Development of turbocharger engine system using 3D and 1D simulation to achieve 50% brake thermal efficiency

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Abstract. In recent years, automobile exhaust gas regulations have become stricter due to environmental problems such as global warming. A project by the Cabinet Office called the Strategic Innovation Promotion Program (SIP) began in 2014. SIP has 11 themes in total. One of them, innovative combustion technology, aimed to improve the thermal efficiency of automobiles from the existing 40% to 50%. To improve the thermal efficiency of the automobile, it was essential to improve the efficiency of the turbocharger. In this study, we developed a turbocharger for gasoline and diesel engines. First, to confirm the efficiency of the conventional turbocharger, experiments and CFD analysis of a commercial turbocharger were performed. ANSYS-CFX was used as a numerical code. To confirm the accuracy of the CFD, the CFD results were compared with the experimental results, and it had good agreement with the experimental results. From the analysis results, the loss region of the conventional turbocharger was clarified. The designed turbocharger compressor was tested as a prototype compressor. The results of the compressor had good agreement with CFD results, so it was confirmed that the accuracy of CFD and design method was valid. Finally, A one-dimensional simulation using GT-Power which is a system analysis software for automobiles was performed to evaluate the developed turbocharger on the engine. In the fifth year of the project, the target efficiency of 50% was achieved.

1. Introduction

In recent years, due to environmental issues such as global warming, regulations of exhaust gas for automobiles have become increasingly strict. A project by the Cabinet Office called the Strategic Innovation Creation Program (SIP) began in 2014. SIP has 11 issues in total, and one of them, innovative combustion technology, aimed to increase the thermal efficiency of automobiles from the existing 40% to 50%. The targets were gasoline engine and diesel engine with a turbocharger, and to improve the thermal efficiency of the automobile, it was essential to improve the efficiency of the turbocharger.
In this study, we developed a turbocharger for gasoline and diesel engines. The developed turbocharger was evaluated using GT-Power, a system analysis software for automobiles. In the fifth year of the project, the target efficiency of 50% was achieved.

2. Engine and turbocharger specifications

The turbocharger designed this time is one for a gasoline engine with specifications of displacement of 2.3L and engine speed at 2000rpm, and another one for a diesel engine with displacement of 2.2L and engine speed at 2250rpm speed at 2250rpm. Table 1 shows the engine specifications, and Table 2 shows the turbocharger specifications.

The specifications of the turbocharger are calculated for the engine shown in Table 1 using the one-dimensional analysis software GT-Power and assumed turbocharger efficiency.

| Table 1. Specification of engine | Table 2. Specification of turbocharger |
|----------------------------------|---------------------------------------|
| **Engine and turbocharger**      | **For diesel engine**                  |
| Specified for gasoline engine    | **For gasoline engine**                |
| Displacement (L)                 | Unit                                   |
| 2.3                              | Mass flow (g/s)                        |
| 2.2                              | Inlet temperature (K)                  |
| 2000 rpm                         | Inlet Pressure (kPa)                   |
| 2250 rpm                         | Outlet temperature (K)                 |
| IMEP (MPa)                       | Outlet Pressure (kPa)                  |

3. Commercial turbocharger test and CFD accuracy verification

Figure 1 shows the turbocharger testing apparatus. The commercial turbocharger was tested at Chiba University. In the turbine test, the measurement was performed under cold conditions where the turbine inlet temperature was low, and the rotation speed was adjusted by changing the operating conditions of the compressor, and the inlet and outlet temperature and pressure were measured. A turbine was used as the driver for the compressor test, and the temperatures and pressures at the inlet and outlet were measured. Both turbines and compressors use laminar flow meters for flow rate measurement.

![Figure 1 Commercial turbocharger test apparatus](image)

The shape of a commercial turbocharger was measured in 3D to make a 3D CAD model, and steady CFD analysis was performed. ANSYS-CFX was used for CFD. The turbine and compressor were analyzed, and the number of mesh elements of turbine was about 20 million, and the number of mesh elements of compressor was about 15 million. As boundary conditions for the turbine, the total pressure
and total temperature at the inlet and the static pressure at the outlet were set. The mixing plane was used at the interface of rotor and stator. As boundary conditions for the compressor, the total pressure and the total temperature at the inlet, and the flow rate at the outlet were set.

Figure 2 and 3 show the experimental results and CFD results of the turbine and compressor, respectively. The efficiency for compressors is defined using Total to Total efficiency and the efficiency for turbine is defined using Total to Static efficiency. The error in the analysis was 1.7% on average for the compressor and 2.6% for the turbine. It was confirmed that the impact on the engine system was sufficiently small.

4. **Turbine and compressor design**

GT-Power was used to examine the efficiency of the turbocharger required to achieve the target engine efficiency. It was 66.4% for gasoline turbocharger and 64.0% for diesel turbocharger of the newly designed turbochargers named SIP turbochargers. The bearing was assumed to be a ball bearing.

