Development of Emission Control Technology to Reduce Levels of NO_x and Fuel Consumption in Marine Diesel Engines

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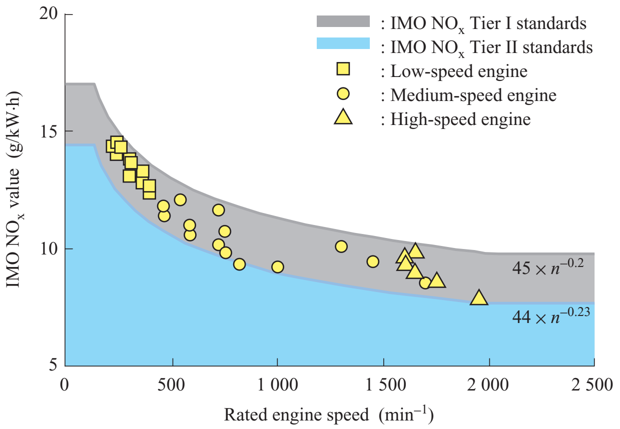
To comply with updated emissions regulations, low NO_x combustion technology for marine diesel engines has been developed. Instead of the trade-off relationship between NO_x emission and fuel consumption, this new technology not only has an effect on NO_x emission levels but also simultaneously reduces fuel consumption. Furthermore, it can be adapted for all 4-stroke diesel engines regardless of their rated speed or rated power. At first, a thermodynamic simulation was performed to estimate effects on engine performance, including emission levels, and the efficiency of this technology was also investigated through an engine performance test. Specifically, user benefits regarding fuel economy during ship operation, which was evaluated by measured load patterns with tug boats, are also described in this paper.

1. Introduction

The IMO MARPOL ANNEX VI regulations on emissions from ships were put into effect by the International Maritime Organization (IMO) in May 2005. After subsequent revisions, stricter standards were adopted at IMO MEPC58 in October 2008. As a result, the NO_x standards for new ships became the Tier II standards that are effective from January 2011, which compared to the current Tier I standards require an approximately 15% to 22% reduction in all sea areas, and the Tier III standards that are planned to come into effect in 2016, which require an 80% reduction in Emission Control Areas (ECA). Niigata Power Systems Co., Ltd. has been working hard to comply with new standards such as these within a reasonable timeframe and without causing a marked loss in efficiency, and the company will continue to do so (**Fig. 1**).

This paper describes low emission technology, based on existing emission reduction technologies, that has been developed to comply with the next standards. The paper also presents the results of the analytical and experimental validation of the technology. Specifically, fuel injection rate was optimized to accomplish the Diesel cycle, and the Miller cycle was implemented with a view to reducing the in-cylinder gas temperature. Experiments and analysis were used to evaluate the effects of these improvements on engine performance. The paper also presents the reduction in fuel consumption that was achieved at the same time, and the effects of fuel consumption reduction that are available to the user.



(Notes) $45 \times n^{-0.2}$: IMO NO_x Tier I standards value
$44 \times n^{-0.23}$: IMO NO_x Tier II standards value
n : Rated engine speed

Fig. 1 Compliance with IMO NO_x Tier I standards

2. Technical strategy for IMO NO_x Tier II standards compliance

To comply with IMO NO_x Tier II standards and achieve a reduction of about 20% from the current limit in the engine unit, some engine components must be modified in a certain way. Factors that have an effect on the NO_x rate include fuel injecting timing and turbo charging pressure, which must be changed, however, in combination with compression ratio and intake and exhaust timing to prevent an increase in fuel consumption. That is, the technology for complying with the IMO NO_x Tier II standards has been developed using both technology for reducing NO_x emissions and technology for improving thermal efficiency.

Work on NO_x reduction of large, medium-speed diesel engines was conducted by Kawakami et al.,[(1)] and it was shown that the ratio of the in-cylinder pressure at the end of the compression stroke to the peak firing pressure, or P_{max}/P_{comp}, is effective as a design index for setting the amount of NO_x emissions. That is, to reduce the amount of NO_x emissions, the primary components of the engine must be designed to decrease P_{max}/P_{comp}. In addition, according to thermodynamic cycle theory, while conventional medium-size diesel engines are built using the Sabathe cycle, they should be more oriented toward the Diesel cycle.

