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Key Technologies Research on Hydrogen Internal Combustion Engine Power Density Enhancement with Synergistic Ultra-low Nox Emission

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Abstract

Hydrogen energy is an ideal alternative to traditional fossil fuels. Hydrogen internal combustion engine can rely on the mature internal combustion engine industry system, which has low requirements for hydrogen purity, ultra-low emissions and higher thermal efficiency. However, hydrogen combustion speed, easy diffusion, wide ignition limit, low ignition energy characteristics of hydrogen also affect the formation of hydrogen mixture, combustion process and NOx emission performance. The combustion and emission characteristics of hydrogen internal combustion engine with intake pressurization and exhaust gas recirculation (EGR) system were studied based on the intake fuel injection hydrogen internal combustion engine test system. The results show that the output power of hydrogen internal combustion engine can be greatly increased by adopting intake supercharging system. Using EGR can increase the ignition delay period and combustion duration of hydrogen internal combustion engine, significantly reduce the maximum pressure and temperature in the cylinder and reduce NOx emission. A high EGR rate is required to significantly reduce NOx emissions at medium and high loads. The combination of EGR and intake supercharging technology can improve the output power of hydrogen combustion engine while reducing NOx emissions.

Keywords

Intake Supercharging; EGR; NO Emission; Power Improvement.

1. Introduction

Today the world is facing two serious problems of energy shortage and environmental pollution, so the development of clean and pollution-free alternative energy has become an inevitable trend. Hydrogen is favored by scientists all over the world for its low ignition energy, wide ignition boundary and fast flame propagation [1-3]. At the same time, the combustion products of hydrogen fuel are very clean compared to petroleum fuel, and do not produce CO, HC and other pollutants that are extremely damaging to the environment. Hydrogen is a gaseous gas with low density, low volume reference and low calorific value (10.2MJ/m3 for hydrogen and 216.4MJ/m3 for gasoline). When inlet injection is adopted, hydrogen expands in the inlet, resulting in a decrease in engine volume efficiency and a decrease in output power of hydrogen engine [4-6]. To solve this problem, Rahman et al. [7] found that the volume efficiency of hydrogen engines increases with the increase of air-fuel ratio and engine speed. Jongtai Lee et al. [8] improved the performance of hydrogen internal combustion engine by controlling valve timing and pressurized lean-burn. The injection system is also an important link that affects the performance of hydrogen internal combustion engine. Hydrogen

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injection pressure is a key parameter of hydrogen injection, which controls the amount of hydrogen injection per unit time and determines the initial velocity of hydrogen injection on the other hand, which has an important influence on the intake process of hydrogen internal combustion engine. Theoretically, hydrogen combustion products only water, but hydrogen fuel engines at high temperatures will also produce a certain amount of NOX, resulting in air pollution. At present, the main NOx reduction methods adopted include sprinkling water into the cylinder, delaying ignition, changing the combustion mode, and adopting EGR [9-11]. Lean combustion can reduce NOx emission of hydrogen internal combustion engine [12,13], but will lead to low power output of hydrogen internal combustion engine, which is difficult to meet the requirements of high load work. Delaying ignition time is also an effective way to reduce NOx emissions [14], but delaying ignition will not only reduce the power output of hydrogen internal combustion engine, but also may cause abnormal combustion of hydrogen internal combustion engine, which limits the adjustment range of ignition time [15,16]. Exhaust gas recirculation (EGR) is an effective method to reduce NOx emission from diesel engines. Research [17,18] shows that both hot EGR and cold EGR can improve NOx emission of diesel engines with little reduction of power performance and fuel economy.

The improvement of output power and reduction of NOx emission of internal combustion engine are two contradictions. Balancing the contradiction between the two can promote the promotion of hydrogen internal combustion engine. Therefore, it is an important problem to reduce NOx in the exhaust while ensuring the power and economy of hydrogen engines. In this paper, the effects of intake supercharging and EGR on NOX emission characteristics of hydrogen internal combustion engine are studied by combining the methods of numerical simulation and theoretical analysis. It provides theoretical reference for optimal design of hydrogen internal combustion engine.