In the design of a turbine, the meridian plane of the SIP turbocharger has changed significantly compared with the meridian plane of the commercial turbocharger. Figure 4 shows the meridian plane. Judging from the CFD results of the commercial turbocharger, it was confirmed that there were little loads at the outlet on the hub side of the turbine wheel and it generates a loss. In the SIP turbocharger, the hub side is cut to reduce the loss. Further, by reducing the curvature of the meridional plane on the shroud side, the loss occurring near the shroud outlet is mitigated. In addition, splitter turbine was used for SIP turbocharger. The inertia of SIP turbine was reduced using splitter blade.
From the CFD results of the commercial turbocharger, it was confirmed that the flow velocity distribution at the housing outlet was larger at the shroud side. Figure 5 shows the flow velocity distribution at the housing outlet. In the SIP turbocharger, the secondary flow generated in the housing was reduced by making the housing shape mortar-shaped. In addition, the distribution of the flow velocity flowing into the wheel became constant, and the loss of the housing and the wheel was reduced.

In the case of the compressors, the design was performed by focusing on the impeller and the housing shape. The impeller reduces the secondary flow generated at the impeller inlet by reducing the load near the inlet. Regarding the housing, attention was paid to the angular momentum ratio of the housing inlet and outlet and the inflow angle. The housing was fabricated using the angular momentum ratio and flow angle that minimized the loss.

These design concepts were used for gasoline and diesel turbocharger. But the shape and distribution of blade angle were not same each other because the specification of engine were not same.

Table 3 shows the final turbocharger analysis results. As can be seen from the table, the target efficiency has been achieved for both gasoline and diesel. The target efficiency is the efficiency required for the engine to achieve a brake thermal efficiency of 50%.

|                           | For Gasoline engine | For Diesel engine |
|---------------------------|---------------------|-------------------|
| Turbine efficiency        | 82.9%               | 85.9%             |
| Compressor efficiency     | 84.8%               | 84.9%             |
| Mechanical efficiency     | 95.0%               | 95.0%             |
| Turbocharger efficiency   | 66.8%               | 69.3%             |

5. Gasoline compressor verification test

A gasoline compressor was actually manufactured and a performance test was conducted at an actual speed. A commercially available turbine having almost the same capacity is used as the drive source of the compressor. The housing wall near the impeller shroud of the compressor housing was set using an abradable material to minimize the clearance. Figure 6 shows a picture of actual compressor.

Figure 7 shows the results of a compressor performance test on an actual machine. Red contour lines indicate efficiency, and blue lines indicate pressure and flow characteristics. Efficiency is defined as Total to Total efficiency. The green plot shows the analysis results. The CFD result has good agreement compared to the efficiency value of the contour line. From the above, it was confirmed that the efficiency value of the turbocharger designed using CFD had enough accuracy and that it met the required compressor specifications.
6. Turbine analysis under pulsating flow

In order to investigate the influence of the pulsating flow, the analysis under the pulsating flow was performed on the designed gasoline turbine. The analysis code used is ANSYS-CFX19.0 and the turbulence model used is RST SST. The boundary condition at the inlet used is the instantaneous flow rate at the turbine inlet obtained by analysis with GT-Power. The outlet was kept at a constant static pressure. As a result, the efficiency was 1.7% lower under pulsating flow than under steady flow.

Figure 8 shows the relationship between the instantaneous efficiency of the turbine and the flow rate. It can be seen that different efficiencies are shown at the same flow rate under pulsating flow as shown by the blue and red points. Figure 9 shows the flow velocity distribution in the wheel at the same flow rate described above. It can be confirmed that the internal flow is different even if the same timestep is encountered.

7. Whole engine system analysis

To investigate the effect of improved turbocharger efficiency on engine performance, each engine loss component was calculated for a commercial turbocharger and SIP turbocharger using GT-Power, one-dimensional analysis software for the engine. The engine conditions were the same as those shown in Table 1.

Figure 10 and 11 show the results of the one-dimensional analysis. The figures show the ratio of energy loss of engine. The loss can be divided into exhaust loss, heat loss, and pumping loss, and the
pumping loss corresponds to the loss of turbocharger. The increment in the turbocharger efficiency reduces the pumping loss and leads to the improvement in thermal efficiency. Therefore, it was confirmed that the pumping loss of the turbocharger was reduced by -0.54% for gasoline engines and -2.19% for diesel engines by this study.

Figure 12 summaries all the results within the project of the innovative combustion technology by year. The green areas of the figure indicate the improvement to engine brake thermal efficiency due to the reduction in losses, not only turbocharger loss reduction but also thermoelectric conversion and friction loss. But the loss of thermoelectric conversion and friction are studied by another team of SIP project.

In addition to the turbocharger, the efficiency has been improved in other ways such as combustion and reduction of friction loss. Combining all the results, a thermal efficiency of 50% has been achieved for both the diesel and gasoline engines.

8. Conclusions

Two turbochargers were designed to achieve an engine thermal efficiency of 50%, and the following conclusions were obtained.

- We designed a turbocharger using CFD that can achieve the target efficiency.
- By conducting experiments and analysis of commercially available turbochargers, the current efficiency was grasped and the accuracy of CFD analysis was evaluated.
- The validity of the design was confirmed by manufacturing and testing an actual compressor.
- The whole engine was analyzed using one-dimensional analysis software, and the effect of improving the efficiency of the turbocharger was investigated.
- We collected the results of all the teams and performed a one-dimensional analysis afterwards to confirm that thermal efficiency of 50% was achieved.

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