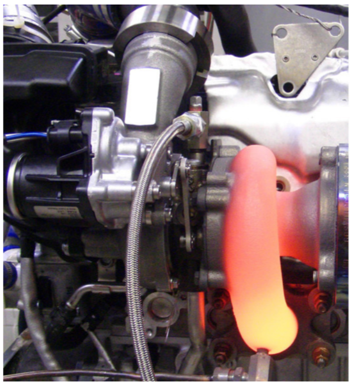
Development of VG Turbocharger for Next-Generation Gasoline Engines



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*In recent years, the application of Miller cycle and EGR to gasoline engines has advanced to improve thermal efficiency. Along with the application of these technologies, the use of variable capacity turbochargers (VG*1 turbochargers) providing better supercharging is rapidly advancing mainly in Europe and China. Mitsubishi Heavy Industries Engine & Turbochargers Co., Ltd. (MHIET) developed the VG turbochargers with a totally-renewed compressor and turbine aerodynamic design, and achieved an overall turbocharger efficiency improvement of +1% at low speed and +9% at high speed compared with the existing product.*

*1: Variable Geometry

1. Introduction

Recently, fuel consumption and exhaust gas in the actual operation of passenger vehicles are attracting increasing attention, and the application of emissions regulations in actual operation is under consideration. Under such a situation, the market share of diesel engines, which require significant cost to meet exhaust gas regulations under actual operating conditions, is decreasing, and on the other hand, the market share of gasoline engines, which offer comparatively-excellent cost performance, is expanding along with technological innovation at a rapid pace.

In recent years, the application of fuel consumption and exhaust gas reduction technology in the actual operation of gasoline engines has advanced compared with further supercharging downsizing because of its completion. Among these advancements, better supercharging, higher efficiency, and greater reliability are required for VG turbochargers with Miller cycle using variable valves, EGR (Exhaust Gas Recirculation), and theoretical air-fuel ratio combustion in a wide range of engine operation (1).

2. Performance requirements for VG turbochargers for gasoline engines

The VG Turbocharger is a turbocharger equipped with a drive mechanism that can variably control the nozzle area upstream of the turbine wheel. The variable nozzle enables the characteristics of the turbine to be controlled according to the engine speed and load. Furthermore, the supercharging efficiency is improved, because the inflow angle of the gas to the turbine wheel can be controlled by the nozzle. **Figure 1** shows the structure of VG turbochargers.

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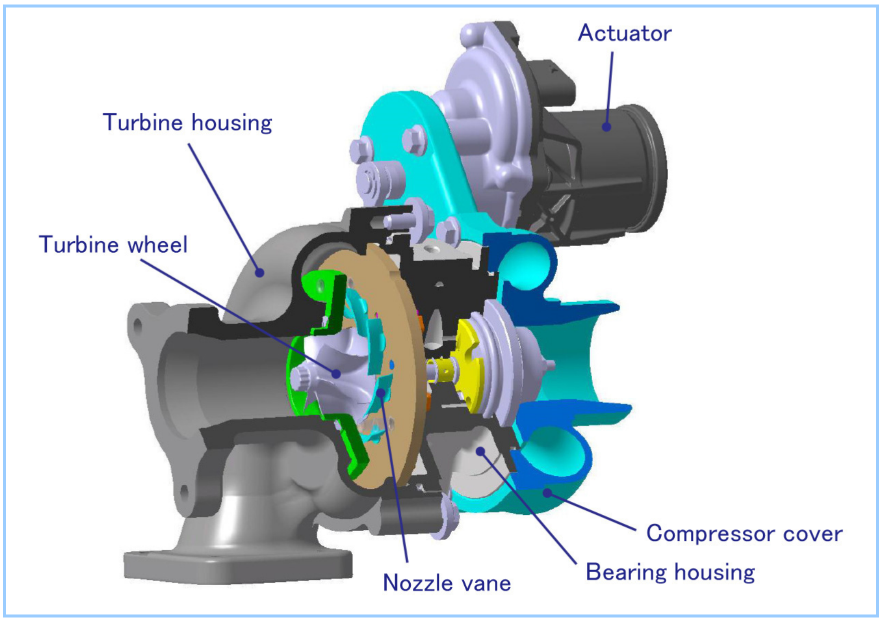

