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Simulation Analysis on Power Performance and NO_x Emission of Engine Under Different Oxygen-Air Ratios

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Abstract: In order to improve the dynamic performance and reduce NO_x emission from the engine, the whole model for a certain type of engine is built with GT-Power, and the main components are displayed in the model. The corresponding properties and parameters for the components are set according to the geometry structure parameters of the engine, and the simulation on dynamic performance and NO_x emission under oxygen-air ratios of normal value, 20%, 24%, 25% and 30% for the engine intake is achieved. The simulation results show that the rated power and torque of the engine increase with the increasing of oxygen-air ratio, but the NO_x emission increases sharply when oxygen-air ratio is over 25%.

Keywords: oxygen-air ratio; NO_x emission; simulation; oxygen enrichment; engine

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Automobile is the essential tool for transportation in the modern life, however a lot of exhaust gases are generated and emitted into the outside atmosphere during the process of moving the automobile. There are a few poisonous substances in the exhaust gas according to the corresponding documents, e.g., NO_x, HC, CO, SO_x and other particles, and some of them are the main components of PM2.5, so they are harmful for the human[1-2]. On the other hand, most of the exhaust gases are harmful for the plant too, furthermore the secondary hazard is generated after the exhaust gases are absorbed into the contaminative vegetables. Besides, the exhaust gases do much harm to the ecological environment, e.g., greenhouse effect. Therefore, some ways must be taken to decrease the damage from the exhaust gases, even eliminate it.

A way is studied and simulated based on a special gasoline engine in this paper, and NO_x emission is measured by adjusting oxygen content in the air, finally the improvement solution is proposed according to the simulation results. The whole contents are arranged as follows: the current studies on combustion with oxygen enrichment are introduced and analyzed, then the special diesel engine is modeled with GT-Power according to its parameters of structure and performance, next NO_x emission is got according its working conditions, finally the simulation results are got and the solution is proposed.

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1 Current Studies on Combustion With Oxygen Enrichment

The studies on emission from the engine was started in 1980s′ abroad. The documents[3-4] propose that particle filter must be adopted in order to meet American emission regulation in 1994. Many studies have been done in the corresponding institutes to decrease emissions from the engine in order to deal with severer and severer emission regulation. Johnson T V summarized the ways on decreasing NO_x emission, e.g., selective catalytic reduction, adsorption reduction, and introduced the development of particle filter of the engine, texture of materials and management for coal smoke etc[5-6]. Document[7] discovers the following results via the theoretical analysis: under the two conditions of constant intake air pressure and enhanced intake air pressure, and the stable air-fuel ratio, the coal smoke of the engine and NO_x emission can be decreased. Besides, under the conditions of oxygen enrichment and exhaust gas recirculation (EGR), the coal smoke and NO_x emission from heavy-duty diesel engine can be decreased.

The studies on emission from the engine and oxygen enrichment was started in 1990s′ at home. The feasibility of controlling NO_x emission and coal smoke with the roles of EGR and oxygen enrichment intake is studied in document[8]. And the experimental results show that NO_x and coal smoke emission can be controlled effectively with the roles of EGR and oxygen enrichment intake, however the effective fuel consumption rate deteriorates a little.

Combustion and emission control of the engine is studied deeply for a long time in some research institutions. Among that, a research group studies the effect of the shutdown time and the angle of the valve on the homogeneous combustion. Under the rule of negative valve overlap, intake gas front backflow with different levels is formed to regulate the ignition time through opening intake valve ahead of time. The research group led by professor Wanhua Su studies the influence regularity of different combustion control parameters on heavy-duty diesel engine during the process of low temperature combustion[2]. Another research group studies the influence regularity of high pressure and low pressure EGR based on two-level pressurization system, and exhaust energy distribution between highlevel and lowlevel turbine based on low pressure EGR on the combustion process, performance and emission of diesel engine, based on common rail heavy-duty diesel engine, aiming at improving the capacity of EGR cycle. The study on the influencing mechanism of EGR on combustion in low temperature shows that NO_x emission depends mainly on the concentration of oxygen. Besides, the influence of the composition of the intake gas on combustion performance and emission characteristics of the diesel engine in low temperature is studied with the experiment and simulation, by contrasting the influence of different composition of the intake gas on the combustion and emission of the engine. The value of coal smoke and the corresponding EGR rate increase with the increase of pressure of intake gas. And the higher EGR rate can decrease NO_x emission further under the condition of the same coal smoke emission[9]. The research elaborates and summarizes the homogeneous compression ignition, combustion theory in low temperature, and extends it to homogeneous compression ignition and combustion in low temperature for gasoline fuel, and homogeneous compression ignition and combustion in low temperature for diesel fuel, and homogeneous compression ignition and combustion in low temperature for fuel characteristics etc[10].

