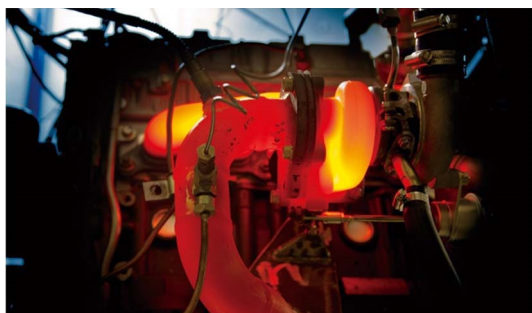


# Development of Automotive Turbochargers Contribute to Environmental Load Reduction



MAKOTO OZAKI\*1

MOTOKI EBISU\*1

YOSUKE DANMOTO\*1

YOUJI AKIYAMA\*2

TAKAO YOKOYAMA\*3

TADASHI KANZAKA\*4

*In recent years, further performance enhancement of supercharging systems has become necessary in response to environmental regulations getting stricter. Major countries plan to make regulations on CO<sub>2</sub> emissions from automobile engines even stricter. In the sector of turbochargers, development that can contribute to improvement in the thermal efficiency of engines is required. We have developed the fundamental elements of a turbocharger including a turbine with enhanced performance in the low-speed ratio region, a compressor with enhanced efficiency in the vicinity of surging, and a bearing, for which mechanical loss was reduced by optimizing the load, and supercharging systems including a VG turbocharger for gasoline engines and an electric compressor. These developed elements and systems are supplied to automobile manufacturers as samples.*

## 1. Introduction

In recent years, environmental regulations have been getting stricter as a measure against global warming. In Europe, CO<sub>2</sub> emissions from automobile engines will be regulated to 95 g/km in 2021, and therefore, automobile manufacturers all over the world are working on developing technologies to deal with the regulation. Supercharging systems represented by turbochargers contribute to improving the fuel efficiency of automobiles, and are effective for reducing CO<sub>2</sub> emissions. Because the supercharging systems have good compatibility to direct injection, they have been increasing their share as direct injection supercharged gasoline engines. In fact, among automobile gasoline engines for automobiles newly released in 2015, the proportion of direct injection supercharged engines increased even in Japan, where hybrid vehicle sales are strong. In the North American market, a clear tendency of shifting to small displacement engines and an increase in the proportion of direct injection supercharged engines has been seen. In addition, over 70% of engines installed in new vehicles in the European market, which is the home of direct injection supercharged gasoline engines, are direct injection supercharged engines.<sup>1</sup>

Automobile manufacturers have been developing various technologies for improving the fuel efficiency of direct injection supercharged gasoline engines. The past trend was improvement in the fuel efficiency mainly by downsizing and downspeeding of engines. In recent years, efforts to further improve fuel efficiency have also been progressing through adoption of cooled EGR (exhaust gas recirculation), mirror cycle using variable valves, lean combustion, HCCI (homogeneous charge compression ignition), and so forth. Keeping in step with such development trends for engine technologies, Mitsubishi Heavy Industries Engine & Turbocharger, Ltd. (MHIET) is developing systems including variable capacity turbochargers and electric compressors, in addition to component technologies for turbines, compressors, bearings, and so forth, to deal with the strict requirements for superchargers. This paper presents the state of our ongoing development of turbochargers for automobiles.

\*1 Chief Staff Manager, Turbocharger Division, Mitsubishi Heavy Industries Engine & Turbocharger, Ltd.

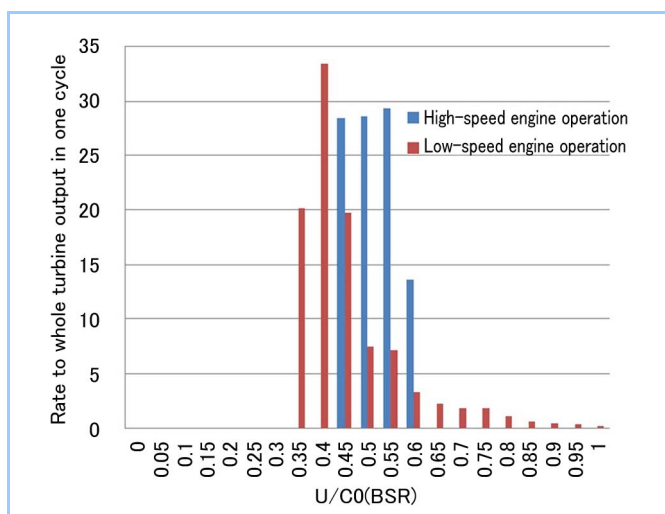
\*2 Turbocharger Division, Mitsubishi Heavy Industries Engine & Turbocharger, Ltd.