Figure 2 compares the Diesel cycle and Sabathe cycle under the same peak pressure and power conditions using a *p*-*V* diagram to represent the relationship between in-cylinder pressure and volume and a *T*-*S* diagram to represent in-cylinder gas temperature and entropy. The Diesel cycle is also known as the constant pressure cycle and is the basic cycle of diesel engines. In this cycle, combustion takes place at constant pressure. At equal peak pressure, the points 3_s and 3_d on the *p*-*V* diagram represent the end of combustion and are at the same pressure. At equal power, that is, if the regions enclosed by 1-2-3-4-1 on the *T*-*S* diagram are made equal in area, $S4_s$ becomes greater than $S4_d$. The amount of released heat is represented by the area of A-1-4-B-A, so the amount of released heat in the Diesel cycle is less than in the Sabathe cycle. In other words, the Diesel cycle is superior in terms of thermal efficiency to the Sabathe cycle. The temperatures at the end of combustion are such that $T3_s$ is greater than $T3_d$. Considering the fact that NO_x is formed by a rise in in-cylinder temperature, it is obvious from cycle theory that NO_x will be reduced if the Diesel cycle is employed.

3. Examination of Tier II standards compliance measures using engine performance calculations

3.1 Test engine

The test engine was a medium-speed, four-stroke diesel engine with a cylinder diameter of 280 mm and a power of 370 kW per cylinder.

The specification of the test engine are shown below:

Bore	280 mm
Stroke	390 mm
Rated speed	800 min^{-1}
Rated power	370 kW per cylinder
Brake mean effective pressure	2.3 MPa

The engine is equipped with a variable intake valve timing system on the intake cam, so it has the feature of being able to change the intake valve opening and closing timing dynamically without stopping the engine. The following test was conducted at the rotation speed and power of each load factor value set according to the marine application power law.

3.2 Optimization of fuel injection system

The effects of fuel injection rate on NO_x emissions rate were examined first. The design concept for a fuel injection rate to reduce NO_x emissions rate followed the proposal of Kawakami et al.[(2)] That is, the initial injection rate is reduced to as low a rate as possible to suppress the NO_x emissions rate, and the late injection rate is increased relatively, while the injection period is kept about the same to minimize increases in fuel consumption. To achieve this concept, this study employed a jerk-type fuel injection pump and evaluated the technique of decreasing the injection period to shorter than the standard, while keeping the injection end timing coincident. Because the fuel injection start timing is in effect retarded by this, the in-