Figure 1 Structure of VG turbochargers

Figure 2 depicts the change in the compressor operating line when the Miller cycle is applied and λ = 1 in the entire operating range of the engine. In the low speed region where the engine speed is 1000 to 1500 rpm, since scavenging[*2] cannot be carried out to achieve λ = 1, the operating point shifts significantly to the low flow rate side, and the conventional compressor enters the surging (vibration of piping system with large reversed flow) region. Furthermore, the requirement of pressure ratio rises in the whole area, because Miller cycle is applied. The operating point of the turbine for operating the compressor is shown in **Figure 3**. To increase the pressure ratio of the compressor at low engine speeds, the characteristics of a lower flow rate than W/G[*3] without the Miller cycle are required, and at high engine speeds, it is necessary to cover a large flow rate region.

*2: Sweep the combustion chamber by overlapping intake and exhaust valves.

*3: Waste Gate: a valve mechanism that bypasses a portion of the turbine flow to the turbine outlet.

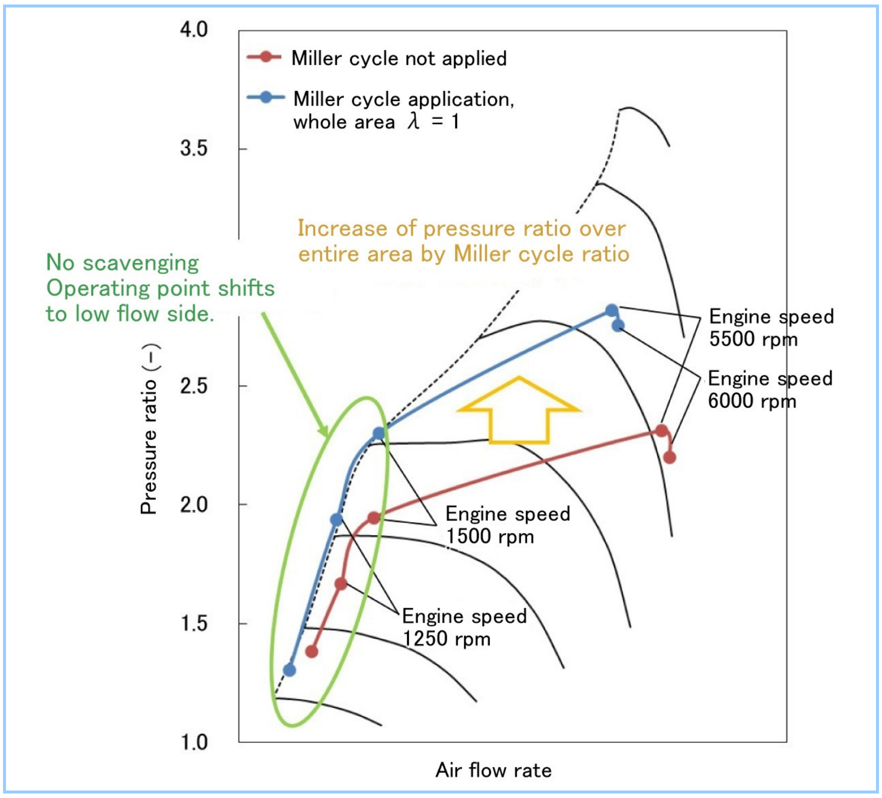

Figure 2 Change in compressor operating point due to application of Miller cycle

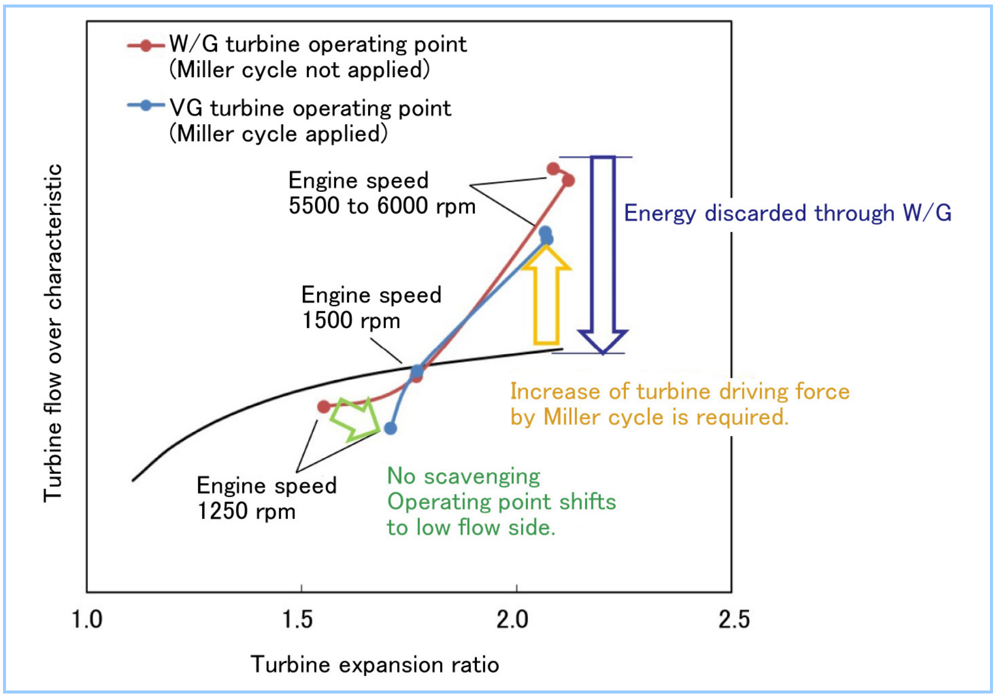

Figure 3　Change of compressor operating point due to application of Miller cycle

3. Technology for improving centrifugal compressor performance

Centrifugal compressors used in next-generation VG turbochargers for gasoline engines require (1) stable operation over a wide flow rate range, (2) the achievement of the high pressure ratio required from the engine and (3) high efficiency throughout the entire operation.

In response to these performance requirements, there are fundamentally strong trade-offs between performance requirements as noted below.

(1) When the flow path area (impeller throat area, diffuser width, scroll area, etc.) is downsized to reduce the surging flow rate, which is the operating limit on the low flow rate side, the maximum capacity decreases.