\*3 Chief Staff Manager, Fluid Dynamics Research Department, Research & Innovation Center, Mitsubishi Heavy Industries, Ltd.

\*4 Fluid Dynamics Research Department, Research & Innovation Center, Mitsubishi Heavy Industries, Ltd.

## 2. Development of turbines

Downspeeded supercharged engines are required to enhance the torque in the low-engine-speed region. For performance enhancement of such engines, a different design from ordinary radial turbines is necessary also in terms of a turbocharger because the effects of the exhaust pulsation are significant when the engine rotation speed is low. One of the dimensionless parameters that represent a turbine efficiency characteristic is a speed ratio ( $U/C_0$  where  $U$  is the circumferential speed of the turbine and  $C_0$  is the theoretical isentropic speed). Many ordinary radial turbines have an efficiency peak at a point around  $U/C_0=0.65$ . When the engine rotation speed is low, performance at an operating point with a low  $U/C_0$  is important because of the effects of exhaust pulsation. **Figure 1** shows the rate of the turbine output at various speed ratios to the whole turbine output in one cycle of a 1.6-liter direct injection gasoline engine under full load conditions. When the engine rotation speed is high, the highest turbine output is obtained at a point around  $U/C_0=0.55$ . When the engine rotation speed is low, however, the highest turbine output is obtained at a point around  $U/C_0=0.4$ . Therefore, it can be confirmed that the performance in the low  $U/C_0$  region is important.



**Figure 1 Rate of turbine output at various speed ratios to whole turbine output in one cycle**

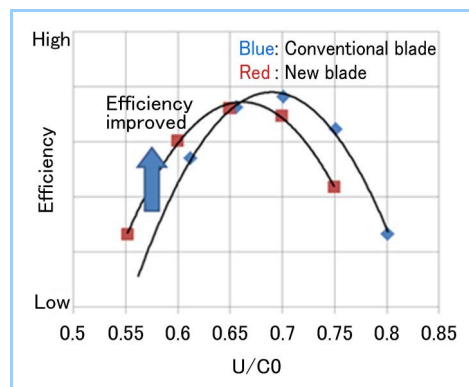
(1.6-liter direct injection gasoline engine: Result of one-dimensional engine simulation)

MHIET changed the turbine blade design from the conventional radial one to a mixed flow one to enhance efficiency in the low-speed-ratio region, and obtained good results. **Figures 2 and 3** show the external view of the new mixed flow turbine and its efficiency characteristics with respect to the speed ratio  $U/C_0$ .

In addition, the new mixed flow turbine described above was installed on a 1.6-liter direct injection gasoline engine and then its torque characteristics were measured. The obtained results were good and indicated an enhancement of the torque in the low engine rotation speed region. **Figure 4** shows these results.



**Figure 2 External view of new mixed flow turbine**



**Figure 3 Characteristic with respect to speed ratio of new mixed flow turbine**

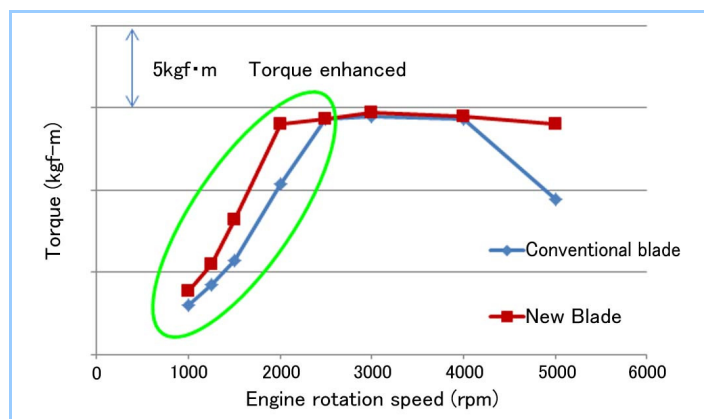


Figure 4 Verification result of torque characteristic of engine equipped with new mixed flow turbine

### 3. Development of compressors

For downsized supercharged engines that generate the maximum torque in the low engine rotation speed region, a different design from ordinary radial compressors is required. In the design of ordinary compressors, the design point is often set at the efficiency peak point to enhance performance. In the design of recent supercharged engines, however, the performance at the off-design point is important. In particular, efficiency at the operation point at a low engine rotation speed, which is in the vicinity of surging, is important. MHIET made the design in the light of the above-described background, and obtained good results. Figure 5 shows the CFD result. For the new blade, the flow of the rotor blade outlet at the operation point near the surging point was made to be uniform to enhance efficiency.

