Effect of Hydrogen Injection Flow Rate on the Performance of In-Cylinder Direct Injection Hydrogen Engines

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When a hydrogen internal combustion engine uses intake manifold injection to supply hydrogen, it must face the contradiction of abnormal combustion (premature combustion, backfire, etc.). The occurrence of abnormal combustion such as backfire can be avoided by using in-cylinder direct injection of hydrogen. In this paper, the In-Cylinder Direct Injection single-cylinder engine is modified, a three-dimensional simulation model is established, and simulation tests using AVL-Fire software on this basis is conducted. Through the analysis of the research results, the optimal hydrogen injection flow rate for the direct injection hydrogen engine to achieve the best power and economy under different working conditions was obtained. The results show that: under the same speed and load, the increase of hydrogen injection flow rate increases the hydrogen injection speed, which promotes the turbulent motion in the cylinder. At the same time, with the increase of hydrogen injection flow rate, the maximum pressure, temperature, indicated power and indicated thermal efficiency in the engine cylinder generally show a trend of first increasing and then decreasing, and there is an optimal hydrogen injection flow rate value.

Keywords: Hydrogen fuel; Hydrogen injection flow rate; In-cylinder direct injection

Introduction

Currently, due to the increasingly serious energy shortage and greenhouse gas problems, the transportation industry is actively exploring the use of clean renewable energy to replace fossil fuels to solve these problems [1, 2]. Hydrogen has zero carbon emissions and renewable energy characteristics, and can be used as an alternative fuel for traditional internal combustion engines [3, 4]. The future direction of engine technology is zero-carbon internal combustion engine, which is regarded as the future trend in the engine field [5]. In particular, hydrogen engines, as a zero-carbon energy solution, have great potential in addressing global energy challenges and mitigating climate change [6, 7].

Over the past few decades, as environmental issues and global warming have become increasingly serious, major automobile producing countries have been working hard to develop clean energy vehicles [8, 9]. Various factors are driving the shift from traditional engine fuels to low-carbon or zero-carbon [10]. Hydrogen is expected to become an ideal alternative fuel for internal combustion engines due to its low conversion cost, excellent combustion performance, zero carbon emissions and

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renewable potential [11, 12]. The in-cylinder direct injection hydrogen engine can completely avoid backfire by injecting hydrogen after the intake valve is closed [13-15]. In-cylinder direct injection hydrogen engine technology has become a hot topic in recent years, which can increase power output by more than 17% [16, 17].

In the field of hydrogen engines, there exist two dominant injection technologies, *i.e.*, direct in-cylinder injection (DI) and port-feed injection (PFI). Among them, PFI hydrogen engines often have problems such as backfire and detonation during use. These adverse factors can easily cause damage to the engine itself and the intake system, which has been confirmed in many studies [18-20]. As a result, DI hydrogen engines have regained the attention of scholars around the globe, because they can significantly avoid such problems. DI technology is able to completely eliminate the risk of backfiring and detonation by injecting hydrogen directly into the engine cylinders and also helps to increase the power output of the engine [21]. However, this technology also faces some challenges, such as how to effectively organize the airflow in the cylinder to optimize the mixing of hydrogen and air, while avoiding uneven combustion of the mixture and excessive combustion temperature, thereby reducing heat transfer losses and NO_x emissions. These requirements make the control strategy of DI hydrogen engines more complex and sophisticated [22].

Wallner *et al.* [23] provided an in-depth review of the effect of injection strategy on the performance of direct-injection hydrogen engines. The data from their study showed that the implementation of a dual injection technique was able to significantly reduce NO_x emissions compared to a single injection technique at an engine speed maintained at 1000 rpm and an Indicated Mean Effective Pressure (IMEP) of 6 bar. Further analysis revealed that when the direction of the hydrogen jet was aligned with the spark plug, either towards or away from the spark plug, the thermal efficiency of the engine was significantly improved. In particular, the indicated efficiency peaked at 31% in the case of hydrogen injection to the spark plug and the ratio of hydrogen between the two injections was optimized to be 7:3.

The study by Park *et al.* [24], on the other hand, revealed the effect of delayed start of injection (SOI) on engine performance. They found that the change in air-fuel ratio caused by delayed SOI had a greater impact on engine performance than the effect of reduced mixing time. Specifically, delayed SOI leads to an increase in fresh air intake and air-fuel ratio. As a result, although the mixing time of hydrogen and air is shortened, the engine's torque and thermal efficiency are improved.

Another study conducted by Yosri *et al.* [25] revealed another effect of SOI delay on engine performance. They found that the mixture layer around the spark plug became very thin when the SOI was delayed, which led to a decrease in the combustion rate and a reduction in thermal efficiency.

Hamada *et al.* [26], on the other hand, experimentally investigated the effect of equivalence ratio and SOI on the combustion characteristics of a direct injection hydrogen engine at an injection pressure of 18 bar. Their results showed that the mixture stratification achieved by delayed SOI can lead to earlier combustion initiation and shorter combustion duration compared to early partial direct injection.

A study by Naganuma *et al.* [27] categorized the injection and ignition strategies for DI hydrogen engines into three groups: early injection with premixed ignition (EI-PMI), late injection with pre-chamber ignition (LI-PHi), and late injection with post-chamber ignition (LI-PTi). The results of the study show that the EI-PMI mode performs well in reducing NO_x emissions, while the LI-PTi mode demonstrates a high thermal efficiency in combination with EGR technology under high load conditions. The optimization resulted in a 1000 ppm reduction in NO_x emissions, while maintaining a stable thermal efficiency throughout the load range, with a maximum Maximum thermal efficiency of 45%.

On the other hand, Oikawa *et al.* [28] proposed the plume combustion concept (PCC) for hydrogen engines, which involves injecting hydrogen near the top dead center and igniting the hydrogen-rich plume at the end to achieve diffusion combustion of the hydrogen-rich mixture. This strategy significantly reduced NO_x emissions and cooling losses. Further studies have shown that delaying hydrogen injection time can improve thermal efficiency but will also lead to increased NO_x emissions.

