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EMISSION CONTROL TECHNOLOGY BY NIIGATA, THE CLEAN MARINE DIESEL ENGINE FOR LOW SPEED, MEDIUM SPEED AND HIGH SPEED

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Abstract: In order to meet stringent emission standards for marine diesel engines, we NIIGATA continue the development of low emission combustion technology and apply the right means to commercial engines according to the emission standard requirement. Our portfolios of marine diesel engine are widely provided.

The low, medium and high speed engines which engine speeds from 290 to 1950min-1 are manufactured and delivered for various types of ship applications by NIIGATA. The low emission combustion technologies to comply with IMO NO_x emission standard are required for these various products independently of engine speed. The low NO_x emission technology consists of the miller cycle and the optimization of fuel injection are considered for every speed of diesel engines, and are also confirmed the feasibility of the reduction of NO_x emission to meet IMO NO_x Tier II.

It is confirmed that there are the possibility way of further NO_x reduction as optimizing earlier miller timing, higher boost pressure and fuel injection timing. This emission control technology and engineering findings are applied for new designed 28AHX diesel engine. This newly developed marine diesel engine, 28AHX, can be complied with IMO NO_x Tier II by engine itself and also keep the good level of fuel consumption from low load to high load. The cylinder size is 280mm, the output power per cylinder is 370kW. However, the described 28AHX paper will be presented at another session on this CIMAC Congress.

When the selective catalytic reduction (SCR) systems will be employed as NO_x reduction method to meet IMO NO_x Tier III, the SCR device should be small and compact design to appropriate with the short in height and narrow engine room for medium speed engine. Since the size of SCR device depends on reduction ratio of NO_x emission, it is necessary to focus on the improvement of emission reduction of diesel engine as the small size of the SCR device. Furthermore, the engine test with extreme miller timing and boost pressure is carried out to aim for remarkable NO_x emission reduction well over the IMO NO_x Tier II requirement. Through these investigations, new challenges on engine design like higher exhaust temperature are confirmed.

In this paper, the obtained results are shown as the effect of the optimized injection and miller cycle on NO_x emission, respectively. Moreover the promising emission control technologies for further emission regulation are described.

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 to be come into force in 2011 and applying to newly-built ships will stipulate reductions of approximately 15 to 22% relative to current 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 next-generation regulations, based on the emission reduction technologies developed to date. This report also briefly describes the development of after-treatment and gas engine technology as ways to meet Tier III regulations.

<u>The development history of emission control technologies by Niigata</u>

As Figure 1 shows, emission reduction initiatives by Niigata date back to the 1970s. The company has consistently been at the forefront in the area of low NOx emissions. Early initiatives seeking to determine the characteristics of direct injection combustion and in-direct injection combustion systems showed that direct injection system increases thermal efficiency while indirect injection system reduces NOx emission rates. In 1974, Niigata developed the NCCS engine with low-NOx emissions technologies to minimize efficiency losses and incomplete combustion by two stages combustion, based on in-direct injection combustion system to minimize NOx emissions and positive use of swirl inside the combustion chamber. While demands for high efficiency pushed subsequent developments in favor of direct injection combustion, the concept of minimizing NOx emission by optimizing fuel injection rate retains its influence to this day. This approach is used in four-stroke marine diesel engines sold by Niigata offering a wide range of engine speeds to meet Tier I regulations, as shown in Figure 2.

The development of low-NOx emissions technologies involved auxiliary equipment as well as improvements in the engine itself. Field-testing done in 1993 and 1994 on marine NOx reduction systems featured land-based NOx reduction technologies developed in the early 1990s, and a low-speed engine launched the following year employed a similar NOx reduction system [1].

To meet increasingly stringent low-NOx emission requirements, Niigata will further expand its study and uses of accumulated technologies developed in the course of reducing exhaust emissions.