Figures 6 and 7 show the external view and the performance test results of the new blade. The low-pressure ratio side surge flow amount and choke flow amount remain at the same level, but the efficiency at the same flow amount point in the vicinity of the surging is enhanced.

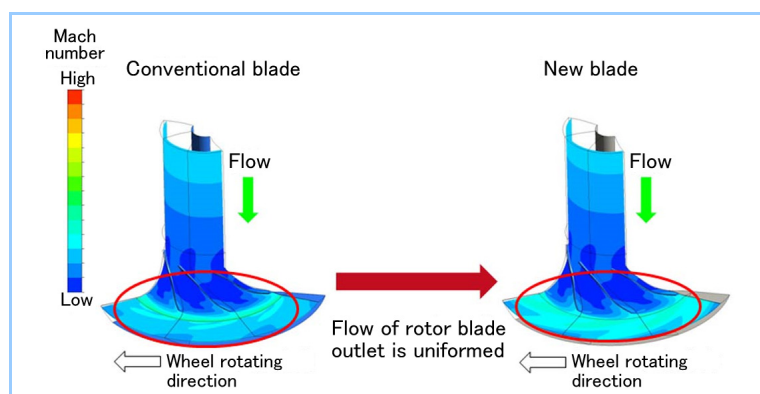


Figure 5 Comparison of flow conditions of rotor blade outlet at operation point near surging point (90% blade height, circumferential speed of 270 m/s)



Figure 6 External view of new compressor

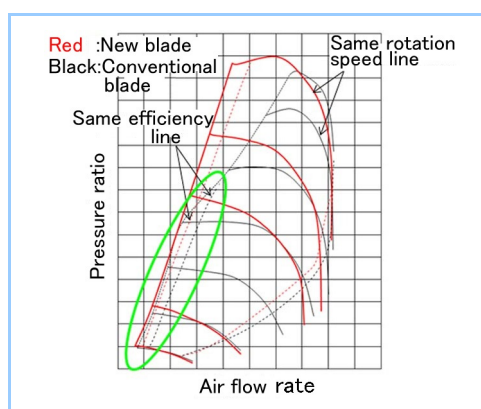
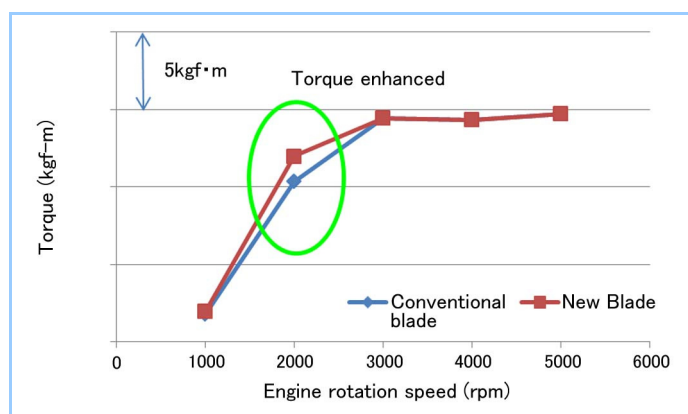


