Development of Low Emission Technology for Marine Propulsion Diesel Engine to Meet IMO NOx Tier II / III

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Abstract

Regarding the emission regulation for marine diesel engines, the IMO Tier II NOx regulation came into effect in 2011 and applying to newly-built ships were stipulated reductions of approximately 15 to 22% relative to Tier I regulations in global regions; Tier III regulations will stipulate reductions of 80% in Emission Control Areas (ECA).

Niigata has consistently worked to meet such environmental demands without significantly deterioration of efficiency and will continue to work to achieve these new goals. This report describes the results of analytical and experimental feasibility testing of various low emissions technologies to comply with the effected regulations, based on the emission reduction technologies developed to date. There are some useful papers to realize low NOx emission for the specific engine. However, the aim of this report is to present effective emission control technology to not only specific engine but also wide speed range.

In this paper, the development of after-treatment, gas engine technology and improvement combustion process as way to meet Tier III regulation are also described. As a result of feasibility study of primary measures, it is suggested that up to 50% NOx reduction is achieved by using severer Miller cycle and 2-stage turbocharging without deterioration of fuel consumption.

***Keywords**:* Emission, Nitrogen oxide, Diesel engine, Gas engine and Selective catalytic reduction

1. Introduction

IMO MARPOL 73/78 Annex VI was enacted in May 2005 to control exhaust gas emissions from ships. More stringent regulations were adopted at the IMO MEPC58 in October 2008 following revisions in regulations. The Tier II NOx regulations came into effect in 2011 and applying to newly-built ships are stipulated reductions of approximately 15 to 22% relative to Tier I regulations in global regions; Tier III regulations will stipulate reductions of 80% in Emission Control Areas (ECA).

Niigata has consistently worked to meet such environmental demands without significantly deterioration of efficiency and will continue to work conscientiously to achieve these new goals. This report describes the results of analytical and experimental feasibility testing of various low-emissions technologies to achieve compliance with the effected regulations, based on the emission reduction technologies developed to date.

There are some useful papers to realize low NOx emission for the specific engine (e.g. [1]). However, the aim of this report is to present effective emission control technology to not only specific engine but also wide speed range.

This report also briefly describes the development of after-treatment, gas engine technology and improvement of combustion process as ways to meet Tier III regulations.

Compared to the Tier I regulations, IMO NOx Tier II regulation require appropriate changes in engine configurations to achieve reductions of approximately 20% for the engine itself. Factors affecting NOx emissions include fuel injection timing and boost pressure, but compression ratio and valve timing must be altered together to minimize deterioration of fuel consumption. In other words, technologies targeting IMO NOx Tier II compliance must address both NOx emissions reductions and thermal efficiency improvements.

According to theoretical engine cycle, the diesel cycle (constant pressure cycle) has greater thermal efficiency than the Sabathe cycle in case of constant maximum pressure condition [2]. And the temperature at the end of combustion of the diesel cycle is lower than the Sabathe cycle. Therefore, when the diesel cycle is applied as design concept for any diesel engine, they can receive benefit both of engine efficiency and low NOx emission, with no distinction between engine size and speeds. This is a principle of emission control technology which is described below.

This paper describes studies using engine performance simulations pertaining to

Bore	280 mm
Stroke	390 mm
Engine speed	800 min-1
Rated output	370 kW/cyl.
BMEP	2.3 MPa

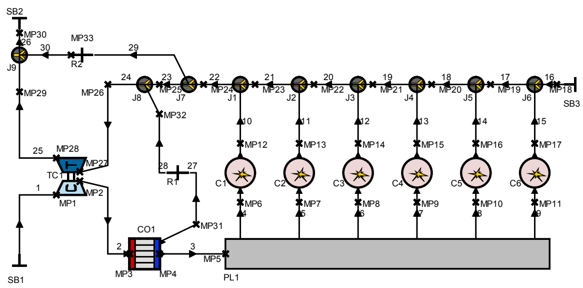


Fig. 1 Calculation model and specification

combinations of various engine parameters to achieve NOx emission targets, confirming engine performance through the engine experiments. These studies changed fuel injection rates to achieve the diesel cycle and used the Miller cycle (increased boost pressure and altered valve closing timing) to further reduction of in-cylinder temperature, examining the effects of each of these changes on engine performance.

