Improvement in accuracy of engine cycle simulations by using a turbocharger prediction model instead of measured efficiency map

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Abstract. In the downsizing concept, the turbocharger (T/C) is one of the key devices for improving thermal efficiency and exhaust emissions of internal combustion engines for automobiles. In order to maximize the supercharged engine performance, the size of the T/C applied for the given engine system has been optimized by using a 1-D engine cycle simulation. For this reason, T/C performance prediction model for engine cycle simulation is required to be accurate over a wide operating range. In the conventional T/C performance prediction model, the turbine performance was predicted by extrapolating from the efficiency map measured under steady flow. However, the accuracy of the extrapolation method is uncertain, and it has been pointed out that the prediction accuracy is low in the low load operations. In this study, a 1-D T/C model developed based on hydrodynamics and thermodynamics was used. Using the 1-D T/C model, a grid efficiency map over the entire operating range was calculated and the grid map was applied to 1-D engine cycle simulation. The accuracy of the T/C model was verified by comparing the experimentally measured efficiency under steady flow.

1. Introduction
Downsizing concept has attracted attention as one of the technologies to improve fuel efficiency of internal combustion engines for automobile. Matching between the engine and the turbocharger (hereinafter referred to as T/C) is important during the engine development process. Because the turbocharger matching process has been often conducted using 1-D cycle simulations, a highly accurate T/C model for the engine cycle simulation is required. For this reason, recent research related to automotive T/C involves measurement and modeling of friction in bearings (1) (2), analysis of the effect of heat loss on T/C performance, and construction of a correction model. In addition to the loss analysis and modeling studies (3)–(5), studies focusing on unsteady performance prediction, such as T/C performance analysis under pulsating flow (6), (7), has been also promoted. Under the pulsating flow conditions, the T/C would be sometimes operated in the range out of the operating range of the steady flow conditions. Therefore, it is important to develop a prediction method that extrapolates the efficiency map that is generally measured in the steady flow. In this study, measurements of the cold map indicated by the isentropic efficiency of the turbine and compressor were conducted. The prediction accuracy of the turbine efficiency in the extrapolated operating conditions of the turbine efficiency map was investigated using the measurement results of the wide range turbine efficiency measurement (Extended test).

2. Objective
The authors have developed a one-dimensional cycle simulation model of turbocharged SI gasoline engine using a commercially available code (GT-SUITE). The developed model includes heat transfer and mechanical friction model in T/C components. To validate the developed models related to the T/C performance prediction, T/C efficiency measurement has been also performed (8). However, the
extrapolation accuracy of the efficiency map for predicting the turbine efficiency operating under strong exhaust pulsation flow has not been sufficiently investigated yet. Therefore, to verify the extrapolation accuracy for the turbine efficiency map, the adiabatic efficiency at the operating point where the extrapolation is necessary was measured, and the extrapolation equation was verified by comparing with the extrapolation prediction result. The objective of this study is to expand the measurement range of turbine adiabatic efficiency under steady flow and to verify the prediction accuracy of extrapolation region of turbine efficiency map in engine cycle simulation.

3. Test equipment and conditions
3.1. T/C performance test equipment
Figure 1 shows a schematic of the T/C efficiency measurement setup. In general, efficiency map measurement is performed with the compressor inlet open to the atmosphere. In this case, the operating area of the turbine is limited by the surge and choke of the compressor. In this study, the authors tried to expand the measurement range of the turbine map by supplying compressed air to the compressor inlet. In other words, it is aimed at increasing the compressor work while keeping the pressure ratio by increasing the compressor inlet pressure (density). The compressor work is controlled by adjusting the flow rate and pressure ratio of the compressor using the inflation valve and the valve attached at the compressor outlet.
A T/C with wastegate valve for a commercial 1.6L downsized gasoline engine was used in the experiment. The compressed air is supplied to the combustor, and the air-fuel mixture is burned and sent to the turbine. City gas 13A was applied as a fuel for the combustor. Using this combustor without supplying a fuel, a cold flow test with compressed air can be conducted. The maximum flow rate and pressure of the gas flowing into the turbine are 0.215 kg/s and 400 kPa (abs), respectively. The maximum exhaust temperature of the combustor is 1000°C. These conditions are enough to be capable of operating T/C at maximum rotating speeds.
A heat exchanger using silicon oil as the heat medium was installed in the combustor outlet, and the working gas temperature at the turbine inlet could be controlled. By controlling the compressor outlet pressure and the working gas flow rate of the turbine, the turbine and compressor performance map can be measured at any rotation speed and pressure ratio.
The temperatures and pressures at the inlet and outlet of the turbine and compressor are measured. At each measurement location, four thermocouples are installed at 90° intervals, and measured temperature by four thermocouples are averaged. The T/C rotation speed was determined by installing a gap sensor in the compressor housing and measuring the frequency of the compressor blade passing above the sensor. The cooling water and lubricating oil temperature can be controlled independently, and controlled from room temperature to about 100°C. The temperature of each part of the T/C wall is measured using a thermocouple.

