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Study and Application of Performance Optimization for General Purpose Engine Based on GT-Power Software

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ABSTRACT
After the installation of three-way catalytic converter, universal gasoline engines often experience significant power loss. In order to solve this problem, we employed numerical engine simulation technique to explore a high-efficiency performance optimization method based on one-dimensional simulated engine by using GT-power software. The optimization method was applied to simulate the performance of a 125 mL universal gasoline engine and optimize its design. A performance optimization approach was formulated and prototype trial-production and experiments were carried out. The optimized engine performed better after the installation of catalytic converter than it did before the installation. The proposed performance optimization method was validated accurate, efficient and worth applying in the engineering field.

Key words: GT-power software, computational fluid dynamics theory, performance optimization, simulation analysis

INTRODUCTION
General purpose engine refers to the gasoline engine except for the vehicle, rating power is generally less than 30 kW (Li, 2008). The main application is in agriculture, garden planting, electric power generation, fire protection, municipal works and entertainment. The application is closely related with the economic development and the people living, providing auxiliary power for generator, lawn machines, golf car, scooter, sledge and rescue equipment. At present our country has ten types of general purpose engine in all. The agricultural purpose has a wide range of applications, greater exports and a good development prospect (Wang *et al*., 2008).

With the rapid development of the application, the emissions of general purpose engine are concerned strongly by society. In order to strengthen the protection of public health and the environment the government have issued and carried out convention of engine emissions, aiming at supervising the production enterprise to control the emissions of new (Sivalakshmi and Balusamy, 2014; Saravanan *et al*., 2013). At present the representative emission regulations system is mainly for USA, European and Japanese emissions regulations system which is widely cited in American and European regulations system (Odaka, 2004). For engine industry, the specific emission regulations system is divided into road class emission standard and non-road class emission standard. The road class emission standard is subdivided into light vehicles (including cars) emission regulations and heavy-duty vehicle emission regulations (Fischer *et al*., 2004).

At present in the engine energy-saving emission reduction, we are mainly achieving the purpose by improving engine combustion mode, reducing engine friction technology and recycling and reusing exhaust gas energy (Rusch *et al.*, 2006; Fuerhapter *et al.*, 2004). In the existing technology and market conditions, we generally equipped with two-grade three-way catalytic converter in the exhaust system of engine to improve the emission performance. This technology improving the emission performance effect is good but increase the resistance of the engine exhaust, decreasing the engine exhaust system flow, making the combustion and emission condition worse. With increasing resistance of the intake and exhaust, engine performance decreased rapidly (Zhang *et al.*, 2006). Especially for small gasoline engine, power and torque dropped more. However, at the same time, customer requirements for all aspects of the performance of the engine are more and more high and the market competition is more intense. So, the technology must ensure that in the condition of controlling emissions, engine performance can have none loss of performance.

This study mainly researched a 125 mL emissions of small gasoline engine installed with three-way catalytic converter. This study used the one-dimensional computational fluid dynamics theory and built one-dimensional simulation model by using software of GT-power. This study analyzed a lot of performance simulation, put forward the performance optimization scheme and prototype. It provided that after being installed three-way catalytic converter engine performance achieved the level of the original engine, even some condition has exceeded the original.

MATERIALS AND METHODS

Engine numerical simulation: With the rapid development of computer technology and computational fluid dynamics, numerical heat transfer, chemical kinetics and other basic theory, we can establish a calculation model which the working mechanism of engine is consistent with the experimental results. It can better predict the engine performance, researching parameter varying widely in a short period of time and provides guidance to the development of a new engine and improving the engine performance (Wei *et al.*, 2013; Hammou and Lacroix, 2006).

The engine cycle simulation theory and numerical simulation technology is more mature. At present, mature market engine cycle simulation software is much, such as: The AVL-BOOST of Austria Lester Company, the GT-POWER of Gamma Technologies Company, the WAVE of Ricardo company and other software. Those pieces of software are applied to the simulation of various structure parameters, the theoretical parameters influence on engine performance. Through the numerical calculation of engine working process, a comprehensive analysis of the whole process to the thermodynamic cycle and the causal relationship of all aspects are obtained, to provide early engine design and post optimization analysis (Shi *et al.*, 2010; Bozza and De Bellis, 2014).