The emission and combustion of the engine is studied and some theories are proposed, e.g., homogeneous compression ignition and combustion in low temperature, however the influence of the diesel fuel with different oxygen-air ratio on NO_x emission and performance of the diesel engine is undefined, so it is urgent to study the above issue in this paper.

2 Modeling for Engine

There are many ways to model engine, e. g. , top to down or down to top, the main modeling tools include AVL FIRE, Star-Ccm, AMESim and GT-Power, however they are different in performance. AVL FIRE is a powerful multi-purpose thermo-fluid dynamics software with a particular focus on handling fluid flow applications related to internal combustion engines and powertrains. Star-CCM is an entire engineering process for solving problems involving flow (of fluids or solids), heat transfer and stress. AMESim offers a complete 1D simulation suite to model and analyze multi-domain, intelligent systems and to predict their multi- disciplinary performance. GT-Power is a tool to simulate the working process of engine, it has powerful auxiliary modeling pretreatment tool, rich combustion model and control function besides optimization function with it can optimize the sound attenuation components in intake and exhaust system. It represents the flow and heat transfer in the piping of the engine system based on one-dimensional gas dynamics[11], therefore, GT-Power meets the requirement of modeling and be adopted to model the engine in this paper.

2.1 Modeling for Engine

The fundamental parameters of the engine detected are shown as follows: 4-cylinder inline engine; displacement 1 390 cm^3; cylinder bore 76. 5 mm; piston stroke 75. 6 mm; compression ratio is 10 to 1. There are many indexes to evaluate the main performance of engine, i. e. , dynamic, environment, economy and reliability.

Among that, the dynamic indexes are applied to indicate the capability of power characterization of engine, which includes brake torque, brake power and rotation speed of engine. Environmental indexes are applied to indicate the quality of exhaust and noise of engine, and emission indexes mainly refer to the amount of harmful emissions contained in gases from the fuel tank and crankcase tank, and the exhaust from cylinder.

Economic indexes are indicated with effective fuel consumption. Reliability indexes are applied to indicate the ability of normal continuous working for engine under the specified conditions and time. The engine is modeled according to the structure, performance parameters and fundamental working principle of the gasoline engine, which is shown in figure 1.

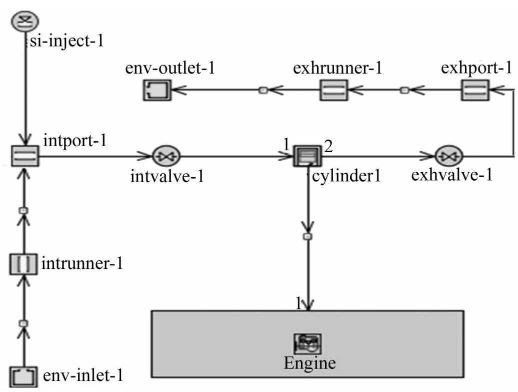

Fig. 1　Simulation model of the engine

图 1　发动机仿真模型

2.2 Oxygen-Air Ratio

As we all know, air-fuel-ratio affects the performance of engine greatly. Among that, air intake, above all oxygen intake, has substantial influence on power, torque and speed of engine. Therefore, oxygen-air ratio (abbr. OAR) is focused to improve the performance and reduce NO_x emission of engine in this paper. The normal volume ratio of oxygen to air is about 21%, and the working status of engine differs as OAR varies. Some experiments show that rich oxygen and poor nitrogen intake can improve the power and torque of engine qualitatively[12], however the influence on NO_x emission with variable OAR is not definite.

2.3 Simulation Setup

The geometry structure and working parameters of the engine are set before simulation, among that, the air intake is set as a reference variable, meanwhile the value of OAR is set as 5 kinds of working conditions, i. e. , normal value, 20%, 24%, 25% and 30%, to achieve the complete relation curve, and the air-fuel-ratio based on OAR is set as follows: attribute, injector delivery rate, fuel ratio specification and fuel ratio are set as objective value, 6, air-to-fuel and 12.5 respectively. Among that, the object value air-to-fuel for fuel ratio specification is an alternative variable. And the geometry structure of the engine is set as follows: attribute, bore, stroke, connecting rod length, compression ratio and TDC clearance height are set as objective value, 76.5, 75.6, 147, 10 and 0.5 respectively., and other fundamental parameters of the engine i.e., attribute, engine type, speed or load specification, engine friction object or FMEP and start of cycle, are set as object value, 4-stroke, speed, r·min^{-1}, friction and −95 respectively. Among that, the object value friction for engine friction object or FMEP is a reference variable.

