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Effect of Compression Ratio on the Performance of Direct-Injection Hydrogen Engines

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Direct injection of hydrogen into the cylinder can avoid abnormal combustion such as backfire, and the hydrogen engine can operate in a wider range of excess air coefficient. However, direct injection hydrogen engines still have problems such as high NO_x emissions under high load conditions, reduced power output due to lean combustion, and low thermal efficiency. This paper adopts a variable compression ratio structural design to study the impact of compression ratio changes on the comprehensive performance of direct injection hydrogen engines. The results show that under the same working conditions, as the engine compression ratio increases, the turbulence in the engine cylinder becomes more intense, increasing the back pressure in the cylinder, inhibiting the diffusion of hydrogen, making the hydrogen distribution more concentrated and the combustion conditions in the cylinder better. The overall performance of the engine is significantly improved.

Keywords: Direct injection; Compression ratio; Hydrogen; Indicated power; Indicated thermal efficiency; Turbulent kinetic energy

Introduction

With the development of automobile engines, the demand for new alternative fuels continues to increase. This trend has promoted the continuous innovation and development of energy technology. The emergence of new alternative fuels not only brings new development opportunities to the automotive industry, but also puts forward higher requirements for the energy industry, environmental protection and sustainable development. The promotion and application of alternative fuels has a positive contribution to the realization of environmental protection and emission reduction goals. The combustion of traditional fuels produces a large amount of greenhouse gases and harmful emissions, which have serious impacts on the atmospheric environment and human health. The application of new alternative fuels often has lower emission levels, which can reduce the emission of air pollutants, improve air quality and protect the ecological environment. In particular, some zero-emission alternative fuels, such as hydrogen fuel and electric vehicles, provide important support for achieving carbon neutrality and responding to climate change [1-3]. Hydrogen is considered a zero-carbon emission fuel with a very low production cost. It can be synthesized through a variety of chemical reactions such as ammonia decomposition, water gas, and water electrolysis. Hydrogen is known as the most promising alternative engine fuel at present, with the characteristics of clean combustion and no pollution. However, when used as a fuel in

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automobile engines, if hydrogen is not properly controlled, abnormal combustion is likely to occur. Common abnormal combustion in hydrogen engines [4-7] includes pre-ignition, backfire, detonation, etc.

As a renewable energy source, hydrogen energy can effectively reduce the emission of harmful substances from automobiles by utilizing its characteristics, providing a better solution to the contradiction between current environmental pollution and automobile emissions [8-9]. Currently, the application of hydrogen in the engine field mainly includes two modes [10-17]: One is to use it as a single fuel to directly drive the engine; the other is to mix it with traditional fuels such as gasoline and natural gas. However, due to the physical properties of hydrogen itself, the density of hydrogen is relatively small. When injecting hydrogen into the intake inlet method is adopted, the hydrogen expands immediately after being sprayed into the intake port, and quickly fills the entire intake port, which has a certain hindering effect on the entry of air. In severe cases, it will cause air to be unable to enter, the filling coefficient is low, and the incomplete combustion of fuel also brings about the negative effects of increased emissions and reduced engine power. In-cylinder direct injection technology solves the problem of hydrogen taking up cylinder volume and enhances the power performance of hydrogen internal combustion engines. Compared with intake inlet injection, direct-injection hydrogen combustion engines are able to inject after the intake valve is closed, effectively preventing backfire caused by hydrogen flowing back into the intake port. Under similar operating conditions, direct-injection hydrogen internal combustion engines can use a leaner combustion method to reduce pumping losses, thereby improving engine thermal efficiency.

Park *et al.* [18-19] investigated the engine performance and emission characteristics of hydrogen-natural gas blended fuels. The results show that when the excess air coefficient is constant, the thermal efficiency decreases with the increase of CO content; the increase of the heat capacity of the mixture reduces the combustion temperature, thereby inhibiting the formation of NO_x. Shivaprasad *et al.* [20] conducted tests on the performance and emission characteristics of a high-speed single-cylinder engine by selecting hydrogen-gasoline mixtures with different hydrogen enrichment levels, and studied the effects of hydrogen addition on the engine's brake mean effective pressure (Bmep), brake thermal efficiency, volumetric efficiency and emission characteristics. The results showed that hydrogen enrichment improved combustion performance, fuel consumption and Bmep. The experimental results also showed that the brake thermal efficiency was higher than that of pure gasoline conditions.. Both HC and CO emissions were reduced after hydrogen enrichment. Sukumaran & Kong [21] numerically simulated the direct in-cylinder hydrogen injection and the formation of the in-cylinder mixture. Early injection can produce a more uniform mixture during ignition. It is more advantageous to place the injector near the intake valve to take advantage of the interaction between the hydrogen jet and the intake flow to produce a more homogeneous mixture

