

Development of VGS Unit (STEP4) for RHV4 Turbocharger

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As emission regulations are increasingly tightened worldwide, the development of fuel-efficient diesel engines that are less burdensome on the environment is progressing. When coupled with engine downsizing, VGS (Variable Geometry System) turbochargers are very effective in reducing diesel engines' fuel consumption and emissions. As further engine downsizing is a major trend, there are strong demands to increase the power density of VGS turbochargers while improving their performance and reliability. To meet such demands, a new VGS turbocharger with improved turbine performance and reliability has been developed. This paper introduces key technologies adopted for the new VGS turbocharger, such as clearance flow control, improved VGS structure, MIM (Metal Injection Molding ; a new technique), and new materials.

1. Introduction

To deal with global warming and other environmental issues, emission regulations have been increasingly tightened worldwide and the development of fuel-efficient engines that are less burdensome on the environment is progressing.

Diesel engines provide higher thermal efficiency, higher fuel efficiency, and emit less CO₂ than gasoline engines. In Europe, the ratio of cars with diesel engines as a percentage of all passenger cars has reached approximately 50%. Diesel engines are generally equipped with turbochargers, which improve diesel engine efficiency. Most conventional wastegate turbochargers have been replaced with Variable Geometry System (VGS) turbochargers. To improve engine fuel efficiency, there are strong demands to increase the power density of turbochargers while improving their performance and reliability.⁽¹⁾

To remain competitive in the growing global turbocharger market, we have developed a new VGS turbocharger with improved turbine performance and reliability and started commercial production in actual engines. This paper introduces the key technologies adapted for the new VGS turbocharger, including an improved VGS structure as well as a new construction method and a new material.

2. Improved turbine performance

2.1 VGS turbocharger structure

A turbocharger is a device that supercharges high-pressure air for the engine by rotation compressor, which is driven by the coaxial turbine which is powered by engine exhaust.

VGS turbochargers can control the supercharging pressure and the engine exhaust pressure by opening and closing the

nozzle vanes in order to increase the rate of Exhaust Gas Recirculation (EGR; circulation of exhaust gases to the air inlet), thereby allowing the generation of nitrogen oxide (NO_x) to be controlled. When the engine is rotating at a low speed with low gas flow, the nozzles are closed to increase the flow velocity of the gas entering the turbine wheel. This increases the turbo rotation speed, thereby improving the engine's transient characteristics and the torque at lower engine speeds. VGS turbochargers require high reliability, such as the durability of the link mechanism that opens and closes the nozzle vanes under unlubricated conditions at a high temperature (800°C or more).

Our VGS turbocharger features a double support structure with shafts on both sides of the nozzle vane. This structure can reduce the sliding friction load caused by opening and closing the nozzles and ensure smooth operation with its excellent durability and transient characteristics. In addition, the VGS unit has a nozzle opening-and-closing link mechanism on the bearing housing side which contributes to reducing the size of the turbocharger (**Fig. 1**).

2.2 Improvement of turbine performance

As emission regulations are increasingly tightened, demand for higher performance turbochargers is increasing. VGS units are operated without lubrication at high temperatures and require clearance among their parts to allow for thermal deformation and workability. Performance is greatly affected by losses (entropy generation), such as the separation that occurs inside the turbine wheel due to clearance flows, which are mainly composed of the radial velocity components, leaking through the clearances (nozzle side clearances) between the nozzle vanes and the sliding surface. These losses are considered to be the primary causes behind turbine performance deterioration.⁽²⁾

