# Development of Turbocharger Dedicated to Series-hybrid Engines

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*With initiatives to reduce greenhouse gas emissions being promoted as a countermeasure to global warming, the trend toward electrification of automobiles is accelerating in order to achieve low-carbon and decarbonized vehicles. Hybrid vehicle engines use a motor assist to achieve higher efficiency, and their operating range is limited. Mitsubishi Heavy Industries Engine & Turbocharger, Ltd. (MHIET) has developed a high-efficiency vaned diffuser compressor and vaned nozzle turbine that meet requirements for such hybrid vehicle engines. In addition, we have studied and evaluated simplified structures to provide these products at low cost. This report describes these matters.*

## 1. Introduction

Due to emissions of greenhouse gases such as $CO_2$, average air and sea temperatures are increasing, resulting in rising sea levels and extreme climate events such as heavy rainfall and drought on a global scale. This has become an issue that needs to be addressed worldwide. In order to solve this issue, various approaches are being taken, targeting carbon neutrality, which means zero emissions of greenhouse gases overall. In the automotive industry, trends toward stricter $CO_2$ emission regulations have been observed, and Europe has set a goal of reducing $CO_2$ emissions by 100% by 2035, compared to the 2021 level (1). In response to these stricter regulations, automakers are accelerating the development of battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs), which do not emit $CO_2$. However, there are many issues to be addressed, including the need to develop infrastructure for supplying electricity or hydrogen to these vehicles, as well as the need to develop manufacturing processes and facilities that use renewable energy so as not to emit greenhouse gases during the production of these power sources. While the sales ratio of BEVs and FCEVs is expected to increase in anticipation of future solutions to these issues, it is assumed that hybrid vehicles, which are propelled by both internal combustion engines and motors, will continue to be produced during the transitional period. In order to achieve lower carbon emissions under these circumstances, it is necessary to lower carbon emissions of hybrid vehicles, and improving the energy conversion efficiency of strong hybrid vehicles, which are highly beneficial for improving fuel efficiency, is particularly effective. We are currently developing and designing turbochargers that contribute to increasing the efficiency of engines for hybrid vehicles. This report describes the development status of a high-efficiency turbocharger that meets the engine characteristics of series hybrid vehicles, which are one of the strong hybrid vehicles, and the structure to realize the reduction in the cost thereof.

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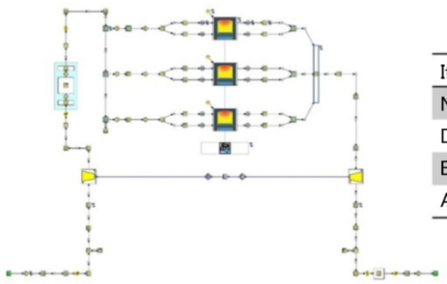
## 2. Characteristics required for turbochargers equipped on engines for series hybrid vehicles

Due to the assistance provided by the motor, engines for hybrid vehicles can mainly utilize their high-efficiency range, and thus can adopt engine specifications that match the main operating range. Among them, for engines for series hybrid vehicles, which specialize in power generation, efforts are underway to achieve a peak thermal efficiency of 50% by searching for a highly efficient operating point (2). In order to achieve this increase in efficiency, lean burn, which can improve theoretical thermal efficiency by increasing the specific heat ratio of the working gas and suppress in-cylinder cooling loss by reducing the combustion temperature, is important. For that, the adoption of an air excess ratio $\lambda > 2.0$ is being examined, taking NOx aftertreatment into consideration. For these engines, the compression ratio, intake and exhaust valve settings, etc., are expected to be changed from the conventional stoichiometric air fuel ratio specifications. In this study, we used the GT-Power cycle calculation model (**Figure 1**), which was constructed using engine test data obtained in-house, to estimate the engine specifications to be adopted for these engines, and analyzed the performance requirements for turbochargers to be used.



| Item | Set value |
|---|---|
| Number of cylinders | 3 |
| Displacement | 1.5 L |
| Brake mean effective pressure | 10bar |
| Air excess ratio | > 2.0 |

**Figure 1 GT-Power model of engine for series hybrid vehicles**
GT-Power cycle calculation model for examining performance requirements of turbocharger equipped on engines for series hybrid vehicles

**Figure 2** shows the results of examining the engine specification conditions necessary to achieve further improvement in the efficiency, based on a released lean-burn engine. We researched the conditions under which the thermal efficiency can be improved by changing the compression ratio, valve timing, and turbocharger efficiency. To improve thermal efficiency, it is effective to use a higher compression ratio and suppress knocking by adopting the Miller cycle with early intake valve closing at the same time. On the other hand, because the Miller cycle's earlier intake valve closing lowers the volumetric efficiency of the engine, and higher $\lambda$ increases the amount of air required, which increases pumping losses due to pressure drop at the intake and exhaust valves, etc., the required turbocharger efficiency tends to be higher.