(2) Increasing the pressure ratio amplifies the risk of backflow and makes surging more likely to occur.

(3) When the impeller is designed in accordance with the flow condition near surging, the flow velocity increases and the efficiency is deteriorated at the high flow rate operation.

Therefore, aerodynamic designs with good balance, that can simultaneously improve all performance requirements, are needed, after phenomena which arise in each part are analyzed quantitatively and in detail.

Figure 4 illustrates the compressor impeller specially designed for the VG turbochargers. At the low flow rate operation point, the loss caused by stalling of the impeller and the flow separation of each part becomes dominant, as does the loss caused by shockwaves from the high flow velocity and wall surface friction at the high flow rate operation point. Here, the blade load distribution was optimized so that stalling at the impeller tip and flow from the blade hub side to the tip side can be reduced, while the flow path area is expanded to ensure the maximum flow rate. **Figure 5** gives the average loss distribution in the circumferential direction at the low speed, low flow rate operating point corresponding to the maximum torque point. In the improved design, it has been proven that reversed flow near blade tip is reduced by blade load distribution correction, and in particular, the loss generation near the impeller inlet can be reduced. **Figure 6** lists the blade tip side relative Mach number distribution at the high speed, high flow rate operating point corresponding to the maximum power point. It is necessary to suppress the strong pressure change before and after the shockwave, because it generates flow strain such as the development of a boundary layer and the extension of the leakage flow region. In existing impeller, a strong shockwave was generated at the minimum channel area position, but the shockwave which was a loss generation factor could be relaxed by the angular distribution correction of the impeller.