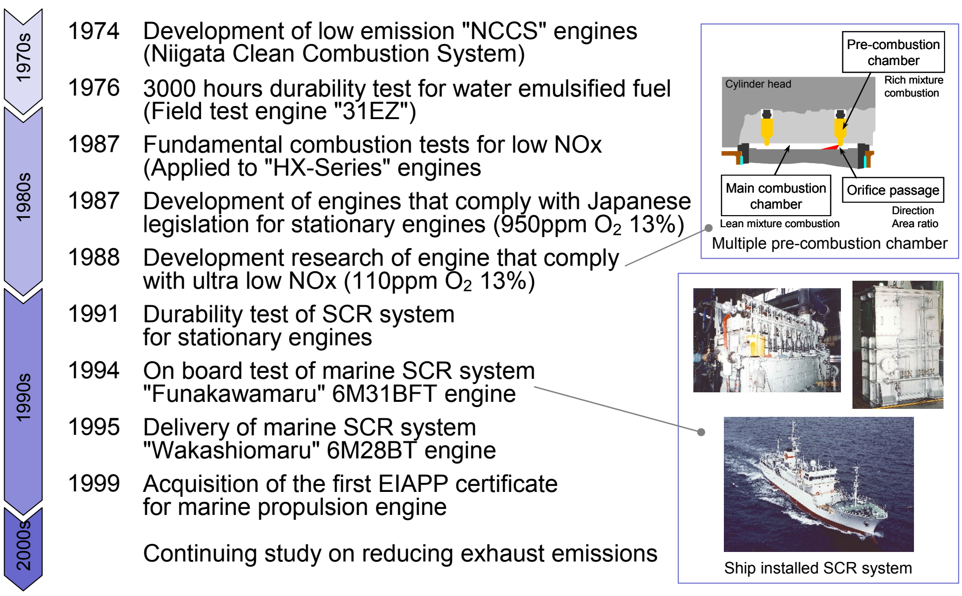

Figure 1 - Development history of emission control technology by Niigata

THE TECHNICAL STRATEGY FOR IMO NOX TIER II COMPLIANCE

Compared to current regulations, IMO NOx Tier II regulations will 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.

Studies to reduce NOx emissions for large medium-speed diesel engines performed by Kawakami et al. [2] demonstrate that the "Pmax/Pcomp", defined as the ratio of in-cylinder pressure at the end of the compression stroke to peak firing pressure, is a useful design index when estimating NOx emission levels. In other words, designs seeking to reduce NOx emission levels require engine configuration that reduce the design index "Pmax/Pcomp". Engine cycle demands a diesel cycle instead of the Sabathe cycle used in current four stroke marine propulsion diesel engines.

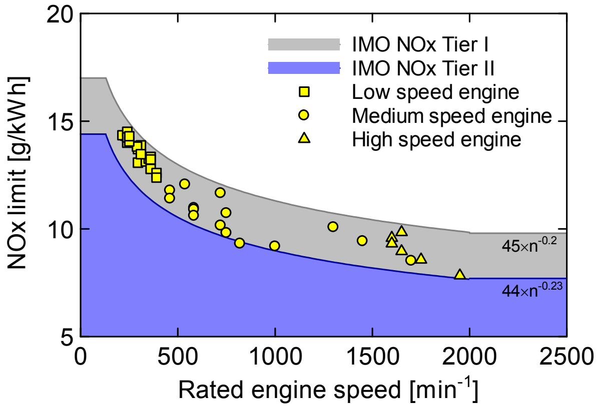

Figure 2 - Situation in IMO NOx Tier I compliance

Figure 3 compares p-V diagram illustrating the relationship between pressure and volume, with T-s diagram illustrating temperature versus entropy for the Sabathe and diesel cycles under the same maximum pressure and output conditions. Also called the constant pressure cycle, the diesel cycle is the basic cycle used in diesel engines, with combustion taking place under a constant pressure. For consistent maximum pressure, points 3s and 3d indicating the end of combustion on the p-V diagram will be equal, while constant output (i.e., the constant area enclosed by 1-2-3-4-1 on the T-s diagram) will entail S4s > S4d. The amount of heat release is indicated by the area A-1-4-B-A. This parameter is lower for the diesel cycle than for the Sabathe cycle. That is, the diesel cycle has greater thermal efficiency than the Sabathe cycle. Since temperatures at the end of combustion are T3s > T3d, if increased temperatures inside the cylinders generate NOx, engine cycle predicts the diesel cycle will result in lower NOx levels.

This report describes studies using engine performance simulations pertaining to 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.

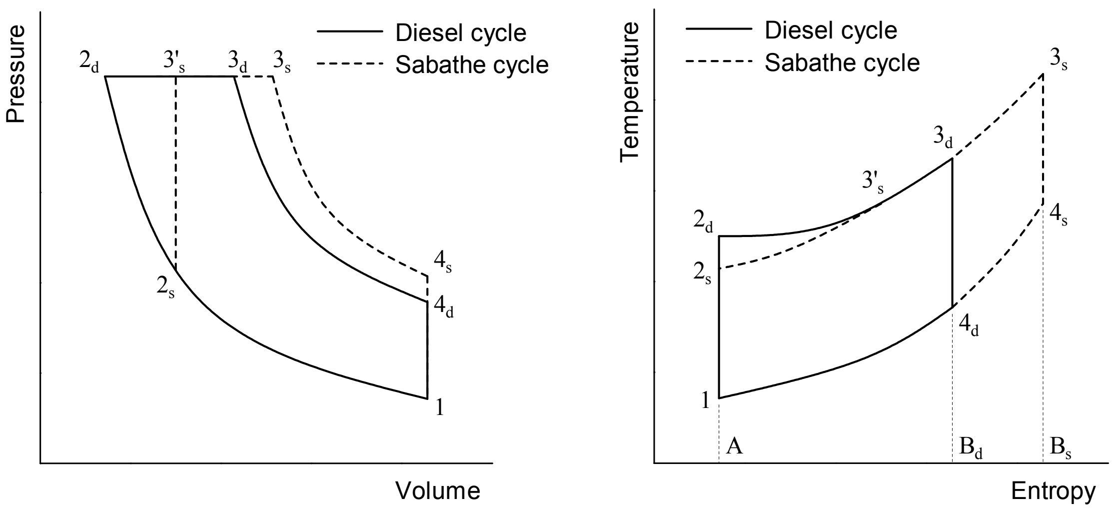

Figure 3 - Comparison of p-V and T-s diagrams between the diesel cycle and the Sabathe cycle

