SCIENCE CHINA
Technological Sciences

January 2010 Vol. 53 No.1: 69–74
doi: 10.1007/s11431-009-0421-9

An integrated turbocharger design approach to improve engine performance

ZHANG YangJun[1*], CHEN Tao[1], ZHUGE WeiLin[1], ZHANG ShuYong[2] & XU JianZhong[3]

[1] *State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing 100084, China;*
[2] *National Key Laboratory of Diesel Engine Turbocharging Technology, P.O.B. 22, Datong 037036, China;*
[3] *Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing 100190, China*

Received October 16, 2009; accepted October 19, 2009

Turbocharging technology is today considered as a promising way for internal combustion engine energy saving and CO_2 reduction. Turbocharger design is a major challenge for turbocharged engine performance improvement. The turbocharger designer must draw upon the information of engine operation conditions, and an appropriate link between the engine requirements and design features must be carefully developed to generate the most suitable design recommendation. The objective of this research is to develop a turbocharger design approach for better turbocharger matching to an internal combustion engine. The development of the approach is based on the concept of turbocharger design and interaction links between engine cycle requirements and design parameter values. A turbocharger through flow model is then used to generate the design alternatives. This integrated method has been applied with success to a gasoline engine turbocharger assembly.

turbocharger design, internal combustion engine, integrated method, through flow model

Citation: Zhang Y J, Chen T, Zhuge W L, et al. An integrated turbocharger design approach to improve engine performance. Sci China Tech Sci, 2010, 53: 69–74, doi: 10.1007/s11431-009-0421-9

1 Introduction

Transportation system represents 20% to 25% of the CO_2 in the atmosphere and this share tends to increase [1]. Improving the efficiency of vehicle internal combustion engine power systems plays a critical role in the implementation of global energy conservation and environment protection strategies.

Turbocharging technology is today considered as a promising way for engine energy saving and CO_2 reduction [2, 3]. Much greater emphasis of turbocharging technology is being placed on downsizing the engines to increasing fuel economy and reducing CO_2 emissions. Advanced turbocharging technology may reduce the engine displacement volume while keeping the same performance in terms of torque and power compared to the initial larger engine, and simultaneously ensure an improvement in engine efficiency. During the last few years, several car makers have presented 1.8–2.0 L turbocharged engines. The performances of these turbocharged engines are typically similar to those of naturally-aspirated engines with 2.5 L displacement. The reduction of fuel consumption is typically more than 10%, with running conditions closer to the best efficiency area [4–6]. The turbocharging for the downsized engine could also lessen the friction loss.

Engine turbocharging is the combination of an internal combustion engine and a turbocharger. A turbocharger design is a major challenge for engine performance improvement [7, 8]. During the traditional engine development process, the turbocharger is selected from available product lists based on the characteristic maps. The chosen turbocharger is one of the series products by the component

*Corresponding author (email: yjzhang@tsinghua.edu.cn)

supplier, which is designed and developed by the turbomachinery experts, and there is a lack of consideration of engine operation conditions, especially at the off-design conditions.

Turbocharger design should be an integrated procedure involving transforming the turbocharger characteristics into specification of the engine performance to satisfy the engine operation requirements. The operation of a turbocharger is fundamentally different from that of a reciprocating engine, so a turbocharged engine has many complex characteristics. The turbocharged engine performance is determined in large part by the processes interaction during operation of the turbocharger and the engine, especially at off-design operations. It may well be necessary to improve the performance of the combination by turbocharger design and engine cycle optimizations at the same time, to encompass new considerations, streamlining turbocharger design and engine system integration, with the consideration of overall operation performance.

To help the turbocharger designer to efficiently generate the most suitable design, the purpose of this research is to establish a new integrated design method taking into account engine cycle requirements in the turbocharger development process as soon as possible. The turbocharger is coordinately designed on the basis of engine cycle optimization and this design will improve engine over performance. A 1.8 L gasoline engine turbocharger was used as a case to illustrate the development of this approach.