Figure 7 Performance test result of new compressor

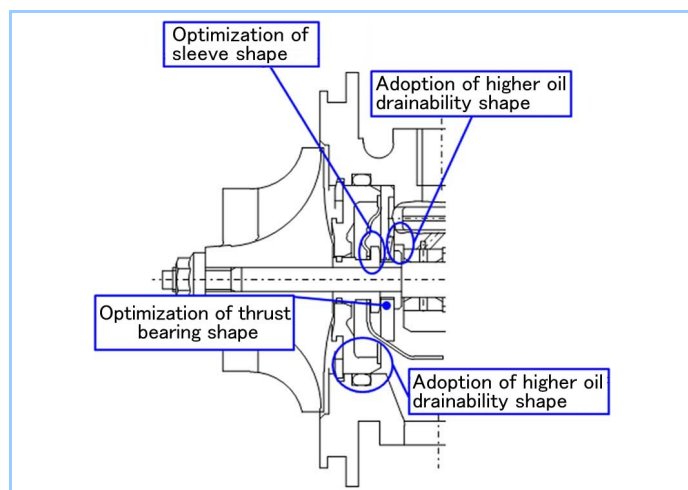
**Figure 8** shows the one-dimensional simulation results of a 1.6-liter direct injection gasoline engine to which the new blade was applied. It was confirmed that the new blade has an effect that enhances the torque at a low engine rotation speed.



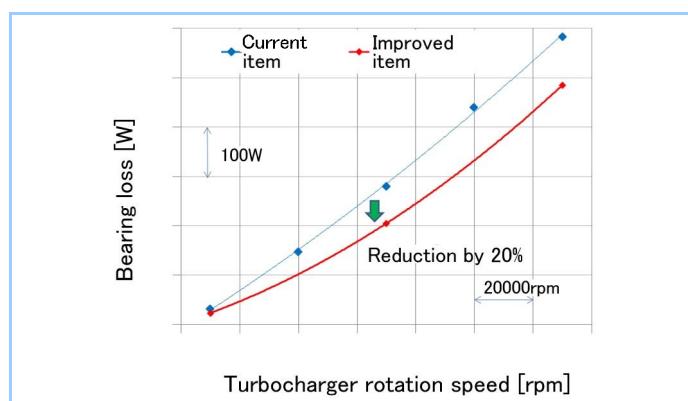
**Figure 8** Result of one-dimensional engine simulation

#### 4. Improvement of bearing performance

During transient response from a low engine rotation speed, the exhaust gas flow amount is small and therefore the amount of energy that can be recovered by the turbine is small. The bearing loss increases roughly in proportion to the square of the rotation speed. Therefore, the bearing loss has a large effect in a low-speed activation where the energy recovered by the turbine is small. We have also been improving continuously the bearing performance. **Figure 9** shows the main improvement items. After performing a review of various design parameters, optimization of the bearing load capacity, and enhancement of the oil drainability, the bearing loss was measured. The obtained results confirmed that the loss was reduced by 20% in comparison to the conventional bearing as shown in **Figure 10**.

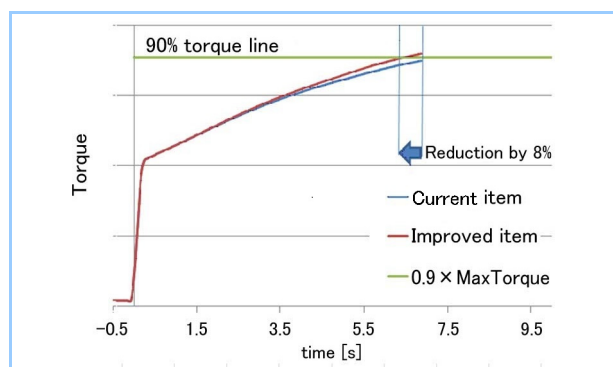


**Figure 9** Improvement items of bearing system



**Figure 10** Measurement result of bearing loss

In addition, one-dimensional simulation of the engine was executed to verify that the improved bearing described above influences the transient responsiveness of the engine. **Figure 11** shows the simulation results. Thus, it was confirmed that the time necessary to reach 90% torque was reduced by 8% in the range between idling at 1,500 rpm to WOT (whole open throttle).



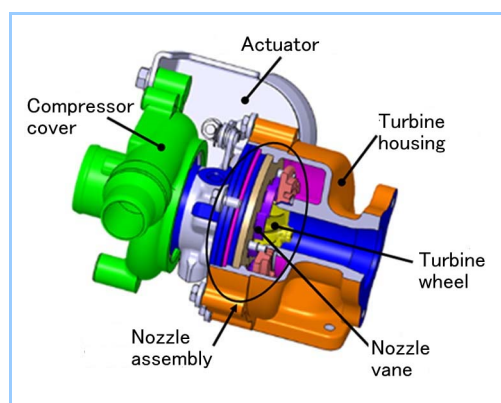
**Figure 11** Analysis result of one-dimensional engine simulation (1.6-liter direct injection gasoline engine, 1,500 rpm)