A study by Wei *et al.* [29] showed that late injection has a positive effect on increasing the thermal efficiency of the engine. This effect was mainly attributed to stratified combustion due to late injection, which reduces heat transfer losses. However, they also observed a significant rise in NO_x emissions with late injection.

Using CFD simulations, the study by Rottenruber *et al.* [30] found that the mixture homogeneity was slightly improved as the direct hydrogen injection pressure was increased from 4 MPa to 15 MPa. This was attributed to the fact that the higher injection pressure increased the turbulent kinetic energy in the cylinder and enhanced the mixing process, thus improving the thermal efficiency.

In summary, compared with the hydrogen engine using inlet channel hydrogen injection, the in-cylinder direct-injection hydrogen engine eliminates the problem of hydrogen occupying the cylinder volume and the possibility of backfire. The direct-injection hydrogen combustion engine has a wider range of excess air coefficients, which allows it to adopt a thinner combustion mode. However, the control strategy of direct-injection hydrogen engine is more complicated, and the improvement of thermal efficiency has a stronger correlation with the increase of emissions. At present, research focuses on the operating parameters of direct-injection hydrogen engines, such as ignition timing, hydrogen injection timing, and equivalence ratio, etc. There is a relative lack of research on the structural parameters of the in-cylinder direct-injection hydrogen, economy and emission of the direct injection hydrogen engine can provide certain theoretical support and data support for the study of the structural parameters of the in-cylinder direct injection hydrogen engine, which plays an important role in the study of the in-cylinder direct injection hydrogen engine.

Based on the characteristics of hydrogen fuel, especially its high anti-knock performance in dilute mixtures, NO_x emissions increase. The combustion of a lean mixture of fuel and air has always been a traditional method to improve thermal efficiency and reduce NO_x. Currently, a mixture of hydrogen and air is formed by injecting hydrogen at the beginning of the compression stroke. However, even under lean mixture conditions, such mixing conditions do not always provide the expected thermal efficiency improvement because mixture inhomogeneity and incomplete flame propagation in the very lean portion can also lead to increased emissions of unburned hydrogen. Therefore, in this paper, the thermal efficiency of a hydrogen internal combustion engine is improved by adopting different hydrogen injection flow rates and controlling the hydrogen injection timing (generally injected in the later stage of the compression stroke) to optimize the distribution of the mixture in the cylinder and reduce exhaust emissions. At the same time, it also explores the impact of different hydrogen injection flow rates on the overall performance of the internal combustion engine. By analyzing the effects of different hydrogen injection flow rates on the in-cylinder mixture and thus on the emissions and performance of the internal combustion engine, the optimal working conditions are derived on this basis. This provides a theoretical basis for the early realization of large-scale popularization of hydrogen engines.

Computational Model and Research Program

Research Object and Geometric Model

In this paper, the single-cylinder Gasoline Direct Injection (GDI) test engine is used as a prototype, and further modified and designed according to the original size data of the prototype, which is transformed into a variable compression ratio in-cylinder direct-injection hydrogen engine to meet the requirements of the experiment. The technical parameters as well as key points of the experimental engine after the modification is completed are shown in Tables 1 and 2, respectively:

Table 1. Engine technical parameters

Engine Parameter	Parameter Value
Displacement (ml)	1054
Cylinder Bore (mm)	108
Piston Stroke (mm)	115
Connecting Rod Length (mm)	137
Valve Number (pcs)	2
Maximum Power (w)	6000
Maximum Torque (N.m)	4500
Ignition System	Spark Ignition Systems

Table 2. Working cycle and key nodes

Key points of the experimental engine	Corresponding Crank Angle Range
Valve Overlap	351~394°CA
Intake	394~634°CA
Compression	634-866°CA
Exhaust	866-1071°CA
Upper Stop	360°CA/720°CA
Lower Stop	540°CA/900°CA
Intake Valve Open	351°CA
Intake Valve Closed	634°CA
Exhaust Valve Open	866°CA
Exhaust Valve Closed	394°CA

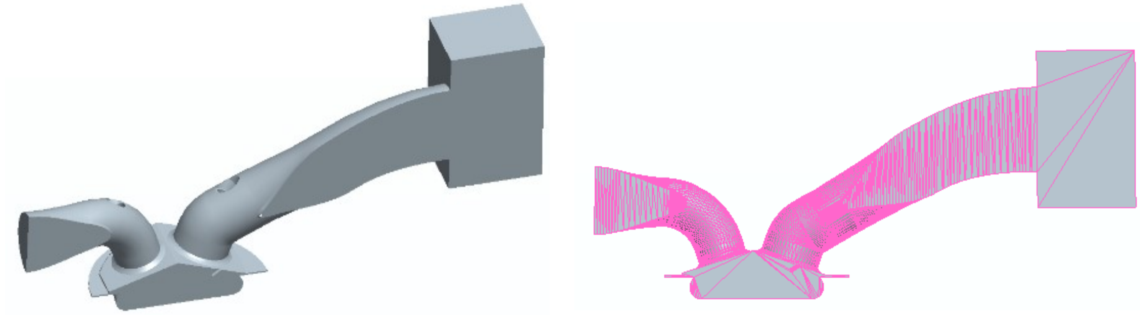


Fig. 1. Engine geometry and mesh model

Grid Division

In the actual operation of the engine, the various parts and the internal space are in the dynamic changes. In order to accurately calculate the entire computer numerical simulation process, initial grid division is required. According to the engine working process, it is divided into valve overlap part, intake part, compression part and exhaust part. The calculation grid can be adjusted according to the requirements of the experiment. To ensure the accuracy of the experiment and the overall efficiency of the experiment, this paper adopts AVL-FIRE software for grid division. The specific process is as follows:

(1) The division of the surface grid and the line grid, the definition and division of the selections of the surface grid will directly affect the subsequent experimental settings and the accuracy of the boundary conditions and initial conditions of the computational process. When drawing the line grid, we use the AVL-FIRE software line grid automatic generation tool, which requires us to set the minimum angle and length of the closed curve according to the specific requirements of the experiment.