2 Integrated design method

2.1 Fundamentals of the design method

It is clear that a turbocharger is not ideally suited to operate in conjunction with an internal combustion engine. Matching of the suitable turbocharger to an engine is of great importance and is vital for successful operation of an engine with a turbocharger. For traditional cycle optimization of engine turbocharging, the turbocharger is pre-designed and manufactured, and defined as performance maps within the internal combustion engine thermodynamic models. It is difficult for the turbocharger designer to draw upon the information of engine operation conditions and engine turbocharger matching optimizations.

A rational turbocharger design process should assist the designer in assuring that the design fits the engine cycle requirements and brings the engine concerns into the turbocharger design process. The proposed turbocharger design approach concept is used to develop an engine-oriented turbocharger design procedure based on the engine characteristics. A diagram of the method is shown in Figure 1.

In turbocharger design approach, the first step is to identify the turbocharger design input and output parameters and their relationships. This identification will be based on turbocharger through flow model. On the basis of the turbocharger through flow model, the geometry and the performance data will be transferred into the engine model for cycle performance simulation. Based on a specific set of engine requirements, the approach will identify possible turbocharger design output parameter values that can meet these requirements.

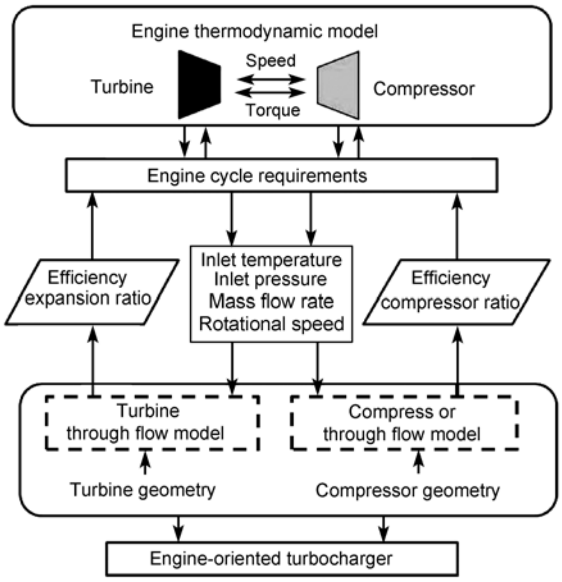

Figure 1 Integrated turbocharger design method.

An optimizing assignment procedure is then employed to generate feasible design alternatives, and then the targeted engine-oriented turbocharger will be obtained.

2.2 Model integration and calibration

The turbocharger through flow model determines the interaction links between engine cycle requirements and design parameter values, and is used to generate the design alternatives. The turbocharger through flow model is a meanline turbomachinery model, based on mass, momentum, and energy conservation equations. The model identifies some key geometry data, such as wheel inlet, wheel exit, hub and tip diameter, blade angles, etc. as the turbocharger design input parameters. Semi-empirical correlations are used so that the three-dimen- sional flow effects such as total pressure losses are taken into account [9–11].

One way to use the turbocharger through flow model is to generate the turbocharger maps by using the geometrical data instead of the test rig measurements and input them into the engine cycle modeling codes to predict the engine performance. In the integrated turbocharger design approach, the turbocharger through flow model is integrated to the engine cycle model. The links between the engine requirements and turbocharger design features are established. The influence of the turbocharger geometry parameters on the engine performance can be investigated, and then the most suitable turbocharger design can be obtained by the integrated optimizing procedure.

As mentioned before, the turbocharger through flow model is based on semi-empirical models and the component geometry parameters. To predict aerodynamic losses several coefficients must be given and calibrated against the experimental data. Figures 2 and 3 give out the turbocharger compressor and turbine performance data at different rotating speeds, calculated by the turbocharger through flow model separately. The solid curves represent the prediction results and the symbols represent the experimental data points. In Figure 2, the results show that the compressor pressure ratio and efficiency prediction error are less than 5% at most points except at high flow (near chocking) points. Since the compressor is rarely operated at near chocking conditions, the prediction inaccuracy at near chocking points is less important. For the turbine, the results in Figure 3 indicate that the pressure ratio prediction error is less than 3%. The maximum error of the efficiency prediction is less than 5% at most points except for one point at the lowest operating speed, the value for which is 6.2%. So the turbocharger through flow model is accurate enough for predicting turbocharger characteristics in engine cycle simulations.

