Development of Variable Geometry Turbocharger for Gasoline Engine

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Abstract: Cooled EGR is an effective technology to improve fuel consumption for gasoline engines, and are under development in various automotive manufacturers. In order to improve the EGR ratio while maintaining the engine performance, it is required to increase the boost pressure across a wide range of operating condition. Variable Geometry (VG) Turbocharger is one of the effective solutions to achieve the point above. However, the exhaust gas temperature of gasoline engine is relatively high compared to that of diesel engine, and can be reached to 1000 deg C. In such a condition, it is necessary to use expensive heat-resistant materials for the moving components of the VG, and it gives a significantly big impact on the cost compared to that of a turbocharger for diesel application. Meanwhile, cooled EGR enables to reduce the exhaust gas temperature of a gasoline engine, and becomes more advantageous in the point of durability.

This paper describes the development of a VG turbocharger for gasoline engine under the assumption that the exhaust temperature is 950 deg C, and the application of cost-effective materials, which aims to achieve a good balance of cost, performance and durability. In addition, the effect of VG turbocharger with EGR on fuel economy improvement is predicted through the 1D engine simulation.

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1 Introduction

The automotive industries are challenging various measures to reduce the fuel consumption for the compliance with recent stringent emission regulations, and the reduction of environmental burden in Europe, North America and Japan. Especially, in the case of gasoline engine, the down-sizing turbo engine shows successful results in Europe. This trend is spreading also in US and developing countries including China, and it is assumed to accelerate for the improvement of fuel consumption by the down-sizing turbo engine.

The down-sizing turbo engine has characteristics of rich torque in low-speed and modest output in high-speed operations. For this reason, a small-size waste gate turbocharger, or twin-scroll turbocharger are generally installed to get the high boost pressure in a low-speed range, and the controlled pressure by opening the waste gate in a high-speed range. This is the general matching method of down-sizing turbo engine.

In the case of diesel engine, balance of the maximum engine output in high-speed range and the rich torque in low-speed range is required. And, from the viewpoint of emission regulation measures, a variable geometry (VG) turbocharger is often adopted for its capability of providing a high-boost pressure from low- to high-speed range. Because of the maximum exhaust gas temperature is up to 850 deg C in diesel engine, which is lower than that in gasoline engine, the utilization of VG mechanism, required to be functional without lubrication and highly reliable in an exhaust gas environment, is comparatively less difficult than in gasoline engine. For this reason, VG turbochargers are widely used in diesel engines.
The exhaust gas temperature of gasoline engine is as high as 950 to 1050 deg C. And, because of the necessity to construct with expensive materials, the cost and technical problems are many to provide the VG mechanism in a high exhaust gas temperature. Moreover, as the back pressure in gasoline engine affects much to the combustion stability, the control of VG mechanism is difficult. Therefore, the adoption of the VG turbocharger for gasoline engine is limited to the special car model.

2 Development Background of Variable Geometry (VG) Turbocharger for Gasoline Engine

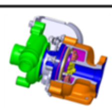
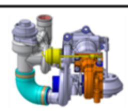
Recently, the cooled-exhaust gas recirculation (Cooled-EGR) is sometimes adopted as a technique to reduce the fuel consumption in gasoline engines.

Regarding the actual utilization of the Cooled-EGR in gasoline engine, some naturally aspirated (NA) engines have used the system, but few turbo engines have used this system for restrictions of the EGR return point and the EGR control method. In the downsizing turbo engine, the Cooled-EGR is started to study the adoption for a better fuel consumption.

The engine torque reduction is concerned when the EGR applying range is expanded to the full-load region for the improvement of fuel consumption of the supercharged engine. For this reason, the engine requires a high boost pressure. For the solution of these requirements, the 2-stage turbocharger, supercharger, or 2-stage turbocharger with electric compressor besides the VG turbocharger is considered. The 2-stage turbocharger, supercharger and electric compressor have advantages in the steady state performances, and also in the transient performances. However, for the application to small-size passenger cars, many restrictions such as cost and weight must be considered. Moreover, countermeasures for engine starting emissions must be considered because of the large heat mass. From the view point of the total balance, the VG turbocharger is supposed to have advantages. The table 1 shows the comparison.