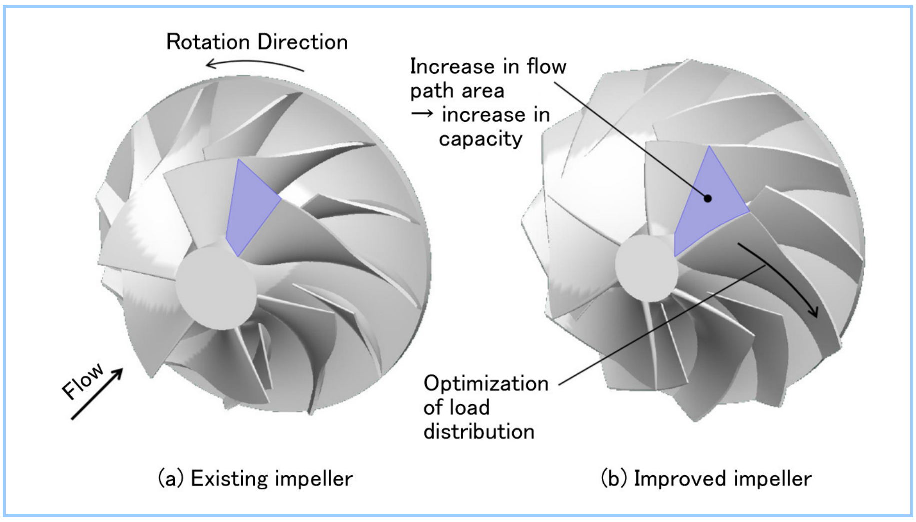

Figure 4 Improvement of compressor impeller

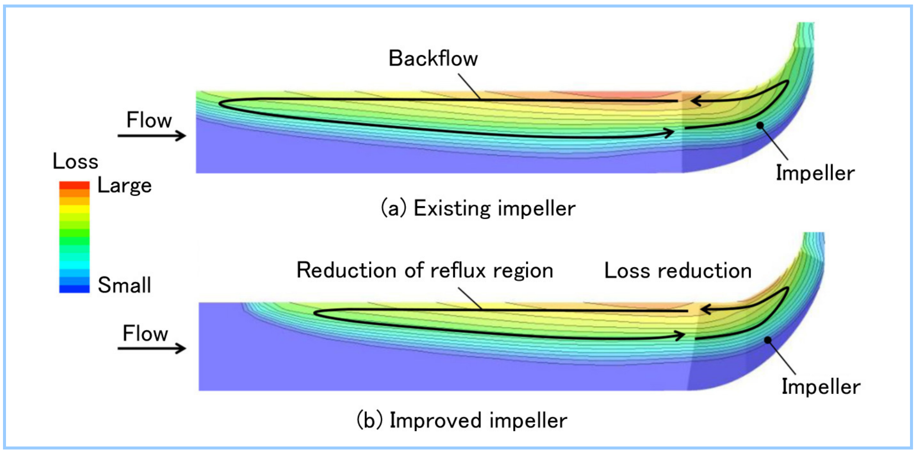

Figure 5 Loss Distribution at Maximum Torque Point

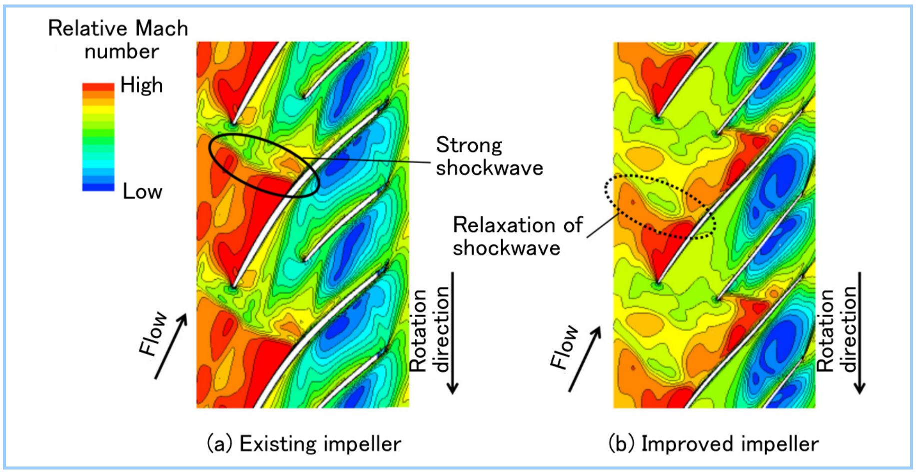

Figure 6 Relative Mach number distribution at maximum output point

Figure 7 depicts the diffuser and scroll specially designed for the improved impeller. Although the diffuser is one of the components of the compressor which recovers the pressure by expanding the channel area, this time we decided to reduce the surging flow rate by suppressing the pressure recovery. In the meantime, the loss generation was suppressed by the shape optimization of the scroll, and the coexistence of high efficiency and a wide operating range was attempted.