2. Tactics for low NOx engine development

The thermodynamic engine cycle simulation tool (AVL BOOST v2009.1) is used to evaluate the change in engine performance due to engine configuration. The calculation model and the specification of test engine are shown in Fig. 1. In this simulation model, the in-cylinder combustion temperature is calculated with fuel injection rate and the NOx emission is estimated by using the enhanced Zel'dovich mechanism.

The test engine is marine propulsion engine which was modified to comply with IMO NOx Tier I regulation, but some additional functions were mounted for this study. The mechanical variable intake valve timing (VIVT) system is adopted, the intake valve timing can be change without engine stop. Concerning the turbocharging system, the air bypass system is employed. Some amount of charge air is fed to exhaust pipe before the turbine via a bypass channel and it helps increase of excess air ratio at low load condition. In addition, the waste gate system is also installed and enabled to avoid over speed of turbocharger. These engine features were reflected to this calculation model. An injection rate which is a result of rig test for the

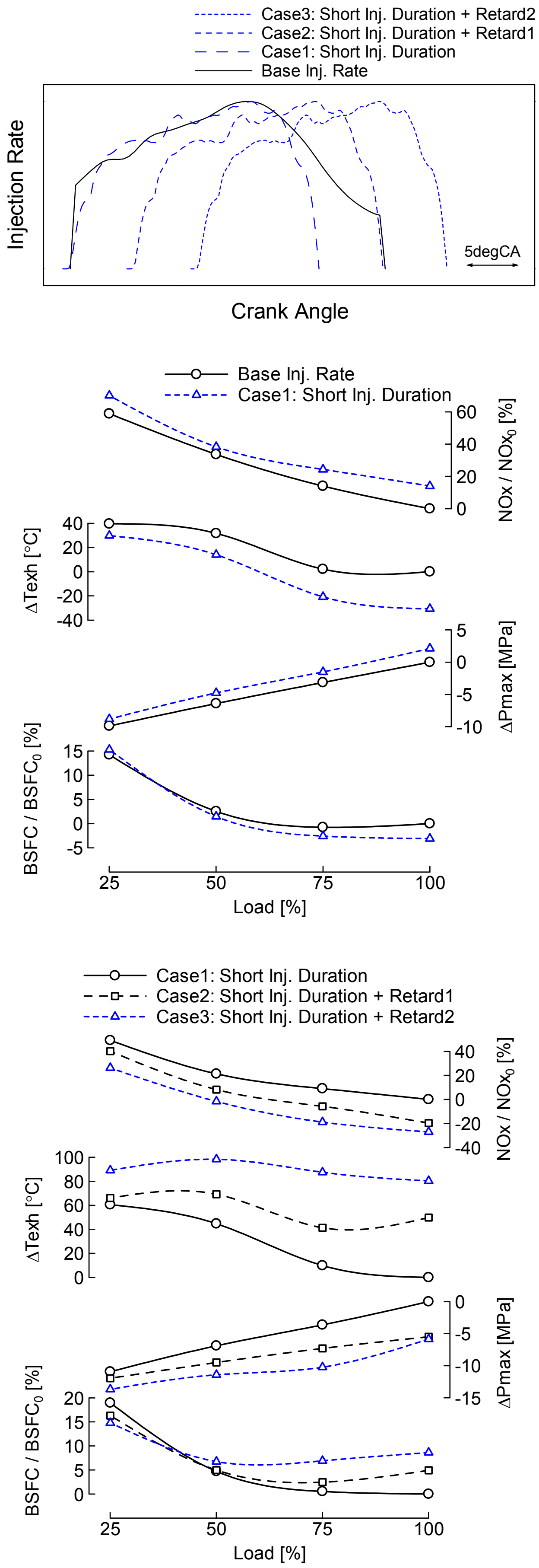


Fig. 2 Optimization of fuel injection system

injection system was applied to this model, and the NOx emission was estimated.

2.1 Optimization of fuel injection system

As first step of this examine, the effect of the fuel injection rate on the NOx emission was investigated. The previous study [3] was researched that there is clear relationship between the NOx emission and the shape of injection rate. In this study, to reduce the NOx emission, the design concept of the fuel injection rate is followed by the study.