2. Research Object and Research Scheme

2.1 Research Object

The research object of this paper is a four-valve igniting single-cylinder hydrogen engine refit from Jialing JH600 gasoline engine. The three-dimensional model of the engine is shown in the figure. The specific parameters of the engine are shown in the table:

Table 1. Main parameters of PFI HICE

Parameter	Value
Bore/mm	94
Stroke/mm	85
Compress ratio	9.7
Maximum power/kW	30
Speed at maximum power/(r/min)	6000
Maximum torque/N·m	51
Speed at maximum torque/(r/min)	4500

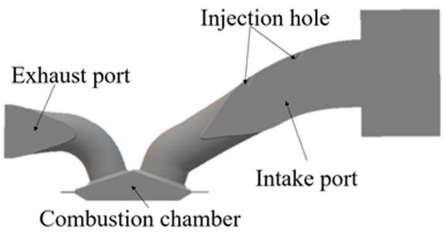

Fig. 1 SP injection mode

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In the calculations, engine intake TDC was defined as 360°CA (Crank Angle), combustion TDC was defined as 720°CA, the entire operating cycle included valve stack (351°CA~394CA), intake (394°CA~634°CA), compression work (634°CA~866°CA), Exhaust (866°CA~1071°CA) four periods. The x-(-F) four-equation model was selected for turbulence model, and SIMPLE algorithm was used to solve the coupling between velocity field and pressure field.

Considering some basic properties of hydrogen fuel. Therefore, the following assumptions are made for the combustion model in this paper:

(1) The slight difference of temperature and pressure distribution at each point in the cylinder is not considered temporarily;

(2) The state of mixture in the engine cylinder is regarded as uniform mixture;

(3) The influence of temperature and pressure fluctuation in the intake is not considered for the time being;

(4) The cylinder is regarded as completely sealed, and the working medium in the cylinder does not leak during the sealing process.

2.2 Initial and Boundary Conditions

Most of the calculation equations in FIRE are partial differential equations. When solving partial differential equations, the setting of initial conditions and boundary conditions is very important, which determines whether the calculation is accurate and convergent in the simulation process. For the model used in this article, the initial conditions need to be set to calculate the inlet and exhaust temperature and pressure in the cylinder at the beginning (351°C crankshaft Angle). Due to the large area of each part, it is not possible to set each point separately, so the value of the pressure and temperature Settings for the same working medium are exactly the same for each selection. The setting of initial conditions is shown in Table 2, and the setting of boundary conditions is shown in Table 3:

Table 2. The setting of initial conditions.

Boundary region	Temperature(K)	Pressure (MPa)
Intake port	293	0.1
Exhaust port	900	0.106
Combustion chamber	950	0.108

Table 3. The setting of boundary conditions

Boundary region	Boundary type	value
Air inlet	Inlet	0.1MPa
Exhaust outlet	Outlet	0.106MPa
Hydrogen inlet	Inlet	0.35MPa
Intake port	No moving wall	320K
Exhaust port	No moving wall	450K
Intake seat	No moving wall	600K
Exhaust seat	No moving wall	650K
Intake valve	Moving wall	500K
Exhaust valve	Moving wall	750K
Cylinder wall	No moving wall	470K
Piston	Moving wall	580K
Combustion chamber	No moving wall	580K
Symmetry wall	Symmetry wall	-

2.3 Research Proposal

With the increase of load, NO emission first increases and then decreases, and the emission is the highest at medium and high load. Therefore, this paper chooses excess air coefficient of 1.5 and rotational speed of 1000r/min for study. The main variables studied in this paper are intake pressurization and EGR. The levels of the two variables are respectively EGR 0, 5, 10, 15 and 20%. Intake supercharged 1, 1.5, 2 and 2.5bar.