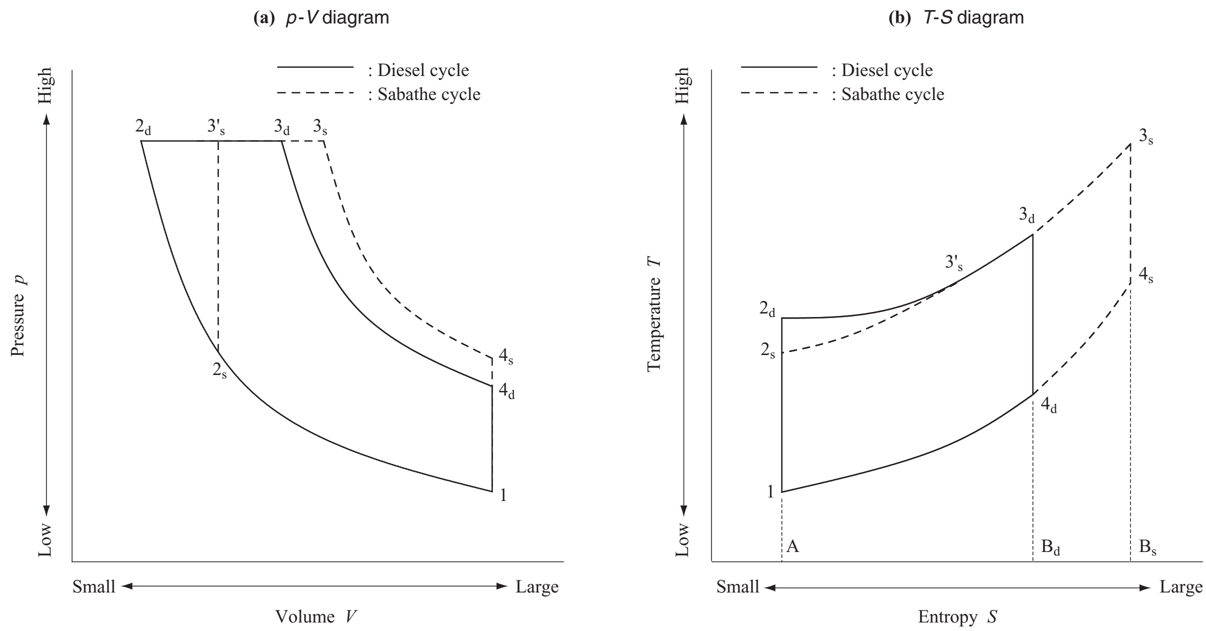


Fig. 2 Comparison of Diesel cycle and Sabathe cycle

cylinder peak pressure decreases and the cycle approaches the Diesel cycle.

The effects of fuel injection rate were investigated in two separate steps, one for injection period and one for injection start timing, and results are described below.

3.2.1 Injection period reduction

The fuel injection rate at 75% load is shown in **Fig. 3**. For the fuel injection rate of the base engine shown by the solid line, a fuel injection rate (Case 1), in which injection rapidly ends at a point of time past the peak value, was newly designed. Engine performance for each of the two fuel injection rates is shown in **Fig. 4**. Because the center of gravity of injection rate shifted forward, the peak firing pressure rose and the NO_x emissions rate increased. On the other hand, from the results of combustion analysis, an exhaust temperature drop due to the shortened late combustion phase was confirmed and the fuel consumption rate and smoke emissions were improved.

3.2.2 Injection start timing modification

Next, the performance of the engine with the injection start timing retarded is shown in **Fig. 5**. The injection end timing of Case 1, whose injection period was shortened, was retarded until it coincided with the original injection end timing. This is Case 2. The injection end timing was further, and this is Case 3.

Because the combustion phase shifts toward the expansion stroke as the fuel injection start timing is retarded, the exhaust temperature and fuel consumption rate worsen. In particular, in Case 2 and Case 3 at 100% load, the combustion pressure is equal to or less than the compression pressure, and the increase in fuel consumption rate is remarkable, because the peak timing of combustion pressure is also retarded. The NO_x emissions rate was greatly influenced by the retardation of fuel injection start timing, and it was reduced at all loads. The reduction rate at 75% load reached about 26%.

3.3 Implementation of the Miller cycle

As a technique for further NO_x emissions reduction, the introduction of the Miller cycle was examined. A feature of the Miller cycle is that the same work can be achieved at low in-cylinder temperature using the right combination