THE INVESTIGATION OF SOLUTIONS FOR IMO NOX TIER II REGULATION BY USING THERMODYNAMIC ANALYSIS

Test engine

The specification of test engine is shown in Table 1. The four stroke medium speed diesel engine was designed for the use of tug boats and supply vessels mainly as bore of 280mm and maximum output of 370kW/cyl. The mechanical variable intake valve timing system is adopted, the intake valve timing can be change without engine stop.(Figure4) 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.

Calculation model

The thermodynamic engine cycle simulation program is used to evaluate the change in engine performance due to engine configuration. The calculation model is shown in Figure 5. Actual engine structure was reflected to this calculation model. An injection rate which is a result of rig test for the injection system was applied to this model, and the NOx emission was estimated.

Increase of compression ratio

Generally, the trade-off relationship between NOx emission and fuel consumption is known, thus, remarkable deterioration of fuel consumption is expected when the investigation of modification of engine configuration to adapt the change of emission regulation from IMO NOx Tier I to Tier II. Here the ideal thermal efficiency of the diesel cycle is followed this below:

$$\eta_{d_{th}} = 1 - \frac{\rho^{\kappa} - 1}{\kappa \cdot \varepsilon^{\kappa - 1} \cdot (\rho - 1)} \qquad (1)$$

η_{dth} : thermal efficiency
ε : compression ratio
κ : rate of specific heats
ρ : cut-off ratio

This equation is represented that this efficiency is a function of the ratio of specific heats efficiency of the gas in the cylinder, compression ratio, and cut-off ratio. Before NOx reduction was prepared to

Table 1 - Specifications of test engine

Bore x Stroke	280 x 390 [mm]
Engine speed	800 [min-1]
Rated output	370 [kW/cyl.]
Pme	2.3 [MPa]
CR	16