3. Analysis of Simulation Results

With the increase of load, NO emission first increases and then decreases, and the emission is the highest at medium and high load. Therefore, this paper chooses excess air coefficient of 1.5 and rotational speed of 1000r/min for study. The main variables studied in this paper are intake pressurization and EGR. The levels of the two variables are respectively EGR 0, 5, 10, 15 and 20%. Intake supercharged 1, 1.5, 2 and 2.5bar.

3.1 Influence on Power Performance of Hydrogen Internal Combustion Engine

The indicated power of hydrogen internal combustion engine is an important index to evaluate the power performance, which determines the working range of hydrogen internal combustion engine. The indicated thermal efficiency of hydrogen internal combustion engine can be calculated by formula 1.

Indicating power calculation formula:

$$P_i = \frac{inW_i}{30\tau} \tag{1}$$

where i is the number of cylinders that the engine contains; n is the engine speed, r/min; Wi is the indicated work, J; t is the number of strokes.

FIG. 2 shows the change of indicated power of hydrogen internal combustion engine with EGR rate at 1000r/min, excess air coefficient of 1.5 and different intake pressure. As can be seen from FIG. 2, the output power of hydrogen internal combustion engine continues to decrease with the increase of EGR rate, and the decrease amplitude is affected by EGR rate and intake pressure.

At intake pressures of 1.0 and 1.5bar, the indicated power decreases rapidly as the EGR rate increases. When the inlet pressure is 1.0bar, the indicating power at EGR rate of 10% is 53.1% lower than that at EGR rate of 0. When the intake pressure is 1.5bar and the EGR rate is 15%, the indicated power is reduced by 75.6% compared with that when the EGR rate is 0. When the intake pressure is 1.0bar and the EGR ratio exceeds 10%, the hydrogen internal combustion engine cannot ignite when the intake pressure is 1.5bar and the EGR ratio exceeds 15.

When the intake pressure is 2.0 bar and 2.5bar, the indicated power decreases slowly with the increase of EGR rate, and decreases rapidly when the EGR rate exceeds 10%. When the intake pressure is not less than 2bar and the EGR ratio is not higher than 20%, the hydrogen internal combustion engine can be ignited normally. When the inlet pressure is 2.0bar and the EGR rate is 20%, the indicated power is 47.8% lower than that when the EGR rate is 0. The indicated power at the inlet pressure of 1.5bar and the EGR rate of 20% is 49.6% lower than that at the EGR rate of 0.

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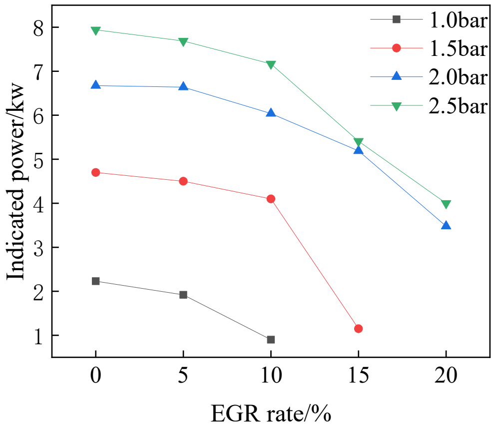

Fig. 2 Variation trend of indicated power with EGR rate at different intake pressures

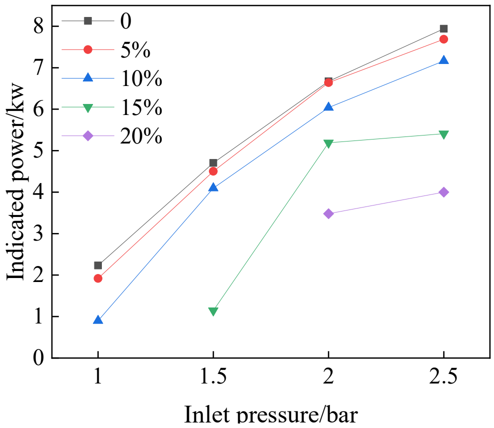

Fig. 3 Variation trend of indicated power with inlet pressure at different EGR rates