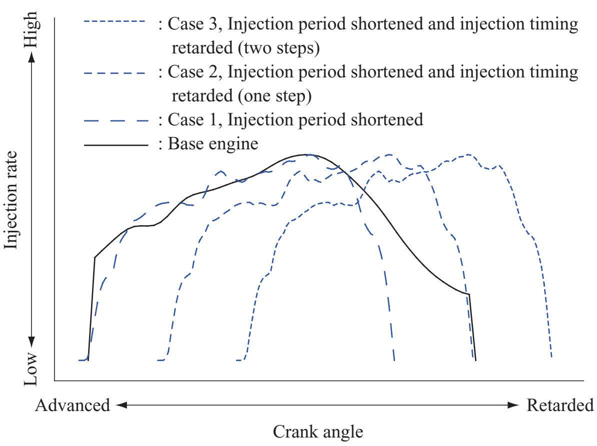


Fig. 3 Modification of injection rate

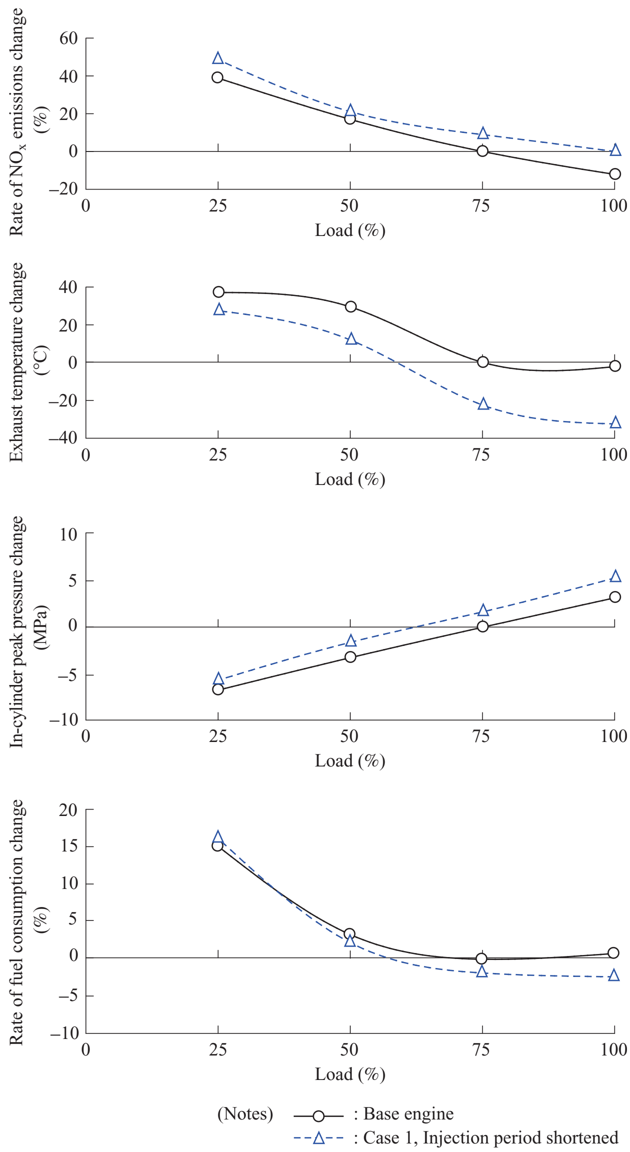


Fig. 4 Improvement in fuel consumption due to shortened fuel injection period

of increasing the amount of intake air by increasing intake pressure and changing the valve closing timing. Here, while bearing in mind feasibility in the actual machine test, the pressure ratio was set within the selectable range for the turbo charger series used with the base engine. Then, the intake valve closing timing was adjusted as shown in **Fig. 6** to keep constant the in-cylinder pressure at the end of a compression stroke. The NO_x emissions reduction rate was investigated for three combinations of compressor pressure ratio and intake valve closing timing set in this way.

Figure 7 shows the changes in fuel consumption rate and exhaust gas characteristics when the compressor pressure ratio is increased by up to about 20% with respect to the initial set value. As the cycle approaches the Miller cycle, the in-cylinder mean gas temperature during the compression stroke lowers, and this leads to a decrease in combustion phase temperature. Therefore, the NO_x emissions rate was greatly reduced regardless of load factor