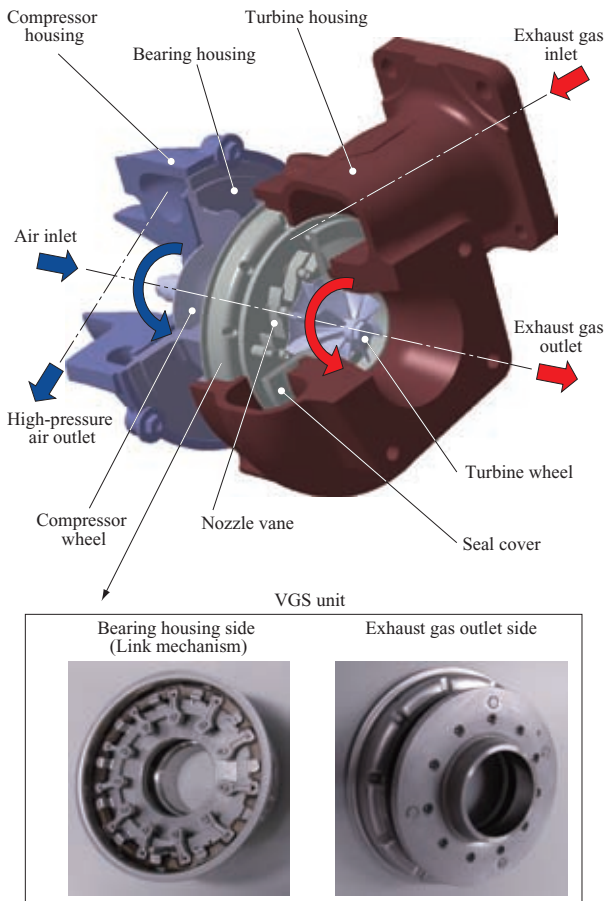


Fig. 1 Structure of VGS turbocharger

To control the losses at the nozzle side clearances and improve turbine performance, a new nozzle vane was developed that features thin nozzles and a long chord (long vane). Its performance is less affected by clearance variations. The new shape of the nozzle vanes was realized

by applying Metal Injection Molding (MIM) to improve the mass productivity. **Figure 2** shows the total pressure distribution near the clearance of these new nozzle vanes. The comparison of pressure loss through the nozzle due to clearance flow indicates that the new nozzle vane (**Fig. 2-(a)**) causes less pressure loss and is less affected by clearance flow.

Controlling the influence of clearance flow improves the performance of the turbine wheel downstream of the nozzle. **Figure 3** shows the results of a CFD analysis on the flow inside the turbine wheel before and after clearance flow control. As shown in the figure, the loss inside the wheel generated before the clearance flow control (**Fig. 3-(b)**) was reduced. This is more efficient and significantly improves turbine performance at lower engine speeds (the nozzle is closed when the gas flow rate is low), where clearance flow greatly decreases turbine efficiency (**Fig. 4**). Clearance flow control improves not only performance but also robustness (reduces variation). Nozzle side clearance increases with clearance flow. This causes increased loss of flow inside the wheel downstream of the nozzle, resulting in variations in turbine performance. However, clearance flow control can decrease such losses at the wheel, thereby decreasing the variation width of performance.

By adopting the new nozzles and using them for clearance flow control, a 48% decrease in the variation width of performance due to variation in the nozzle side clearance was achieved compared to the conventional structure and the robustness of performance was improved (**Fig. 5**).

2.3 Modification of seal structure

The VGS turbocharger must be designed to reduce the external forces on the VGS unit and prevent the nozzle vane from sticking. To this end, the VGS unit is secured on the bearing housing, which is subject to lower temperatures as well as less thermal deformation and has a structure