Figure 4 shows the torque and break specific fuel consumption (BSFC) curves of the turbocharged gasoline engine calculated by the engine model. Good agreements

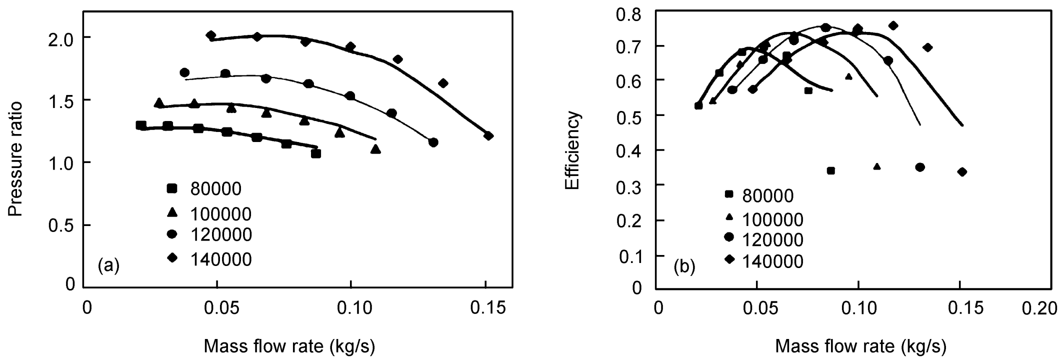

Figure 2 Compressor through flow model calibration. (a) Pressure ratio curves; (b) efficiency curves.

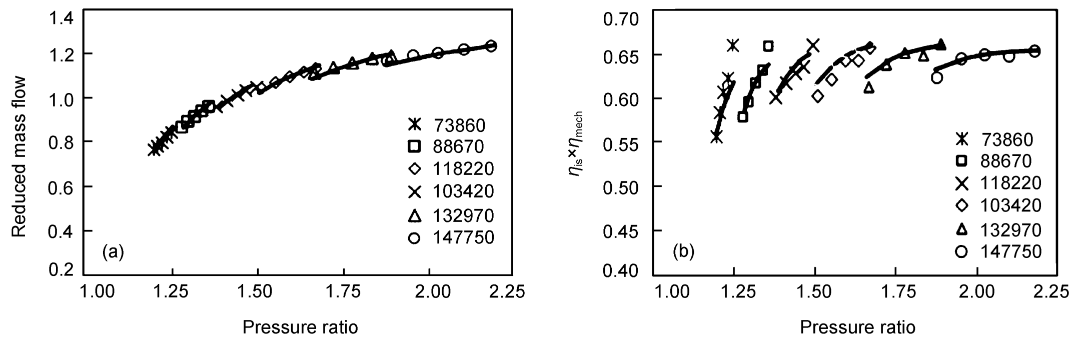

Figure 3 Turbine through flow model calibration. (a) Pressure ratio curves; (b) efficiency curves. η_{is}, Turbine isentropic efficiency, η_{mech}, mechanical efficiency of the rotating axis.