(2) Dynamic mesh division, dynamic mesh division is a key link in the simulation of engine internal fluid dynamics. The Fame Engine Plus dynamic mesh module in AVL-FIRE software is used for the complex mesh division process. The steps include: Creating and configure the fep file, importing the geometric data containing the surface mesh and line mesh, sub-dividing the mesh according to the different operating cycles of the engine (manifested as the range of crankshaft angle changes), determining the trajectory of the piston surface and its direction, setting up a reasonable value of the valve lash, and importing a valve lift curve file to further define the mesh in a refined way. The quality of the mesh is evaluated by color coding, with green indicating high quality and suitable for computation, yellow indicating average quality and barely usable, and red indicating low quality and not usable for computation. After the above series of steps, high quality dynamic mesh data that meets the requirements is successfully generated and exported to fmo file for subsequent calculation and analysis.

Initial Conditions and Boundary Conditions

In this paper, the initial conditions mainly refer to the pressure and temperature in the intake and exhaust tracts and cylinders at the beginning of the calculation, which need to be met at 351°CA. At this time, the engine state is that the intake valve has just opened. In the early stage of valve stacking period, in order to ensure the calculation speed, accuracy and convergence of the results, it is assumed that the gas satisfies the ideal gas state equation, and the external conditions and the initial state of the engine all meet the ideal state. It also assumes that the initial intake tract is full of fresh air, and the cylinder and the exhaust tract are the combustion exhaust from the previous cycle. At the same time, it is necessary to set corresponding boundary conditions for each region of the engine. The boundary conditions mainly include import and export boundaries, wall boundaries, and symmetry surface boundaries. The wall boundaries are divided into fixed walls and moving walls. Various boundaries are mainly divided into pressure and temperature types, according to the actual process of the corresponding type of setting. As shown in Tables 3 and 4, the air inlet and exhaust port are inlet and outlet boundaries, and the type is set to pressure boundary; the inlet and exhaust channels are fixed wall boundaries, and the inlet and exhaust valves are moving wall boundaries, and the type is set to thermostatic boundary, and so on.

Table 3. Setting of initial conditions

Parameters	Intake Tract	Combustion Chamber	Exhaust Tract
Temperature (K)	293	950	900
Pressure (MPa)	0.1	0.108	0.106

Table 4. The setting of boundary conditions

Boundary area	Boundary types	Set Values
Air inlet	Inlet	0.1 MPa
Exhaust Air Outlet	Outlet	0.106 MPa
Air Inlet	Stationary wall	300 K
Exhaust tract	Stationary wall	600 K
Inlet valve seat	Stationary wall	450 K
Exhaust Valve Seat	Stationary wall	650 K
Intake Valve	Moving wall	500 K
Exhaust Valve	Moving wall	750 K
Cylinder Wall	Stationary wall	470 K
Piston	Moving wall	580 K
Cylinder head	Stationary wall	580K
Symmetrical surface	Symmetry	580 K

Model Validation

To verify the reliability of the model, the model was validated under normal combustion conditions when the JH600 engine was converted into a hydrogen internal combustion engine. The engine specifications include a cylinder bore of 94 mm, a stroke of 85 mm, and a compression ratio of 15:1. During the test, the engine was operated at a speed of 3000 r/min with an equivalent transmission ratio of 0.4. The injection timing was set at 394 °CA and the ignition advance angle was 715 °CA. The average in-cylinder pressure was chosen as the comparison parameter, and the results are shown in Figure 2.

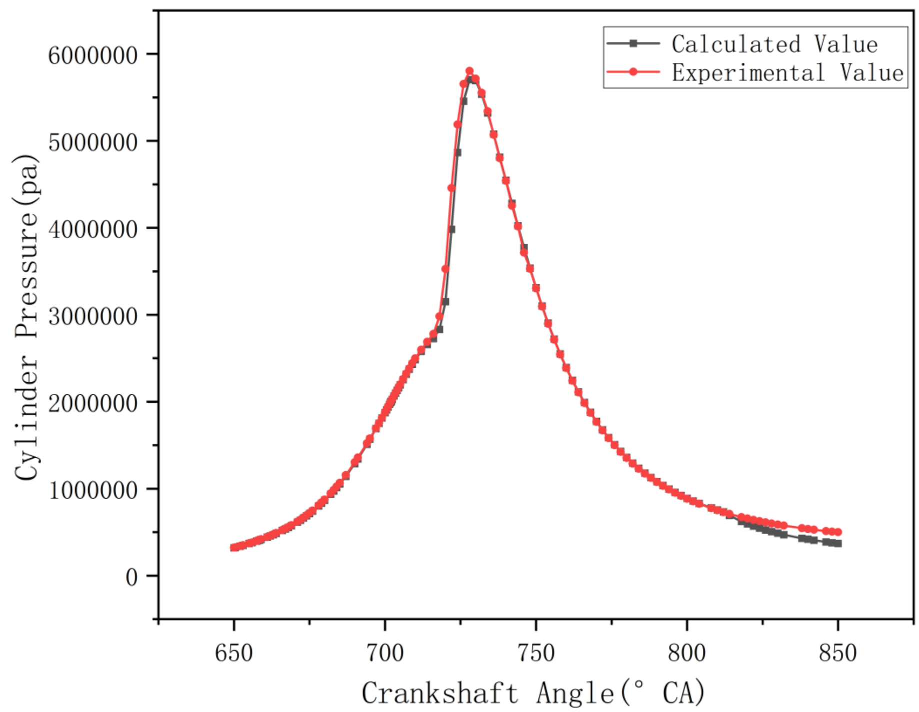


Fig. 2. Comparison of test and simulation in-cylinder pressure

Figure 2 shows that the relative error between test data and simulation data is within 5%, which is within the allowable error range. Therefore, the improved model method in this paper can effectively reflect the actual operation process of the direct injection hydrogen engine, and the simulation results are practical and reliable.