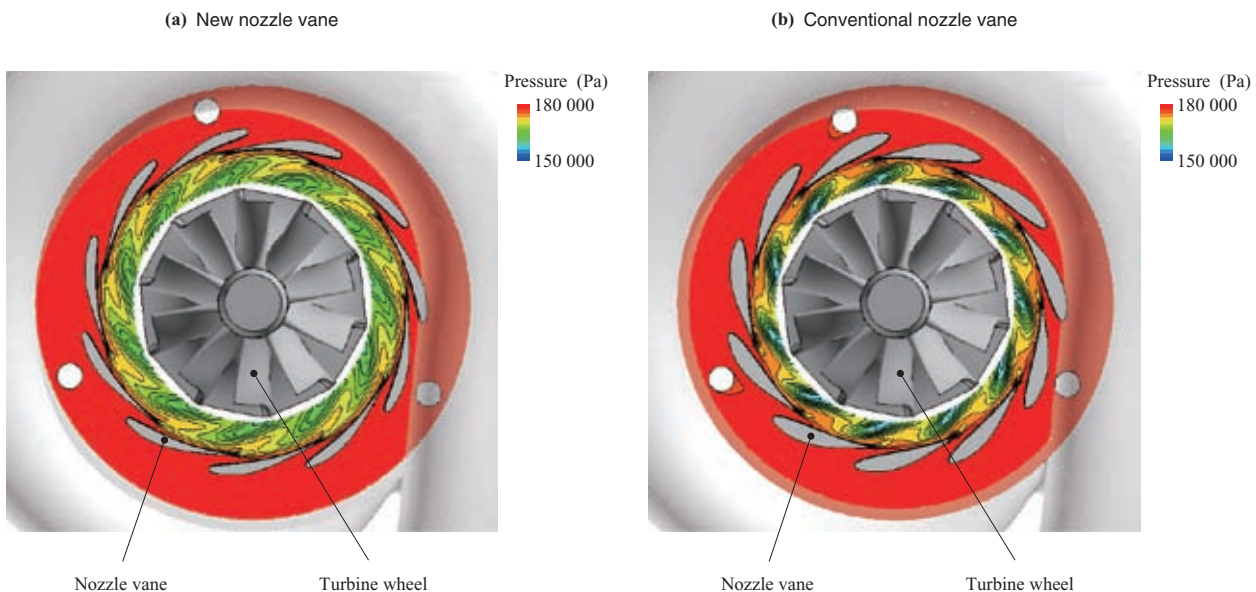
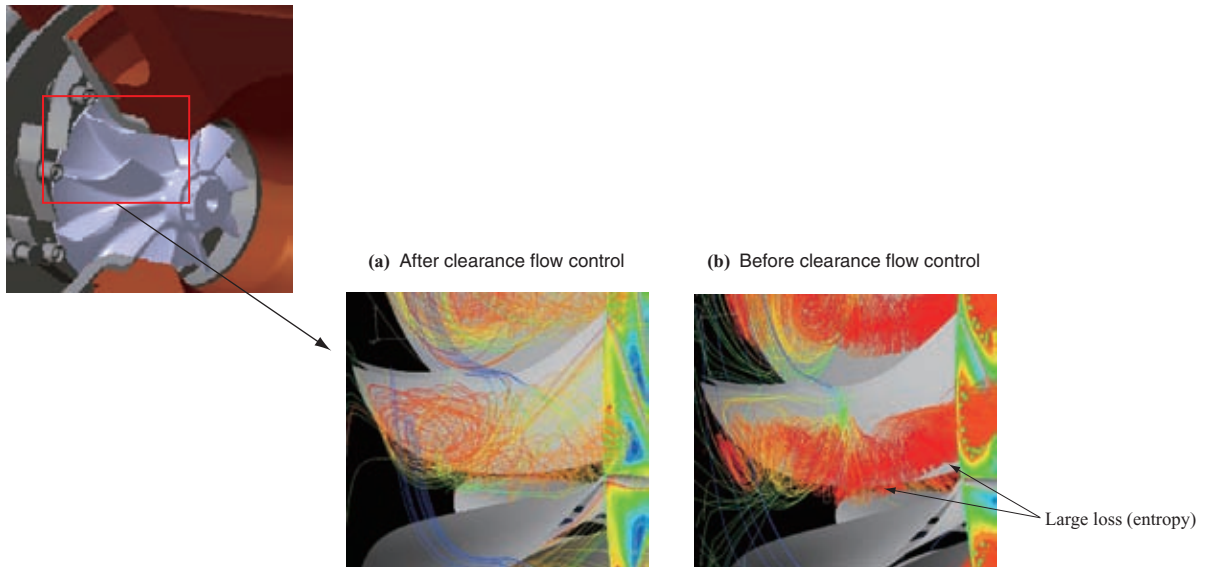


Fig. 2 Total pressure distribution around nozzle side clearance



(Note) The color maps show the flow lines and entropy at the turbine wheel outlet.