As the applied concept, the injection rate at early stage was reduced as much as possible to minimize NOx emission, at the same time, the injection rate at late stage was increased to maintain the injection duration. Hence the deterioration of fuel consumption was prevented. In this study, this injection concept was achieved with conventional jerk type fuel injection pump, through means of short duration injection and constancy of the injection end. As these reasons, when the start of injection is retarded substantially, the maximum pressure will be reduced and approaches the diesel cycle. The effects of fuel injection rate are summarized separately, as injection duration and start of injection.

2.1.1 Shortening of injection duration

The fuel injection rate for high load operation is shown in Fig. 2. The fuel injection rate of base engine is indicated by solid black line, the new injection rate which is named "Case1" and indicated by long dash blue line was designed with prompt closure after peak of injection rate. Fig. 2 shows the change of engine performance due to two different injection rates, respectively. Because the centroid of injection rate was shifted forward and approached TDC, the peak firing pressure and NOx emission were increased. However, the exhaust temperature was reduced due to shortened late combustion phase, the fuel consumption and smoke were also remarkably improved.

2.1.2 Change of the injection start timing

Secondly, the engine performance in case of retarded injection timing was investigated. The end of injection duration of "Case1" was retarded to initial timing as "Case2", and "Case3" was retarded further from "Case2".

The exhaust temperature and fuel consumption are became worse when the combustion period is shifted backward due to retard of fuel injection timing. For 100% load of Case2 and Case3, as the peak firing pressure is equal to or less than the in-cylinder pressure at the end of compression stroke, and timing at peak firing pressure is also retarded remarkably, then the fuel consumption is significantly deteriorated. Regarding the NOx emission, it was severely affected by the retard of injection timing in any load case and found that the reduction of NOx emission reached to 27% at 100% load condition.

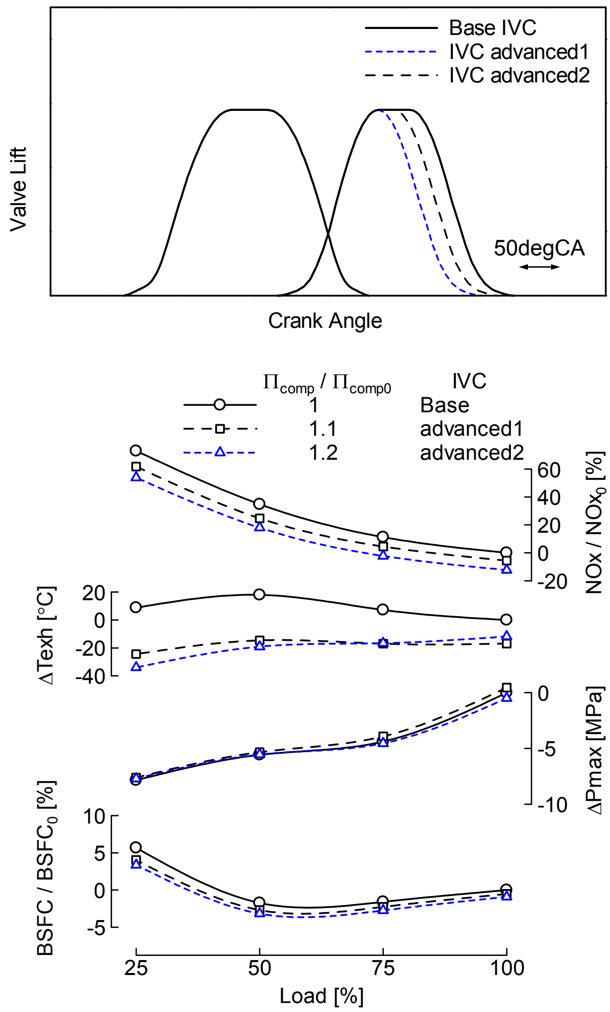


Fig. 3 Effect of Miller cycle on NOx reduction

2.2. Miller cycle

The Miller cycle was introduced and examined as further low NOx technology. The Miller cycle is characterized as a technology to achieve the same work at less in-cylinder temperature due to the combination of the increase of trapped air quantity by higher boost pressure and appropriate intake valve close timing. As the feasibility of the actual engine test was considered, the range of pressure ratio of compressor was determined from same series of the turbocharger which is employed on the base engine. Then, the intake valve close timing is adjusted as shown in Fig. 3 to maintain the in-cylinder pressure at the end of compression stroke as constant. As the determined intake valve close timing and compressor pressure ratio, thus three ways of combination for the reduction of NOx emission were investigated.