This study adopts a higher compression ratio to improve thermal efficiency. However, as higher compression ratios are applied, NO_x emissions also increase. The traditional method to improve thermal efficiency and reduce NO_x is to burn a lean mixture of fuel and air. Currently, this is done by injecting hydrogen at the beginning of the compression stroke to form a mixture of hydrogen and air. In this paper, the thermal efficiency of a hydrogen internal combustion engine is improved by using at different compression ratios. It also further explores the effect of compression ratio on the thermal

efficiency of the hydrogen engine at the same rotational speed, and analyzes the effects of different compression ratios on the in-cylinder mixture, emissions and performance of internal combustion engines.
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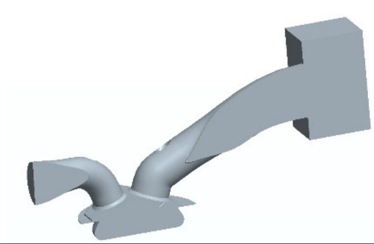
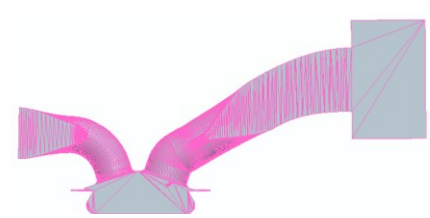
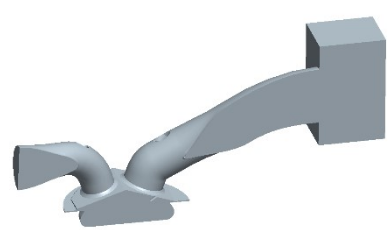
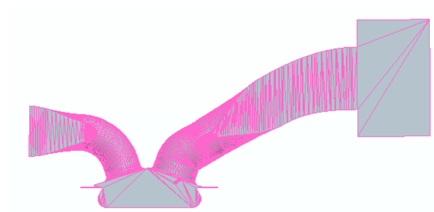
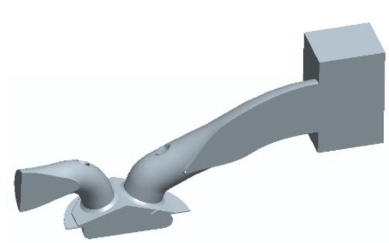
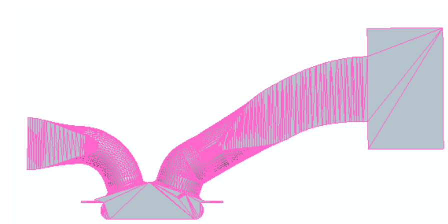
Computational Models and Research Programs

This study uses a single-cylinder gasoline direct injection (GDI) test engine as a prototype, and further modifies the design based on the original size data of the prototype, converting it into a variable compression ratio in-cylinder direct injection hydrogen engine to meet the experimental requirements. The technical parameters of the experimental engine have been described in pervious publication [22].

Geometric and Mesh Models

In this experiment, based on the designed variable compression ratio engine combustion structure and the actual engine specifications, four groups of experimental engine models with different compression ratios were established using the 3D modeling software Creo. The four groups of models with different compression ratios were exported in stl format to obtain a preliminary mesh model. The specific model is shown in Figure 1.

Compression ratio	**Engine Geometry Model**	**Initial mesh model of the engine**
10:1		
12:1		
15:1		

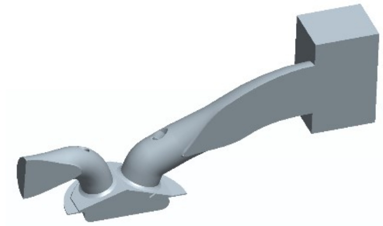
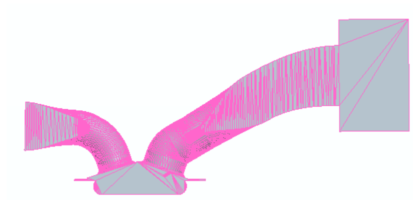
18:1		

Fig. 1. Engine geometric model and mesh under different compression ratios

Initial and Boundary Conditions

The boundary conditions mainly include inlet and outlet boundaries, wall boundaries, symmetry surface boundaries, etc., among which wall boundaries are divided into fixed walls and moving walls. Various boundaries are mainly divided into pressure type and temperature type, and the corresponding type can be set according to the actual process. For example, 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 constant temperature boundary, etc. Both initial and boundary conditions have been described in pervious publication [22].