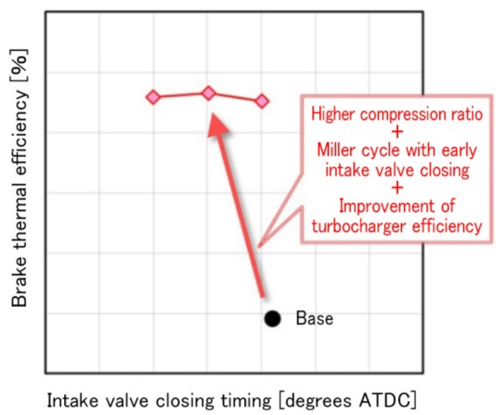



**Figure 2 Result of examination of high-efficiency specifications of engines for series hybrid vehicles**
Result of parameter study conducted to improve efficiency of engines for series hybrid vehicles

**Figure 3** shows the results of estimating the required turbocharger operating point to achieve the target thermal efficiency for the power generation point of an engine for series hybrid vehicles based on these calculation results. In contrast to the operating line of a conventional passenger vehicle engine also shown in the figure, both the compressor and turbine operate at lower pressure ratios than those of the conventional application because the engine of series hybrid vehicles is mainly operated in the mid-load range for power generation. Thus, it is assumed that higher turbocharger efficiency is required in these ranges. The following chapters specifically describe our efforts to achieve higher turbocharger efficiency.

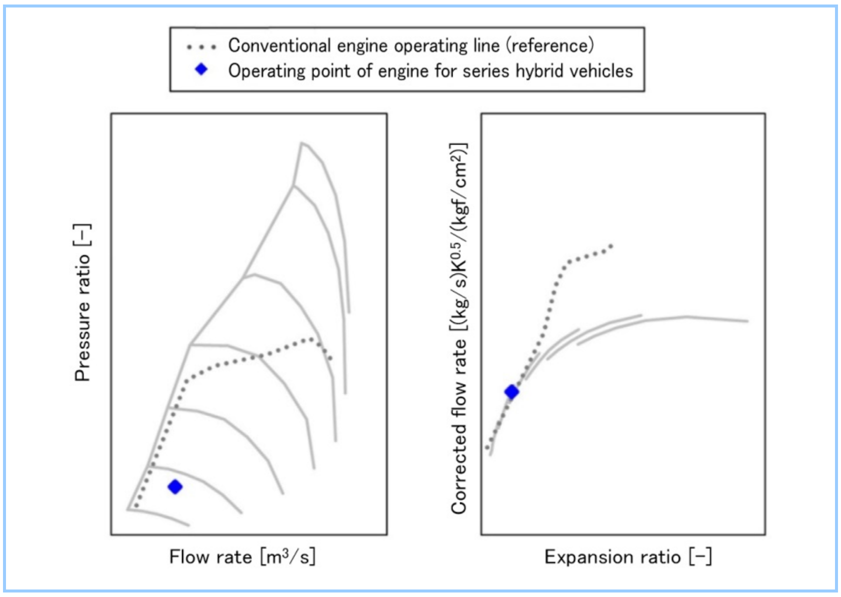



**Figure 3 Operating point estimation result of turbocharger equipped on engines for series hybrid vehicles**
Comparison of operating point of turbocharger equipped on engines for series hybrid vehicles obtained by studying required performance and operating point of turbocharger for conventional engines (reference)

## 3. Improvement of compressor performance

We have been developing centrifugal compressors that suit the characteristics of hybrid engines by reducing shock wave losses, leakage losses, friction losses, and mixing losses generated inside centrifugal impeller to increase the efficiency [(3)]. As described in Chapter 2, engines of series hybrid vehicles, which specialize in power generation, mainly operate at a high-efficiency operating point. Thus, the compressor efficiency can be further improved at the engine operating point by employing vaned diffuser which is equipped in the downstream of compressor impeller trailing edge. So, we worked on the development of a centrifugal compressor, which applies a vaned diffuser.

