas analyzer was carried out in the shop test, the sea trial and the commercial operations. The main results about NOx emission measurement are summarized as follows.

1. In the measurement result in service operation, the exhaust gas mass flow using carbon balance method give close agreement with that using oxygen balance method. The fuel component in the same fuel has the influence of 2 % at the maximum to NOx emission value.

2. C.O.V. of engine power in steady operation is stable at below 3 %. The engine power stability can confirm using the C.O.V. of oxygen concentration without measuring engine power.

3. The temperature/humidity correction factor depends on the measurement location. The measurement in engine room is necessary for the accurate evaluation to NOx emission value.

4. The temperature/humidity correction factor, $K_{Hdies_{2}}$ was calculated with multiple regression analysis. The humidity correction factor of large 2-stroke engine should be necessary to increase the humidity influence more than the correction factor by IMO.

5. The difference of intake air flow and temperature at intercooler outlet air causes the disagreement between NOx emission on shop test and the one on board. Also, the temperature/humidity correction factor based on data of the in-service operation could not correct the result on the shop test.

Acknowledgments

The authors would like to thank NYK Line Corporation for their valuable assistance with the measurements. They would also like to acknowledge the support from related companies.

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