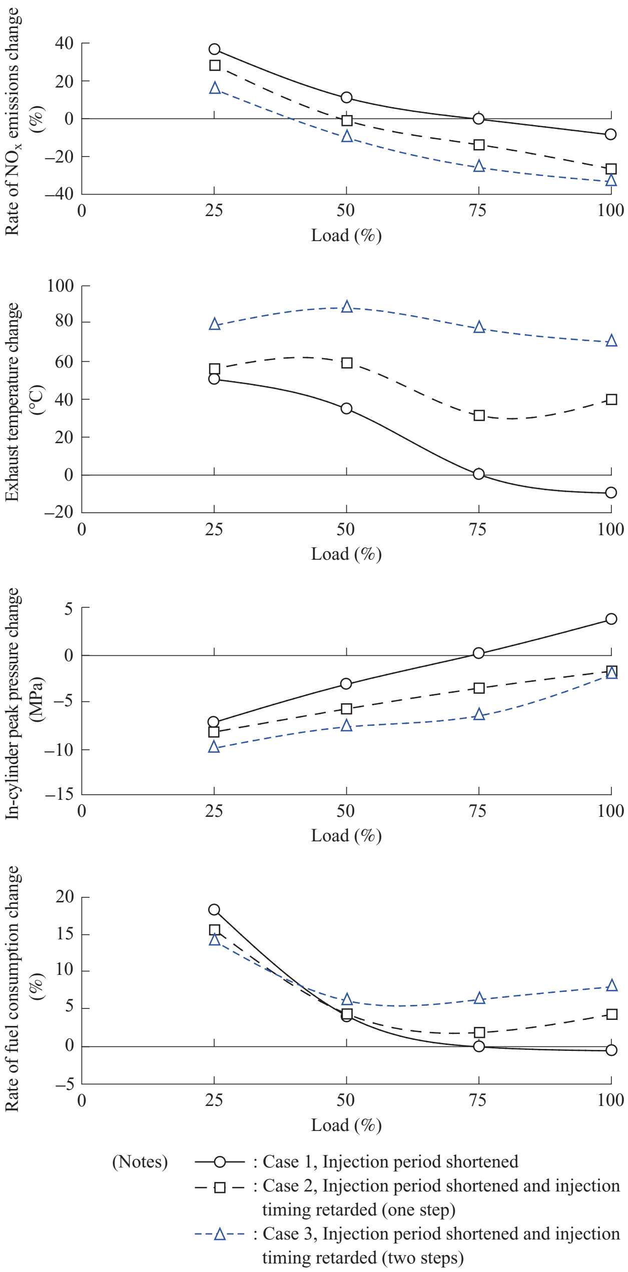


Fig. 5 NO_x emissions reduction by retarding injection timing

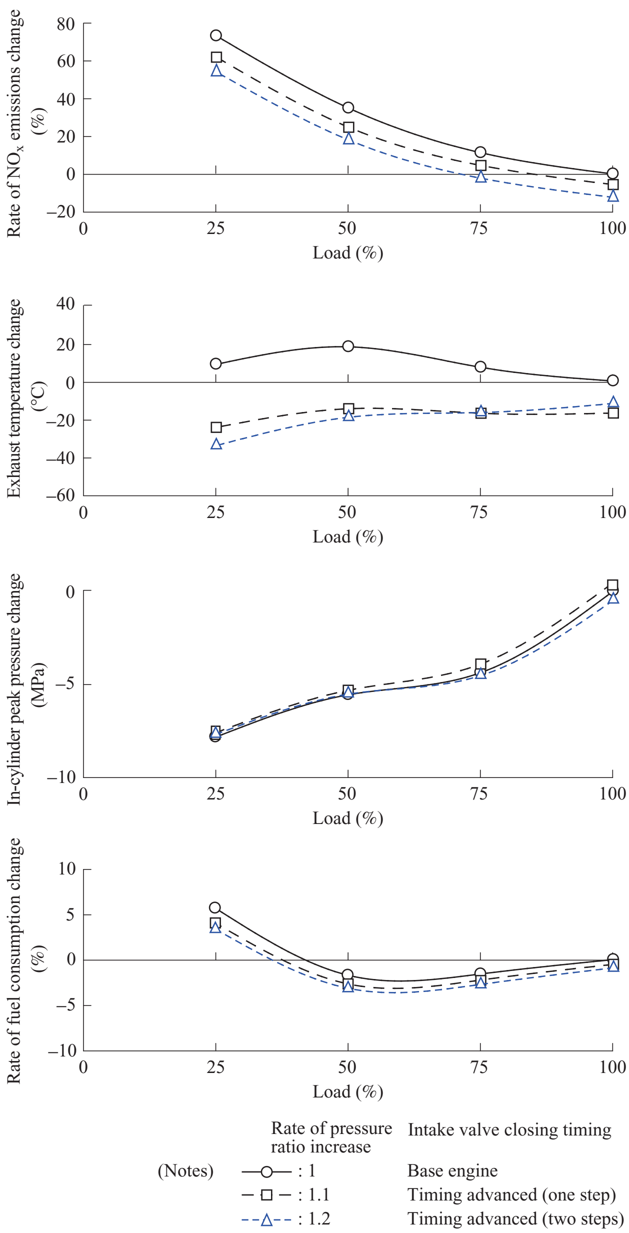


Fig. 7 Simultaneous reduction of NO_x emissions and fuel consumption by the Miller cycle implementation

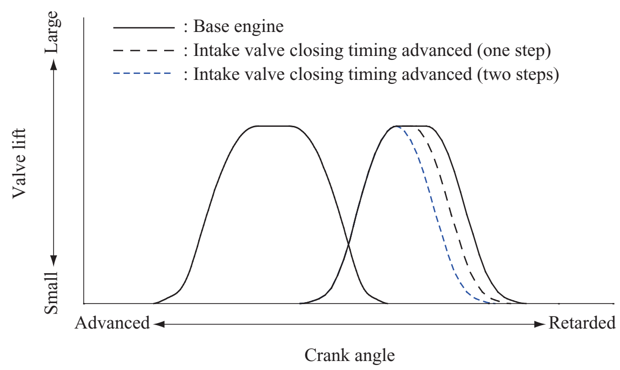


Fig. 6 Intake valve closing timing when the Miller cycle is used

and a reduction rate of 14% was achieved at 75% load. Furthermore, from a comparison of the *p*-*V* diagram during the intake and exhaust strokes, an improvement of low-pressure work and an approximately 1% reduction in fuel consumption rate were confirmed.