**Figure 4** shows the three dimensional schematic view of the newly designed impeller and vaned diffuser. As for the impeller, the blade shape was adjusted to match the engine operating point to reduce the losses inside the impeller. In addition, the blade loading was increased to reduce mechanical losses of bearing by reducing operating speed. For the diffuser vanes, an optimization algorithm was used to search for the vane profile with the lowest loss.

**Figure 5** shows the performance maps and test results of the newly designed compressor. In the compressor map, operation is limited on the left by the surge line. The surging limit of the newly designed compressor has moved to the high flow rate side and the operating range has shrunk compared to the conventional compressor with vaneless diffusers. On the other hand, the engine operating point is within the operating range, and it can be confirmed that the efficiency near the engine operating point improved by 4.7 points. Furthermore, since the operating turbocharger speed was reduced by 6.6%, a reduction in mechanical loss can be expected.

Moving forward, we will work on improving the scroll, one of the key components of the compressor, to further increase turbocharger efficiency.

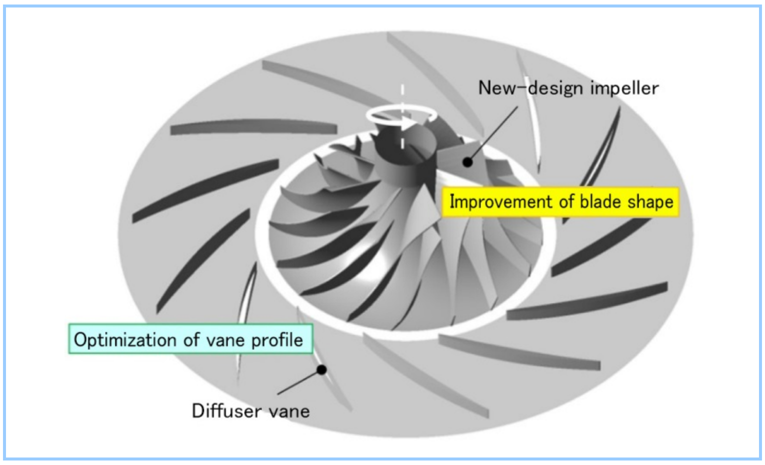



**Figure 4 Schematic view of centrifugal compressor**
New-design compressor appearance and efficiency enhancements

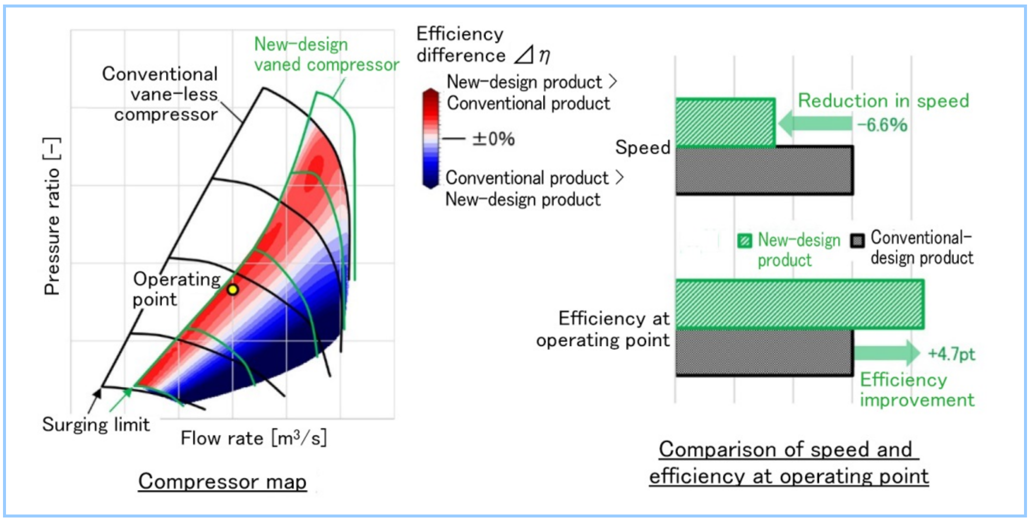



**Figure 5 Performance test result of centrifugal compressor for series hybrid vehicles**
Performance test results of centrifugal compressor for series hybrid vehicles compared to conventional compressor

## 4. Improvement of turbine performance

In addition to the compressor, we have designed an improved turbine that aims to achieve high-efficiency specifically at the point of power generation. In order to ensure a wide operating range, existing turbines for passenger vehicles use vaneless nozzles without guide blades at the turbine inlet or variable vaned nozzles with variable guide blades. However, for engines for hybrid vehicles, which do not require a wide operating range, we consider that vaned nozzle turbines with a fixed guide blade placed at the turbine inlet are advantageous because they can form an ideal flow field at the design point. The vaned nozzle has the advantage over the vaneless nozzle in reducing losses at the scroll and nozzle, and also has the advantage over the variable vaned nozzle in reducing leakage flow at the end of the guide blades. For this reason, we have been developing a vaned nozzle for use in engines for hybrid vehicles [(3)].