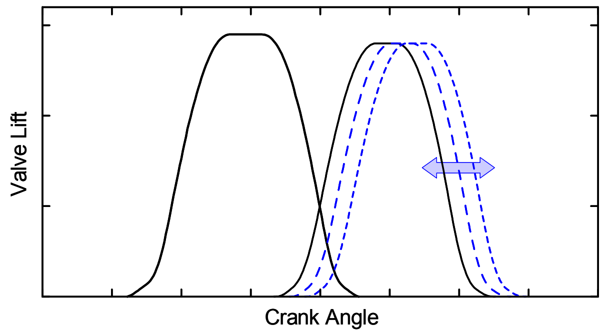

Figure 4 - Variable intake valve timing system

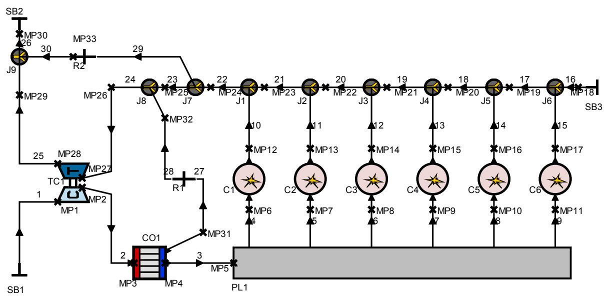

Figure 5 - Calculation model

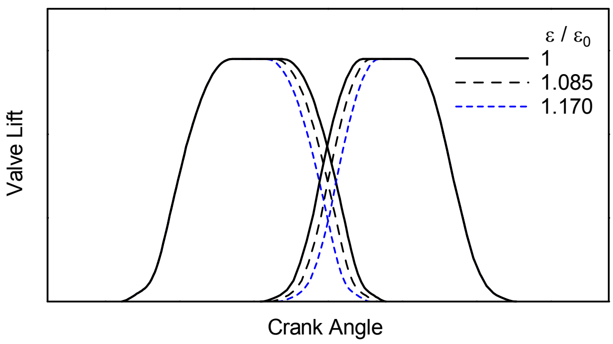

Figure 6 - Change in valve lift curve

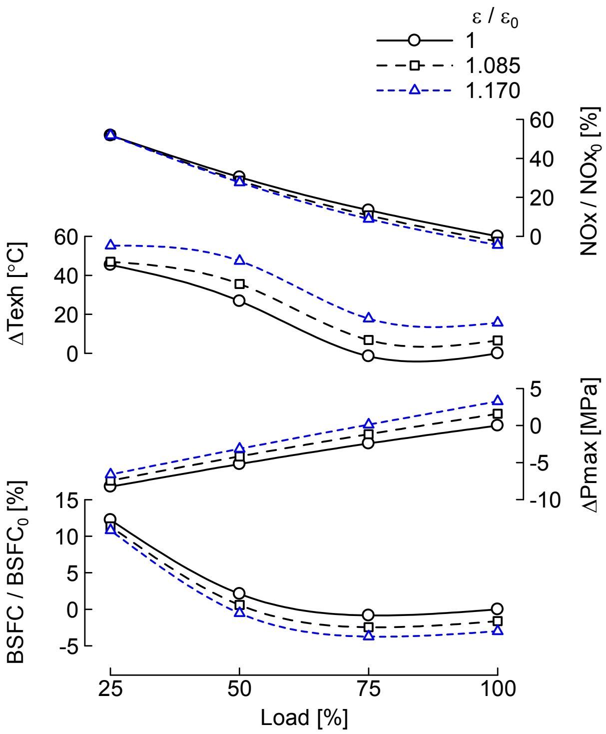

Figure 7 - Improvement of fuel consumption due to increased compression ratio

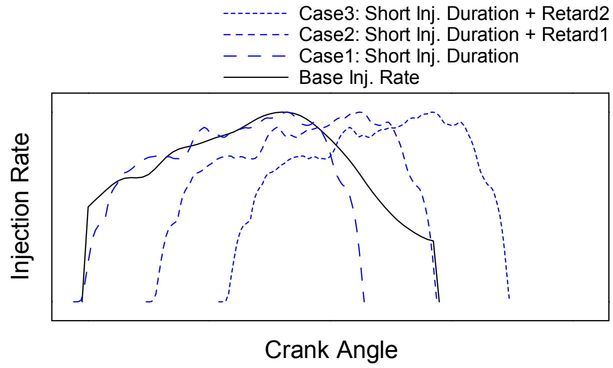

Figure 8 - Modification of injection ratio

apply, compression ratio was increased to improve thermal efficiency at first. In particular, the change of fuel consumption and emission performance were confirmed when the compression ratio was increased from the base condition to allowed maximum value which is bounded by engine structure. As the constant distance from the top of piston to intake and exhaust valves was kept, the advance of exhaust valve close timing and the retard of intake valve open timing are set as shown in Figure 6. And the other engine configuration (e.g. fuel injection timing, boost pressure, and so on.) were held constant. It is shown in Figure 7 that the change of the engine performance and exhaust emission when the compression ratio was increased by 8.5% and 17%, respectively. The fuel consumption was improved significantly with varied load condition due to increased compression ratio, the minimum fuel consumption was decreased 3% at 75% load operation. For increased compression ratio, the open and close timing of intake and exhaust valves were adjusted, thus, the valve overlap was also reduced. Then the exhaust gas temperature at turbine inlet was increased due to reduction of charge air flow through valves. Furthermore, the obtained results indicated that the NOx emission was reduced at the high load condition, however the maximum variation of reduction was 4% at most.

Optimization of fuel injection system

Secondly, 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.

Shortening of injection duration

The fuel injection rate for high load operation is shown in Figure 8. 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. Figure 9 and 10 show the change of engine performance and time history of heat release 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

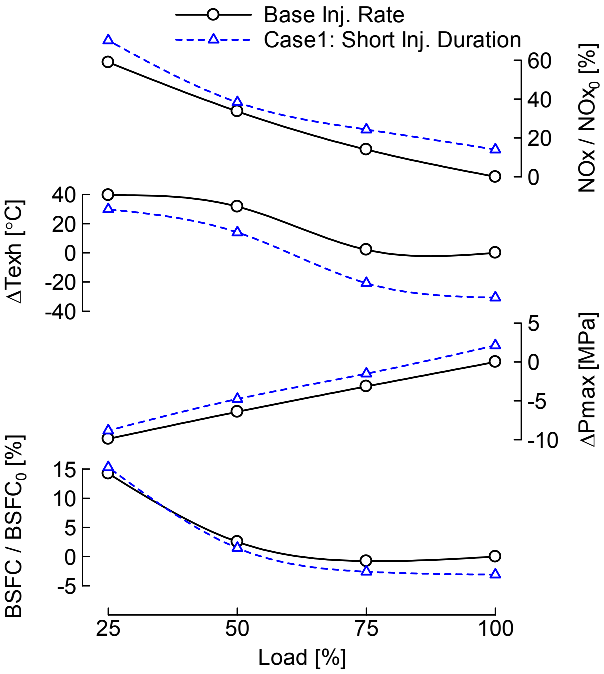

Figure 9 - Improvement of fuel consumption due to shortened fuel injection duration