The change in fuel consumption and emission characteristic when the pressure ratio of compressor was increased up to 20% than original value are shown in Fig. 3. Because of severe Miller cycle effects lower in-cylinder gas temperature at the end of compression stroke, it follows decreased in-cylinder gas temperature of combustion duration. Therefore, the NOx emission was remarkably reduced for each engine load, especially as 12% at 100% load condition. Since turbocharger pressure ratio was higher, the exhaust temperature was much lower due to increasing of charge air flow through valves at valve overlap period. In addition, as the comparison of p-v diagram for gas exchange, some improvement of pumping work and reduction of fuel consumption of 1% were confirmed.

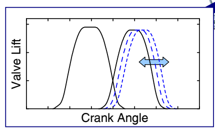
3. Application to all portfolios of Niigata product

As mentioned above, the effects of thermodynamic factors - fuel injection rate, injection timing and the Miller cycle - on engine performance have been investigated by thermodynamic calculation. The effect of these developed technologies to meet the IMO NOx Tier II regulation was validated by modification of existing engine and successfully development of new engine. In this article, the state of the compliance with Tier II and advantage of the latest developed marine propulsion engine - 28AHX - is introduced.

The 28AHX was designed for the use of tug boats and supply vessels, mainly. The specification shows the maximum continuous rating from 2070kW to 3105kW by in-line 6 to 9 cylinders (Fig. 4). The design concept for engine performance is not only low NOx emission but also low fuel consumption and smokeless operation. To achieve these conflicting design goals, the developed low emission technologies are fully included with specially designed devices like mechanical VIVT system, high pressure ratio turbocharger, air bypass system and waste gate system. Especially, the VIVT system was installed as a key technology to satisfy both of low smoke emission at part load and low NOx at high load.

Fig. 5 affords an instance of engine development test result, and each characteristic is normalized by the performance at 100% load of the base existing engine.

Model		28AHX	
Bore		280 mm	
Stroke		390 mm	
Engine speed		800 min-1	750 min-1
MCR	6L	2220 kW	2070 kW
	8L	2960 kW	2760 kW
	9L	3330kW	3105 kW
BMEP		2.3 MPa	
Peak firing pressure		18 MPa	



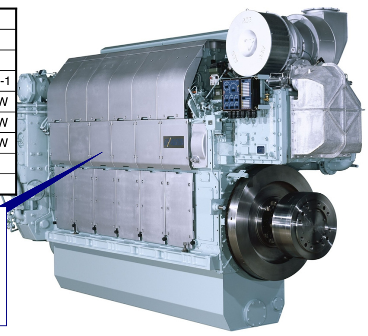


Fig. 4 Newly developed 28AHX engine, low NOx, high efficiency and invisible smoke