The concern to use the VG turbocharger in a gasoline engine was the exhaust gas temperature. The exhaust gas temperature is lowered by adopting the Cooled-EGR, and this is also supposed to give advantages to the reliability and cost of the VG mechanism.
MHI think the obstacle against the VG turbocharger adoption is less in the gasoline engine with EGR.
MHI started the development of VG turbocharger having a high reliability in a high-temperature exhaust gas up to 950 deg C, while considering the cost without using expensive heat-resistant materials.

Table 1: Turbocharger & Supercharger comparison

Turbo	WG Turbocharger	VG Turbocharger	Two-Stage Turbochargers (TC+TC)	Roots Type SC (TC+SC)	Electric Supercharger (TC+SC)
appearance					
cost	0	-	- -	- - -	- - -
weight	0	-	- -	- - -	- -
package	0	-	- -	- - -	- -
Steady performance	0	+	++	++	++
transient response	0	+	++	+++	+++
Heat mass	0	-	- -	0	0

3 Verification of Fuel Consumption Improvement with EGR + VG Turbocharger

The simulation with GT-Power was conducted to verify the validity of VG turbocharger on a gasoline engine with Cooled-EGR.

A 1.6 L direct-injection turbo gasoline engine was used for the GT-Power simulation model to compare the W/G turbocharger and VG turbocharger.

A target torque was configured, and a W/G turbocharger and a VG turbocharger which can attain the target torque were selected. And, considering the down-sizing engine, the same small-size turbine was seleted for the W/G turbocharger and VG turbocharger. Also, for a clear comparison of the turbine, the same compressor was used for both turbochargers.

The recirculation method of Cooled-EGR has the HPL method and LPL method. The HPL-EGR could not increase the EGR rate with both W/G and VG turbochargers, and the LPL-ERG was used for the consideration.

The comparison of W/G turbocharger and VG turbocharger was made in:

1) Maxmum EGR rate at the full-load performance, and
2) Maxmum Engine break efficiency when the EGR was applied.

3.1 EGR Rate Comparison at Full-load Condition

The maximum EGR rate to attain the target torque was calculated respectively in W/G turbocharge and VG turbocharger. The knocking limit was considered in the calculation model.

Figure 1 shows the calculation result of maximum EGR rate at the target torque. The result shows that VG turbocharger allows the higher EGR rate than WG turbocharger across the engine operational range.

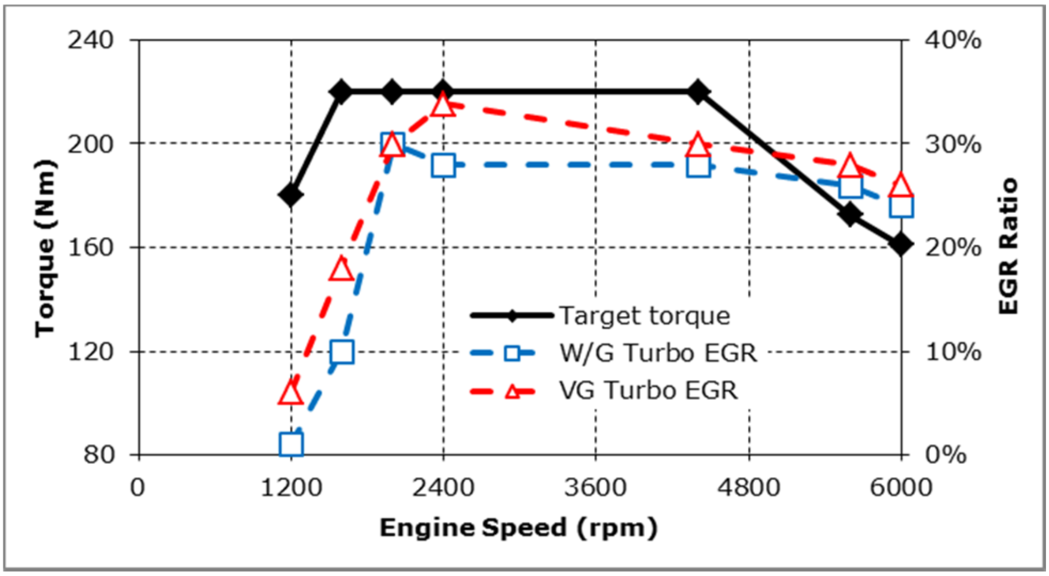


Figure 1: Target Torque and Maximum EGR ratio comparison

3.2 Comparison of Maximum Engine Brake Efficiency with Cooled EGR System

Next, the break efficiency of engine when applying EGR was compared for the verification of the fuel consumption improvement. The conditions were the maximum break efficiency of engine and EGR rate to attain the target torque considering the knocking limit as in the section 3.1. Figure 2 shows the simulation result.