Model Validation

When the JH600 engine was converted to a hydrogen internal combustion engine, the model was validated under normal combustion conditions. The engine specifications include a cylinder diameter of 94 millimeters, a stroke of 85 millimeters, and a compression ratio of 15:1. The validation data has been described in pervious publication [22].

Results

Effect of Compression Ratio on In-Cylinder Mixture Velocity Field under Different Operating Conditions

Figure 2 shows the in-cylinder velocity field at 667° CA, 680° CA, 698° CA, respectively, when the compression ratio is 10:1. The effect of compression ratio on the mixture of in-cylinder direct hydrogen injection engine is mainly concentrated in the rear part of the upward movement of the piston after the intake closes. After the high-speed hydrogen is sprayed onto the cylinder wall, part of it moves with the bottom of the piston, and part of it moves upward along the cylinder wall. At the same time, as the crankshaft rotates and the piston moves upward, part of the fuel in contact with the cylinder wall is impacted by the piston movement and forms a new vortex at the bottom of the cylinder. With the injection of hydrogen, the speed of the mixture in the cylinder is further increased, and the mixture flowing outward from the top of the combustion chamber is affected by the crowding effect. The turbulent motion of the mixture at the top of the combustion chamber is restricted, and the mixture flowing outward from the top of the piston and the mixture flowing outward from the top of the combustion chamber are more turbulent. The turbulent motion in the combustion chamber is generated by the piston combustion chamber structure. The vortex formed by the hydrogen jet after touching the bottom of the piston further expands, which accelerates the velocity of the mixed gas at the bottom of the piston and gradually develops upward. At the end of the piston stroke, the turbulent flow from the bottom of the piston develops upward to the top surface of the combustion chamber, and then forms a head-on downward after contacting the top surface of the combustion chamber. In this way, the velocity of the mixed gas at the bottom of the spark plug is at a larger position, which is beneficial to the flame propagation speed.

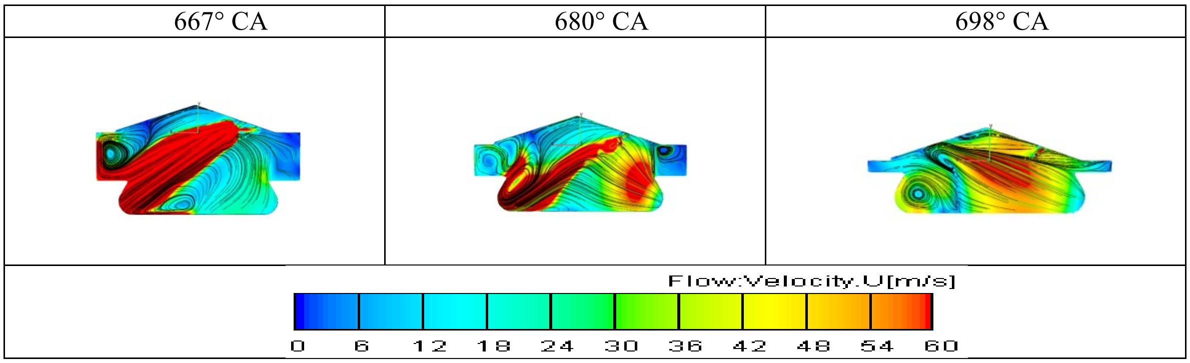


Fig. 2. In-cylinder mixture velocity field distribution at the compression ratio of 10:1

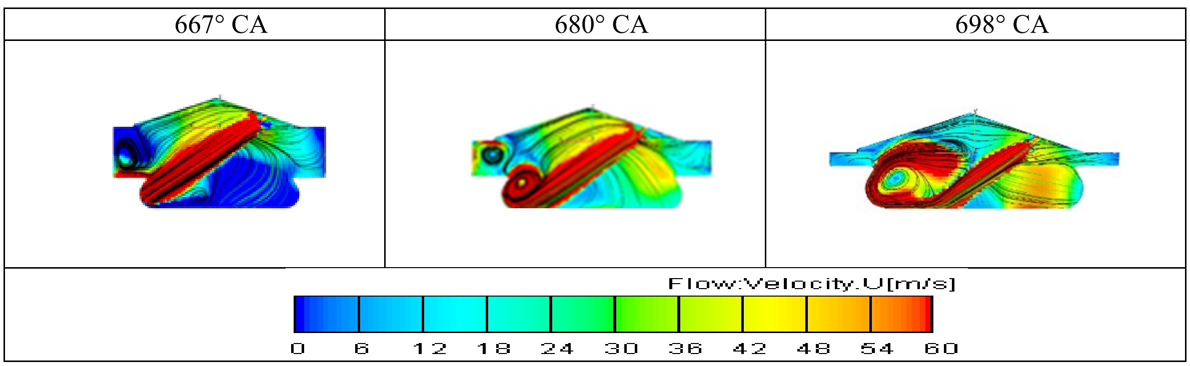


Fig. 3. In-cylinder mixture velocity field distribution at the compression ratio of 12:1