After finishing the setup for the components of the engine, simulation parameters with GT-Power are set. The speed of the engine is set between 4 600 r·min^{-1} and 1 800 r·min^{-1} with 400 r·min^{-1} increments, so 8 cases are set in the simulation process.

3 Simulation Results and Analysis

According to geometry structure, working principle of the gasoline engine detected and the above setup, the simulation for the engine is done with GT-Power, and the relation curves for speed-power, speed-torque and speed-NO_x are achieved under the value of OAR is set as normal value, 20%, 24%, 25% and 30% respectively. Among that, the three curves under normal OAR, i.e., 21%, are shown in figure 2, 3, 4. In figure 2, 3 and 4, the symbol P, T, $\rho(NO_x)$ and n indicate brake power, brake torque, mass concentration of NO_x and speed respectively.

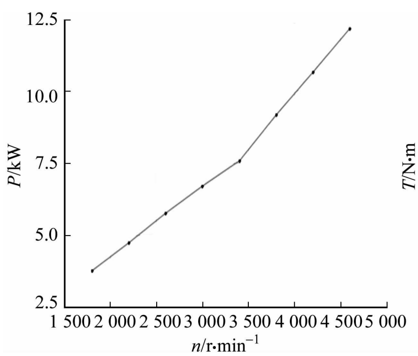

Fig. 2 Speed-rated power of the engine under normal OAR

图 2 自然氧空比条件下发动机转速-额定功率关系曲线

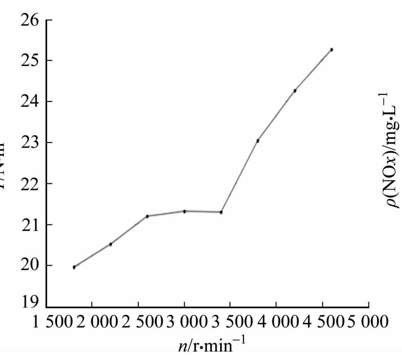

Fig. 3 Speed-rated torque of the engine under normal OAR

图 3 自然氧空比条件下发动机转速-额定扭矩关系曲线

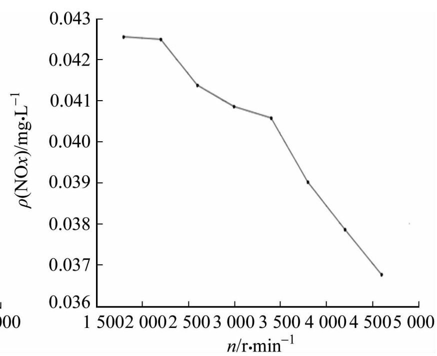

Fig. 4 Speed-NO_x emission of the engine under normal OAR

图 4 自然氧空比条件下发动机转速-NO_x 排放关系曲线

Figure 2 and 3 indicate that the brake power and torque both increase with the increase of the rotation speed of the engine under normal OAR, which are consistent with the characteristic curve of gasoline engine. Meanwhile figure 4 shows that NO_x emission decreases gradually with the increase of the rotation speed under the same OAR.

In order to achieve the complete variation tendency of performance-OAR and NO_x-OAR, the relation curves of speed-brake power under the value of OAR is set as normal value, 20%, 24%, 25% and 30% respectively are achieved and drawn in figure 5. Among that, the line decorated with rhombus shape, the line decorated with square shape, the line decorated with triangle shape, the line decorated with cross shape and the line decorated with asterisk shape represent the relation curves of speed-brake power under 20%, normal, 24%, 25% and 30% OAR respectively. It can be inferred that the brake power improves with the increase of OAR obviously.

The relation curves of speed-brake torque under 5 kinds of OAR got in the same way are shown in figure 6, and the brake torque improves with the increase of OAR too. The relation curves of speed-NO_x under 5 kinds of OAR got in the same way are shown in figure 7. In figure 5, 6 and 7, the symbol $\varphi(O_2)$ indicates the volumetric oxygen-air ratio. Among that, the decorated shape of the line in the figure represents the relation of speed-NO_x in the same OAR as the figure 5 and 6. NO_x emission increases with the increase of OAR, however NO_x emission is approximately close to 0 when OAR is between 20% and 25%, so the relation curves closely coincide. The relation curve of speed-NO_x under 25% OAR shown in figure 8 shows that NO_x emission increases sharply. Therefore a deduction is made that a huge increase of NO_x emission arises under 30% OAR according to the relation of speed-NO_x under different OAR.