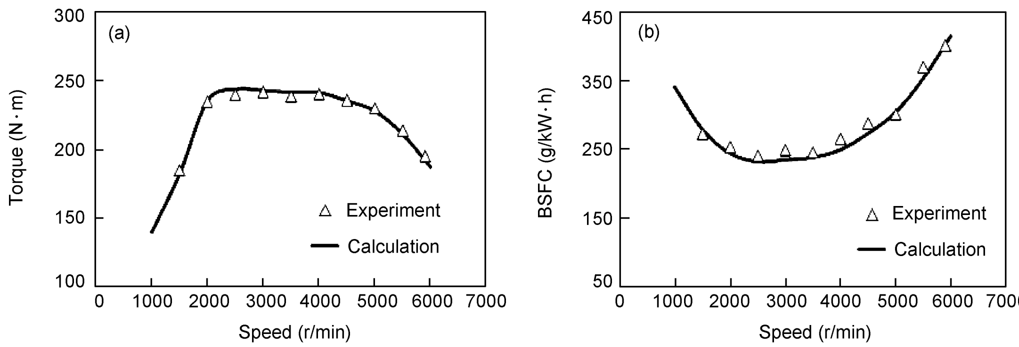

Figure 4 Engine thermodynamic model calibration. (a) Torque; (b) break specific fuel consumption (BSFC).

can be seen from the torque curve by the comparison with the test data. The torque prediction error is less than 3% and the fuel consumption prediction error is less than 5% because of the output fluctuation of the fuel flowmeter when the engine was running. For the comparison of different turbocharger designs, the simulation results of the same engine model will be used.

3 Engine-oriented turbocharger design

3.1 Turbocharger design parameters

The research is present in conjunction with a turbocharger redesign of an automotive engine to demonstrate the feasibility and advantages of the integrated design approach. This 1.8 L engine is an in-line four-cylinder turbocharged, intercooled, four-stroke gasoline engine which operates from 880 to 6000 r/min. Table 1 shows the main parameters of the gasoline engine.

For gasoline engines that operate at a wide range of speeds and loads, the turbocharger design should be an integrated procedure involving transforming the turbocharger characteristics into specification of the engine performance to satisfy the engine operation requirements.

However, the turbocharger of this 1.8 L engine is selected from available product lists by the turbocharger supplier, and there is a lack of consideration of engine operation conditions. To improve the engine performance, a new turbocharger has been redesigned by the integrated turbocharger design method presented above to replace the prototype turbocharger by the product supplier.

In most of the time, and especially when the vehicle is driven at a constant speed, the engine is run under low load conditions. This leads to a poor engine efficiency especially for gasoline engine for which load is controlled by a throttle [12–14]. According to the engine cycle simulations, the impeller, diffuser and volute of a turbocharger compressor should be carefully designed for sufficient surge margin, which is of great importance to improve low speed torque and transient response of the gasoline engine. In order to improve the overall efficiency of the engine, the compressor efficiency needs to be increased near the surge line at the low mass flow region.

Table 2 shows the main design data of the new turbocharger centrifugal compressor by the integrated design approach. The new compressor impeller has 12 blades and 6 of them are cut back at the inlet (splitter blades). The impeller has an outlet diameter of 54.6 mm and width of 4.2 mm. A left overhung volute connects to the vaneless diffuser.

From the engine cycle optimizations, the effective section of the turbocharger turbine exhaust gas passage needs to be carefully chosen to meet the gasoline engine torque requirements at low engine speed operating points and the efficiency and reliability at high engine speed conditions. Table 3 presents the main design parameters of the new turbocharger radial turbine by the integrated design approach.

Table 1 Gasoline engine specifications

Parameters	Value
Number of cylinders	4
Displaced volume	1.793 L
Bore	81 mm
Stroke	87 mm
Maximum power	125 kW@5500 r/min
Maximum torque	235Nm@3000 r/min
Compression ratio	9:1

Table 2 Compressor design parameters

Parameters	Value
Inlet tip radius	19.7 mm
Inlet hub radius	6.6 mm
Inlet blade angle (tip, hub)	−69°, −40°
Leading edge thickness at shroud	0.46
Number of vanes at the inlet	6
Exit tip depth	4.2 mm
Exit tip radius	27.3 mm
Impeller backsweep angle	−50°
Blade thickness	0.6 mm
Number of vanes at exit	12
Diffuser exit radius	45 mm

Table 3 Turbine design parameters

Parameters	Value
Inlet tip radius	23.5 mm
Inlet hub radius	23.5 mm
Inlet blade height	6.5 mm
Exit tip radius	19.25 mm
Exit hub radius	7.5 mm
Exit blade angle	57°
Number of blades	12
Volute radius	50 mm
Throat area	584.2 mm^2

3.2 Turbocharger and engine performance

Figure 5 gives out the compressor performance of the prototype turbocharger and the compressor performance of the new turbocharger. The new turbocharger is coordinately designed on the basis of engine cycle optimization, and will be more suitable to the engine operations. It can be seen that the new turbocharger design compressor has a high efficiency area at the low mass flow region, and will result in a better matching of the turbocharger to the gasoline engine.