The result shows that VG turbocharger has better engine break efficiency than WG turbocharger across the engine operational range.

The result of simulation above shows that VG turbocharger has the possibility to increase the engine break efficiency, and improve the fuel consumption across the engine operational range than W/G turbocharger in the case of application to the turbo gasoline engine with Cooled-EGR.

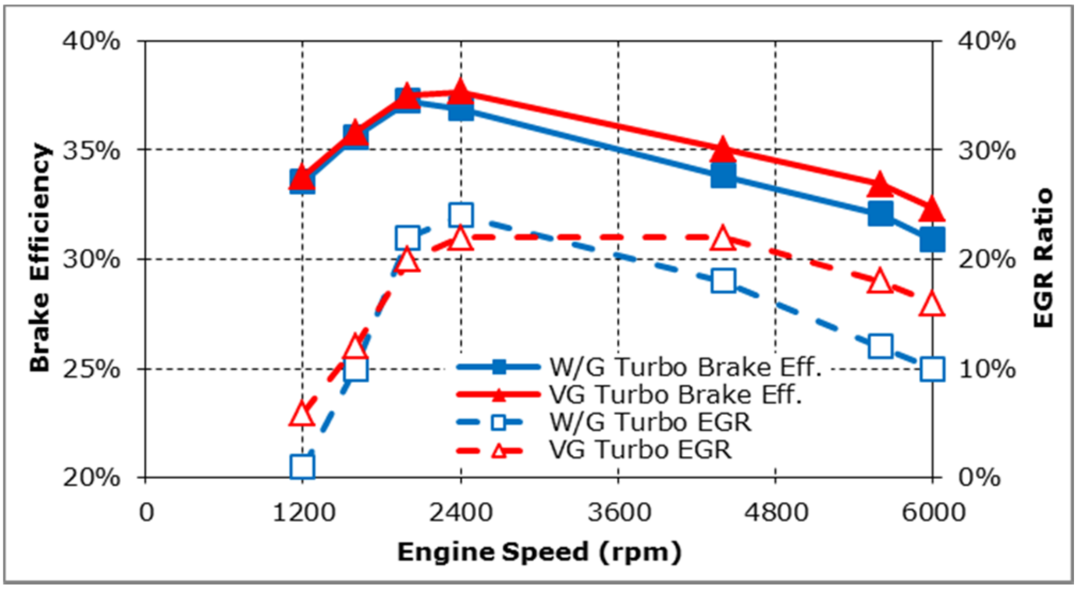


Figure 2: Engine Brake Efficiency comparison

4 Design of Nozzle Assembly for Gasoline VG turbocharger

4.1 Investigation on Failure Modes of Nozzle Assembly

In VG turbocharger, a variable nozzle assembly is one of the important parts. Especially reliability of the nozzle assembly influences total reliability of the VG turbocharger.
VG turbocharger model is shown in Figure 3.