Figure 1. Schematic diagram of the T/C test stand
3.2. Test conditions
Table 1 shows the experimental conditions. The turbine speed was varied from 45,000 to 93,000, and the gas temperature at the turbine inlet was varied from 40 to 64 °C. In general, the higher the rotational speed, the more the workload of the turbine increases, causing a larger temperature drop between the inlet and outlet of the turbine. When the test was performed with the turbine inlet gas temperature set at room temperature, the outlet gas temperature dropped below room temperature. The temperature drop between turbine inlet and outlet is larger under higher rotation conditions. In order to reduce the effect of the heat transfer between the housing and working fluid on measurement results of the adiabatic efficiency, the turbine inlet gas temperature is changed for each rotation speed.

| Reduced Speed (RPM / √K) | Speed (RPM) | Turb_in (°C) |
|--------------------------|-------------|--------------|
| 2550                     | 45000       | 40           |
| 3050                     | 54000       | 42           |
| 3710                     | 67000       | 50           |
| 4390                     | 80000       | 58           |
| 5060                     | 93000       | 64           |

4. Results
4.1 Measurements of Turbine Map
A turbine map was measured with the compressor inlet was opened to the atmosphere (referred to as Standard Test). Figure 2 shows the operating point of the turbine corrected flow rate and pressure ratio. Figure 3 shows the efficiency with respect to the pressure ratio for each T/C speed. The operating point with the maximum turbine work at a given rotating speed is defined by the maximum work absorbed by the compressor. At this operating point, the compressor back pressure valve is fully opened and the compressor pressure ratio is the maximum at this rotating speed. Since the measurement range of the turbine map for each T/C speed is defined by the limit of the work absorbed by the compressor, in the Standard Test, the peak turbine efficiency at higher rotating speed conditions could not be obtained.

Figure 2. Turbine Reduced MFR at the standard test
Figure 3. Measured turbine efficiency map with the standard test
4.2 Extension of measurement range

To expand the measurement operating conditions of the turbine map, so-called the Extended Test was conducted. As mentioned in the previous section, the measurement of the turbine map is limited by the range in which work that the compressor can absorb. To measure the turbine efficiency at higher load operating conditions (high pressure ratio), the work absorbed by the compressor was increased by increasing the compressor inlet pressure, i.e. density. Equation 1 shows the definition of compressor work.

\[ W_{\text{comp}} = M_{\text{comp}} C_p(T_{\text{out}} - T_{\text{in}}) \]  

(1)

Based on Equation 1, the compressor work increases with increasing the compressor mass flow by using compressed air to the compressor inlet. It would be worth noting that the measurement range of Standard Test is covered in that of the Extended Test. At the operating point in the measurement range of the Standard Test, compressor inlet pressure is set at atmospheric pressure, even in the Extended test. Figure 4 shows the compressor work under the conditions of a T/C speed of 80000 RPM, a corrected rotation speed of 4390 rpm/√K, and an inlet temperature of 58 °C. The plots indicated by circle shows the results measured in the Standard Test, and the triangle plots show the compressor work measured in the Extended Test. In the Extended Test, it can be seen that the higher compressor work could be attained with the same pressure ratio. Please note that inlet pressure is increased even the pressure ratio is the same in the Extended Test. Also, in the range of standard test, it can be said that there is reproducibility when comparing the result of the standard test with the compressor inlet open to the atmosphere and the result of the expansion test with the pressure increased to about atmospheric pressure.

**Figure 4. Compressor Work**

With the above method, the turbine efficiency measurement in the expanded operating range was carried out. Figure 6 shows a relation between the corrected mass flow rate and pressure ratio of the turbine. Figure 7 shows a relation between the turbine efficiency and pressure ratio. The range of the turbine pressure ratio that can be measured under a constant rotation speed was approximately doubled in the Extended Test compared to the Standard Test.