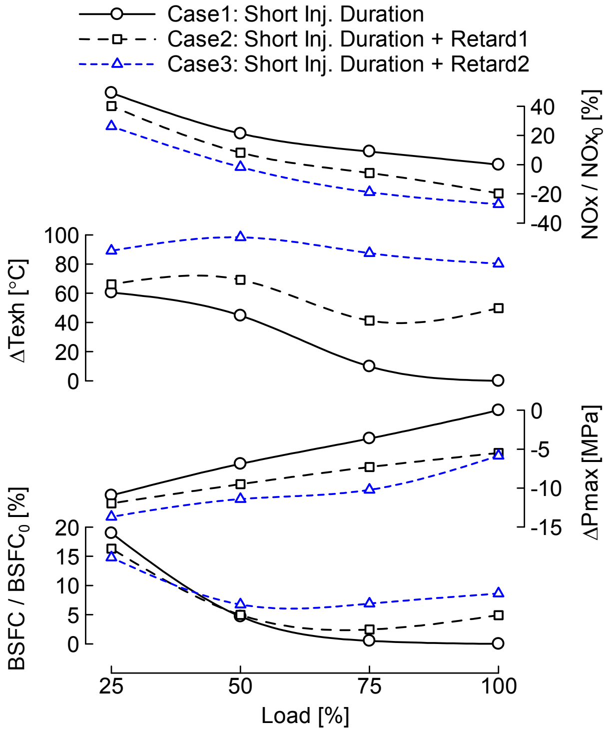

Figure 11 - NOx emission reduction due to injection timing retard

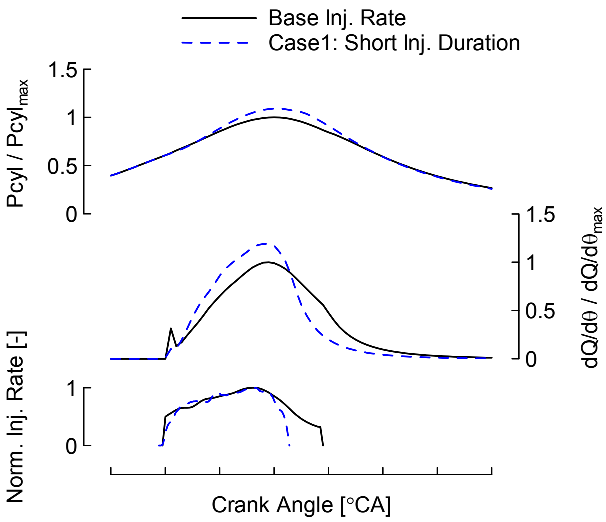

Figure 10 - Change in heat release due to shortened fuel injection duration

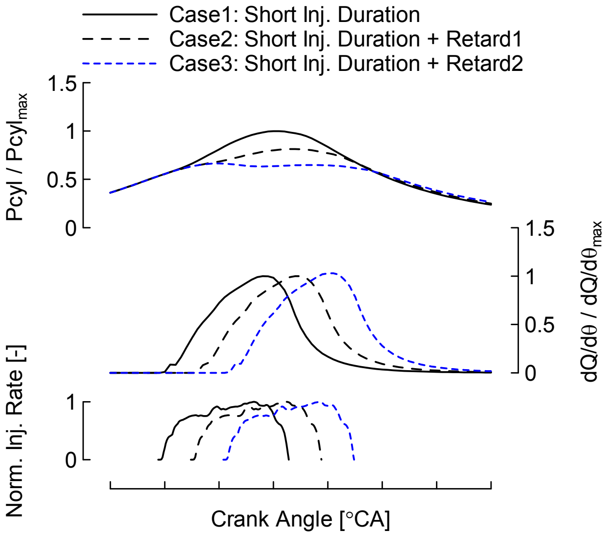

Figure 12 - Change in in-cylinder pressure curve due to injection timing retard

phase, the fuel consumption and smoke were also remarkably improved.

<u>Change of the injection start timing</u>

The engine performance and heat release in case of retarded injection timing are shown as Figure 11 and 12. 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,

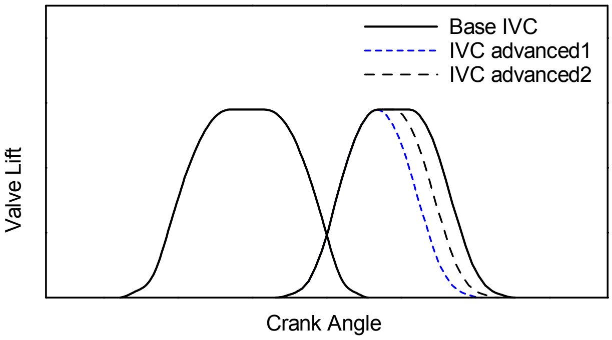

Figure 13 - Change in intake valve close timing for variety of the Miller cycle

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.