The engine working cycle simulation, refers to using the method of numerical calculation to analyze the flow of intake and exhaust system, then coupling multidimensional or zero dimensional thermal model of describing the in cylinder combustion and heat transfer processes, thereby simulating the engine thermodynamic cycle and the working process (Li *et al.*, 2013). For working process in engine cylinder, according to the first law of thermodynamics can obtain control equation as follows (Li and Chen, 2010):

$$\frac{d(m_c u)}{da} = -p_c \frac{dv}{da} + \frac{dQ_f}{da} - \sum \frac{dQ_w}{da} - h_B \frac{dm_B}{da} \tag{1}$$

Where:

m_c = Quality of working fluid in cylinder
u = Specific internal energy
α = Crank angle
p_c = Pressure of working fluid in cylinder
ν = Working volume of cylinder
Q_f = Releasing heat of fuel combustion in cylinder
Q_w = Heat loss of cylinder wall
h_B = Specific enthalpy
m_B = Quality of enthalpy

For intake system and exhaust system, with taking a one-dimensional fluid (gas) dynamics equations to mathematical describe, control equations are as follows:

Continuity equation as follows:

$$\frac{dm}{dt} = \sum_b mflx \tag{2}$$

Energy equation as follows:

$$\frac{dme}{dt} = p\frac{dv}{dt} + \sum_b (mflxH) - h_g A(T_{gas} - T_{wall}) \tag{3}$$

Momentum equation:

$$\frac{d(mflx)}{dt} = \left[dpA + \sum_b (mflxu) - 4C_f \frac{\rho u^2}{2}\frac{dxA}{D} - C_p\left[\frac{1}{2}\rho u^2\right]A \right] / dx \tag{4}$$

Where:

m = Quality of control volume
ν = Volume of control volume
p = Pressure of control volume
ρ = Density of control volume
A = Flow area
e = Internal energy
H = Total enthalpy
H_g = Heat transfer coefficient
D = SD equivalent diameter
u = Boundary velocity of control volume
C_f = Surface friction coefficient
C_p = Pressure loss coefficient

RESULTS

Analysis of the engine performance before installing three-way catalyst converter: For the original machine (no three-way catalyst converter), we take the evaluation and benchmarking analysis of a full range of exhaust process, combustion characteristics, performance of the engine, so, determine the potential and direction to improve the performance of general purpose engine.

Analysis of primary machine external characteristic: Through engine stand tests, the external characteristics of the original machine is obtained, such as in Fig. 1-2. Figure 1 is the variation curve of external characteristics of the engine according the Indicated Mean Effective Pressure (IMEP), the Brake Mean Effective Pressure (BMEP), the Friction Mean Effective Pressure (FMEP). As is shown in Fig. 1, the FMEP curve is smooth and the value are generally large, especially with low speed; the BMEP curve is normal but the value is numerical generally small, so it needs to optimize process to improve, the IMEP value in the interval of 5000-8000 rpm is