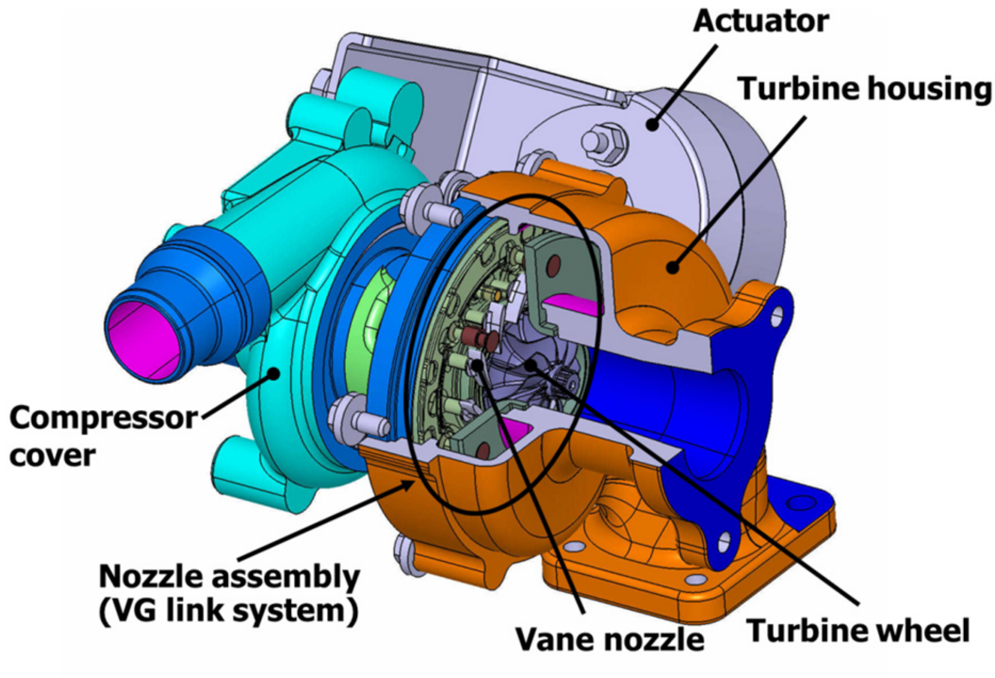


Figure3: VG Turbocharger

On reliability of the nozzle assemblies of VG turbochargers for gasoline engines, temperature of exhaust gas is very important factor. The temperature of exhaust gas in gasoline engines is higher than that of diesel engines, so the nozzle assembly should be run under a higher temperature condition. When temperature becomes higher, thermal deformation and stress become larger in addition to the reduction of strength of materials used in the nozzle assembly. From these reasons, it is considered that the failure of the nozzle assembly occurs more easily in gasoline engines than in diesel engines.
In order to understand the failure mode of nozzle assembly, a heat cycle test on the hot gas test bench has been carried out. In the heat cycle test, inlet gas temperature was changed from 150 deg C to 980 deg C in one cycle, and the heat cycle was repeated 300 times in this test. In order to confirm the failure mode, a nozzle assembly designed for diesel engines,

which can be used under low temperature condition, was prepared for the heat cycle test. Figure 4 shows pictures of the nozzle assembly after the heat cycle test. From this test, following failures are observed.

- On the nozzle mount, cracks are generated on the inner wall.
- On the nozzle plate, cracks are generated around holes for nozzle supports.