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 Figure 13 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 Figure 14, and, Figure 15 shows the rate of heat release at 75% load. 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

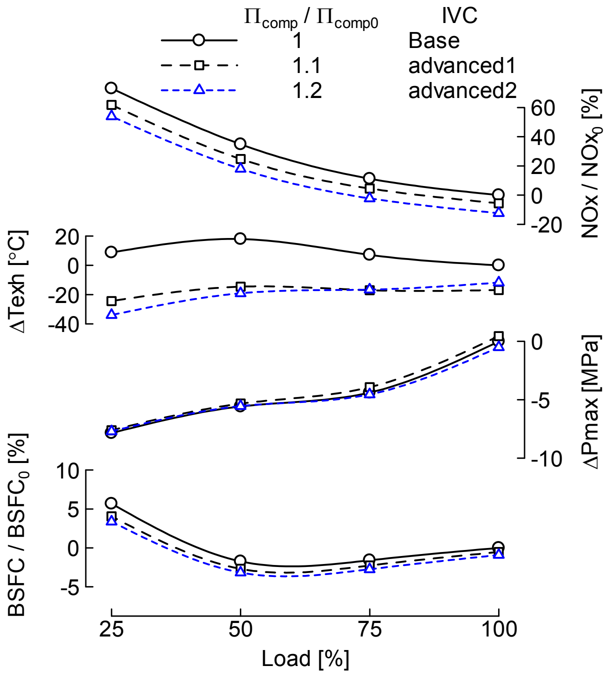

Figure 14 - Simultaneous reduction of NOx and fuel consumption due to the Miller cycle

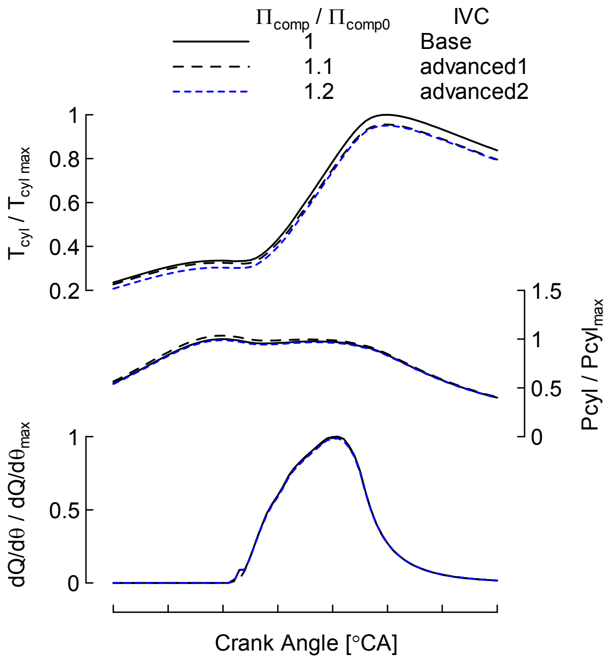

Figure 15 - Decrease of in-cylinder temperature due to application of the Miller cycle

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.

CONFIRMATION BY ENGINE EXPERIMENT

As mentioned above, the effects of thermodynamic factors - compression ratio, fuel injection rate, injection timing and the Miller cycle - on engine performance have been investigated by thermodynamic calculation. To verify these analysis results, the engine experiment was carried out with combination of changed factors. The test result is shown in Figure 16, and each characteristic is normalized by the performance at 100% load of the base engine. In this experiment, start of injection timing for each load were determined respectively by using specific plunger of fuel injection pump with upper helix design. Thus, the improvement of fuel consumption for part load condition and the reduction of NOx emission at higher load were pursued. As the result, the NOx emission for all engine loads were 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.

The rate of heat release at 100% load is shown in Figure 17. 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. Figure 18 shows the comparison of p-V diagram between the base engine and improved engine for 25% and 100% load operation. Regarding the improved engine, the constant-pressure combustion was achieved at 100% load condition, namely, the diesel cycle was realized. The relationship between the NOx emission and the pressure ratio between the peak firing pressure and in-cylinder pressure at the end of compression stroke (Pmax/Pcomp) which is calculated by expression (2) is shown in Figure 19. There is certain correlation, and it is reaffirmed that the NOx emission can be predicted by applying this correlation. Incidentally, the Pmax/Pcomp was decreased from 1.26 to 0.80 at 100% load through the engine tests.

$$\frac{P_{max}}{P_{comp}} = \frac{P_{max}}{P_{IVC} \cdot \varepsilon_{eff}^{\ \kappa} - P_{amb}} \qquad (2)$$

P_{max} : peak firing pressure
P_{comp} : pressure at the end of compression stroke
P_{IVC} : in-cylinder pressure at intake valve close
P_{amb} : ambient pressure