Results

The Effect of Hydrogen Injection Flow on the In-Cylinder Mixture Velocity Field under Different Working Conditions

Figure 3 shows the in-cylinder velocity field at different hydrogen injection flow rates and moments. The effect of hydrogen injection flow rate on the mixture of the in-cylinder direct injection hydrogen engine is mainly concentrated in the second half of the process of the piston upward after the intake is closed. It can be seen from the cloud diagram that in the pre-injection of hydrogen, a high-speed hydrogen jet begins to appear and concentrates in the axial direction of the hydrogen injection hole, impacting the cylinder wall and a part of the high speed of the hydrogen jet as the piston. After impacting the cylinder wall, part of the high-speed hydrogen jet moves with the bottom of the piston, and part of it moves upward along the cylinder wall. At the same time, with the crankshaft running the piston upward, part of the fuel forms a new vortex at the bottom of the cylinder under the influence of the piston movement after contacting the cylinder wall. When influenced by the structure of the piston combustion chamber, the hydrogen jet will expand its vortex after hitting the bottom of the piston, causing the flow velocity of the mixture at the bottom of the piston to accelerate and gradually develop upwards. At the end of the piston stroke, the turbulent flow developing upward from the bottom of the piston contacts the top surface of the combustion chamber, forming a front that increases the flow velocity of the mixture at the bottom of the spark plug, which is beneficial for improving the flame propagation speed. At the same time, as the hydrogen injection flow rate increases, the flow rate of the mixture in the cylinder also increases, enhancing the turbulent movement in the cylinder. Compared with the low-flow situation, at the end of the compression stroke, the velocity of the mixture in the cylinder is more concentrated and evenly distributed, and the turbulent movement near the spark plug is stronger, which is more conducive to the formation of the flame front, thereby facilitating the propagation of the combustion flame and accelerating the combustion speed.

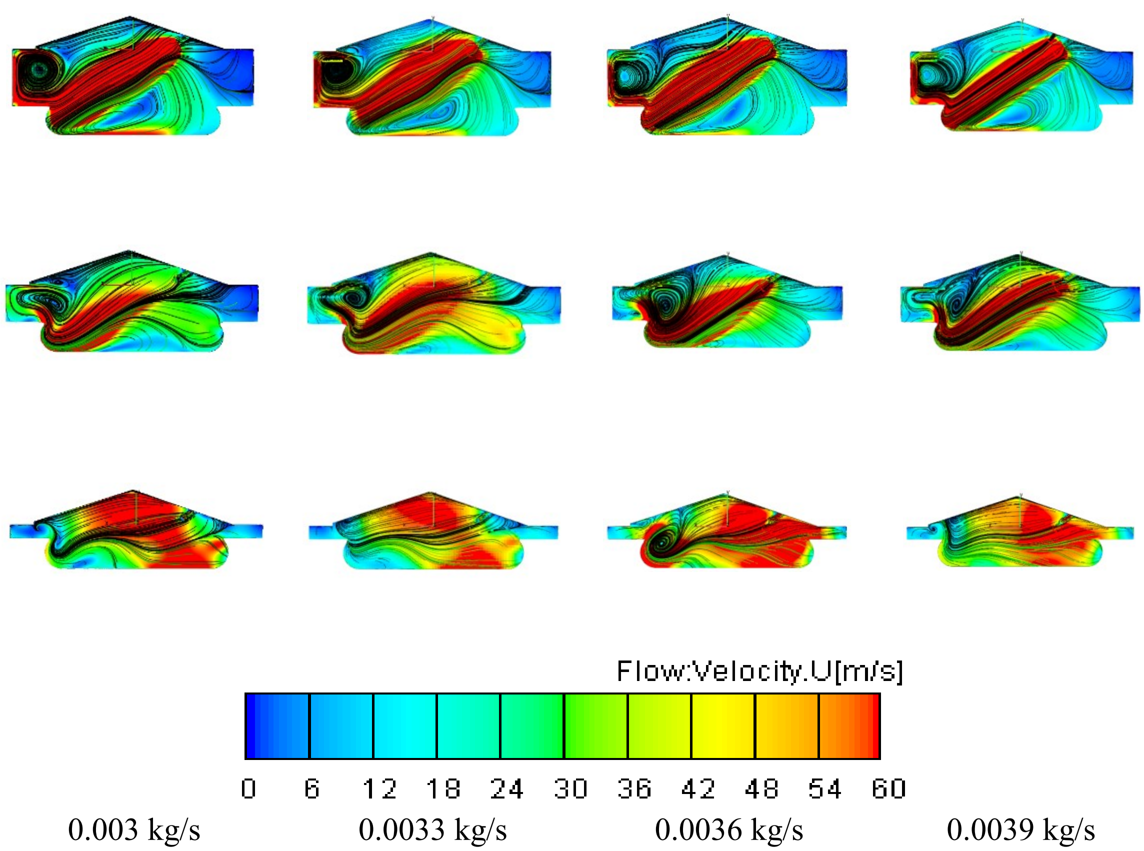


Fig. 3. Variation of velocity field of cylinder mixture with hydrogen injection flow rate

Influence of Hydrogen Injection Flow Rate on Cylinder Pressure and Temperature of Direct-Injection Hydrogen Engine under Different Working Conditions

During the operation of a direct injection hydrogen engine, the changing trends of the pressure and temperature in the cylinder are important indicators of the fuel combustion performance. This paper summarizes the changing trends of the maximum pressure and temperature in the cylinder under various operating conditions, analyzes the changing trends of the maximum pressure and temperature, and explores the influence of the hydrogen injection flow rate on the changing trends of the maximum pressure and temperature in the cylinder of a direct injection hydrogen engine.