To further improve the efficiency of the existing vaned nozzle turbines, we worked on improving the design of the rotor blades and vaned nozzle, and developed a vaned nozzle turbine with higher efficiency. **Figure 6** indicates the efficiency improvement, which was 2.9 points compared to the existing product at the operating point.

There were two factors that contributed to the efficiency improvement. The first was the reduction in leakage flow between the rotor blades and the housing. Turbocharger turbine rotor blades have a clearance at the blade tips to avoid contact with the housing, and the pressure difference between the front and back of the blades causes leakage flow at the clearance, resulting in loss. Smaller turbochargers have a larger percentage of the clearance relative to the channel height, so the effect of leakage flow tends to be larger. **Figure 7** compares the flow velocity distribution in the cross-section perpendicular to the flow path between the conventional and improved designs resulted from the analysis results. It is observed that the improved blade shape reduces the leakage flow velocity. As a result, the internal flow of the turbine rotor blade was improved, resulting in increased efficiency. The second was the reduction in blade thickness of the rotor blades. As described in Chapter 2, turbochargers for engines for series hybrid vehicles are operated only in the lower pressure ratio range compared to conventional turbochargers for passenger vehicles, resulting in lower operating speed and lower stress on the rotor blades. This reduces strength requirements and enables thinner blade designs. Thus, the mixing loss in the wake of the rotor blades was reduced and the efficiency was improved.

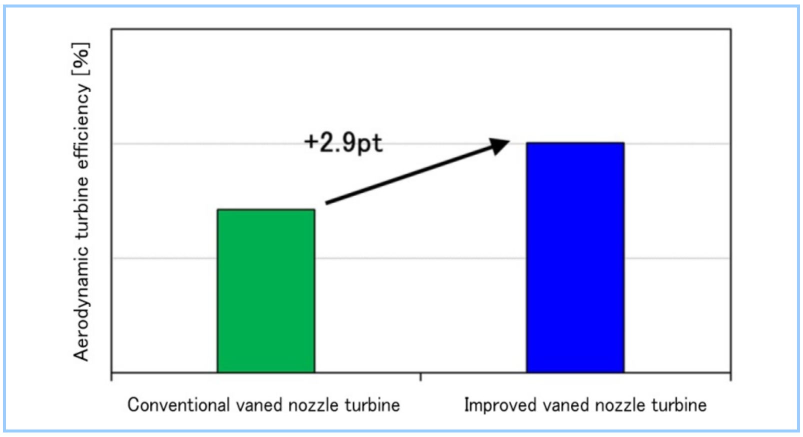



**Figure 6 Improvement of aerodynamic efficiency due to improved vaned nozzle turbine**
Improvement of aerodynamic efficiency of improved vaned nozzle turbine design compared to conventional design

