Development of 2-Stage Turbocharging Technology on Medium Speed Diesel Engine*

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This study aims to investigate the potential of a 2-stage turbocharging system to reduce NOx emission. First, 1D cycle simulation model implementing high boost pressure, which imitates 2-stage turbocharging system, was calculated, and it was confirmed that with the combination of early intake valve closing, there is a potential to reduce NOx from conventional single turbocharging engine model without any fuel consumption penalty. Then, the 2-stage turbocharging system was coupled to a medium speed 6-cylinder experimental diesel engine, and test runs were carried out to confirm the potential. Results of the test run show that 2-stage turbocharging system has the potential to reduce NOx as estimated, and as a co-product, BSFC improvement was confirmed when allowing Tier II level NOx emission. Furthermore, engine output increment was possible, without deteriorating BSFC-NOx trade-off relationship. Further development is planned to meet IMO NOx Tier III regulation.

1. Introduction

International Maritime Organization (IMO) MARPOL 73/78 Annex VI was enforced in May 2005 to regulate exhaust gas emissions from ships. More stringent regulations were adopted at the IMO MEPC 58 in October 2008 following revisions applicable to newly-built ships. IMO NOx Tier II regulation also came into force in 2011, and stipulated approximately 15 to 22% reduction of NOx compared to Tier I regulations in global regions. IMO NOx Tier III regulation, which becomes effective in 2016, stipulates reductions of 80% in emission control areas compared to IMO NOx Tier I regulation. Fig.1 shows IMO NOx limits versus engine speeds for IMO Tier I, II and III. To overcome strict regulation of IMO Tier III NOx regulation, Niigata Power Systems (Niigata) has already developed two strategies. One is a Selective Catalyst Reduction (SCR) after treatment system, and the other is a direct drive dual fuel engine for marine use [1, 2].

In the development of SCR system, the system was tested for 1000 hours, 300 hours on the test bed

Fig.1 IMO NOx Limit

and 700 hours on the test ship. The control system was constructed based on feed-forward urea control method, which estimates NOx concentration from engine operating conditions, and based that estimation SCR control unit injects urea into the SCR system. This method does not require special sensors such as NOx sensor or O₂ sensor; the system requires parameters such as engine speed, engine load signal, fuel pump rack position, etc. which can be measured by conventional sensors. NOx emission reduction rate was measured during the tests, and NOx reduction rate of more than 80%,

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with ammonia slip of less than 10 ppm was confirmed. Evaluation of catalyst durability was also conducted after the on-board test, and it became apparent that reactivation rate of the catalysts had not degraded during the 1000 hour operation.

In the development of a dual fuel engine, an experimental gas engine was modified into a dual fuel engine. The engine was modified to operate in both diesel mode and gas mode, in aim of complying IMO Tier II regulation in diesel mode operation, and complying IMO Tier III regulation in gas mode operation. However, difference of characteristics between diesel engine and gas engine was one of a big issue. The combustion process of conventional diesel engines is diffusive combustion, which have tolerance to the change air-fuel ratio. On the other hand, conventional gas engines are very sensitive to the change of air-fuel ratio; high air-fuel ratio triggers engine knock, and low air-fuel ratio leads to misfire. Therefore, the development also focused on the optimization of air/fuel control, and common rail injector system was applied to provide turbocharger the sufficient energy at the right timing. Also, combustion status was constantly monitored with knock sensors and exhaust gas temperature sensors, to avoid abnormal combustion by controlling injection timing dynamically. Test results have proved that diesel mode operation fulfills IMO NOx Tier II regulation and gas mode operation fulfills IMO NOx Tier III regulation. Moreover, optimization of air/fuel ratio control and dynamic change of fuel injection timing improved transient performance in gas mode operation; time required for increasing the load was shortened by 25% compared to the reference operation. Redundancy of the dual fuel engine was also examined in the tests. Switching of operation mode during the engine operation was tested, and the control system was capable of switching from diesel mode to gas mode at 15% load and above. Also, switching from gas mode to diesel mode could be conducted at any load range, including emergency diesel mode which takes over the control of the engine from gas mode when severe knocking occurs and cannot recover, or fatal error occurs in the engine control devices.

Throughout various patterns of tests mentioned above, Niigata has verified that these

two strategies have potential to overcome the regulation, and are reliable.