Figure 8 gives the individual performance characteristics of the compressor. Compared with the existing product, the improved product has a capacity of +20% while maintaining the surge flow rate and the operating range has been expanded by 12%. The pressure ratio has been improved from 3.5 to 3.7 at the same rotational speed, and the maximum output point has been achieved at a rotational speed 7% lower than that of the existing product. This contributes to not only the requirement being met with some leeway, but also to the improvement of the response and increased output. The efficiency was improved drastically by +0.2% at the maximum torque point and +5.3% at the maximum output point, and the effectiveness of this improved design was verified.

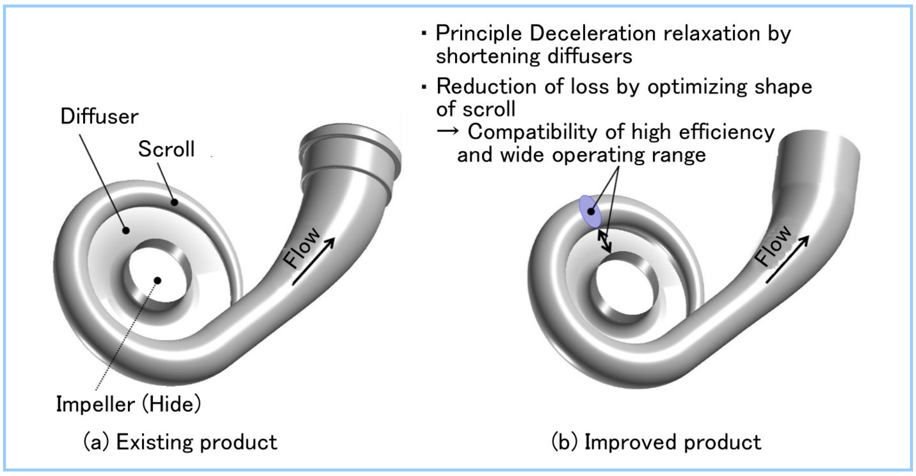

Figure 7 Diffuser and Scroll Improvements

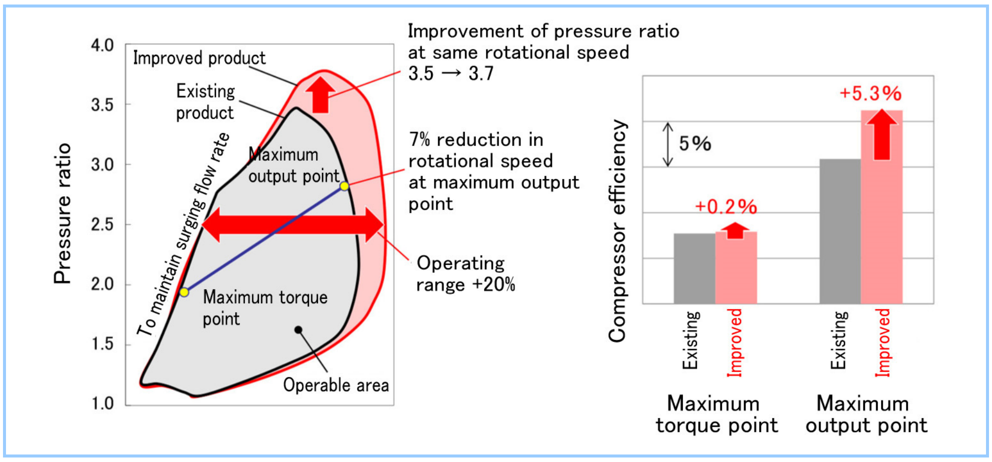

Figure 8 Performance Improvement by Improved Compressor

4. Aerodynamic design of the turbine

Since the aerodynamic design of the VG turbine affects not only performance, but also reliability, development was carried out to satisfy the following three requirements:

(1) Improvement of aerodynamic performance at required operating points
(2) Ensuring flow controllability (Reduction of flow hysteresis*4)
(3) Reduction of drive parts wear

To satisfy above three requirements, the flow of each scroll, nozzle and rotor blade was focused on, and design improvements were implemented.