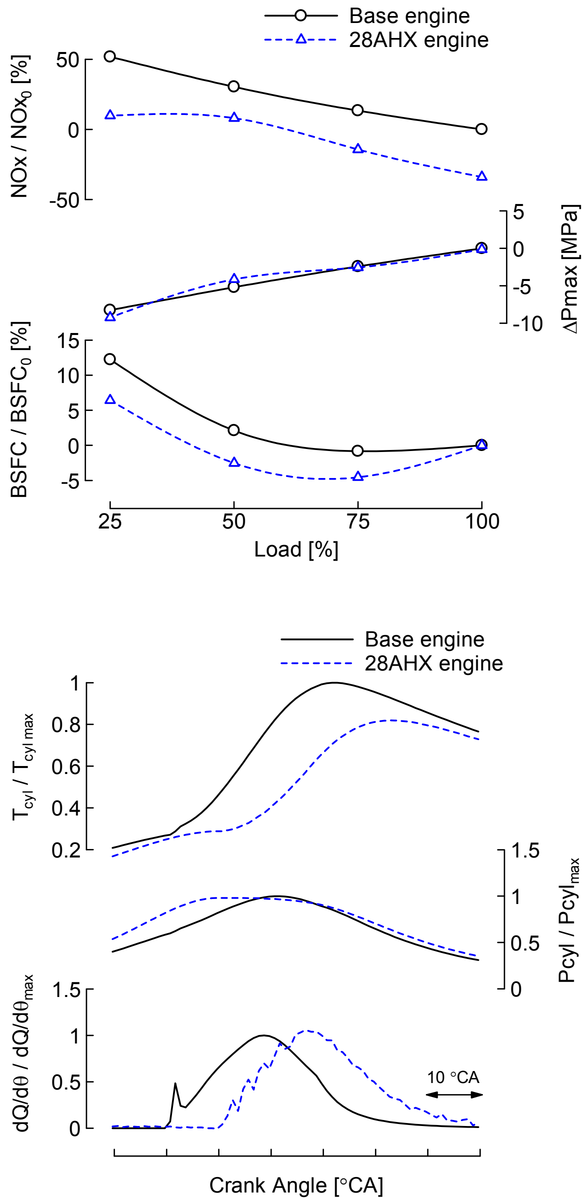


Fig. 5 Engine test result of 28AHX

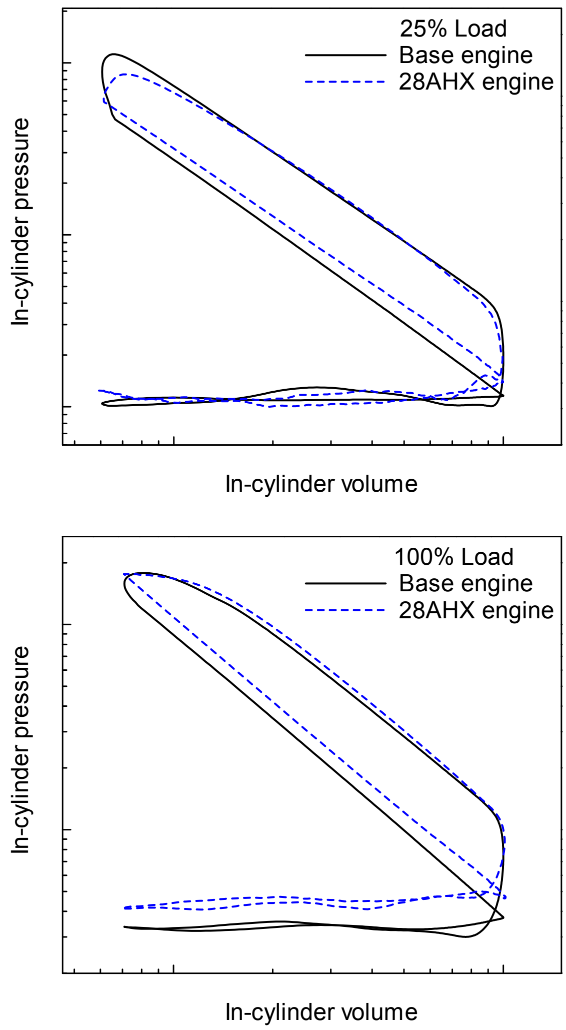


Fig. 6 Tier II ready performance with constant pressure combustion concept

Due to optimized engine configuration, the NOx emission of 28AHX engine for all engine loads was reduced significantly, and the target level to comply with IMO NOx Tier II regulation was achieved. Meanwhile, the fuel consumption was not deteriorated at rated power, and could be improved extremely at part loads. In addition, the smoke emission was also decreased, it stays below 0.5 FSN at any given engine load.

The rate of heat release at 100% load is shown in Fig. 5. However, the clear peak of in-cylinder pressure curve does not appear due to retarded fuel injection timing. Although the ignition occurred near TDC and the appearance timing of the peak of heat release curve was delayed, the late combustion phase was immediately finished as a result of shortened combustion duration. Fig. 6 shows the comparison of p-V diagram between the base existing engine and 28AHX engine for 25% and 100% load operation. Regarding the 28AHX engine, the constant-pressure combustion was achieved at 100% load condition, namely, the diesel cycle was realized.