In addition, Niigata is working on combustion improvement technologies for marine diesel engine. In one of those technologies, Niigata has been working on a combination of Miller cycle with high boost pressure to reduce combustion temperature and improve NOx emission, and at the same time minimize the deterioration of fuel consumption as small as possible. In order to comply with IMO NOx Tier III regulation, it is necessary to reduce approximately 75% of NOx emission from IMO NOx Tier II compliance engine, therefore stronger Miller cycle is needed to decrease combustion temperature further and reduce NOx emission. This paper describes the effect of strong Miller cycle combined with higher boost pressure confirmed from 1D thermodynamic simulation study and engine experiments on 6-cylinder medium speed diesel engine. Furthermore, to provide additional value to the engine, output increment is also tested.

2. Estimating the effect of strong Miller cycle with higher boost pressure on 1D thermodynamic simulation

Application of Miller cycle is a well-known measure to reduce NOx emission, while maintaining thermal efficiency of the engine. In the development of Niigata's IMO NOx Tier II compliance engine "28AHX" [3], Miller cycle was applied to achieve high engine thermal efficiency, low fuel consumption and low NOx emission at the same time. In order to reduce NOx emission further and comply with IMO NOx Tier III regulation, even stronger Miller cycle, in other words much earlier Intake Valve Closing (IVC) timing is necessary. However, to maintain the engine rated output with earlier IVC, much higher boost pressure would be required to push in the requisite quantity of air into combustion chamber within shorter period of intake valve opening duration. Since single-stage turbocharging system has a limit in maximum pressure ratio and efficiency, it is considered that 2-stage turbocharging system will be necessary to aim higher boost pressure. Therefore, a 1D thermodynamic simulation model was constructed and used to examine the needed magnitude of

Miller cycle and increase of boost pressure. This simulation model was constructed based on the specification of the experimental engine of 170 mm bore size. Its rated engine speed is 1200 min⁻¹, rated output per cylinder is 125 kW and P_{me} is 2.2 MPa.

As a first step, the needed increase in the magnitude of Miller cycle was estimated by the simulation. In this step, IVC timing was advanced while keeping the peak firing pressure constant. In this case, boost pressure was adjusted as appropriate to keep peak firing pressure constant. Change of intake valve opening profile is shown in Fig.2. Timing of intake valve close was advanced gradually as shown in "Miller 1", "Miller 2" and "Miller 3", up to 30 °CA (Crank Angle) faster than the baseline.

The effects of IVC timing on engine performance are shown in Fig.3. On Fig.3, NO_x emission and Brake Specific Fuel Consumption (BSFC) were normalized by base performance of the experimental engine. As IVC timing was advanced and magnitude of Miller cycle was increased, boost pressure was increased additionally, as shown in the figure. Both BSFC and NO_x emission rate starts to decrease as IVC timing is advanced by 20 °CA. However, BSFC started to increase noticeably when IVC was advanced up to 30 °CA from the baseline. This result may come from the loss of turbocharger work, as quantity of charged air mass which passes through the intake valve to the exhaust valve during the valve overlap period increases, however this does not contribute to the improvement of combustion quality.

From these simulation results, it became apparent that to improve the combustion quality, reduce NO_x emission rate and fuel consumption further, it is necessary to increase quantity of air delivered into the combustion chamber.

Therefore, on a second step, peak firing pressure limit was allowed to increase by 5 MPa from the baseline with constant IVC (IVC timing is the same as the baseline), and the influence of higher boost pressure on engine performance was examined through 1D thermodynamic simulations. Influence of peak firing pressure increase on heat capacity, normalized BSFC rate and normalized NO_x emission rate are shown in Fig.4. In Fig.4,

Fig.2 Intake and Exhaust valve lift profile used in 1D thermodynamic simulation

Fig.3 Effect of IVC timing on engine performance

Fig.4 Effect of peak firing pressure increase on engine performance

Fig.5 Time history of in-cylinder pressure and temperature

boost pressure is raised to increase peak firing pressure. As boost pressure is raised heat capacity inside the combustion chamber increases, and NOx emission rate and BSFC are improved. It is estimated that higher boost pressure supplies more air into combustion chamber, which improves combustion quality and increases in-cylinder heat capacity. From Fig.4 it can be assumed that increase in heat capacity lowers the combustion temperature; therefore the NOx emission is reduced. Fig.5 shows time history of in-cylinder temperature and pressure. The gas temperatures for both burned and unburned zone were reduced by increasing in-cylinder pressure. Fig.6 shows relationship between heat capacity inside the combustion chamber and NOx emission rate. This result shows increase in heat capacity has a severe effect on NOx emission rate. From this second step, increase of peak firing pressure was confirmed to be effective in both reduction of NOx and improvement of fuel consumption.