The appearance of the scroll is illustrated in **Figure 9**. I In the developed scroll (Figure 9 (b)), the shape from the inlet to the scroll, the structure of the scroll cross section and the change of the cross section in the circumferential direction were optimized to suppress flow distortion in the scroll circumferential direction and to make the flow uniform for multiple nozzle vanes. The scroll internal flow is shown in Figure 9. In the existing scroll, the loss was generated by flow distortion formed in the scroll flowing into the nozzle, but in the improved scroll, the loss is reduced from circumferentially the second quarter of the scroll. Furthermore, it can be confirmed that the low pressure region decreases in the improved scroll near the tongue part where the effect of the flow distortion is the highest, and thus the loss is suppressed.

In the design of the nozzle vane, a design in which turbine performance improvement in the nozzle low opening angle, improvement in controllability and reduction in the wear amount of the drive section were compatible was implemented. In the nozzle low opening angle, a vortex is formed by the interference of the main flow from the nozzle channel (throat section) and leakage flow from the side clearance, and the loss inside the rotor blade seemingly increases due to this vortex. In the improved nozzle, to limit this leakage loss, the flow interference was reduced and vortex formation was suppressed (**Figure 10**) by narrowing the throat width at the tip of the nozzle and adopting a three-dimensional shape to guide the flow to the blade center span side. The vane profile was also designed to optimize the aerodynamic moment and load generated by the pressure distribution around the nozzle vane, aiming at the reduction of flow hysteresis and drive wear. MBD*5 was used for the wear evaluation of the drive section, and the temperature, pressure fluctuation and vibration measured in the actual engine were input. The design was implemented so as to minimize FV*6, which is a parameter expressing the wear severity of each sliding part.

*4: Difference in flow rate between the closing → opening operation and the opening → closing operation at the same drive unit operating position feedback value