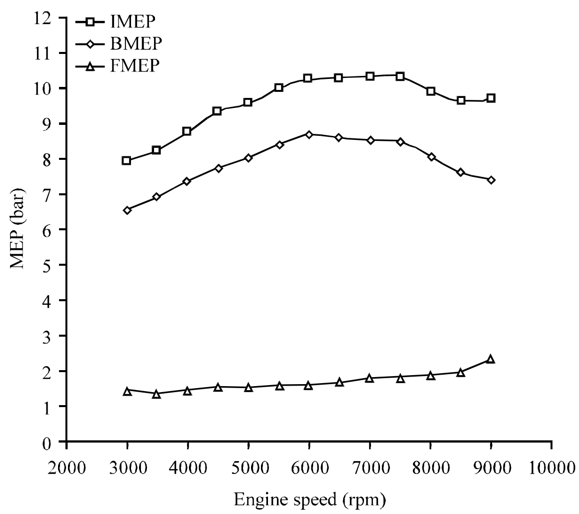

Fig. 1: Variation curve of external characteristics of the engine

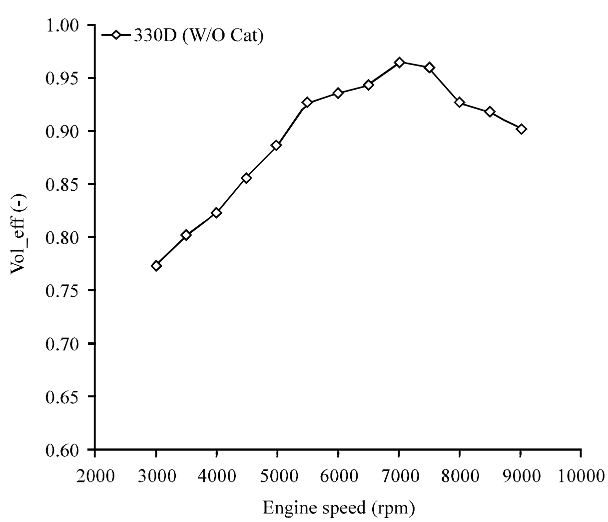

Fig. 2: Curve of volumetric efficiency of the engine

smaller, so, it needs to improve. Figure 2 is the engine volumetric efficiency curve. As is shown in Fig. 2 volumetric efficiency is low at low speed, so, it is necessary to improve the optimization of intake and exhaust system.

Analysis of primary machine external characteristic: In order to obtain more detailed and realistic understanding of engine combustion, this study analyzed combustion by AVL combustion analyzer, get the results such as shown in Fig. 3 and 4.

Figure 3 is a curve which shows the external characteristic of engine combustion pressure changes with the crank angle and combustion pressure under different speed. As is shown in Fig. 3, exothermal efficiency is more low in the 3000 rpm, resulting in cylinder pressure low and low combustion lag; due to inflation coefficient increased gradually in 5000-7000 rpm, the residual