Then, on a third step, above mentioned strong Miller cycle and peak firing pressure increase were applied at the same time. The relationships between normalized BSFC rate and normalized NOx emission rate are summarized in Fig.7, with the effect of changing fuel injection timing indicated in bold and dotted lines.

By utilization of strong Miller cycle and increased peak firing pressure at the same time,

Fig.6 Relationship between heat capacity and NOx emission rate

Fig.7 Improvement of trade-off relationship between NOx emission and fuel consumption

NOx emission is reduced 46% from Tier I NOx level, and fuel consumption has also improved by approximately 1%. Moreover, by optimizing the fuel injection timing, NOx reduction of 50% from Tier I level can be possibly achieved, without any deterioration of fuel consumption.

3. Verification of 2-stage turbocharging system with strong Miller cycle on an experimental engine

To verify the improvement of BSFC-NOx trade-off relationship seen in the 1D thermodynamic simulations, 2-stage turbocharging system was coupled with medium speed 6-cylinder experimental diesel engine, and experimental runs were carried out to confirm the potential. Furthermore, possibility of engine output increment

was also tested in the experiments.

3.1 Specification of the base engine

Specification of the base engine is the same as the parameters used for 1D thermodynamic simulation, except for the compression ratio, which was increased up to 16.0. This engine is a 6-cylinder medium speed diesel engine, which comply with IMO NO_x Tier II regulation. The test result taken with the single turbocharger configuration was set as a benchmark to compare with the results with 2-stage turbocharging system and strong Miller cycle.

3.2 Application of 2-stage turbocharging system and strong Miller cycle

For the engine test, base engine was modified into 2-stage turbocharging configuration with intake valve cam to implement strong Miller cycle. The purpose of this test is to reduce NO_x emission from the engine by combustion improvement technology. The target of NO_x reduction rate is 50% from IMO NO_x Tier I regulation, as analyzed in the simulations. Fig.8 shows the picture of the engine setup, and Fig.9 shows the simplified model of the engine setup. 2 turbochargers; low pressure turbocharger (LP-TC) and high pressure turbocharger (HP-TC) are arranged in series, intercooler is installed between LP-TC compressor outlet and HP-TC compressor inlet, and after cooler is installed at the outlet of HP-TC compressor. Outlet of HP-TC turbine and inlet of LP-TC are connected directly.

First, intake air is compressed at the compressor of LP-TC. Then compressed air goes through the intercooler, where the temperature of compressed air is cooled down to specified value. After that, compressed air is compressed up to target pressure at HP-TC compressor, then cooled down at after cooler, and fed to charge air receiver. On the other hand, exhaust gas from each combustion chamber is gathered at exhaust pipe, and then is blown into HP-TC turbine and LP-TC turbine in sequence, and energy from the exhaust gas is delivered to intake air. Cams driving intake and exhaust valves were also modified to apply strong Miller cycle effect. Fig.10 shows the exhaust and intake valve lift curves for base engine and the curves for stronger Miller cycle. Bold lines

Fig.8 Experimental engine setup with 2-stage turbocharging system

Fig.9 Simplified model of 2-stage turbocharged engine setup

Fig.10 Valve lift profile for engine test

(Base_EV and Base_IV) show valve lift profile of intake and exhaust valves for base engine configuration. For strong Miller cycle test cases, two cases "Ver_A" and "Ver_B" were defined. These two valve lift profiles were defined for two reasons; one is to confirm the NO_x reduction effect of strong Miller cycle, and the other is to verify how the magnitude of Miller cycle affects the potential of NO_x reduction. Valve lift profile Ver_A has a slightly stronger Miller cycle compared to base case, and IVC timing is 16 °CA advanced from the base IVC. Intake valve lift profile Ver_B is a profile for

Fig.11 IMO NOx emission and BSFC with Ver_A

Fig.12 IMO NOx emission and BSFC with Ver_B

extensively strong Miller cycle, IVC timing is advanced by approximately 30 °CA than base IVC. This valve lift profile is designed to work at high load, where turbochargers supply sufficient boost pressure. However, at low load, early IVC timing and low boost pressure causes lack of intake air supplied to combustion chambers. To prevent this issue, it is under consideration to match-up valve lift profile for part load or low load. For cases Ver_A and Ver_B, lift profile 2TC_EV is coupled for exhaust valve lift. Closing timing of this valve lift is slightly modified from Base_EV to fine-tune the valve overlap duration.