*5: Multi Body Dynamics, Mechanism Analysis

*6: Product of force and sliding speed

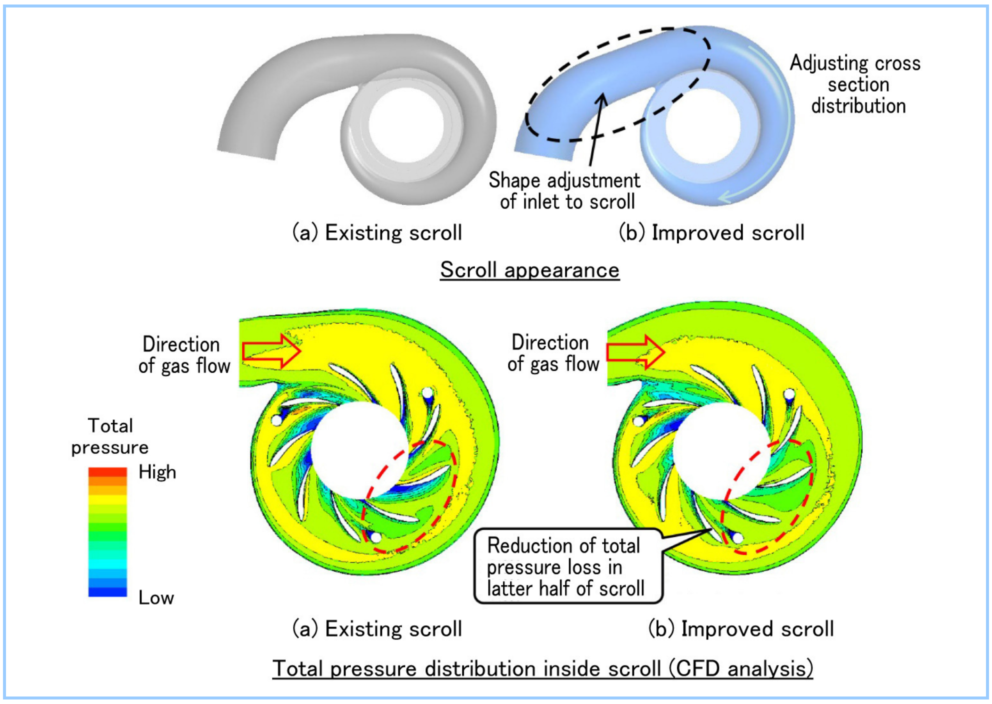

Figure 9 Improved design of turbine scroll

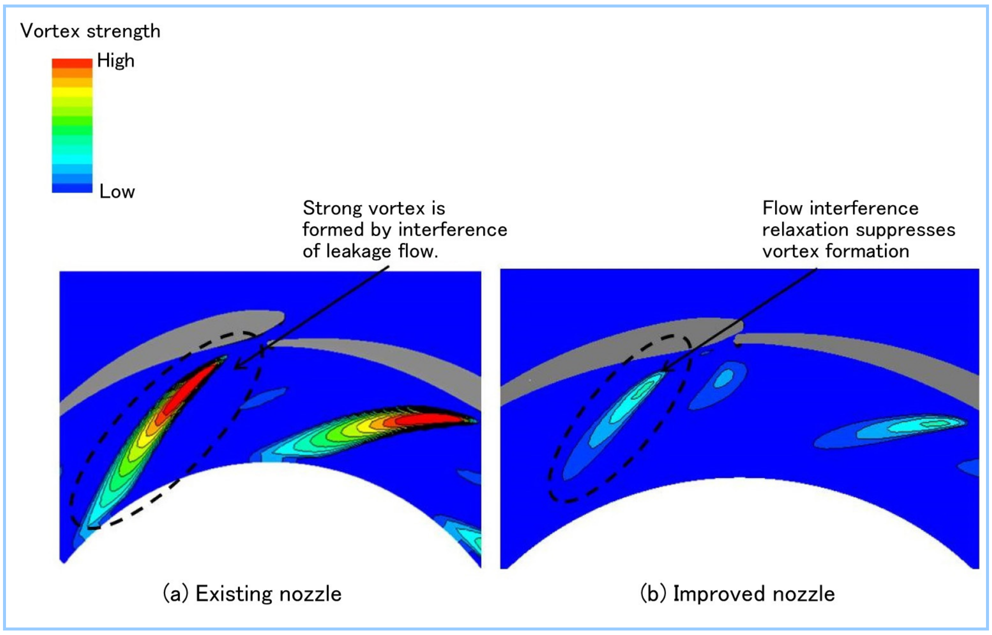

Figure 10: Flow inside turbine nozzle

The performance of the rotor blades of the VG turbine was improved over the entire range from low flow rates to high flow rates by adjusting the blade size and optimizing the blade shape assuming the flow rate range for small vehicles. In particular, loss structure caused by leakage from blade clearance was focused on to attempt performance improvement in the middle flow quantity. **Figure 11** shows the flow pattern inside the rotor blade. In the existing shape, the leakage flow from the clearance forms a vortex at the blade tip side, and the vortex which diffuses in the process in which this vortex flows on the blade surface increases the loss region. Although the vortex itself is generated on the improved rotor blade, performance improvement was attempted by suppressing the diffusion of the vortex and reducing the loss region by optimizing the blade load.