Fig. 3 Comparison of entropy in turbine wheels

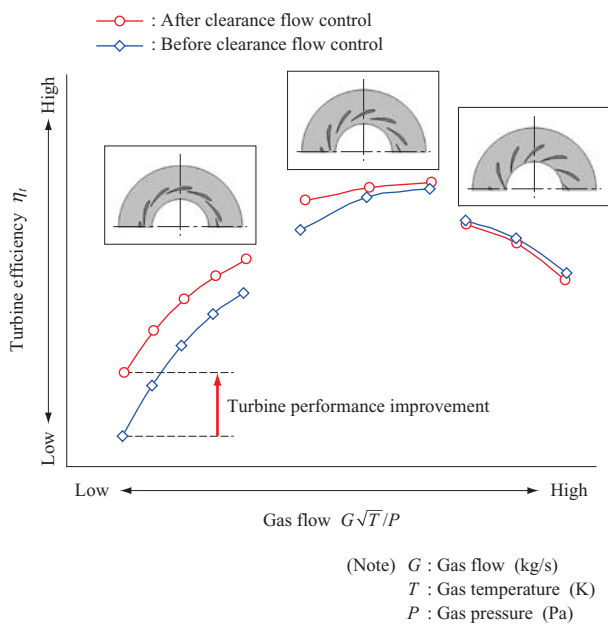


Fig. 4 Turbine performance

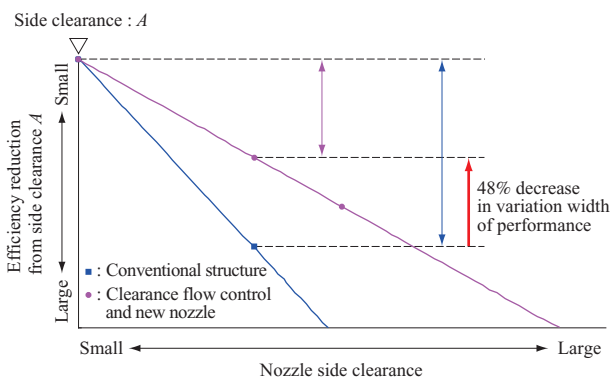


Fig. 5 Turbine efficiency after change to nozzle side clearance

unaffected by thermal deformation of the turbine housing, which is subject to higher temperatures and relatively large thermal deformation. In this structure, the VGS unit and the turbine housing are not fastened together; the resultant gap accompanies the clearance gas flow or leakage. Therefore, the internal sealing of the gap must be maintained. A seal structure satisfying these conditions was adopted.

A seal cover structure (STEP 4) with reduced leakage was developed by improving the sealing method of the piston ring structure (STEP 3) adopted for conventional VGS (Fig. 6). The leakage measurement results shown in Fig. 7 indicate that the new sealing method maintains a better sealing ability than the former method.

3. Adoption of a new technique and a new material

3.1 Adoption of the MIM technique

With the development of mature, high-precision technologies in recent years, thin and complicated three-dimensional parts such as nozzles can now be manufactured by using the MIM technique.

MIM is the process of manufacturing metal parts by mixing metal powders with resin binders, injecting the resulting liquid mixture into a mold, removing the resin content from the molded parts by heating or chemical treatment (degreasing), and then sintering the parts.⁽³⁾ Such mold injection enables manufacturing of high-precision components. An MIM technique of IHI Turbo that is now being adopted is highly precise and enables manufacturing without machining. By using this MIM technique, it is now possible to make lighter weight components as shown in Fig. 8. This weight saving should improve resistance to abrasion (impact wear) caused by the vibration of the engine.