As can be seen from FIG. 3, at all EGR rates, the indicating power increases with the increase of the intake pressure, and at different EGR rates, the indicating power has a different trend with the increase of the intake pressure. The smaller the EGR rate is, the greater the indicating power is with the increase of the intake pressure. With the increase of EGR rate, the power increase caused by the increase of the intake pressure decreases. The main reason is that the higher the intake pressure, the fresher charge into the cylinder, the higher the combustion heat release; With the increase of EGR rate, the residual exhaust gas content in the fresh charge increases, and the inlet pressure is increased in time, the combustion cannot be improved, and the power improvement effect is not obvious.

3.2 Economic Impact on Hydrogen Internal Combustion Engine

Indicative thermal efficiency is another important index to judge the second largest performance -- economy of hydrogen internal combustion engine, and can be calculated by Formula 2.

Indicates the calculation formula of thermal efficiency:

$$\eta_{it} = \frac{W_i}{Q_i} \tag{2}$$

where ηit is the economy of HICE, Wi is the indicated work, J; Qi is the accumulated release in cylinder, J.

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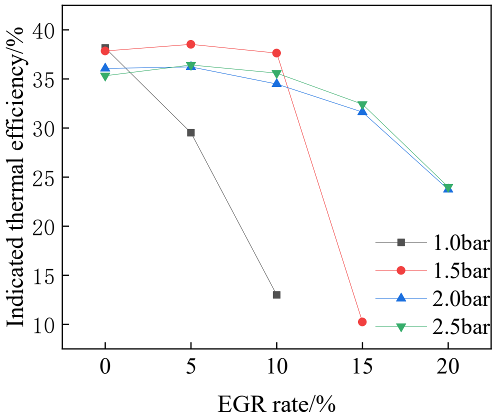

Fig. 4 Variation trend of indicated thermal efficiency with EGR rate at different intake pressures

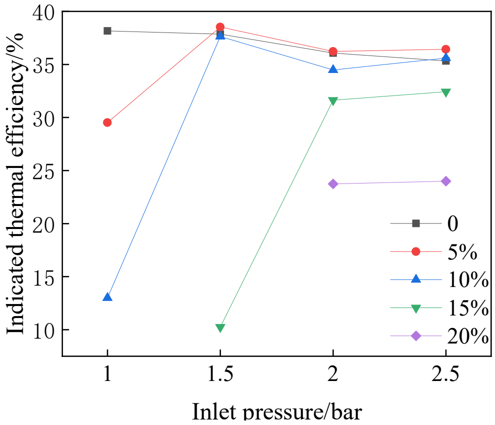

Fig. 5 Variation trend of indicated thermal efficiency with inlet pressure at different EGR rates

FIG. 4 shows the change curve of indicated thermal efficiency of hydrogen internal combustion engine with EGR rate under different intake pressures. As can be seen from FIG. 4, the output power of hydrogen internal combustion engine continues to decrease with the increase of EGR rate, and the decrease range is affected by the intake pressure. At the intake pressure of 1.0 bar and 1.5bar, the indicating thermal efficiency decreases rapidly with the increase of EGR rate. At the intake pressure of 1bar, the maximum decrease is 65.9%, and at the intake pressure of 1.5bar, the maximum decrease is 72.9%. When the intake pressure is 2.0 bar and 2.5bar, the indicated power decreases slowly first and then increase with the increase of EGR rate. When the intake pressure is 2bar, the maximum decrease is 34.2%, and when the intake pressure is 2.5bar, the maximum decrease is 32%.