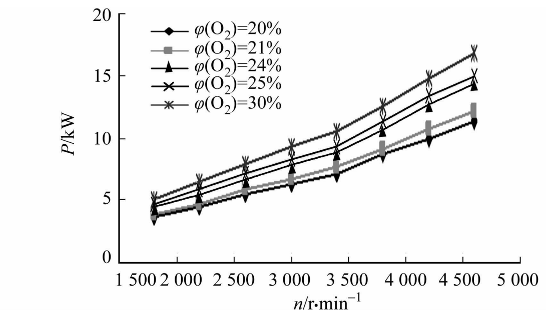

Fig. 5　Speed-rated power of the engine under different OAR

图 5　不同氧空比条件下发动机转速-额定功率关系对比曲线

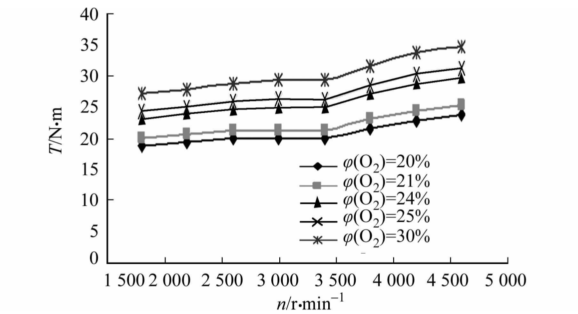

Fig. 6　Speed-rated torque of the engine under different OAR

图 6　不同氧空比条件下发动机转速-额定扭矩关系对比曲线

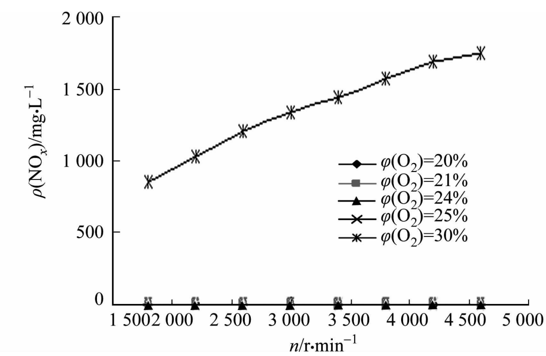

Fig. 7　Speed-NO_x emission of the engine under different OAR

图 7　不同氧空比条件下发动机转速-NO_x 排放关系对比曲线

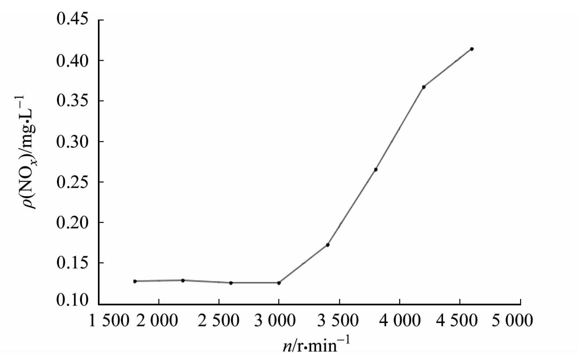

Fig. 8　Speed-NO_x emission of the engine under 25% OAR

图 8　氧空比为 25%时发动机转速-NO_x 排放关系曲线

4　Conclusions and Prospect

In order to improve the performance and reduce the emissions of the engine, a special gasoline engine is modeled with GT-Power according to its geometry structure and working parameters, and the relation curves of speed-brake power, torque and NO_x of engine under 20%, normal, 24%, 25% and 30% OAR are got.

The simulation curves show that the brake power and the brake torque improve with the increase of OAR. Meanwhile NO_x emission is close to 0 when OAR is between 20% and 25%, however it increases sharply under over 25% OAR, and sharp increase arises under 30% OAR.

According to the simulation results, the optimal way considering both the dynamic performance improvement and NO_x emission reduction of the engine will be studied in future works.

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不同氧空比下发动机动力性能与 NO_x 排放仿真分析

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摘要： 为提高发动机动力性并减少 NO_x 排放，采用 GT-Power 对某型发动机进行整机建模，并列出主要组件. 根据发动机几何结构参数设置各组件的对应属性和参数，在发动机进气氧空比分别为正常值，以及 20%，24%，25%及 30%条件下进行了动力性能与 NO_x 排放仿真实验. 实验结果表明：随着氧空比增大，发动机额定功率与扭矩增大；当进气氧空比超过 25%时，NO_x 排放急剧增大.

关键词： 氧空比；NO_x 排放；仿真；富氧；发动机

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