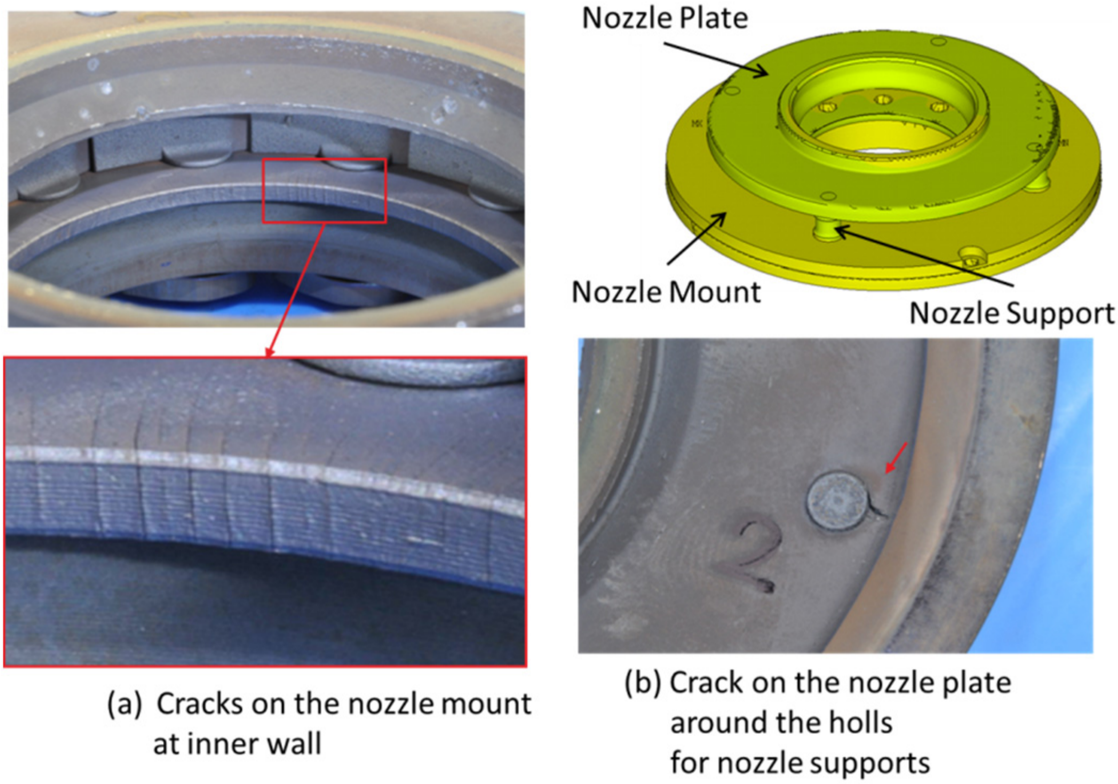


Figure 4: Failure modes of the nozzle assembly by heat cycle test

To discuss the failure mechanism, FE analysis has been performed. Calculation procedure is as follows:

- To give pressure and temperature condition of exhaust gas considering heat cycles
- To calculate distribution of gas flow speed and gas temperature in the nozzle assembly by 1D-simulation
- To obtain heat transfer coefficient by using gas flow speed on each position of the nozzle assembly
- To calculate temperature distribution inside of the parts of the nozzle assembly by using distribution of the gas temperature and the heat transfer coefficient obtained above as boundary conditions
- To calculate thermal deformation and stress of the nozzle assembly by using the temperature distribution inside of the parts

From the calculation results, two main failure mechanisms have been found out.

- Thickness of the nozzle mount is not constant. At the inner perimeter the thickness is larger than that at the outer perimeter, therefore heat mass in the nozzle mount is different. When nozzle mount is heated, temperature at inside is lower than that that at outside because of the larger heat mass. By this mechanism, tensile stress is generated at inner wall of the nozzle mount and cracks are generated.
- The nozzle mount and the nozzle plate are heated from one side, so temperature is different in both sides of the nozzle mount and the nozzle plate. By this temperature distribution, the nozzle mount and the nozzle plate are curved by thermal deformation. When this deformation occurs, stress around the nozzle supports becomes higher and cracks are generated around the holes for the nozzle supports.

From the test and the calculation results, new designs of the nozzle assembly for gasoline engines were considered. And, FE analysis has been carried out to confirm the effect of the new design to reduce the thermal stress of nozzle assembly

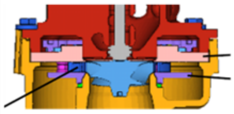
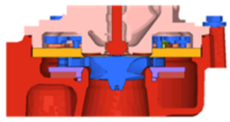
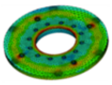
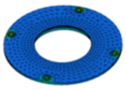
4.2 Consideration of New Design of Nozzle Assembly for Gasoline Engine

As the results of investigation on the failure modes of the nozzle assembly, two countermeasures are considered to prevent the nozzle mount and the nozzle plate from cracking.

- To change thickness of the nozzle mount to be almost constant
- To add ribs on the nozzle plate to prevent the plate from curving

Table 2 shows safety factors on low cycle fatigue obtained by FE analysis considering the design change of the nozzle mount and the nozzle plate. In the FE analysis it is considered that materials used in the nozzle assembly are the same used in the nozzle assembly for diesel engines. From Table2, in case the change of shapes of both the nozzle mount and the nozzle plate, safety factors for both failure modes became larger than 1, i.e. cracking does not occur, in exhaust gas temperature 900 deg C. On the other hand, In case exhaust gas temperature is 950 deg C, there is risk to generate cracks on the nozzle plate around the holes for the nozzle supports. To prevent the risk, change of the width from the holes to the outer edge of the nozzle plate was applied, and the nozzle assembly based on the analysis was prepared for the endurance test by gasoline engine.

Table 2: Change of safety factor by design change of the nozzle mount and the nozzle plate

Failure mode	Exhaust gas temperature, deg C	Safety factor		
		Original 	Change of nozzle mount (constant thickness) 	Change of nozzle mount and nozzle plate (with ribs) 
Cracking on inner wall of nozzle mount 	900	0.93	1.07	1.24
	950	0.87	1.00	1.15
Cracking on nozzle plate around holls 	900	0.87	0.91	1.05
	950	0.79	0.82	0.94

5 Assessment and Verification of VG Turbocharger for Gasoline Engine

A sample VG turbocharger was produced for the verification of analysis result in section 4, and various assessment tests were conducted.
The selected turbocharger for the development was TD025 (T/W dia. φ37) targeting from 1.4 to 1.6 litter class displacement engine. The nozzle assembly was produced based on the structure of latest generation VG developed for diesel engines, and the shape and materials were optimized as a condition of using iron base material for the consisting parts based on the analysis result in section 4. The produced VG turbocharger model and nozzle assembly are shown in figure 5.