FIG. 5 shows the change curve of indicated thermal efficiency of hydrogen internal combustion engine with inlet pressure at different EGR rates. FIG. 5 shows that under different EGR rates, the indicated thermal efficiency varies greatly with the intake pressure, but they all maintain a similar rule. After reaching a critical value, the indicated thermal efficiency does not change with the intake pressure. When EGR rate is 0, the indicated thermal efficiency hardly changes with the increase of inlet pressure and remains at a high level. At the lower EGR rate (5-15%), it indicates that the thermal efficiency tends to a stable level with the increase of the intake pressure, and the higher the EGR rate, the smaller the value after stabilization. At a higher EGR rate (20%), the indicated thermal efficiency fluctuates little with the intake pressure and remains at a low level.

The indicated thermal efficiency of hydrogen internal combustion engine varies greatly under different intake pressure and EGR rate, and is mainly affected by EGR rate. The influence of intake pressure on indicated thermal efficiency is only a process, and the final stability result is mainly determined by EGR rate. The main cause of this phenomenon is indicated thermal efficiency represents the degree of the stand or fall of the whole hydrogen internal combustion engine

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combustion process, and the influence of the main causes of this metric is the uniformity of mixture, hydrogen combustion speed, mixing evenly, mixture combustion effect is good, can in a short time, complete combustion, the combustion process of constant volume degree is high, thermal conversion efficiency is increased. The EGR ratio has the greatest influence on the composition of the mixture. If the EGR ratio is too high, the proportion of burned waste gas in the mixture increases, the combustion effect is not good, and the heat release rate decreases naturally.

3.3 Influence on Emission of Hydrogen Internal Combustion Engine

Economy and power performance are of course important for the evaluation of hydrogen internal combustion engine, but under the trend of increasingly strict emission regulations, emission is the primary consideration to determine whether an internal combustion engine can be widely used commercially. This section mainly analyzes the effects of inlet pressure and EGR rate on the emission of hydrogen internal combustion engine. The main pollutant emitted by hydrogen combustion engine is NOx, most of which is NO. There are three main paths for hydrogen engine to produce NO: the first is thermal NO path; The second is the NNH path; The third is the N2O path; The thermal NO path is the main source, accounting for more than 90% of the total NO emissions, mainly because nitrogen in the fresh charge reacts with excess oxygen at high temperature (higher than 1832K) to generate A large amount of NO. Therefore, NO should be chosen as the main emission model of NOx. Based on three ideal assumptions, the extended Zeldovich model is chosen in the simulation process.

FIG. 6 and FIG. 7 Shows the variation trend of NO mass fraction with EGR rate and intake pressure. It can be seen from FIG. 6 that under all intake pressures, NO mass fraction decreases with the increase of EGR rate, and the overall decline trend is first rapid and then slow, but there are certain differences under different EGR rates. It can be seen from FIG. 7 that at all EGR rates, the mass fraction of NO increases with the increase of intake pressure, but has different growth ranges at different intake pressures. It can be concluded from FIG. 6 and 7 that the intake pressure and EGR rate have a mutual influence on NO emissions, EGR rate can reduce NO emissions, and intake pressurization can increase NO emissions. When an EGR rate to zero or low, affected by the mass fraction of inlet pressure to the NO, EGR rate is zero, for example, EGR to 0, under the four kinds of inlet pressure, all can normal hydrogen internal combustion engine ignition, and with the increase of inlet pressure, the mass fraction of NO change is bigger, the inlet pressure is 1.5 bar compared with inlet pressure is 1 bar, The quality score of NO increased by 78.8%. When EGR is high, with the increase of inlet pressure, the mass fraction of NO increases slowly and tends to be stable. The value after stabilization depends on EGR rate. The higher THE EGR rate, the lower the mass fraction of NO after stabilization.