Figure 4 shows the trend of the maximum in-cylinder pressure with the hydrogen injection flow rate under different operating conditions. In Figure 4(a), it can be seen that the maximum in-cylinder pressure increases with the increase of load at 3000 r/min, which is due to the fact that when the load is increased to achieve the target equivalence ratio, the mass of the combustible mixture in the cylinder increases, and more combustible mixture is involved in combustion. As a result, the maximum pressure in the cylinder is further increased. In addition, under most working conditions, the maximum pressure in the cylinder increases first and then decreases with the increase of hydrogen injection flow rate. Under medium and high load conditions, the maximum pressure in the cylinder generally reaches its peak at 0.029kg/h. However, under low load conditions, the maximum pressure in the cylinder reaches its peak level at 0.026kg/h and gradually decreases with the increase of flow. This is because after the hydrogen reaches the target equivalence ratio, in order to increase the mass of the combustible mixture in the cylinder, more combustible mixture participates in the combustion. The highest pressure in the figure gradually decreases after reaching its peak, because hydrogen has a wide ignition limit, strong diffusion ability, and fast flame propagation speed after ignition. Under low-speed and low-load conditions, a larger hydrogen injection flow rate shortens the duration of hydrogen injection, and the diffusion ability of hydrogen is strong. Hydrogen rapidly diffuses in the cylinder to form a relatively dilute mixture. In addition, the higher hydrogen injection flow rate also accelerates the gas flow velocity inside the cylinder, and the turbulent motion of the mixture also accelerates the diffusion of hydrogen gas, forming a relatively lean mixture and ultimately leading to a decrease in the maximum pressure inside the cylinder during combustion. The increase in mixture turbulence also accelerates the diffusion of hydrogen, forming a leaner mixture and causing a decrease in the maximum pressure in the cylinder during combustion. Under medium and high load conditions, in order to achieve the target equivalence ratio, it is necessary to adjust the size of the hydrogen injection flow rate to achieve a good distribution of the mixture in the cylinder. The smaller the hydrogen injection flow rate, the longer the hydrogen injection duration is required, which is not conducive to the enrichment of hydrogen. When the hydrogen injection flow rate is large, the hydrogen injection duration is greatly shortened, which intensifies the fuel diffusion. Finally, the best mixture is obtained at 0.0029kg/h, and the combustion state is the best at this time.

Figures 4 (b) and (c) show the trend of the maximum in-cylinder pressure at 4500 r/min and 6000 r/min under each working condition with the increase of different hydrogen injection flow rates, respectively. From the overall point of view, with the increase of rotational speed, the maximum in-cylinder pressure under various working conditions increases to varying degrees compared with 3000 r/min. As the engine speed increases, the piston movement of the engine intensifies. The only way to achieve stratified combustion is to increase the hydrogen injection flow rate while keeping the hydrogen injection timing unchanged, so that the fuel near the spark plug becomes concentrated. At medium and high speeds, the maximum in-cylinder pressure first increases and then decreases with the increase of flow rate. The optimal hydrogen injection flow rate increases from 0.0026kg/h at 3000r/min to 0.0036kg/h and 0.0041kg/h. This is because the in-cylinder pressure increases to varying degrees with the increase of speed. This is because as the rotation speed increases, the flow rate of the mixed gas in the cylinder increases. The initial turbulence intensity in the cylinder increases, and it is necessary to increase the hydrogen injection flow rate to improve the penetration of the hydrogen jet, reduce the duration of the hydrogen injection cycle, and achieve local hydrogen-rich stratified combustion. At the same time, under medium and low loads, with the increase in hydrogen injection flow rate, the increase in the maximum pressure in the cylinder is large and the change range is large, while under high loads, the increase in the maximum pressure in the cylinder is small, that is, the maximum pressure in the cylinder is low at low loads, and the increase in the maximum pressure in the cylinder is large at high loads. This shows that the maximum pressure in the cylinder is strongly influenced by the hydrogen injection flow rate when the load is small.

In general, under different working conditions, the maximum in-cylinder pressure increases and then decreases with the increase of hydrogen injection flow rate, and there exists an optimal hydrogen injection flow rate. In addition, with the increase of rotational speed, the optimal flow rate of hydrogen injection in the cylinder is also increased accordingly, and the change of cylinder pressure under high load is significantly less affected by the flow rate than that of the low and medium load conditions. Therefore, when the working state of the direct injection engine changes, the appropriate flow rate needs to be adjusted to achieve optimal performance.