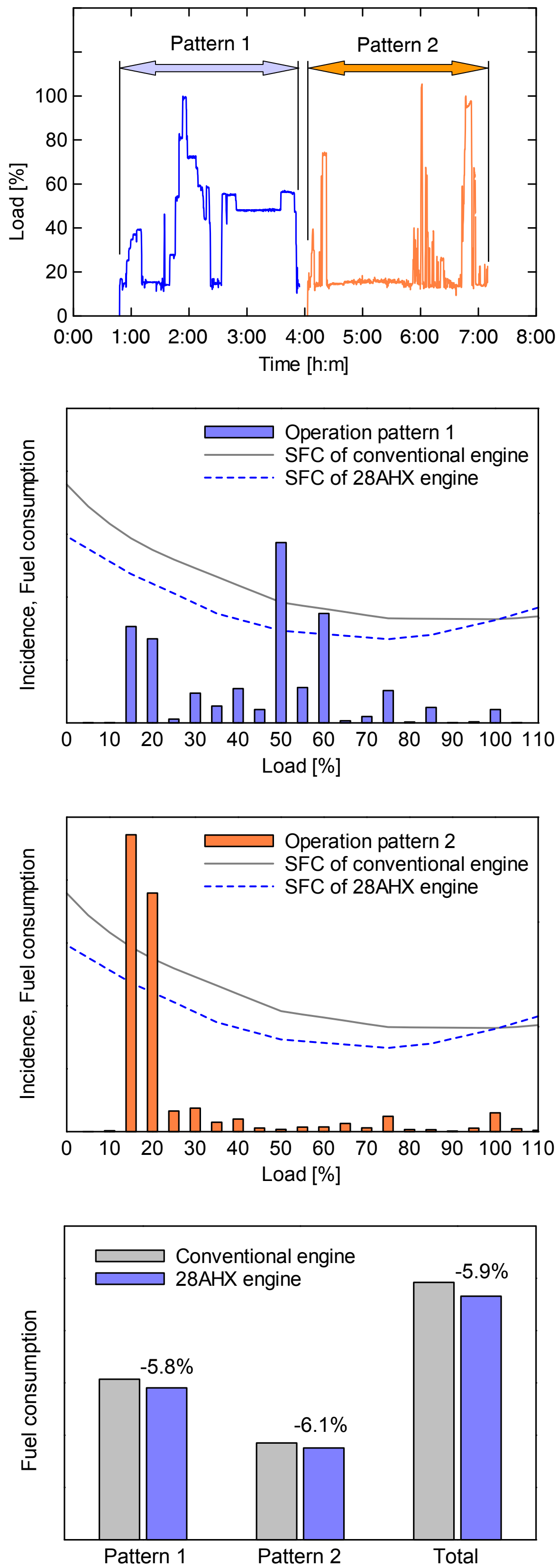


Fig. 7 6% operation cost saving for tug-boat use

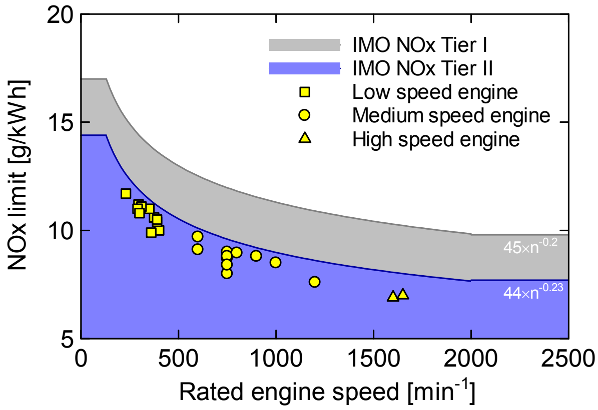


Fig. 8 Compliance with IMO NOx Tier II for all of NIIGATA portfolio

And now, the reduction in fuel consumption in actual ship operation shall be discussed.

The reduction in fuel consumption obtained when a ship is equipped with 28AHX was simulated with respect to actual ship operation. The investigation used a tug boat equipped with an engine of the same power class as the test engine and measured actual ship operation.

Fig. 7 shows an example of actual operation of the tug boat. Taking one operation to be from engine start to engine stop, two patterns were extracted. The frequencies of occurrence of loads measured at an interval of 5% are shown with the corresponding fuel consumption curves. It is generally known that there is a larger proportion of low and medium load operations in tug boat operations, and operation patterns 1 and 2 support this fact. The fuel consumption during one operation was calculated by taking the sum of the frequency multiplied by the fuel consumption at each load, and a comparison of the values for the conventional engine and 28AHX engine. As a result of the great improvement in fuel economy in the low and medium load range, a reduction in fuel consumption of approximately 6%, that is, a 6% reduction in costs, can be expected in actual operations. A reduction in fuel consumption means a direct reduction in CO2 emissions, so the achievements of this study will not only help to reduce NOx emissions but also greenhouse gas emissions.