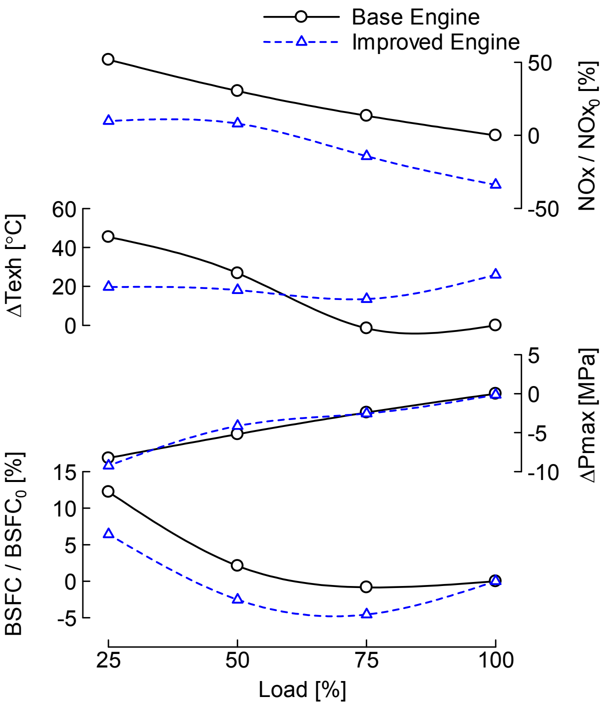

Figure 16 - Confirmation of engine performance as IMO NOx Tier II ready engine

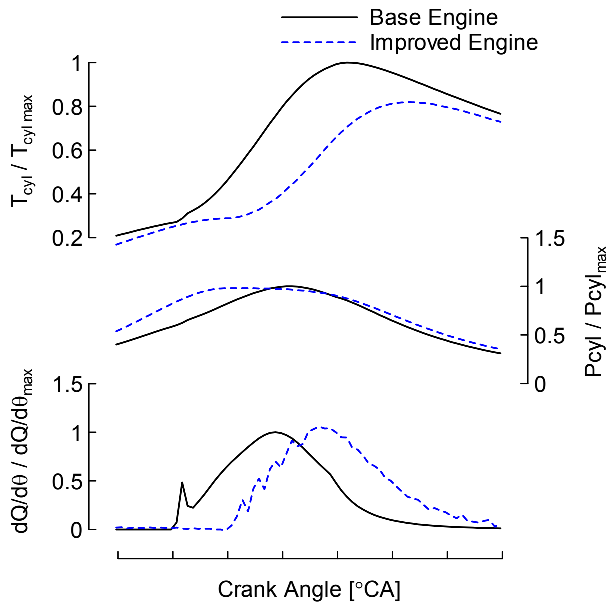

Figure 17 - Remarkable reduction of in-cylinder temperature for low NOx emission

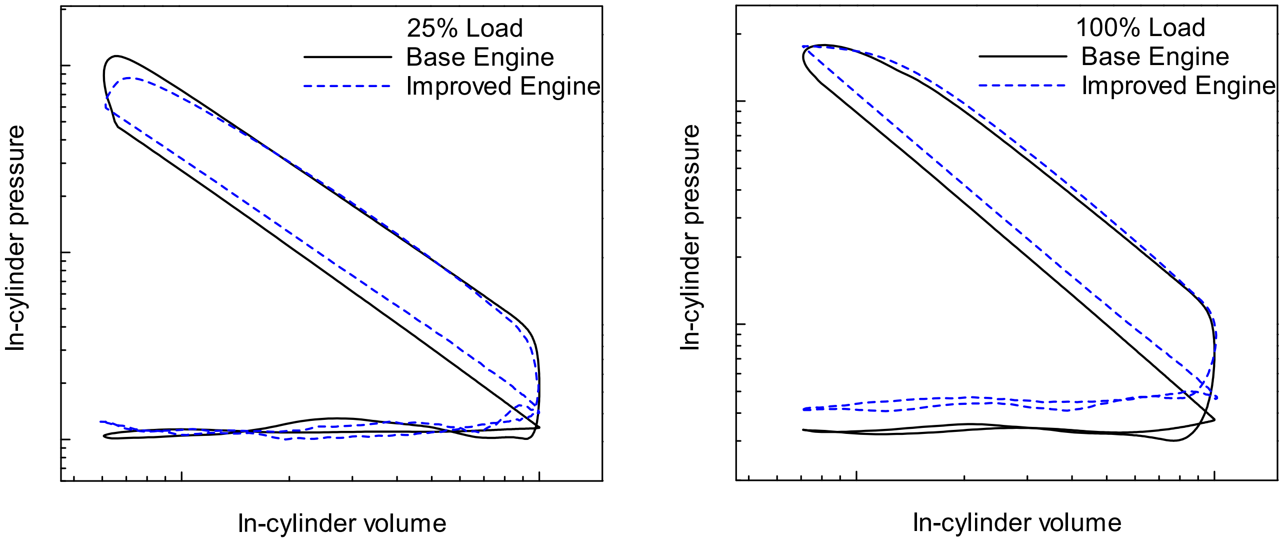

Figure 18 - Achievement of constant-pressure combustion at high load condition

APPLICATION TO ALL PORTFOLIO OF PRODUCTS

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 Figure 20. For the test 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, and consequently, Niigata continues to provide all portfolio of diesel engine for customers after 2011 when new emission regulation will be effected.