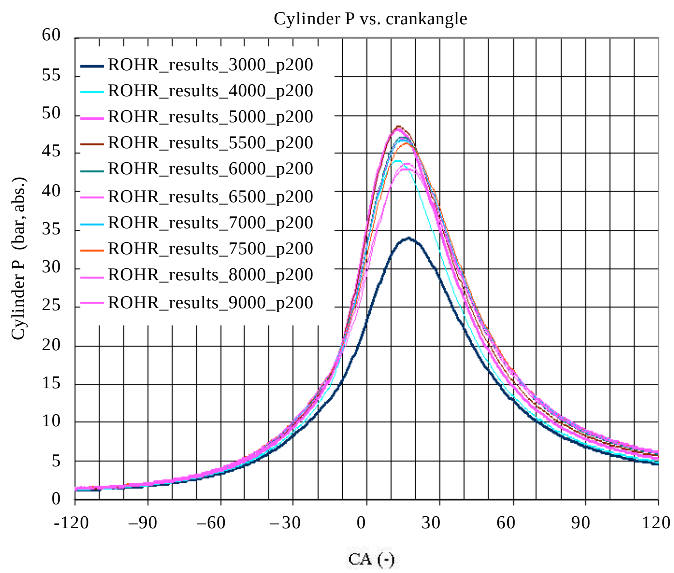

Fig. 3: Curve of combustion explosive pressure

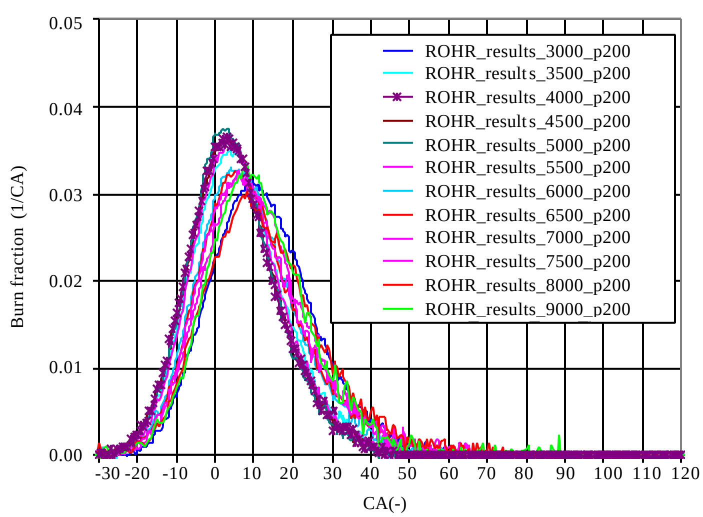

Fig. 4: Curve of combustion exothermal efficiency

waste coefficient is decreased gradually, with airflow disturbance increasing, the combustion speed is more fast; here cylinder pressure is more higher and the maximum cylinder pressure is in the range of 13-18° and the result is moderate; the combustion time is too short to keep on burning rate in 8000-9000 rpm and the maximum explosion pressure delayed and reduced.

Figure 4 is a curve which shows combustion exothermal efficiency changes with the crank angle in engine external characteristic. From the combustion heat release rate curve: Heat release rate is more low in 3000 rpm which mainly because the resumption of efficiency is more low, the high concentration of the mixed gas and high coefficient of residual waste; the heat release rate is more high in 4000-5000 rpm but before TDC exothermic the speed is so fast that it reduced IMEP; heat release rate has been on a downward trend in 6000-8000 rpm but heat decreases in the rage of 7500 rpm to TDC which is favorable for improving the IMEP, combustion heat release rate obviously cannot keep up with the requirements of the engine speed in 8000-9000 rpm which leads to the indicated mean pressure dropping.

Analysis of engine performance after being installed three-way catalytic converter: In order to accurately analyze the impact of three element catalytic converter performance of the original machine, we tested engine performance after being installed three-way catalytic converter, get the result shown in Fig. 5-8.

Figure 5, installed three-way catalytic converter general purpose engine in high speed (4500-8000 rpm) torque dropped faster. Figure 5 is the measured general purpose engine torque characteristic value after being installed three-way catalytic converter. Figure 6 is the calculation of the engine torque characteristic value after being installed three-way catalytic converter. Analyzing from the figure, calculated values with measured values basically showed a similar trend, installed three-way catalytic converter engine torque is decreasing more fast in the high speed, especially in the range of 5500-6500 rpm. So, accord the above description, we can prove GT-power engine one dimensional simulation model is correct, can be used for subsequent performance optimization.

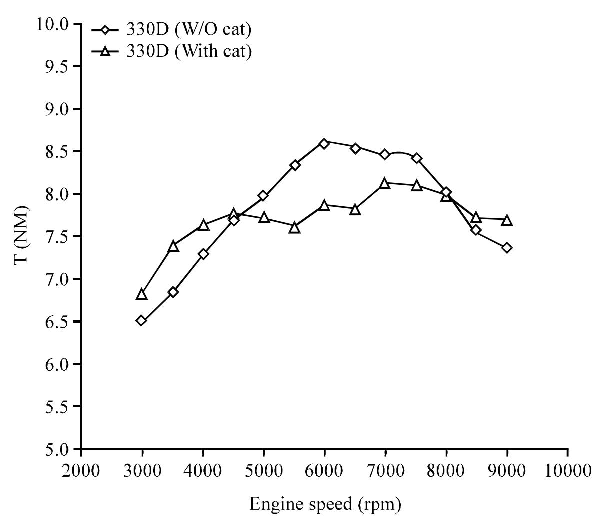

Fig. 5: Measured influence of engine torque value after being installed three-way catalytic converter