To verify the validity and universality of technical methods to comply with IMO NOx Tier II regulation, more stringent requirement of NOx reduction for low-speed engine was optimized as Fig. 8. For example, an engine as engine speed of 310 min-1 but four stroke marine propulsion diesel engine, the NOx reduction was required about 2.5g/kWh (-18%) to meet Tier II regulation, the development target was certainly achieved without deterioration of fuel consumption. It follows that our emission control technology for IMO NOx Tier II regulation are valid for all our diesel engines with no distinction between engine speeds. Consequently, Niigata continues to provide all portfolio of diesel engine for customers after IMO NOx Tier II regulation became effective.

4. Tactics to meet IMO NOx Tier III

IMO adopted Tier III regulation as target for further NOx emission reduction. The Tier III regulation stipulate NOx reduction of 80% below the requirement set under current regulation. The following main techniques are considered as ways to achieve these targets.

(1) Exhaust after-treatment
(2) Use of alternative fuels
(3) Combustion improvement using CR, EGR with 2-stage turbocharging

4.1 Exhaust after-treatment

Already in use in Europe, selective catalytic reduction (SCR) system enables NOx emission reductions of over 80% on its own, making it a promising technology for use in meeting Tier III requirements. Niigata has practical experience in this area with engines it has sold in the past and has demonstrated the effectiveness of this approach in reducing NOx emissions.

Four-stroke engines are installed in a narrow engine room, imposing constraints on the size of the SCR system. Thus, the NOx converter added midway in the exhaust gas duct was made as efficient as possible to enable the smallest possible external dimensions. Recently, 80% NOx reduction by space velocity value of about twice a past product was studied through engine test. It is confirmed that Tier III requirements can be satisfied by using the higher space velocity converter to the medium speed engine described earlier.

4.2 Use of alternative fuels

Alternative fuels also offer effective solutions, including methods that use gaseous fuels such as natural gas in place of conventional liquid fuels. To date, gas engines have primarily been used for land-based power generation and co-generation. With pre-mixed lean burn gas engines, adiabatic flame temperature is lower and NOx formation, namely thermal NOx, is dramatically low compare to diffuse combustion of liquid fuels. The potential of low NOx emission for gas engine is known as less than 10% of those for diesel engine [4].

The NIIGATA AG series gas engines comprise six models of one of two types that cover the range of outputs from 1 to 6 MW (Fig. 9) [5]. These models are charge air-cooled, turbocharged, and lean burn gas engines incorporating 6 to 18 cylinders. Fig. 9 shows a product engine type of 12V22AG. IMO NOx emission levels for E2 of these gas engines have confirmed, and their values meet IMO NOx Tier III.

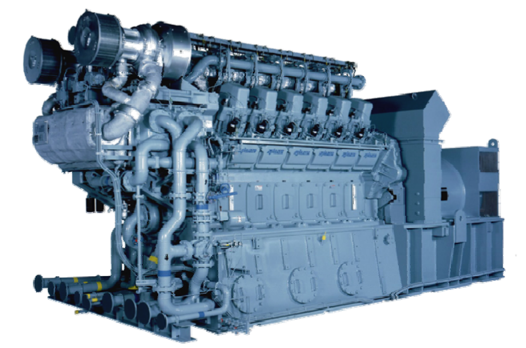
A lean burn technique has big benefit of increasing BMEP and improving thermal efficiency by the reason of higher knocking resistance potential. On the contrary, secure ignition source and keeping combustion stability are one of key technical issues. A performance of existing modern gas engine is almost competing to that of diesel engine. It is thinkable gas engine's performance will be over the diesel engine's performance including efficiency and emission.

However, when considering not diesel electric but direct-drive of propeller, gas engines perform poorly for operations that involve rapid change of load. Use as marine engines entails rapid load changes that may trigger knock or misfire due to excessive fuel and insufficient charge air in mixtures due to lags in exhaust turbocharger response. Thus, this potential solution raises concerns about the stability of engine operations in situations requiring increased speed - for example, for acceleration or position control in rough seas. The development of practical technologies, specifically technologies capable of meeting ship operational requirements, remains an issue that must be addressed.