## 5. Development of VG turbochargers

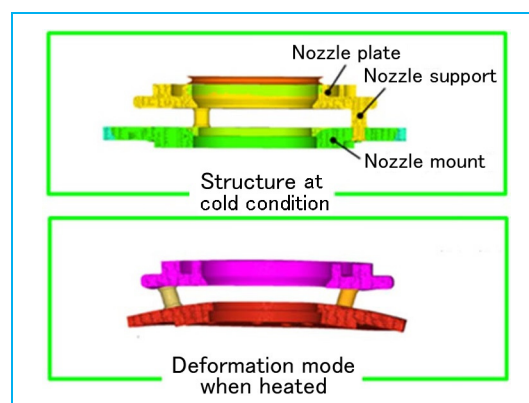
VG (variable geometry) turbochargers, which have stator vanes having a variable mechanism located at the turbine rotor blade inlet nozzle part, can maintain high supercharging efficiency from the low engine rotation speed to the high engine rotation speed in comparison to W/G (waste gate) turbochargers. Currently, the VG turbocharger is used in combination with a mirror cycle direct injection gasoline engine in some cases, and is an effective method to improve the fuel efficiency of engines. However, the VG turbochargers have a complicated variable mechanism, and therefore, a VG turbocharger for gasoline engines, the exhaust gas temperature of which is high, is very expensive because the components need to be made of materials with high heat resistance. In addition, because of knocking generated by the high supercharging pressure, the number of gasoline engines that adopted the VG turbocharger was limited. As the knocking limit is improved due to direct injection, cooled EGR, and so forth, however, the environment that allows adoption of the VG turbocharger has been established. Therefore, we developed VG turbochargers adaptable to gasoline engines. **Figure 12** shows the external view of our VG turbocharger for gasoline engines.

Our VG turbocharger for gasoline engines was developed on the premise that expensive heat-resistant alloy was not used in consideration of economic efficiency. In the design of the VG turbocharger, the shape and materials were optimized by analysis and the functions of the variable mechanism could be satisfied even at the exhaust gas temperature of 950°C.<sup>2</sup> **Figure 13** shows the example analysis for thermal deformation of a nozzle assembly executed in the development phase. Based on the result of this analysis, the thermal fatigue strength and various clearances were optimized.

The developed turbocharger was durability-tested in the MHIET test specifications and it was confirmed that the durability is enough for use for actual equipment.



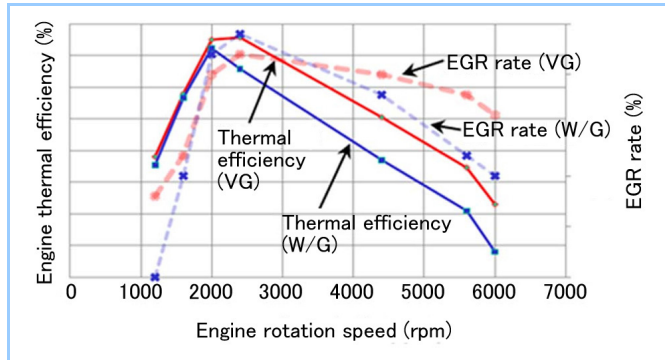
**Figure 12** VG turbocharger for gasoline engine



**Figure 13** Example of thermal deformation analysis of nozzle assembly



**Figure 14** shows the calculation result of engine one-dimensional simulation that was performed to confirm an engine thermal efficiency improvement effect of a VG turbocharger applied to a gasoline engine<sup>(2)</sup>. Based on this result, it was confirmed that the VG turbocharger installed on an engine equipped with cooled EGR could enhance the EGR rate under a full load condition in comparison to a W/G turbocharger. The result indicates that a VG turbocharger can enhance thermal efficiency, and it is expected that the VG turbocharger is effective for improving the fuel efficiency of gasoline engines.