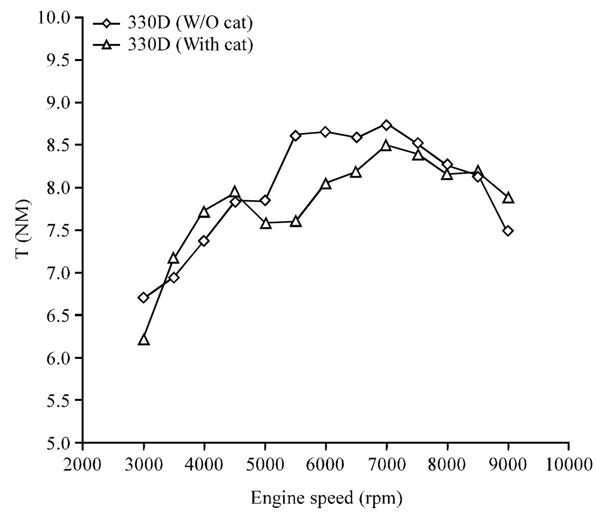

Fig. 6: Computed influence of engine torque value after being installed three-way catalytic converter

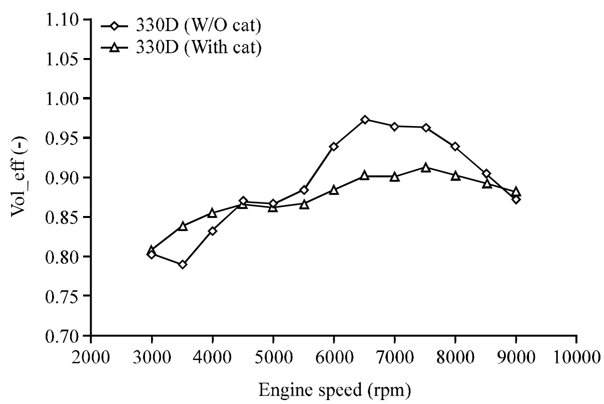

Fig. 7: Influence of engine volumetric efficiency after being installed three-way catalytic converter

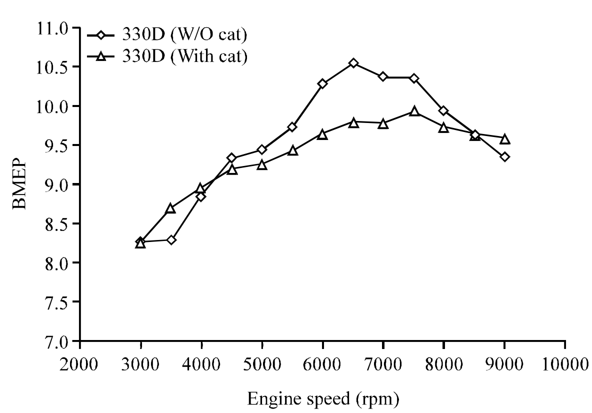

Fig. 8: Influence of engine BMEP after being installed three-way catalytic converter

Analyzing from Fig. 7 and 8 installed three-way catalytic converter general purpose engine in the range of 4500-8000 rpm, the engine volumetric efficiency is too low, caused the engine BMEP too low, thus affecting the engine torque in the range of 4500-8000 rpm is too low.

Performance optimization method analysis and practice

Performance optimization method: Through and testing the general purpose engine which response is good in market, combined with analysis of test data in this case, we mainly compared the difference of combustion exothermic characteristics and combustion efficiency characteristics and get the result as follows: For the external characteristics and combustion characteristics of the general purpose engine, there is still much room for improvement.

Combined with the engineering practice experience and theoretical knowledge, we optimized the performance of the machine from the following aspects: (1) The exhaust pressure wave resonant frequency and amplitude (by changing the length and diameter), (2) The intake pressure wave resonant frequency and amplitude (by changing the length and diameter), (3) By changing the valve timing and lifting curve to cater pressure fluctuation under the condition of the limited exhaust system, pipe diameter, length adjustment and (4) By the ignition timing to optimize (fine-tune) engine performance.

Performance optimization practice: Combined with the analysis of the experience and theory, using GT-power simulation tested the specific data of various schemes. The results are shown in Fig. 9-12.