4. Verification by actual engine test

This paper has so far described the effects of fuel injection rate, fuel injection timing, and the Miller cycle implementation on NO_x emissions rate. Engine performance was examined by actual engine tests with these conditions changed in combination, and the results are shown in **Fig. 8**. Each of the performance values is normalized by taking the value of the base engine to be

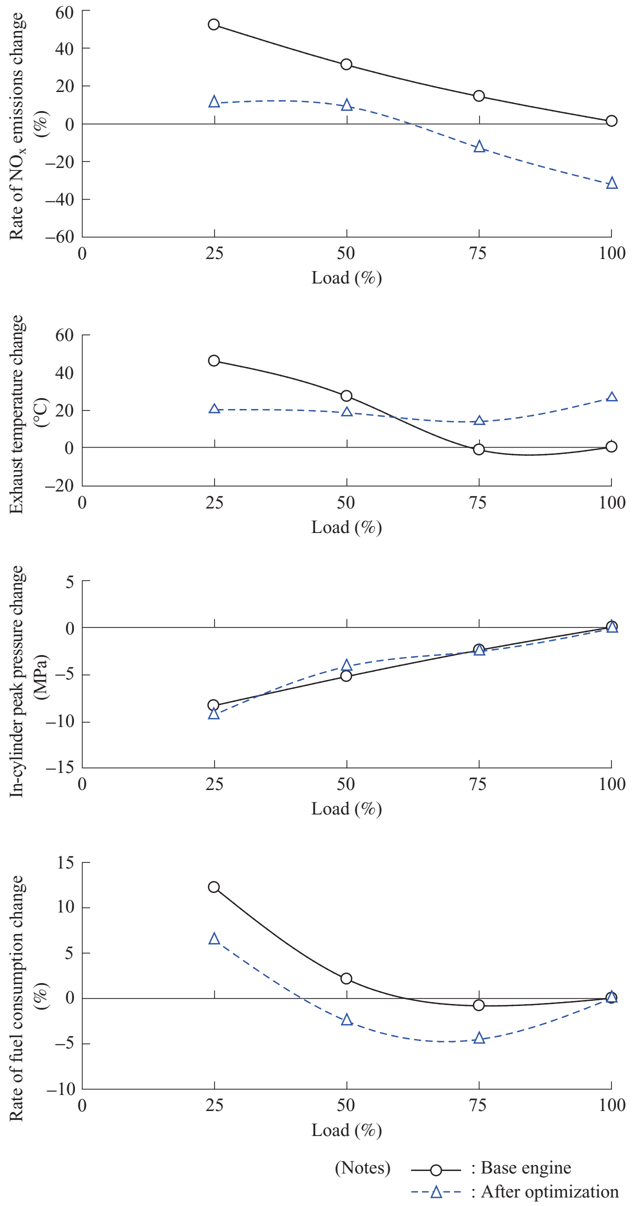


Fig. 8 Engine performance when IMO NO_x Tier II compliance technology is applied

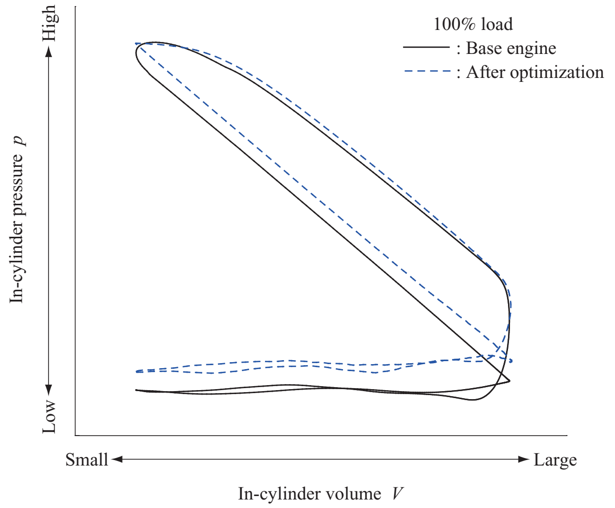


Fig. 9 Change in *p*-*V* diagram when IMO NO_x Tier II compliance technology is applied