3.3 Test results of case Ver_A

First, tests with intake valve lift profile Ver_A were conducted to investigate the potential of Miller cycle on NOx emission reduction and the possibility of output increment. First, engine tests with rated output were conducted with three different fuel injection timing. The relationship between BSFC and NOx emission from these three tests are plotted on Fig.11 in diamonds. The relationship between BSFC rate and NOx emission rate changes as the fuel injection timing is adjusted. These three results fit on a single curve, so called BSFC-NOx trade-off curve. It can be estimated that performance from this engine configuration moves along this line when the fuel injection timing is adjusted.

By applying strong Miller cycle and fuel injection timing adjustment, NOx reduction rate of

approximately 32% from Tier I is achieved, with 0.5% of BSFC improvement. Also from this result, it can be estimated from the trade-off curve that when allowing the same NOx emission level as Tier II, BSFC improvement of 2.5% can be possibly obtained from the base case. From this result, it has become apparent that 2-stage turbocharging and strong Miller cycle have potential in improving both NOx emission and BSFC.

Then, engine output increment tests were conducted with three different fuel injection timing, the same injection timing as in the former engine tests. In these tests, the engine output was increased up to 850 kW, which is 100 kW above the rated output. The results are shown on Fig.11 in pentagonal plots. From the test results, NOx emission reduction of 35% was achieved, without any BSFC deterioration. Moreover, diamond plots and pentagonal plots show same BSFC-NOx trade-off relationship. This indicates 2-stage turbocharging system combined with Miller cycle can provide the engine an additional allowance to increase output without deteriorating the engine performance.

3.4 Test result of case Ver_B

After confirming the effect of strong Miller cycle on BSFC and NOx emission rate with case Ver_A, tests with intake valve lift profile Ver_B were conducted to verify the effect of extensively strong Miller cycle. In this test, boost pressure increased

0.09 MPa and peak firing pressure increased 1.4 MPa from the single turbocharger engine configuration.

Fig.12 shows the 100% load BSFC rate and IMO NOx emission rate of case Ver_B, compared to the engine test results plotted in Fig.11. In this case, start of fuel injection timing was greatly advanced by approximately 6 °CA from the base engine setup. Fig.12 indicates the possibility of reaching NOx reduction rate of 50% using valve lift profile Ver_B. If trade-off curve of Ver_B has the same tendency with the trade-off curve of Ver_A, trade-off curve of Ver_B would be as shown in Fig.12, and from this trade-off curve it can be estimated that NOx reduction rate of 50% from Tier I level can be achieved by the adjustment of fuel injection timing. Moreover, BSFC reduction of 6.4% from base case was confirmed if NOx emission of IMO NOx Tier II level can be permitted.

From this result, it has become apparent that 2-stage turbocharging system combined with extensively strong Miller cycle indicates a possibility in 50% reduction of NOx emission, and notable improvement on BSFC consumption when allowing NOx emission of IMO NOx Tier II level. Further studies are to be conducted to reach the target NOx emission.

3.5 Combination with EGR system

Although possibility of 50% NOx reductions from IMO NOx Tier I regulation was confirmed, it is not enough to meet IMO NOx Tier III regulation. To comply with the tight regulation, one of the ideas is a combination with an exhaust gas recirculation (EGR) system. The EGR system for engine experiments is under development, and will be coupled with 2-stage turbocharging system to confirm the effectiveness on NOx reduction.

4. Conclusions

In order to reduce NOx emission and improve engine performance, potential of 2-stage turbocharging system with strong Miller cycle was investigated in two aspects; 1D thermodynamic simulation and experimental engine test. Concluding remarks are as follows.

(1) From the investigation on 1D thermodynamic

simulations and experimental engine tests, it has become apparent that the combination of 2-stage turbocharging system with strong Miller cycle show potential of reducing NOx emission by up to 50% from IMO NOx Tier I regulation, without any deterioration of fuel consumption.

(2) It has become apparent that combination of 2-stage turbocharging system and strong Miller cycle improves fuel consumption by allowing NOx emission of Tier II level. BSFC improvement of 6.4% was confirmed in the engine test.

(3) 2-stage turbocharging system and strong Miller cycle provide the engine an additional allowance to increase output without any deterioration of BSFC-NOx trade-off relationship.

(4) Although possibility of 50% NOx reductions from IMO NOx Tier I regulation was confirmed, it is not enough to meet IMO NOx Tier III regulation. To comply with the regulation, combination with EGR system is planned, and is under development.

References

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