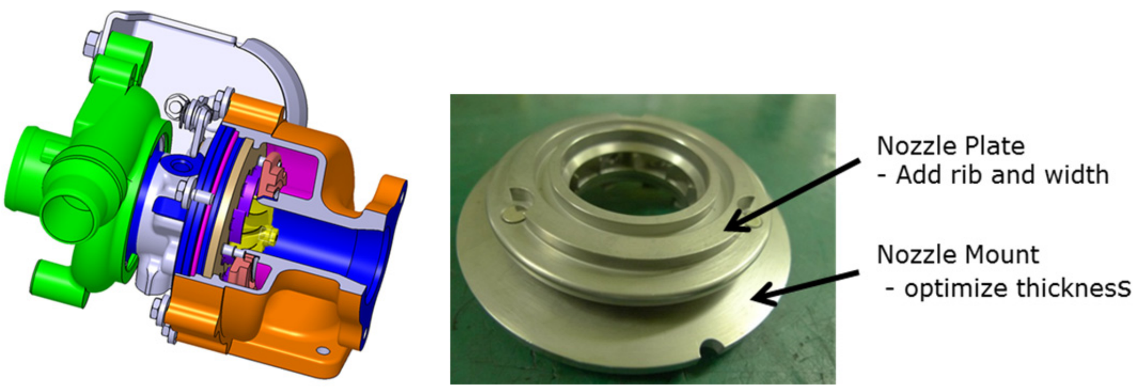


Figure 5: VG Turbocharger and Nozzle Assembly for Gasoline Engine

5.1 VG Function Test on Hot Gas Stand

The purpose of this assessment test is the verification of anti-sticking function of the nozzle assembly and linkage in the ambient condition of high-temperature gas, and anti-sticking function and durability in the heat cycle test. These tests were conducted with a turbocharger on the hot gas stand.
First, the anti-sticking function was tested by keeping the turbine inlet at a temperature of 950 deg C for a specified period, and the movement free from defects was verified. Next, the heat cycle test of 950 deg C and 150 deg C of the turbine inlet temperature was conducted, and no-sticking was observed during the test period.

With the result of these tests, the VG turbocharger for gasoline engine was proved to work in the ambient condition of 950 deg C exhaust gas. The measurement of vane side clearance after the test showed that the nozzle assembly did not change the clearance from the initial condition. And also, no damage or significant wear was observed on the consisting parts.
Thus, MHI could check the VG turbocharger anti-sticking function in 950 deg C exhaust gas.

5.2 Heat Cycle Test on Gasoline Engine

Then, the turbocharger was installed on a gasoline engine to conduct the endurance test for the assessment of durability. A 1.5 liter gasoline engine was used for the assessment test.

The endurance test was conducted for 200 hours (1000 cycles) in heat cycle test of maximum 950 deg C and minimum 450 deg C gas temperature at the turbine inlet.

During the test, the nozzle assembly did not show any sticking. In the inspection of nozzle assembly after the test, a crack which was one of concerns was not observed on the outer peripheries of nozzle plate and inner peripheries of nozzle mount. And more, the vane side clearance after the test was verified to be secured.

These results showed that the nozzle assembly was free from a serious damage, and additional test with more severe conditions were conducted. The following endurance test was conducted with extended heat drop of maximum 950 deg C and minimum 300 deg C at the turbine inlet for 200 hours (1750 cycles). It was test of total 400 hours (2750 cycles). The difference of the cycle number was caused by the change of cycle period to lower the minimum temperature, and accelerate the test. During this test also, the nozzle assembly did not show any sticking. A crack or other defects were not seen on the nozzle mount and nozzle plate, and the vane side clearance change rate was the equivalent to that for diesel engine after the test. And, the reliability was verified to be enough. The nozzle assembly condition after the endurance test is shown in figure 6 and the change of side clearance in figure 7.