The torque and fuel consumption curves of the gasoline engine matched with the prototype turbocharger and new designed one are illustrated in Figure 6.

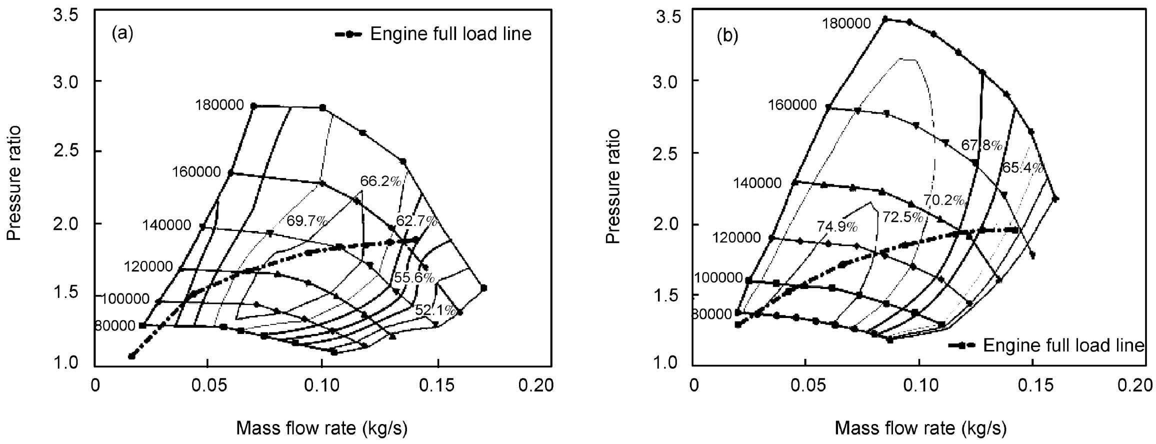

Figure 5 Compressor maps and engine full load operating lines. (a) Prototype compressor; (b) new designed compressor.

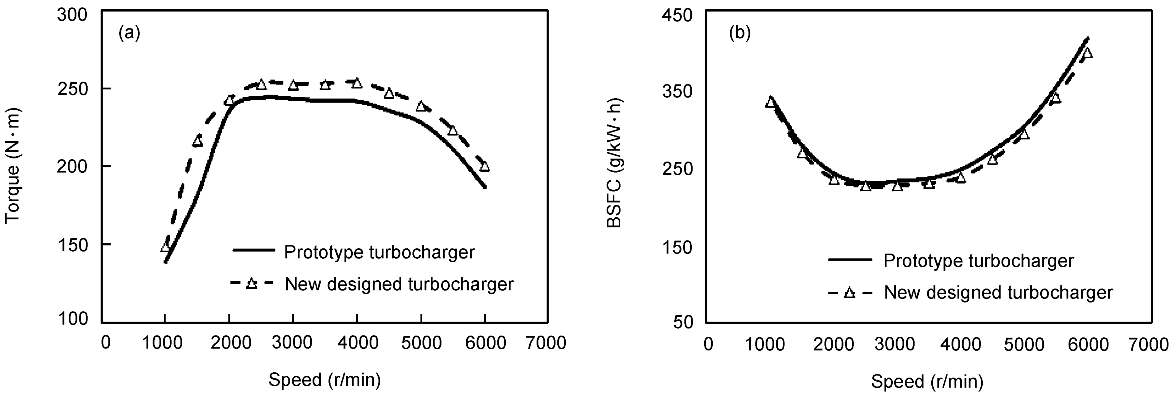

Figure 6 New engine performance curves compared with the prototype engine. (a) Torque curves; (b) BSFC curves.