Figure 9 is the only optimized intake system results. As shown in Fig. 9, if only changed the intake system length condition, the optimized general purpose engine performance at low speed reached or even exceeded the level of the original machine, at medium speed engine performance has improved but has not reached the performance of the original machine, at high speed almost has no change. Figure 10 is the only optimized the exhaust system results. As shown in Fig. 10, if only change the exhaust system length condition, the general purpose engine performance at low speed reached or even exceeded the level of the original machine but the high speed engine performance improvement is not obvious and performance even below three-way catalytic converter level in 4000-6000 rpm.

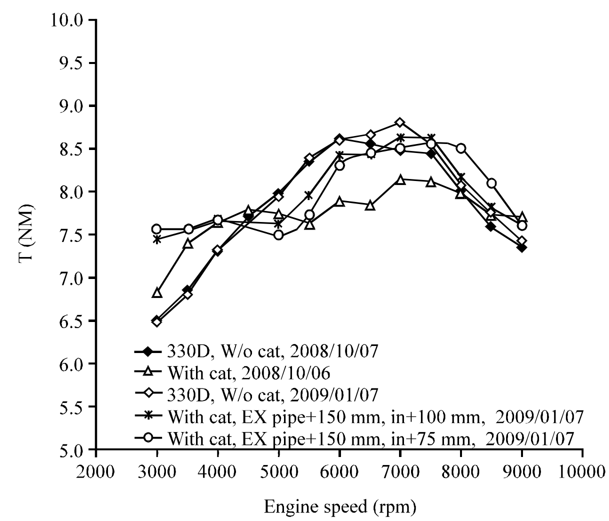

Fig. 9: Optimized results of the intake system

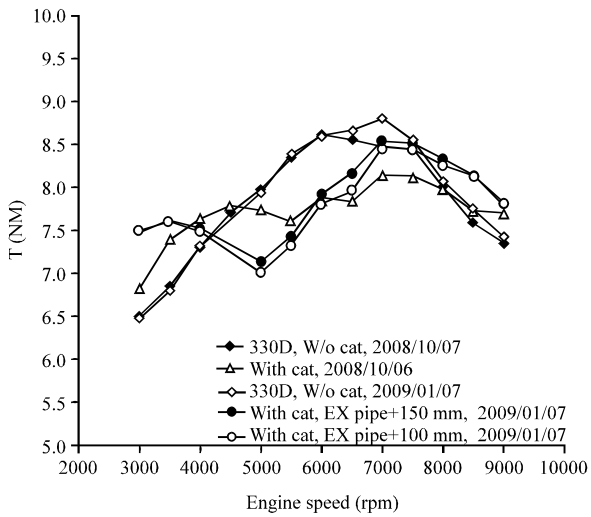

Fig. 10: Optimized results of the exhaust system

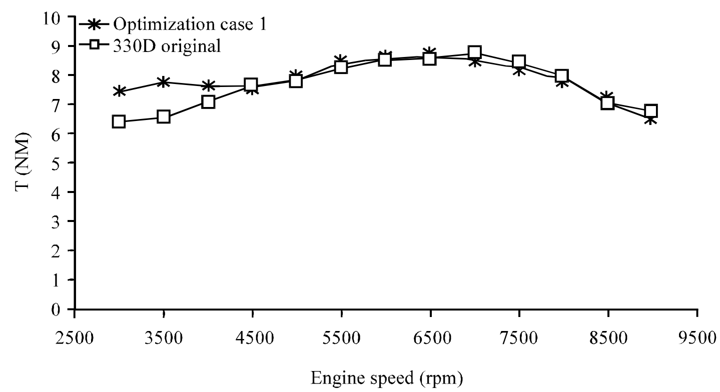

Fig. 11: Torque comparison of the comprehensive optimized system with the original