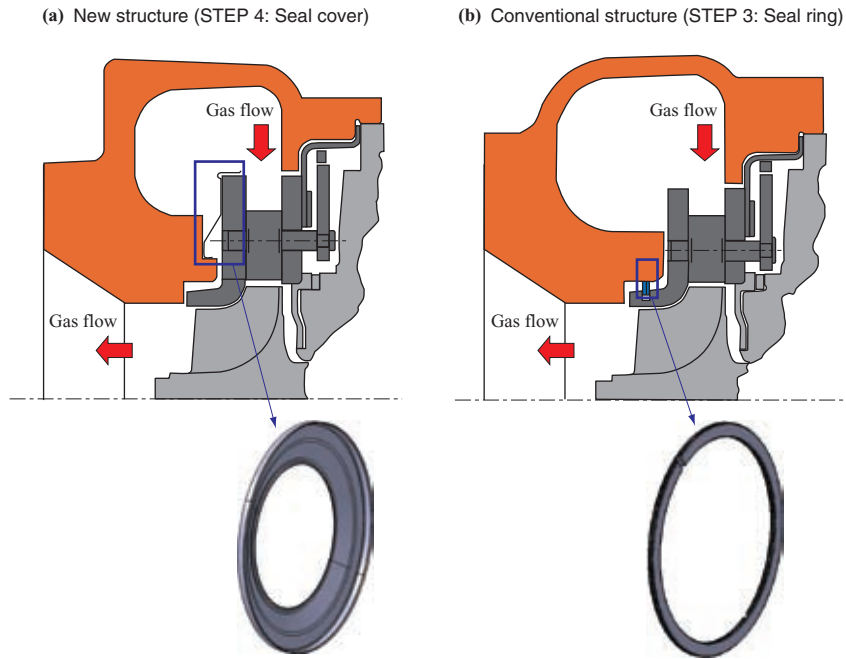


Fig. 6 Comparison of seal structures

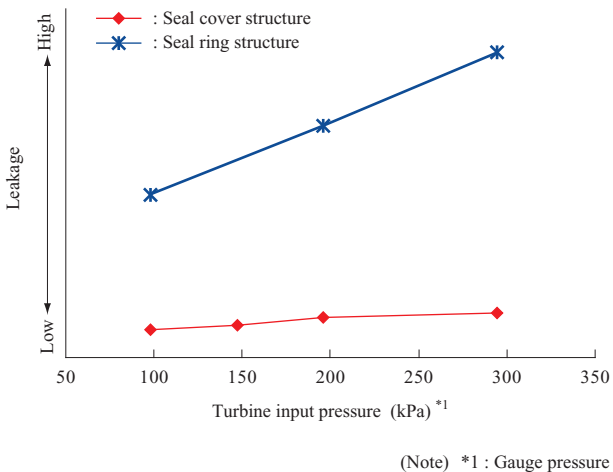


Fig. 7 Measurement of leakage

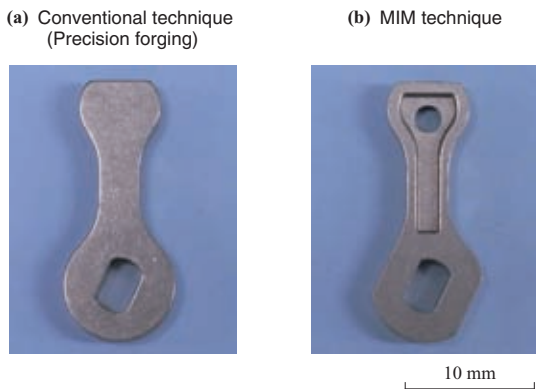


Fig. 8 MIM product (Link plate)

3.2 MIM material evaluation

Sintered parts with low filling factors have low strength; also, there are concerns about breakage due to oxidation in the high-temperature gas atmosphere. For this reason, they were not used in turbochargers previously. However, the adopted MIM technique enables a high filling factor of 95% or more.

To validate this technique, tensile, fatigue, creep, and other kinds of strength evaluation tests were conducted by using samples cut from actual parts and it was confirmed that the MIM material has strength equal to or higher than that of forging.

In addition, to make sure that the MIM material is not susceptible to high temperature oxidation, oxidation tests were conducted in the high temperature gas atmosphere and it was confirmed that the MIM material has oxidation resistance equal to or higher than that of forging (Fig. 9).

3.3 Application of the developed material

At high temperatures, the VGS repeatedly opens and closes the nozzle vanes through the link mechanism. Excellent tribological characteristics (friction and abrasion) are required for the sliding surfaces of the nozzle shafts as well as the nozzle vane edges (Fig. 10).