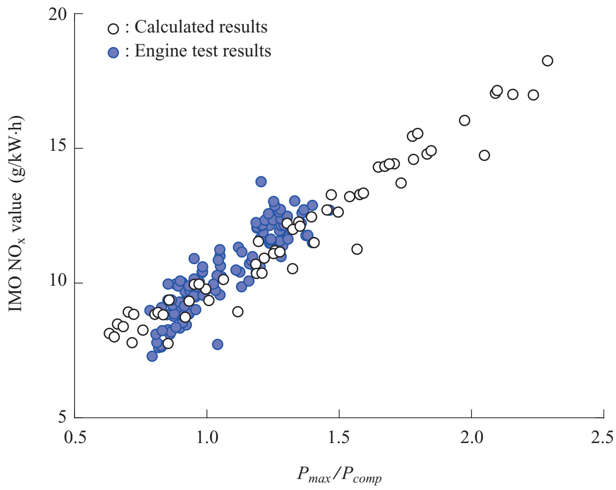


Fig. 10 Correlation between P_{max}/P_{comp} and IMO NO_x value

100%. As a result, the NO_x emissions rate was markedly reduced at all load factors and met the IMO NO_x Tier II limits. Meanwhile, there was further improvement in the fuel consumption rate in the low and medium load range and no decline at the rated load.

Figure 9 compares the *p*-*V* diagrams at 100% load. The two engines compared differ in compression ratio as well as in stroke length. For easy comparison of in-cylinder pressure change during the combustion phase, the in-cylinder volume was divided by the displacement volume to make it dimensionless. Looking at the pressure changes near the ignition time, combustion takes place at a nearly constant pressure on the diagrams after the some of the main specifications were changed, and thus it was confirmed that the Diesel cycle was achieved. As can be from **Fig. 10**, NO_x emissions rate is roughly proportional to the ratio of the in-cylinder pressure at the end of the compression stroke to the peak firing pressure (P_{max}/P_{comp}). This confirms that P_{max}/P_{comp} is an effective index for predicting NO_x emissions rate.

The results of applying the above-stated technology to achieving compliance with the IMO NO_x Tier II standards are shown in **Fig. 11**. From low-speed engines, for which NO_x reduction requirements are stricter, to high-speed engines, the standards were met without an increase in fuel consumption, thus confirming that our Tier II standards compliance technology can be universally applied.

5. Reduction in fuel consumption obtainable in actual ship operation

The emission standards compliance technology developed in this study not only reduces NO_x emissions sufficiently but also has the effect of lowering fuel consumption. The reduction in fuel consumption obtained when a

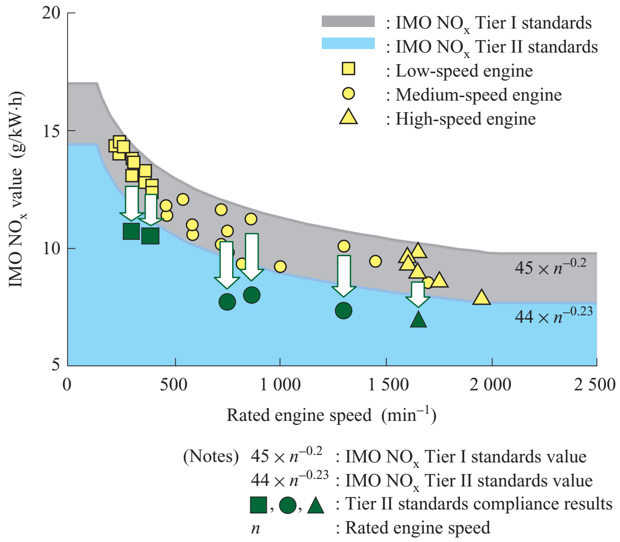


Fig. 11 Compliance with IMO NO_x Tier II Standards

ship is equipped with an engine using this technology 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.

Figure 12 shows the actual operation of the tug boat. **Figure 12-(a)** shows an example of engine load over time. Taking one operation to be from engine start to engine stop, two patterns were extracted. The frequency of occurrence of loads measured at an interval of 5% are shown with the corresponding fuel consumption curves in **Figs. 12-(b)** and **-(c)**. 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 (in **Figs. 12-(b)** and **-(c)** respectively) both 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 the engine using the developed technology is given in **Fig. 13**. 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 CO_2 emissions, so the achievements of this study will not only help to reduce NO_x emissions but also greenhouse gas emissions.