4.3 Combustion improvement using CRS, EGR with 2-stage turbocharging

The EGR is well known as techniques for NOx reduction. CRS, common rail system, can operate with injection timing and rate flexibility. It enables to optimize for injection in the purpose of NOx reduction according to load operation. To get positive solution of trade off between NOx and thermal efficiency, the optimized combination with flexible of CRS, EGR and 2-stage turbocharging together with Miller cycle [6].

To achieve remarkable NOx reduction by decrease in-cylinder temperature, sharper Miller timing is indispensable. Although sharper Miller - early intake valve closing - has the potential to improve the trade off relationship between NOx emission and fuel consumption, the higher boost pressure is required to maintain engine output. Since there is a limit of pressure ratio and



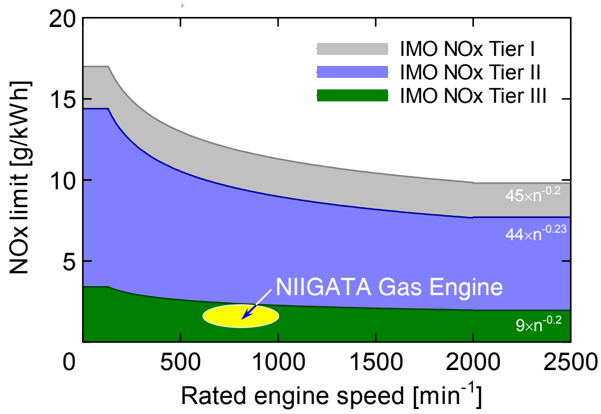


Fig. 9 Potential of low NOx emission for NIIGATA gas engine

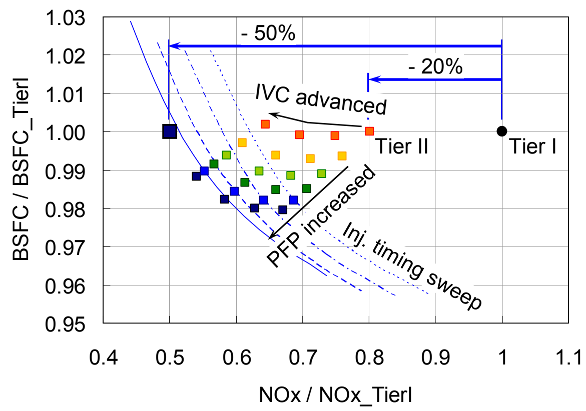


Fig. 10 NOx reduction by 2-stage turbocharging

efficiency of single stage turbocharger, 2-stage turbocharging will be necessary. In that case, the charge air mass delivered is enlarged, the increased pressure loss at charge air and exhaust duct must be considered. In addition, there is anxiousness for cold starting and high smoke density in part loads due to low effective compression ratio. The VIVT system like a device which installed on 28AHX engine is considered of value to overcome this issue.

The feasibility study with engine cycle simulation for 2-stage turbocharging and severe Miller cycle was carried out. The intake valve close timing and boost pressure were changed independently, however, the engine output is kept through this study. Fig. 10 shows the change in NOx emission and fuel consumption form Tier I engine condition. The NOx emission is drastically decreased due to early Miller timing and the increase of peak firing pressure by employing high boost pressure helps improvement of fuel consumption. The NOx reduction rate is further enhanced with fuel injection timing retard, from this calculation result, it is explained that 50% NOx reduction from Tier I condition is achieved without deterioration of thermal efficiency. This fact also suggests the save on running cost like reducer of the SCR system when the engine combines the exhaust after treatment.

5. Summary

The low NOx emission technology to meet the IMO NOx Tier II regulation was investigated by using four stroke medium speed marine propulsion diesel engine, some concluding remarks on the emission control technology are obtained as follows.

(1) By a combination of optimized injection rate, injection timing, compression ratio and the Miller cycle as engine configuration factor, the compliance with IMO NOx Tier II regulation can be achieved without the deterioration of engine efficiency.

(2) The developed low NOx emission technology is also effective in low and high speed diesel engine, namely, all Niigata's portfolio of diesel engines can be delivered as IMO NOx Tier II ready engine.

(3) The development of application technologies for Gas engine, SCR system and EGR system with 2-stage turbocharging will be also investigated as promising emission control technology to comply with IMO NOx Tier III regulation.

(4) The feasibility study about 2-stage turbocharging and severer Miller cycle was carried out, and the NOx reduction from Tier I condition of 50% is estimated.

6. Acknowledgement

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