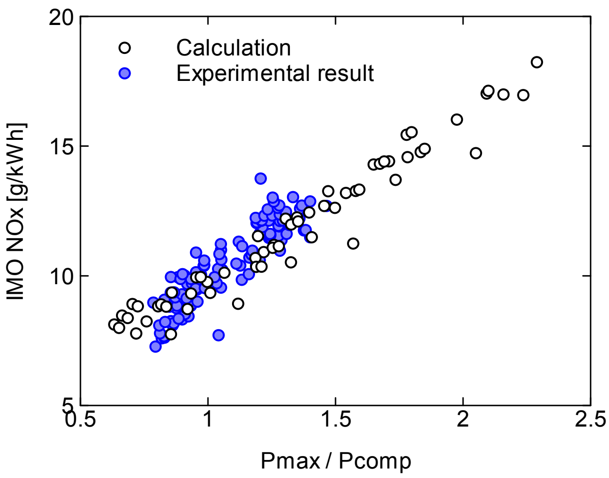

Figure 19 - Correlation between Pmax/Pcomp and IMO NOx

COMPLIANCE WITH 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 being examines as ways to achieve these targets.

(1) Exhaust after-treatment

(2) Use of alternative fuels

Regarding these promising technologies, Niigata offers extensive experience for reducing exhaust emissions.

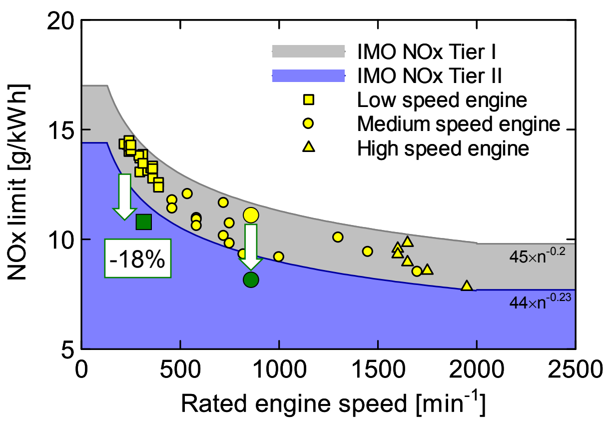

Figure 20 - Application of low-NOx technology to all portfolio of products

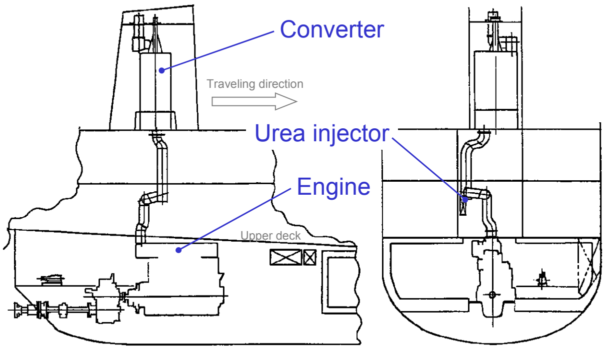

Figure 21 - Installation of SCR system on a coaster

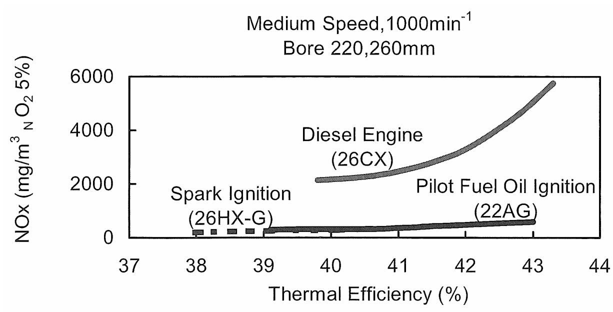

Figure 22 - Comparison of NOx emission level between diesel and gas engines

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. As mentioned above, 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.

Figure 21 is a schematic of the SCR system, together with an example of configuration when combined with a four-stroke low-speed diesel engine. 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. Bench testing of the NOx converter demonstrated NOx reductions of at least 80% were feasible even under the space velocity (SV) value of approximately 9000 h^{-1}, making it likely that Tier III requirements can be satisfied provided it can be applied to the medium-speed engine described earlier.

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. As shown in Figure 22, this results in low NOx emission levels, less than 10% of those for diesel engines [4].

This suggests the potential for meeting Tier III stipulations by converting diesel engines to gas engines. 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.

CONCLUSIONS

The low NOx emission technology to meet the IMO NOx Tier II regulation are 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 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 speed diesel engine which is required more reduction of NOx emission than medium speed engine, namely, all Niigata's portfolio of diesel engines have the potential to meet the IMO NOx Tier II.

(3) There is a possibility to comply with IMO NOx Tier III regulation by combination of the developed low NOx emission technology and SCR system.

(4) The development of application technologies for SCR system and gas engine will be also continued as promising emission control technology to comply with IMO NOx Tier III regulation.

NOMENCLATURE

BSFC	Brake specific fuel consumption
$dQ/d\theta$	Rate of heat release
Norm. Inj. Rate	Normalized fuel injection rate
Pcyl	In-cylinder pressure
Tcyl	In-cylinder mean gas temperature
ΔPmax	Change in peak firing pressure
ΔTexh	Change in exhaust gas temperature at turbine inlet

Subscripts

0	Base conditions

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