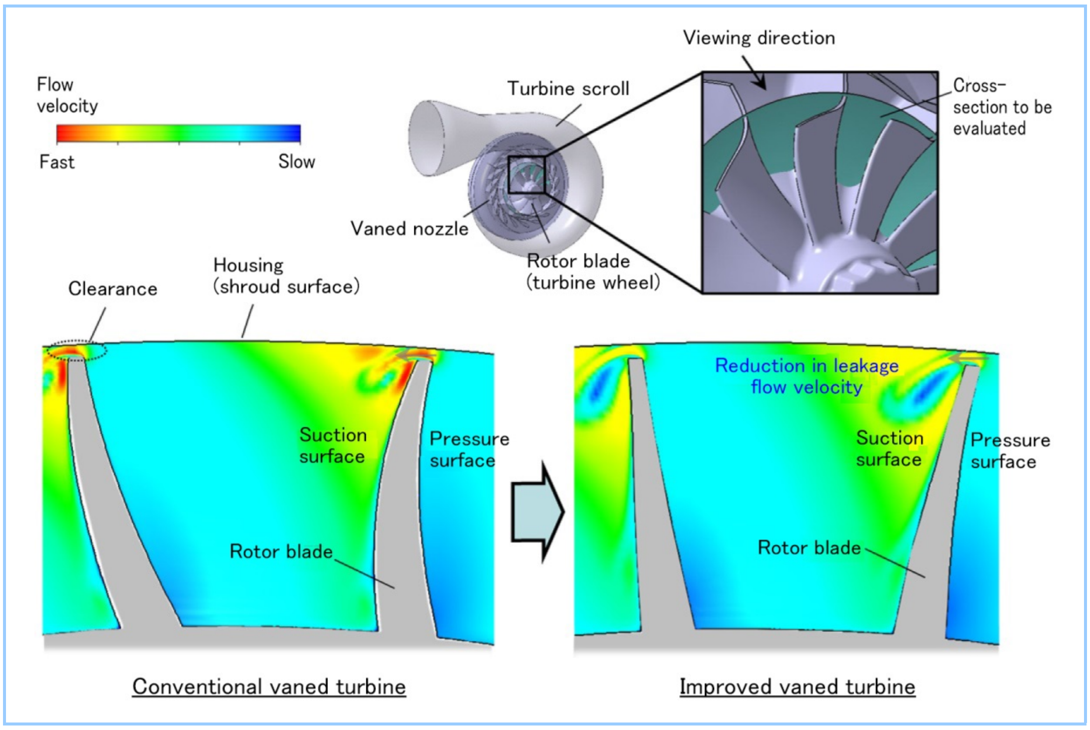



**Figure 7 Reduction in leakage flow velocity at blade tip due to improvement of blade shape**
Flow velocity distribution in cross-section perpendicular to flow path between conventional and improved vaned turbines resulted from analysis results

## 5. Improvement of vaned nozzle turbine structure for lower cost

As described in Chapter 4, we are developing a vaned nozzle turbine in order to improve the efficiency of turbines for engines for series hybrid vehicles. Vaned nozzle turbines operate under severe high temperature conditions caused by exhaust gas from the engine, and thus are required to have high reliability. On the other hand, since they use heat-resistant alloys, their cost tends to be high. Therefore, they are required to be low-cost through structural innovations and the selection of appropriate materials. In response, we sought to develop a cost-reduced structure with fewer parts and smaller components compared to the conventional structure, as shown in **Figure 8**. The conventional structure was based on a fastening structure that has been used in turbochargers for large power generation engines, and was designed to rigidly fix the heavy nozzle ring. The newly developed structure takes advantage of the lighter weight of the nozzle ring due to the downsizing of the turbocharger to use the spring force of the back plate to press the nozzle ring against the turbine housing. This eliminated the nozzle plate and spring ring, reducing the number of parts and also the size of the nozzle ring.