In addition, it can be found that there are about 3% pt. variations in measured efficiency between Standard and Extended tests. It is considered that the measurement results contain about 3% error due to the measurement conditions reproducibility, especially due to that of heat insulation conditions. In the cold test, turbine efficiency is measured under the assumption that there is no heat transfer between the housing and the working fluid. However, it is considered that some heat transfer is generated even under the condition of temperature adjustment in consideration of the adiabatic state.
Figure 6. Measurement range in the Extended Test

Figure 7. Turbine efficiency measured by the Standard test (solid line) and Extended test (dashed line)
4.3 Reduction of T/C system heat transfer
T/C heat transfer mainly occurs from gas to housing, housing to atmosphere, turbine housing and bearing case, between bearing case and compressor housing. In the cold test, the temperature distribution varies for each measurement conditions and operating points. It is important to make the temperature boundary conditions to minimize the effect of heat transfer on measurement results of turbine efficiency.
To measure the cold map under the adiabatic state, the temperature was determined as follows.

\[ T_{turb \_in \_total} = T_{bearing \_case} \]
\[ T_{oil} = \text{const} \ T_{coolant} \Rightarrow T_{bearing \_case \_Control} \]

The wall temperature of the bearing case is controlled by the cooling water temperature, to set the bearing case temperature at the temperature to the working gas temperature at the turbine inlet. This temperature setting could reduce heat transfer between the turbine housing and the bearing case. Heat radiation to the surroundings is reduced by wrapping the thermal insulation around the T/C housing.

4.4 Extrapolation method of turbine efficiency
The equation (3) is the Blade Speed Ratio, which is the ratio between the blade peripheral speed and the rotor exit flow velocity. The Figures 8 and 9 show the results obtained by normalizing the Blade Speed Ratio in the Standard Test and Extend Test. The red line shows result of fitting the normalized efficiency at each operating point. The extrapolation method of turbine efficiency in 1D simulation is performed by fitting the normalized Blade Speed Ratio and the normalized efficiency. Compared to the Standard Test, in the Extend Test, it can be said that the accuracy of the fitting on the high load side has been improved by expanding the measurement range.

\[ BSR = \frac{U}{C_s} \]
\[ U = \frac{2\pi N}{60} \left(\frac{D}{2}\right) \]
\[ C_s = \left[2C_p T_{in} \left(1 - PR \frac{1-k}{k}\right)\right]^\frac{1}{2} \]

\( N \) – Turbine Speed [rpm]
\( D \) – Diameter [m]
\( T_{in} \) – Inlet Temperature [K]
\( C_p \) – Specific heat at constant pressure [J/kg \cdot K]
\( k \) – Ratio of specific heat
4.5 Prediction accuracy of extrapolated area

Efficiency maps were generated using the measured efficiency by the Standard and Extended Tests with minimized heat transfer effect conditions mentioned in the previous section. Figure 10 shows the turbine efficiency map generated from the Standard Test results. Figure 11 shows the turbine efficiency map generated from the Extended Test results. The color bar indicates the turbine efficiency, with the dark blue area showing 10% efficiency and the red area showing operating conditions with high efficiency. Although there was no significant difference between the two maps, there are differences in efficiency around the low pressure ratio and flow rate conditions, and the maximum efficiency region.
5. Conclusion
In this study, a method for expanding the measurement range of turbine efficiency was constructed to investigate the effect of measurement range on turbine efficiency map. By increasing the compressor inlet pressure (i.e. density), the compressor work could be increased with similar pressure ratio, leading to expending the measurement range on the high-load area of the turbine map. As a result, it is found that the measurement range of turbine efficiency affects the efficiency map at low pressure ratio, low rotation speed, and operating point around the maximum efficiency.

References
[1] Silvia M, Simone G, and Massimo C Experimental and Numerical Analysis of Mechanical Friction Losses in Automotive Turbochargers, SAE Technical Paper, 2016-01-1026 (2016).
[2] Dominik L, et al.: Advanced Measurement and Modelling Methods of Turbochargers, MTZ worldwide, June 2016, Volume 77, Issue 6 (2016), pp. 80-87.
[3] Bjorn H, et al.: Analysis of the Dynamic Behaviour of Turbocharged Gasoline Engines, MTZ worldwide, May 2015, Volume 76, Issue 5 (2015), pp. 38-45.
[4] Silvia M, et al.: Heat Transfer Effects on Performance Map of a Turbocharger Compressor for Automotive Application, SAE Technical Paper, 2015-01-1287 (2015).
[5] Habib A and Hans: Improving Turbocharged Engine Simulation by Including Heat Transfer in the Turbocharger, SAE Technical Paper, 2012-01-0703 (2012).
[6] Silvia M, Massimo C, Giorgio Z: Pulsating flow performance of a turbocharger compressor for an automotive application, International Journal of Heat and Fluid Flow 45 (2014) 158-165.
[7] Rainer Z, et al.: Investigation on Pulsating Turbine Flow Radial Turbines, 24th Aachen Colloquium Automobile and Engine Technology 2015 (2015).
[8] Kuboyama, T: Analysis of heat transfer and friction loss in turbochargers, JSAE 20175329 (2017)