6. Conclusion

Using a four-stroke, medium-speed marine engine, our NO_x emissions reduction technology was examined for compliance with IMO NO_x Tier II standards, and the following findings were obtained.

(1) It was confirmed that a suitable combination of fuel injection rate, injection timing, and the Miller cycle implementation enables the Tier II standards to be met without any increase in fuel consumption.

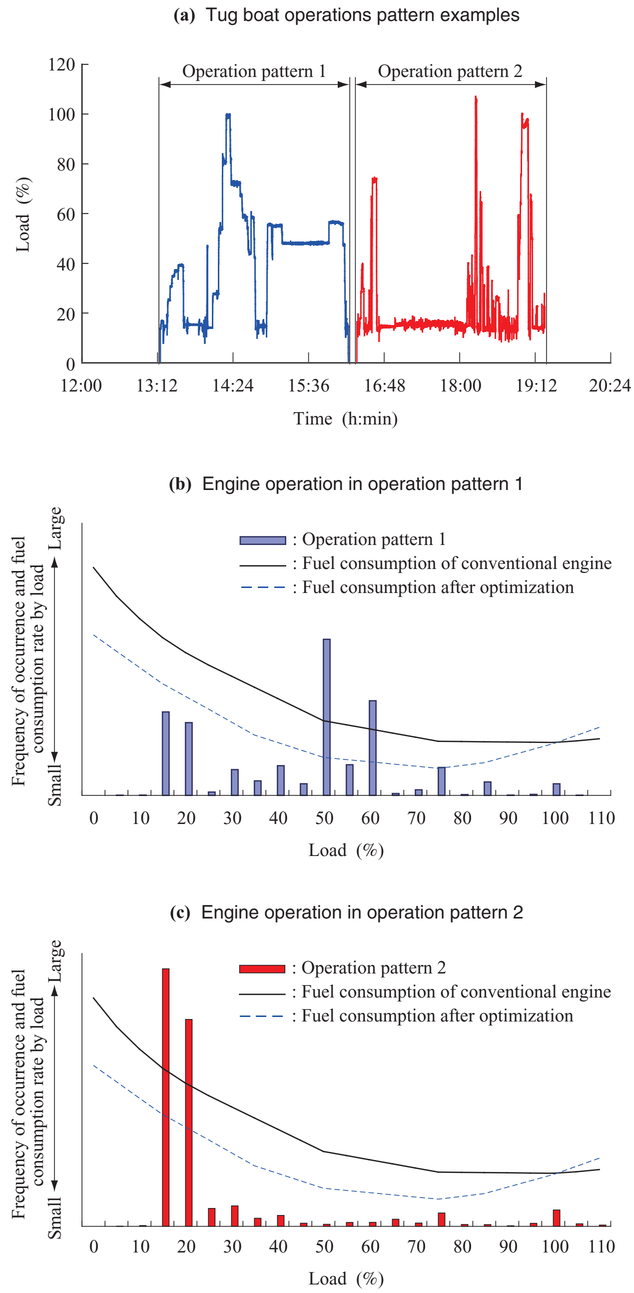


Fig. 12 Actual operation situation of tug boat

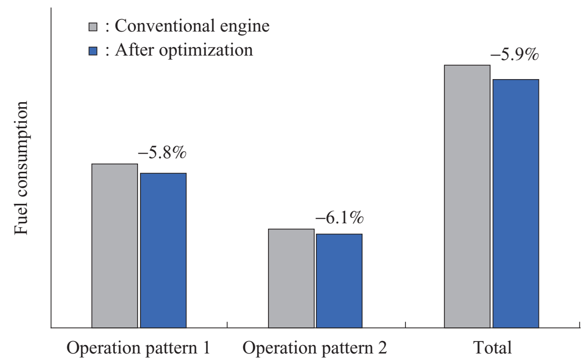


Fig. 13 Reduction in operating costs from new emission control technology

(2) The developed NO_x emissions reduction technology is effective for any marine engine regardless of its engine speed, which confirms the technology as a viable means of complying with Tier II standards.
(3) If the achievements of this study are applied to tug boat engines, fuel consumption in actual operation is reduced by about 6%.

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