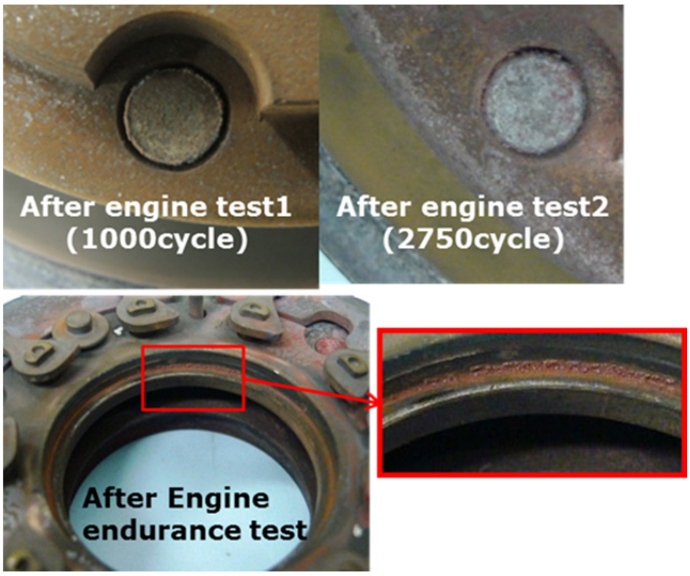


Figure 6: Nozzle Assembly after 2750 Cycle Engine Endurance test

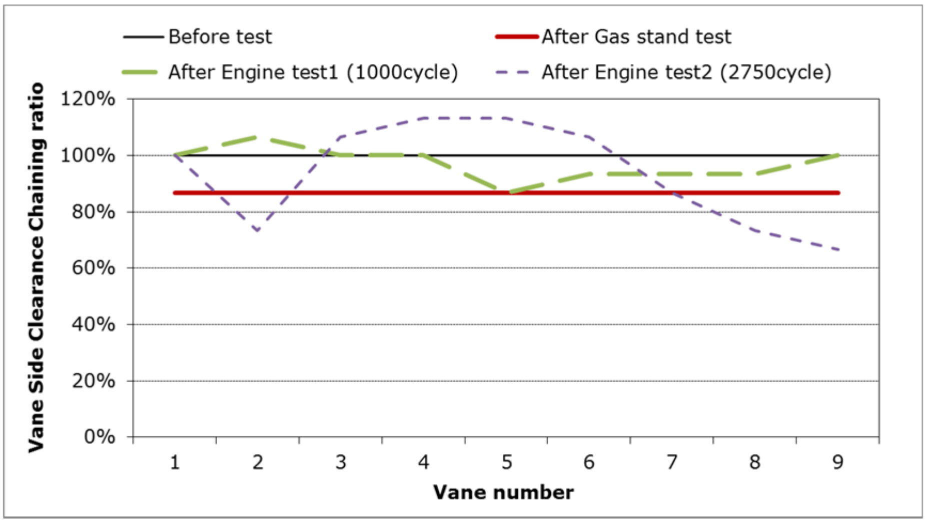


Figure 7: Vane side clearance measurement result after endurance test

The basic structure of nozzle assembly for gasoline engine, assumed to be used for the exhaust gas temperature of maximum 950 deg C, was verified to be free from problems from results of the movement test on gas bench and the endurance test on engine.

The VG turbocharger was verified to work without problems in an exhaust gas temperature of 950 deg C although the expensive heat resistant material was not used. However, the endurance test above does not include all the endurance conditions in the market. MHI will continue to verify the endurance limit by conducting tests for the improvement of reliability.

6 Summary

VG turbocharger is expected to be an effective technique to improve the fuel consumption of down-sizing turbo gasoline engine with EGR from the view point of turbocharger efficiency.
However, various challenges are still remained for implementation of LPL Cooled EGR like EGR control optimization by related parts as well as VG turbocharger, durability of related parts for the significant improvement of fuel consumption.
In this investigation, the possibility of break efficiency improvement in the turbo engine is shown in the 1D simulation of VG turbocharger+EGR. Also, a VG turbocharger considering the exhaust gas temperature of 950 deg C is developed, and the validity of fundamental design is verified.
MHI will continue the study for the improvement of VG turbochargers for gasoline engines, and MHI would like to devote ourselves for the development of high-performance and highly reliable products considering the needs from automobile manufacturers.

Acknowledgements

We would like to thank Chiba University to work for the 1D engine simulation in section3.

References

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