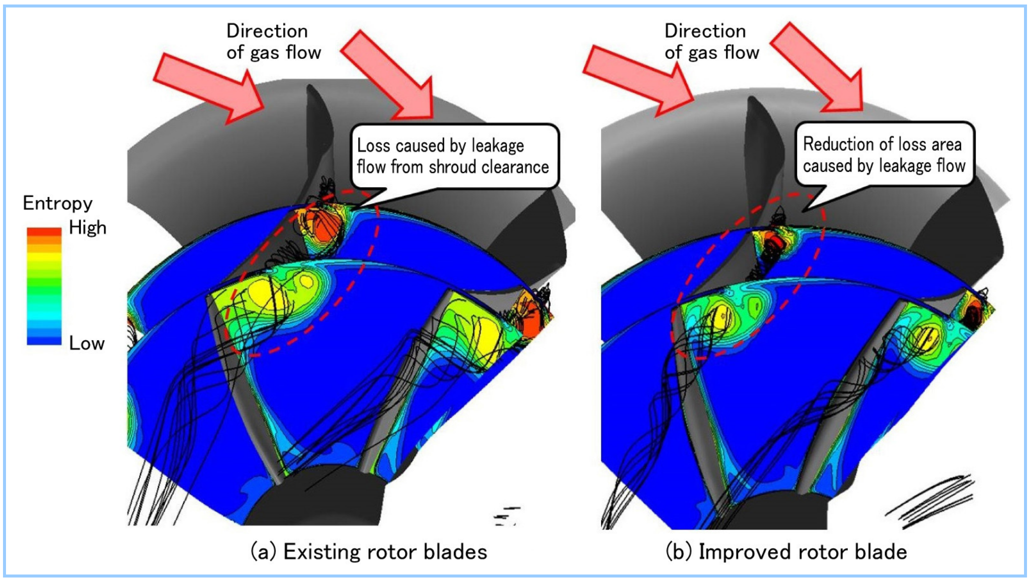

Figure 11 Entropy distribution and flow line inside rotor blade

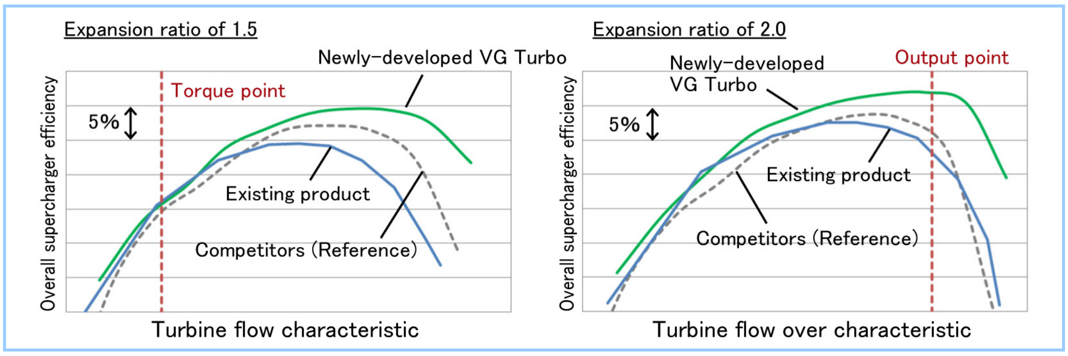

Figure 12 Improvement of turbocharger efficiency by newly developed VG turbochargers

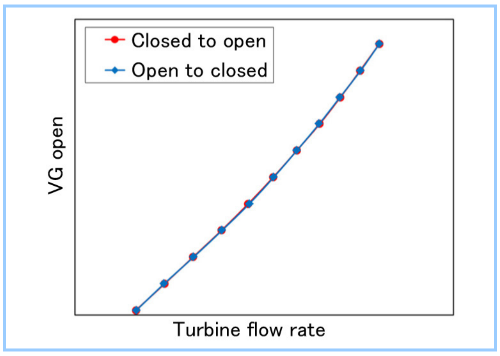

Figure 13 Flow hysteresis evaluation test results

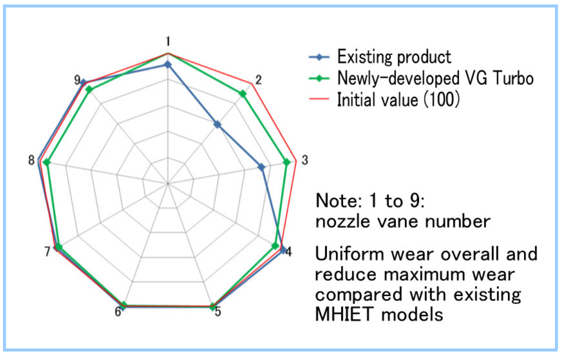

Figure 14 Improvement of wear on drive part during engine endurance test

Figure 12 presents the performance test results of the VG turbochargers to which these newly-developed technologies were applied, **Figure 13** gives the measurement results of flow hysteresis, and **Figure 14** provides the wear amount evaluation results after the engine endurance test. In terms of the performance, the total efficiency at the torque point and output point was improved by 1% and 9%, respectively, compared with the specifications before the improvement. It was confirmed that there were no problems in terms of flow hysteresis. The amount of wear on the drive section tended to increase partially before the improvement, but it was confirmed that the newly-developed product wore more uniformly and the maximum wear amount was reduced.

5. Conclusion

For the purpose of compatibility of high performance and high reliability of the VG turbochargers, the improvement of aerodynamic design, the improvement of total turbocharger efficiency and the wear reduction of the drive section were achieved, while also maintaining controllability.

In recent years, the technological innovation of turbochargers for gasoline engines has been advancing at a dizzying speed. It is necessary to develop high-performance and high-quality products in a timely manner, and MHIET will continue to improve performance and reliability.

References

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