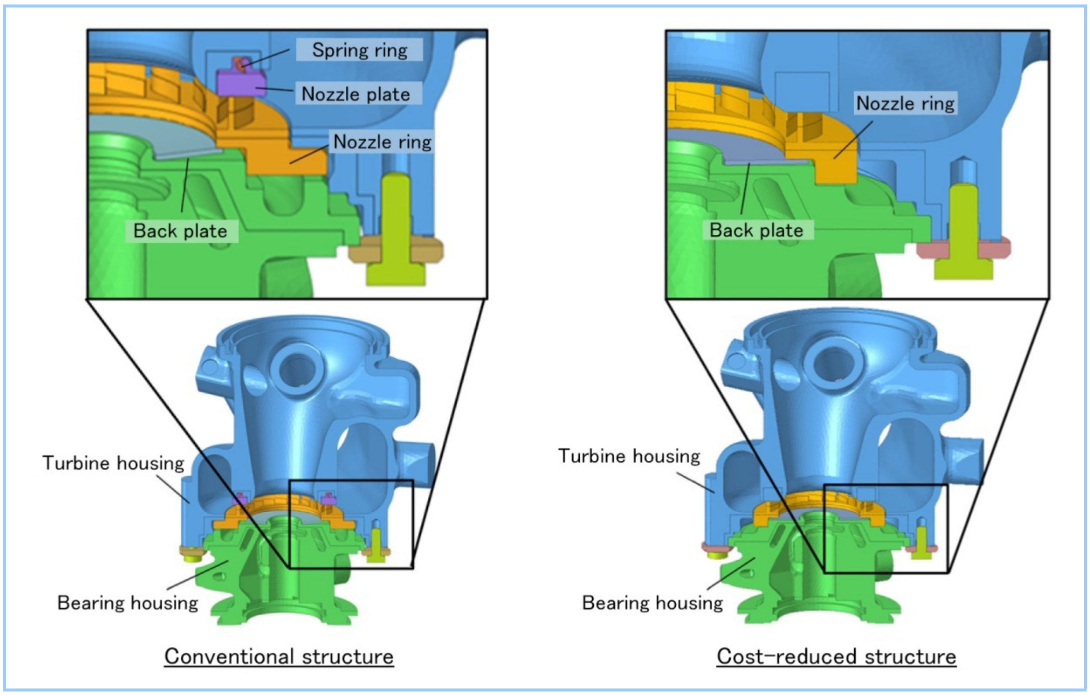



**Figure 8 Comparison of conventional and cost-reduced structures**
Comparison of conventional and cost-reduced vaned nozzle turbine structure

To evaluate the reliability of this structure, we performed a structural analysis using a large-scale 3D-FEM (Three Dimensional Finite Element Method) model. **Figure 9** shows a metal temperature contour diagram and a total strain range contour diagram as examples of the analysis results. Figure 9 (a) indicates that by supporting the nozzle ring by a spring, the temperature in the part becomes uniform and thermal stress due to temperature distribution can be kept low. The total strain range contour diagram shown in Figure 9 (b) indicates that thermal fatigue strength evaluation of high-temperature components such as the nozzle ring, turbine housing, and back plate resulted in satisfying the target life. In addition, we also performed a wide range of other strength evaluations, such as spring force of the back plate, contact surface pressure of the nozzle vane and bolt tightening force, to ensure the reliability of the vaned nozzle turbine. Furthermore, we also conducted structural analysis with different exhaust gas temperatures and materials for each component. The selection of appropriate materials according to the customer's engine exhaust gas temperature can reduce the material cost.

In this manner, we developed a low-cost and highly reliable vaned nozzle turbine by using large-scale 3D-FEM structural analysis for strength design and material selection.

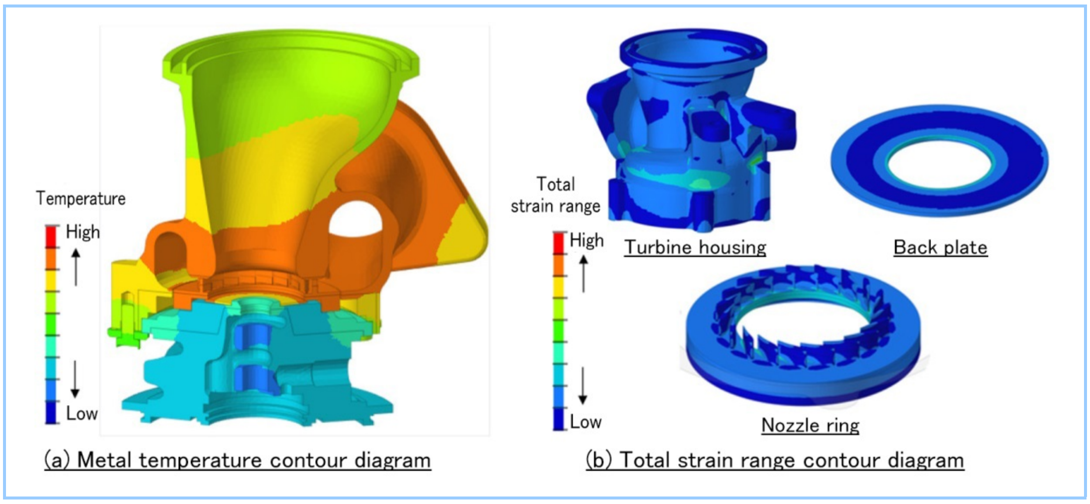



**Figure 9　Strength evaluation by unsteady thermal stress analysis**
Result of evaluating strength of cost-reduced structure by unsteady thermal stress analysis

## 6. Conclusion

This report described the development of a vaned nozzle turbine and vaned diffuser compressor to achieve high efficiency in turbochargers for engines for series hybrid vehicles, which contribute to the reduction in carbon dioxide emissions from automobiles. It also introduced an improved structure to provide the turbocharger at low cost and the status of its reliability evaluation.

We will continue to develop highly efficient and reliable turbochargers and contribute to the achievement of a sustainable low-carbon society through the practical application and diffusion of these technologies by proposing them to automakers.

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