A specially developed high-silicon stainless steel material was applied to the sliding parts (parts opposite the nozzle) to reduce the friction coefficient and improve their abrasion resistance instead of the conventional stainless steel material.

As an element test for selecting the optimal combination of materials, a high-temperature sliding test for A (the combination of conventional materials) and B (the combination of specially developed materials) was

Item	MIM (Filling factor : 83%)	MIM (Filling factor : 95%)	Conventional technique (Forging)
Before test			
After 20 hours			
After 100 hours			
Test result	Large amount of oxidation	Small amount of oxidation	Small amount of oxidation

(Note) Test conditions
- Temperature : 900°C
- Gas flow velocity : 95 m/s

Fig. 9 Results of oxidation test

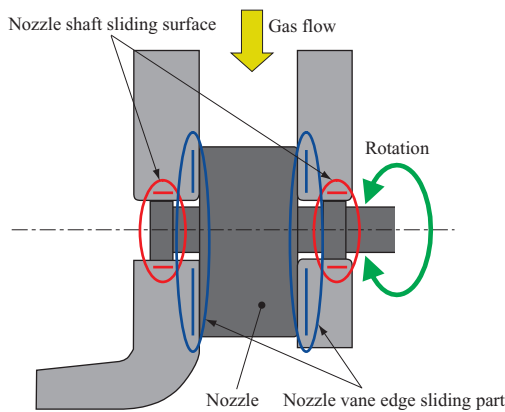


Fig. 10 Schematic of nozzle movement

conducted. The test results are shown in **Figs. 11** and **12**. The atmospheric temperature, load, and sliding speed were determined based on the actual operating conditions of the turbochargers.

A comparison of the friction coefficients reveals a 14% decrease in average value and 12% decrease in maximum value, proving that the developed material offers improved wear properties at high temperatures.

A comparison of adhesion height after the test reveals that both the flat plate made of the developed material and the opposite cylinder have low adhesion. The good results prove that this combination offers improved abrasion resistance.

Indicator	Combination of materials		Three-dimensional abrasion measurement		Abrasion state after test *1	Diagram of test
	Flat plate	Cylinder	Flat plate	Cylinder		
A	Conventional material (Stainless steel)	Stainless steel				
B	Developed material (High-silicon stainless steel)	Stainless steel				

(Note) *1
- Atmospheric temperature : 800°C
- Cycle : After 100 cycles

Fig. 11 Material condition after wearing test

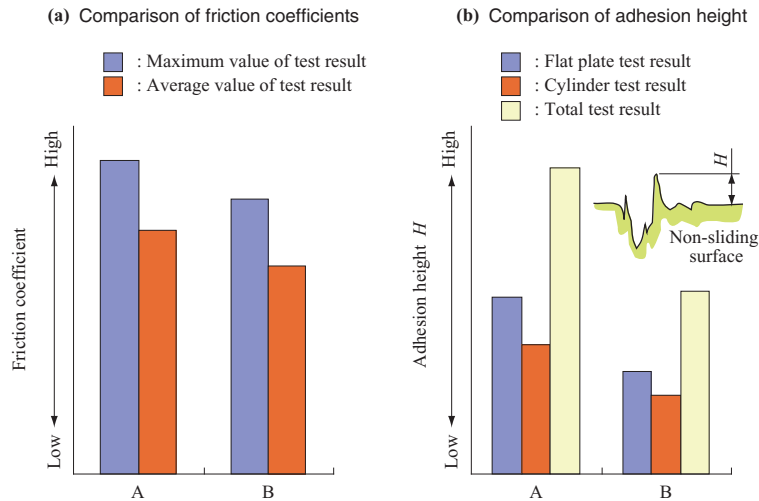


Fig. 12 Comparison of wearing test result

4. Conclusion

We have completed development of the RHV4 VGS turbocharger which features improved reliability by improving clearance flow control and the seal structure in addition to increasing turbine efficiency through adoption of a new technique and material. Mass production of this turbocharger was started in 2011 and this VGS technique will be applied to other models in the future to expand the series.

We will continue to make efforts to improve performance and assure high reliability to meet demands for higher performance turbochargers compatible with smaller, higher-output engines.

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