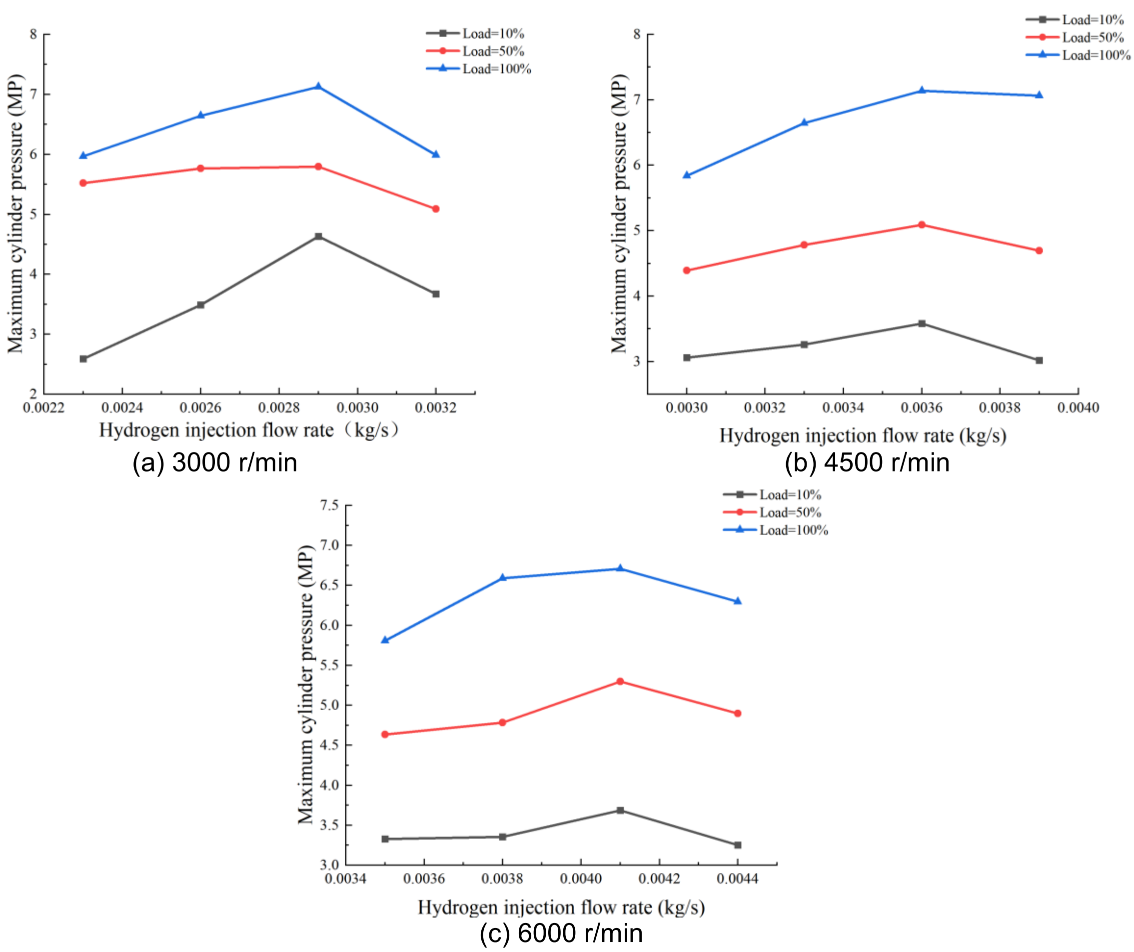
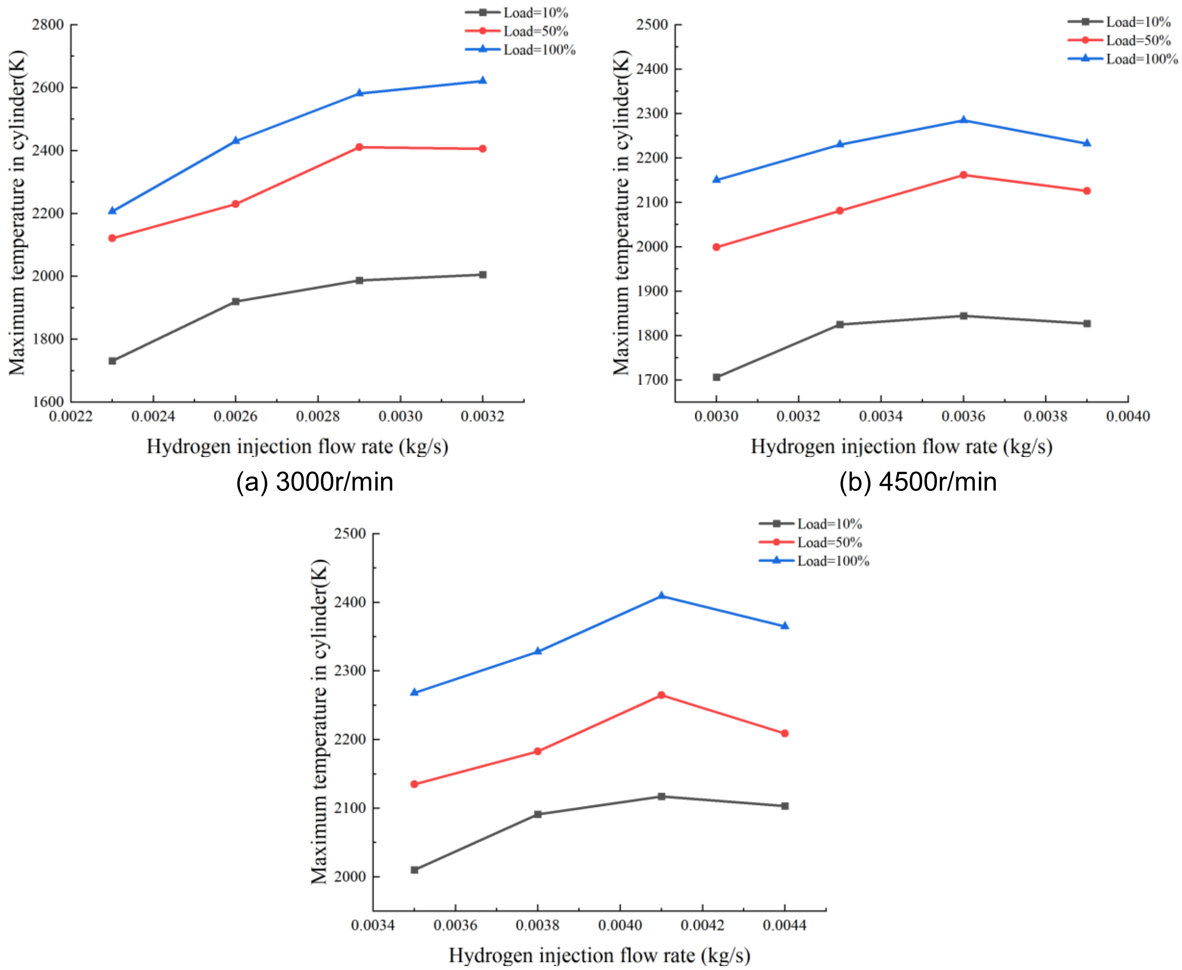