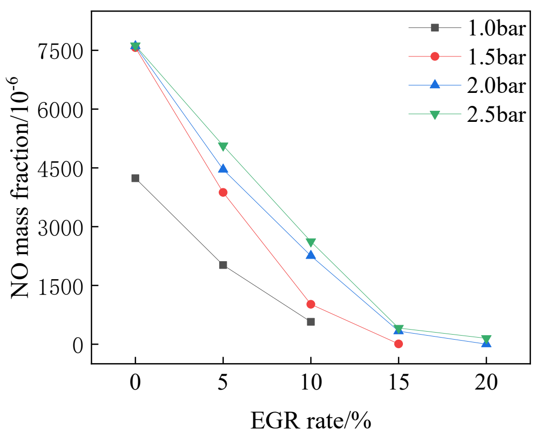

Fig. 6 Variation trend of NO mass fraction with EGR rate at different inlet pressures

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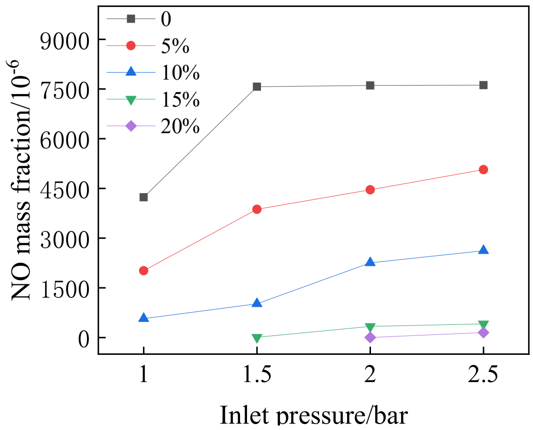

Fig. 7 Variation trend of NO mass fraction with inlet pressure at different EGR rates

This phenomenon is mainly caused by the generation mechanism of NO. The generation condition of NO is "high temperature and rich oxygen". The excess air coefficient selected in this study is 1.5 and oxygen is sufficient, so the mass fraction of NO is mainly affected by temperature, which is mainly affected by the fresh charge into the cylinder and combustion process. The higher the intake pressure, the higher the fresh charge into the cylinder, the higher the combustion temperature, the higher the mass fraction of NO; The higher the EGR rate, the higher the non-combustible waste gas in the mixture into the cylinder, the less the combustible mixture, and the higher the EGR rate, the lower the initial temperature in the cylinder. Limited by these two reasons, the increase of EGR rate reduces the combustion temperature in the cylinder and reduces the emission of NO.

3.4 The Synergistic Effect of Intake Supercharging and EGR on Hydrogen Internal Combustion Engine Performance

3.4.1 Combination Weighting Method

Intake supercharging and EGR rate have different influence trends on various indicators of hydrogen internal combustion engine. In order to make the evaluation more accurate, the combination weighting method is adopted to normalize different evaluation indicators and then carry out weighted treatment to get a new evaluation index, which makes the new evaluation index more accurate. The combination weighting method adopted in this paper is obtained through subjective weighting method -- analytic hierarchy Process (AHP) and objective weighting method -- entropy value weighting method through the idea of game theory.

(1) Subjective weighting method

Analytic Hierarchy Process (AHP) is a decision-making method that decompositions the elements always related to decision-making into the levels of objectives, criteria and schemes, on the basis of which qualitative and quantitative analysis is carried out. The following is a brief introduction to the operation steps of AHP method.

(a) Establishment of hierarchical structure model;

(b) Construct the judgment matrix;

(c) Consistency test.

The weight distribution of economy, power and emission obtained by AHP method is 0.2:0.5:0.3.

(2) Objective weighting method

Entropy value method is a kind of completely assign weights method based on the experimental data, in theory, the experimental data, the more the more accurate the distribution of weight, with the increase of the experimental data, the distribution of the weight, the more stable, often with less number of sets of experimental data, and even there might be abnormal data, so the combination of subjective evaluation makes weights allocation more reasonable.

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(a) Negative indicators are positive;

(b) Calculate the information entropy of the JTH indicator;

(c) Calculate the objective weight of the JTH indicator;

The weight distribution of economy, power and emission obtained by the entropy weighting method is: 0.4:0.25:0.35.