The high efficiency of turbocharger compressor at the low-mass flow region will induce more fresh air into the cylinder, which will be very helpful to improve engine performance at low speed operation conditions. From Figure 6, the torque of the gasoline engine at low rotating speed has been increased by about 16% by the new design turbocharger.

The new engine-oriented turbocharger design process is an integrated procedure involving transforming the turbocharger characteristics into specification of the engine performance to satisfy the engine operation requirements. This efficient turbocharger design has improved engine power and fuel consumption performance greatly. The notable reduction of the brake specific fuel consumption is seen at the medium and high engine speeds, for example, by about 4% at 5500 r/min (rated point).

4 Conclusion

Turbocharger design is a complicated task, and is a major challenge for a turbocharged engine performance improvement. The information of engine operation conditions and an appropriate link between the engine requirements and design features must be considered in generating the most suitable turbocharger design.

The research presented in this paper describes an integrated turbocharger design approach for better turbocharger matching to an internal combustion engine. The turbocharger through flow model determines the interaction links between engine cycle requirements and design parameter values, and is used to generate the design alternatives. The integrated method has been applied with success to an automotive engine turbocharger assembly.

Note that the proposed design procedure can be extended and made applicable to many other areas, such as engine cooling pump and fans, turbo generators, etc. The proposed design procedure will provide turbocharger designers with a useful way to generate feasible design alternatives and assess the quality of the turbocharger design recommendations while still in the process of solving the design problem. Furthermore, this procedure allows the turbocharger designers to connect engine requirements with design output parameter values, leading to the development of not only a turbocharger design information system but also a turbocharger design expert system.

1 Leduc P, Dubar B, Ranini A. Downsizing of gasoline engine: an efficient way to reduce CO_2 emissions. Oil & Gas Sci Technol, 2003, 58: 115–127
2 Kasseris E P, Heywood J B. Comparative analysis of automotive powertrain choices for the next 25 years. SAE Paper 2007-01-1605, 2007
3 Heywood J B, Welling O Z. Trends in performance characteristics of modern automobile SI and diesel engines. SAE Paper 2009-01-1892, 2009
4 Petitjean D, Bernardini L, Middlemass C. Advanced gasoline engine turbocharging technology for fuel economy improvements. SAE Paper 2004-01-0988, 2004
5 Lake T, Stokes J, Murphy R. Turbocharging concepts for downsized DI gasoline engines. SAE Paper 2004-01-0036, 2004
6 Lecointer B, Monnier G. Downsizing a gasoline engine using turbocharging with direct injection. SAE Paper 2003-01-0542, 2003
7 Albrecht A, Knop V, Corde G. Observer design for downsized gasoline engine control using 1D engine simulation. Oil & Gas Sci Technol, 2006, 61: 165–179
8 Korakianitis T, Sadoi T. Turbocharger-design effects on gasoline engine performance. J Eng Gas Turb Power, 2005, 127: 525–530
9 Japikse D, Baines N C. Introduction to Turbomachinery. Wilder, Vt: Concepts NREC, 1997
10 Zhuge W, Zhang Y, Zheng X, et al. Development of an advanced turbocharger simulation method for cycle simulation of turbocharged internal combustion engines. Proc IMechE, Part D: J Auto Eng, 2009, 223 (D5), doi: 10.1243/09544070JAUTO975
11 Chen T, Zhang Y, Zhuge W. Integrated system simulation for turbocharged IC engines. SAE Paper 2008-01-1640, 2008
12 Watson N, Janota M S. Turbocharging the Internal Combustion Engine. England: MacMillan, 1982
13 Krain H. Review of centrifugal compressor's application and development. ASME Paper GT2003-38971, 2003
14 Eckardt D. Detailed flow investigations within a high-speed centrifugal compressor impeller. ASME J Fluid Eng, 1976, 98(3): 390–402