Fig. 4. The variation of the maximum in-cylinder pressure with the hydrogen injection flow rate under different working conditions

Figure 5 shows the trend of the maximum in-cylinder temperature with the hydrogen injection flow under different working conditions of the in-cylinder direct-injection hydrogen engine at engine speeds of 3000 r/min, 4500 r/min, and 6000 r/min. It can be seen from the figure that under different working conditions and different speeds, the maximum temperature in the cylinder shows a trend of first increasing and then decreasing with the increase of hydrogen injection flow rate. When the hydrogen injection flow rate is 3 000 r/min, the maximum temperature in the cylinder reaches a peak at 0.0029 kg/h. When the cylinder temperature reaches the peak value, the minimum hydrogen injection flow rate is 0.0029kg/h. As the speed increases further, the highest cylinder temperature is obtained when the hydrogen injection flow rate is 0.0036kg/h at 4500 r/min, and the cylinder temperature reaches the peak value when the hydrogen injection flow rate is 0.0041kg/h at 6000 r/min. This is because, compared with other hydrogen injection flow rates, the combustion conditions under this condition are significantly better than other conditions. Stratification occurs in the mixture in the cylinder, the hydrogen fuel is enriched near the spark plug, and the combustion speed is fast, resulting in an increase in the temperature in the cylinder.

At the same speed and different loads, as the load increases, the maximum temperature in the cylinder gradually increases. At 3000r/min, the maximum temperature is 2461K at the optimal hydrogen injection flow rate; at 4500r/min, the maximum temperature is 2661K at the optimal hydrogen injection flow rate; and at 6000r/min, the maximum temperature is 2789K at the optimal hydrogen injection flow rate. When the hydrogen injection flow rate is 0.032kg/s and the load is 100%, the maximum temperature inside the cylinder is 2789K.The greater the load, the more power the engine requires. Therefore, in order to achieve the target equivalence ratio, during the combustion process of the engine, as the amount of fuel in the cylinder increases, the total heat released by combustion also increases accordingly, which causes the maximum temperature that can be reached in the cylinder to also increase. By comparing the combustion characteristics under different operating conditions, it can be observed that there is a significant difference in the maximum temperature that can be achieved in the cylinder under low-speed and low-load conditions, compared to high-speed and high-load conditions. This is due to the longer duration of hydrogen injection at low speeds and the diffusivity of hydrogen, which tends to form a thinner mixture, leading to an increase in the duration of combustion. This reduces the stability of the combustion process and results in a lower maximum temperature in the cylinder.

From the effect of hydrogen injection flow on the maximum temperature in the cylinder, it can be seen that the overall trend of temperature change is roughly consistent with the change of the maximum pressure in the cylinder, both of which show a trend of first rising and then falling with the increase of flow. The pressure and temperature in the cylinder are relatively high during combustion under medium and high load conditions, which is conducive to improving the power of the engine. However, the high temperature and high pressure environment is the most favorable environment for the production of nitrogen oxides, the most important pollutant in the direct injection hydrogen engine. Therefore, choosing the appropriate hydrogen injection flow rate while ensuring power will minimize the generation of contamination.



(a) 3000r/min (b) 4500r/min (c) 6000r/min

Fig. 5. The variation of the maximum temperature in the cylinder with the hydrogen injection flow

Influence of Hydrogen Injection Flow Rate on the Dynamics of In-Cylinder Direct Injection Hydrogen Engine under Different Operating Conditions

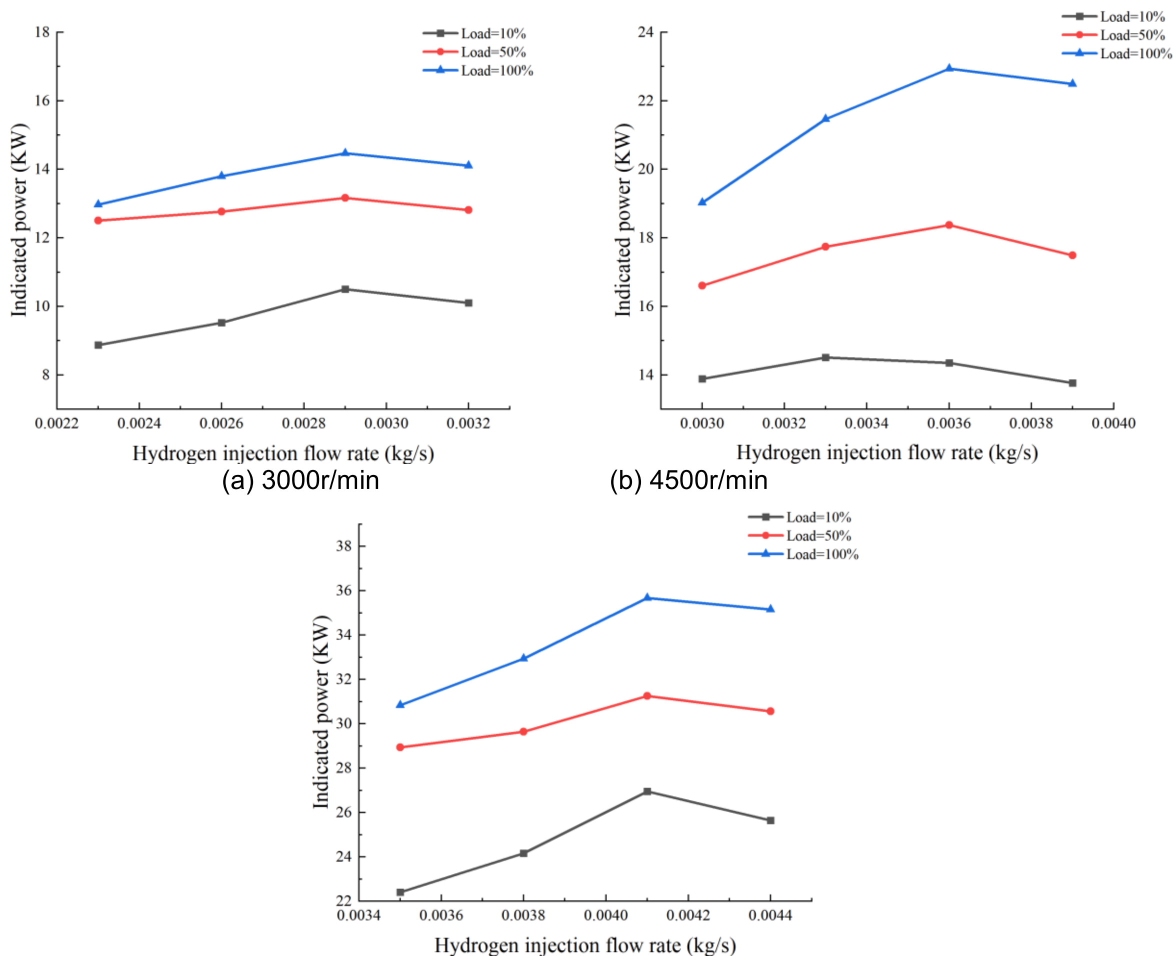
As an energy conversion device, the basic principle of an engine is to effectively convert the heat energy released by the chemical energy of the fuel into usable mechanical energy through a series of orderly working cycles. The indicated performance index of the engine is based on the work done on the piston after the combustion in the combustion chamber is completed. It can be directly reflected in a working cycle. The quality of the work done on the piston in the cylinder after the combustion is completed is an important parameter for evaluating the comprehensive performance of the engine. The indicated power refers to the indicated work done by the combustion engine per unit time, and the unit is KW. The indicated power is an important parameter for evaluating the power of the engine. Its calculation formula is as follows:

$$P_i = \frac{W_i n i}{30\tau} \quad \text{Eq. 1}$$

$$W_i = \int p \, d_V \quad \text{Eq. 2}$$

where n is the engine speed with a unit of r/min, i is the number of cylinders, τ is the number of engine strokes, and W_i is the engine indicated power.

The variation trend of indicated power under different operating conditions with hydrogen injection flow rate obtained in this section based on the simulation of the full experimental design scheme is shown in Figure 6. The indicated power of each working condition increases to varying degrees with the increase of rotational speed. This is because the higher the speed, the shorter the unit working cycle time of the engine, the more intense the turbulent motion in the cylinder, the more intense the piston motion, and the better the engine power. At the same time, under the same compression ratio, the indicated power of the engine increases as the load increases. At low load, as the hydrogen injection flow rate increases, the indicated power of the engine changes rapidly. Under high load conditions, the change of the indicated power is relatively gentle. Under low and medium load conditions, the indicated power of the engine is greatly affected by the hydrogen injection flow rate. And as the load increases, the influence of the hydrogen injection flow rate on the change of the indicated power of the engine is small.



(a) 3000r/min (b) 4500r/min

(c) 6000r/min

Fig. 6. The effect of hydrogen injection flow rate on the indicated power under different working conditions.

By analyzing the effect of hydrogen injection flow on the engine indicated power under different working conditions, it can be seen that the trend of the indicated power of the hydrogen engine under various working conditions is generally the same as the trend of the highest pressure in the cylinder. The change of combustion pressure in the cylinder can reflect the ability of the fuel to convert chemical energy into thermal energy and then into mechanical energy for external output, while the corresponding relationship between pressure in the cylinder and power ensures the accuracy of factor analysis. In general, the indicated power under each working condition gradually increases with the increase of hydrogen injection flow rate. At the same time, due to the fixed hydrogen injection time, the flow rate for obtaining the best indicated power also gradually increases. When other conditions are the same, the flow rate for obtaining the highest indicated power under low load is significantly smaller than the flow rate for obtaining the highest indicated power under medium and high loads.

Conclusion

As the hydrogen injection flow rate increases, the initial velocity of the hydrogen jet increases, thereby accelerating the flow of the mixture in the cylinder, enhancing the intensity of the turbulence in the cylinder, and increasing the vortex in the cylinder. On the one hand, it increases the collision probability between the spark plug electrode and the combustible mixture molecules, shortens the reaction time of hydrogen and oxygen, and accelerates the formation and development of the flame center. On the other hand, the enhanced in-cylinder vortex enhances the intensity of hydrogen turbulent combustion and accelerates the in-cylinder combustion process.

The maximum pressure in the cylinder increases first and then decreases with the increase of hydrogen injection flow rate, and there is an optimal hydrogen injection flow rate. In addition, as the speed increases, the optimal hydrogen injection flow rate in the cylinder also increases accordingly. Under high load conditions of 3000, 4500, and 6000 r/min, the maximum pressure in the cylinder reached its peak value when the hydrogen injection flow rate was 0.0029, 0.0036, and 0.0041 kg/s. Moreover, the change of cylinder pressure under high load is significantly less affected by flow rate than that under medium and low load. Therefore, when the operating conditions of a direct injection engine change, the appropriate flow rate needs to be adjusted to achieve optimal performance. The overall trend of the maximum temperature change in the cylinder is basically consistent with that of the maximum pressure change in the cylinder, that is, it shows a trend of first rising and then falling with the increase of flow rate. In addition, the combustion pressure and temperature in the cylinder are relatively high under medium and high load conditions, which is conducive to improving the engine power. By analyzing the effect of hydrogen injection flow rate on engine power under different working conditions, it can be seen that the overall trend of the indicated power of the hydrogen engine under various working conditions is roughly the same as the trend of the maximum pressure in the cylinder.

CONFLICTS OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this paper.

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