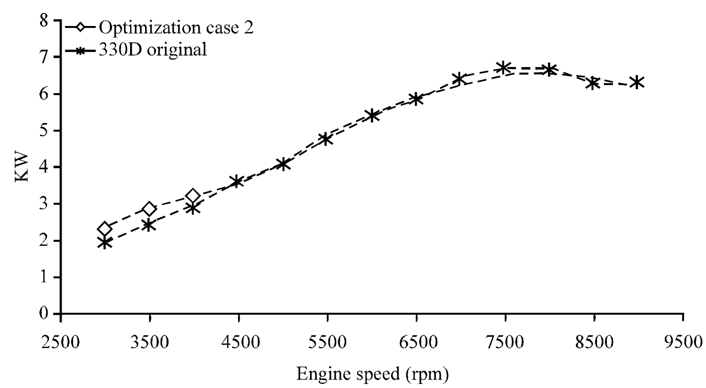

Fig. 12: Power comparison of the comprehensive optimized system with the original

Conclusionly, if only changed the inlet and exhaust system, installed three-way catalytic converter the engine performance is very difficult to restore to the original state, so need for valve timing and lift optimization. Figure 11 and 12 is compared by optimizing the intake and exhaust system, air distribution mechanism of the engine with the original machine. Seen from the figures, after optimizing exhaust and gas distribution system, the engine performance basically reached the level of the original machine and at low speed even more than the level of the original machine. After sample processing and manufacture, test results showed: The optimization method is correct and feasible, the cost is acceptable, the optimization method is in line with market and enterprise design requirements.

DISCUSSION

The operating parameters of engine, such as the gas flow, mean effective pressure, pressure rise per unit of crank angle, excess air coefficient and exhaust temperature, etc., have vital impact on the overall performance improvement of the engine and all these parameters are restricted by each other. The changes of these parameters are determined by the structural parameters and design requirements of the engine to a great extent. Experimental data and empirical statistics are generally important bases of these parameters but they are no longer able to meet the ever-increasing requirements for optimization design and control of the engine. In the past, experiment was the main method of researching the engine performance and its working process, however, the cycle of this method is long and the cost is high, so it doesn't adapt to the present requirements of developing the market any more. Simulation usually takes the simulation experimental data and experience as the important reference and based on simulation calculation of several major key operating points or relevant main performance parameters in the working process of the whole engine, it makes simulation calculation of the whole engine model and obtains the overall performance parameters of the engine. Along with the continuous update of computer simulation software, a series of software for simulating the working process of engine is emerging one after another. At the same time, the efficiency of simulation calculation on the platform of the simulation software is constantly enhanced and the relative error is constantly decreased. Therefore, using one-dimensional simulation software to research working process of engine has become a fast, accurate and effective mean of developing engines.

In the study by Mohanty and Pattnaik (2005), the author got a more convenient model whose numerical simulation results about the muffler were close to the experimental results through the further optimization of the four-pole network. Xie Tianfeng ran a simulation of the engine and the muffler with GT-power software to predict the characteristics of muffler and figure out the impact on the performance of engine by mufflers with different structures (Xie *et al*., 2003). Zhang *et al*. (2007), verified the GT-power software had a good fitting degree in a wider frequency brand range through the study of insertion loss of muffler with plugged parallel tubes and double expansion chambers. In study, the design of the muffler at first the one dimensional plane wave theory and semi empirical and empirical formula make preliminary identification of several design schemes and then we can use the software to simulate the engine and exhaust system, compare and verify them by engine bench tests to choose the best solution for further optimization among them.

CONCLUSION

In this study, we used the one dimensional engine simulation software GT-power, in-depth study the impact of the general purpose engine intake and exhausts system and a gas distributing mechanism for the performance of the engine and also optimized the engine performance. The conclusion is get as follows.

By using the optimization method of this study, the general purpose engine exceeded the design goal and the market response is good. The optimization method is correct and efficient; the engine simulation analysis technique for early performance development of engine and lately the performance optimization is relatively mature. By the application of simulation technology, the problem in engineering can be more quickly and effectively solved, In the general purpose engine performance optimization, we should take the whole engine optimization of intake and exhaust system, timing and other system to achieve design optimization goal and only by the optimization of a single system is difficult to achieve the desired objectives. General purpose engine performance development has reached the bottleneck stage and room for improvement on the performance is more narrow and performance become more and more difficult, so we must use more advanced technology together to improve work performance now.

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