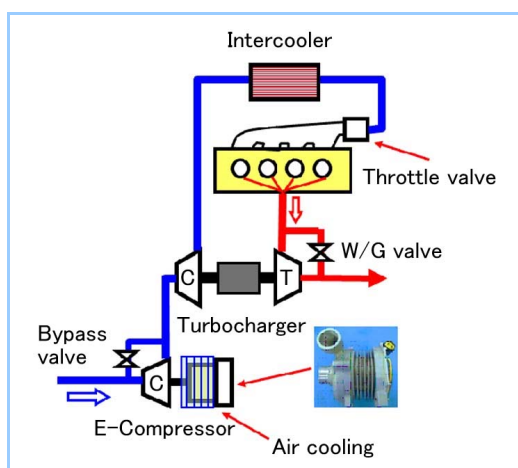


**Figure 14** Comparison of thermal efficiency between W/G turbocharger and VG turbocharger

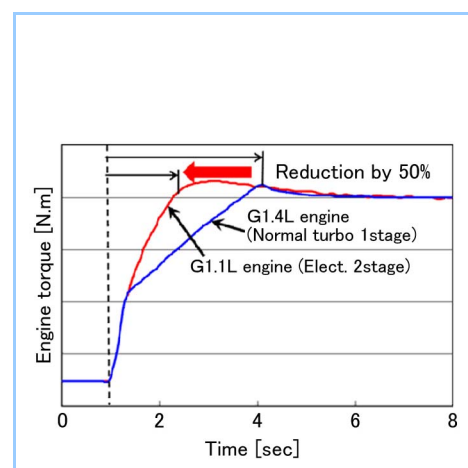
## 6. Development of electric compressors

Above is described the improvement of the supercharging efficiency of turbochargers. We have been developing an electric compressor to improve the fuel efficiency of vehicles with further higher supercharging pressure and transient responsiveness. In addition, we developed a supercharging system having an electric compressor instead of the high-pressure or low-pressure side turbocharger of an ordinary two-stage turbocharger.<sup>3</sup> **Figure 15** shows an example of the electric two-stage turbocharger system. The advantages of the developed system over an ordinary two-stage turbocharger are enhancement of the transient responsiveness, reduction of pumping loss caused by lowering the engine exhaust pressure, shortening of the catalyst activation time period after starting the engine through reduction of the exhaust side heat mass, and so forth.

For verification of fuel-efficiency-improving effects of the developed system, comparison to a 1.4-liter single turbocharged gasoline engine was estimated. As a result of this estimation, it was verified that the fuel efficiency could be improved by 8% even with the engine displacement reduced approximately 20% while maintaining an equal or higher steady engine torque. Also, transient performance was improved and the torque rising time period could be reduced by approximately 50% as shown in **Figure 16**. Thus it can be said that the electric compressor is an effective method to improve fuel efficiency.



**Figure 15** System diagram of electric two-stage turbocharger system



**Figure 16** Comparison of transient response time

For electric supercharging, energy management is important. We believe that the hurdle of energy management to use an electric compressor will be lowered in the future due to performance enhancement of on-vehicle power sources, increase of the voltage, and enhancement of the energy recovery efficiency. In addition, it is also effective to combine the electric compressor with methods to improve the fuel efficiency such as cooled EGR, mirror cycle, and lean combustion.

## **7. Conclusion**

We developed the fundamental elements of a turbocharger that meets the needs for reducing environmental load including a turbine having enhanced performance in the low speed ratio region, a compressor having enhanced efficiency in the vicinity of surging, and a bearing, for which mechanical loss was reduced by optimizing the load, and supercharging systems including a VG turbocharger for gasoline engines and an electric compressor. These are turbochargers that match the conventional engine development trend including downsizing and downspeeding. By combining with the mirror cycle and the cooled EGR, the developed technologies can also deal with rightsizing engines, aiming to improve the thermal efficiency of the engine, and are expected to be developed actively in the future. We believe that the developed technologies will contribute to environmental protection. We are willing to disseminate the technologies described in this paper in cooperation with automobile manufacturers to enable such technologies to be commercialized and used throughout the world.

## **References**

1. Maeda, Y., Gasoline Engine, Journal of Society of Automotive Engineers of Japan Vol. 70 No. 8 pp. 92-100 (2016)
2. Ebisu, M. et al., Development of Variable Geometry Turbocharger Contributes to Improvement of Gasoline Engine Fuel Economy, Mitsubishi Heavy Industries Technical Review Vol. 53 No. 3 (2016)
3. An, B. et al., Development of Two-stage Electric Turbocharging system for Automobiles, Mitsubishi Heavy Industries Technical Review Vol. 52 No. 1 (2015)