(3) Combination weighting method

AHP method belongs to the subjective values. the method, will there be no objectivity in weight distribution, the entropy value method is a kind of completely assign weights method based on the experimental data, in theory, the experimental data, the more the more accurate the distribution of the weight, with the increase of the experimental data, the distribution of the weight, the more stable, often with less number of sets of experimental data, and even there might be abnormal data, So the combination of subjective evaluation makes the weight distribution more reasonable. The different weights obtained by analytic Hierarchy Process (AHP) and entropy weight method were solved by the method of equilibrium solution of game theory, and the final weight distribution was obtained.

The subjective weight determined by AHP method W1=(w11, w12, w13), Objective weight determined by entropy weight method W2=(w21,w22,w23).

$$W=\begin{bmatrix}\lambda_1 w_{11}+\lambda_2 w_{21}\\ \lambda_1 w_{12}+\lambda_2 w_{22}\\ \lambda_1 w_{13}+\lambda_2 w_{23}\end{bmatrix}=\begin{bmatrix}w_{11} & w_{21}\\ w_{12} & w_{22}\\ w_{13} & w_{23}\end{bmatrix}\begin{pmatrix}\lambda_1\\ \lambda_2\end{pmatrix}=\lambda_1 W_1+\lambda_2 W_2 \tag{3}$$

Where λ_1 and $\lambda_2$are linear combination coefficients

From the point of view of game theory, the sum of the deviations between W1 and W2 and the combined weight W is minimal. According to the differential principle, it is sought that λ_1^* and λ_2^*minimize the sum of the deviations between W1 and W2 and the combined weight W, and the equations in the following equation should be satisfied:

$$\begin{cases}\lambda_1 W_1 W_1^T+\lambda_2 W_1 W_2^T=W_1 W_1^T\\ \lambda_1 W_2 W_1^T+\lambda_2 W_2 W_2^T=W_2 W_2^T\end{cases} \tag{4}$$

The linear combination coefficientsλ_1 and λ_2 obtained by Formula (4) are normalized as follows:

$$\begin{cases}\lambda_1^*=\dfrac{|\lambda_1|}{|\lambda_1|+|\lambda_2|}\\ \lambda_2^*=\dfrac{|\lambda_2|}{|\lambda_1|+|\lambda_2|}\end{cases} \tag{5}$$

The optimal weight combination weight of evaluation indexes is:

$$W^*=\lambda_1^* W_1+\lambda_2^* W_2 \tag{6}$$

The final weight distribution obtained by the combination weighting method is 0.27:0.42:0.31.

3.4.2 Analysis of Actual Results

After the final weight distribution is obtained, the original data after dimensionless processing is weighted, and the original data is converted into a range of 0~1 according to the dimensionless method selected

Table 4. Comprehensive performance index values of hydrogen internal combustion engines under different EGR rates and intake pressures

Pressure \ EGR	0%	5%	10%	15%	20%
1 bar	0.354	0.346	0.302	—	—
1.5 bar	0.301	0.325	0.378	0.301	—
2 bar	0.235	0.298	0.335	0.321	0.289
2.5 bar	0.215	0.289	0.325	0.354	0.297

It can be seen from Table 4 that under different intake pressures, the comprehensively of hydrogen internal combustion engine increases first and then decreases with the increase of EGR rate. According to Table 4, the optimal intake pressure is 1.5bar and the optimal EGR rate is 10% under the condition of 1000r/min rotation speed and 1.5 excess air coefficient.

4. Conclusion

1) The intake pressure plays a good role in promoting the output power of hydrogen internal combustion engine, but the higher intake pressure will lead to the rapid increase of NO emission.

2) The increase of exhaust gas recirculation system can greatly reduce the emission of NO, but the higher EGR rate will greatly reduce the output power of hydrogen internal combustion engine.

3) Intake supercharging combined with EGR can improve the output power of hydrogen combustion engine while reducing NOx emission. The results show that the comprehensive performance of hydrogen internal combustion engine is the best when the intake pressure is 1.5bar and EGR is 10%.

Acknowledgments

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