Figure 3 shows the velocity field distribution of the mixture in the cylinder at three moments when the compression ratio is 12:1, 667° CA, 680° CA, and 698° CA, respectively. From the velocity cloud diagram of the mixture in the cylinder at each moment, it can be seen that the movement law of the mixture in the cylinder when the compression ratio is 12 is basically the same as the development trend when the compression ratio is 10. However, as the compression ratio is further increased, the depth of the combustion chamber on the top surface of the piston continues to decrease, and the corresponding combustion chamber volume also decreases accordingly. At the same time, the squeezing effect of the piston bottom and the combustion chamber wall is also strengthened, which also promotes the turbulent movement of the mixture in the cylinder. As it can be seen in the figure, the depth of the combustion chamber is reduced due to the increase in compression ratio before hydrogen injection. Hydrogen injection promotes the movement of air flow in the cylinder, forming a vortex on the left side of the cylinder. At the same time, with the movement of the piston and the squeezing effect of the cylinder head, the center of the vortex located on the outside gradually moves toward the center of the cylinder. After the hydrogen injection is completed, the center of the vortex gradually moves toward the center, and then moves closer to the center. Simultaneously, with the movement of the piston and the squeezing effect of the cylinder head, the center of the side vortex gradually moves toward the center of the cylinder. After the hydrogen injection is completed, the velocity distribution of the mixed gas in the cylinder is uneven due to the influence of the side vortex.

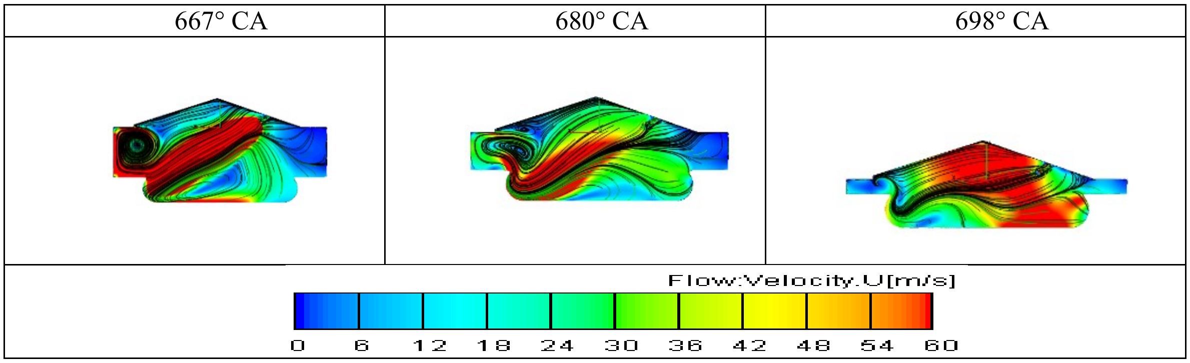


Fig. 4. In-cylinder mixture velocity field distribution at the compression ratio of 15:1

Figure 4 shows the velocity field and turbulence development trend of the mixture in the cylinder, when the compression ratio is 15:1. The increase in compression ratio further reduces the depth of the concave cavity on the top surface of the piston, and the volume of the combustion chamber also decreases accordingly. When the volume of the combustion chamber decreases, the movement of the mixture in the cylinder is enhanced under the impetus of the hydrogen jet, and the scope of influence is also expanded. After being squeezed by the cylinder wall, a new vortex is formed along the cylinder wall at the bottom of the cylinder. After encountering the hydrogen jet, the upper vortex moves along the center of the cylinder and promotes the movement of the hydrogen jet. On both sides of the hydrogen jet, after being squeezed by the cylinder wall, new vortices are formed along the cylinder wall. The vortex at the bottom of the cylinder moves along the center of the cylinder and drives the hydrogen jet to move. The upper vortex moves toward the middle of the cylinder under the enhancement of the circulation and finally forms a front, which enhances the flow rate of the mixture in the middle of the cylinder.

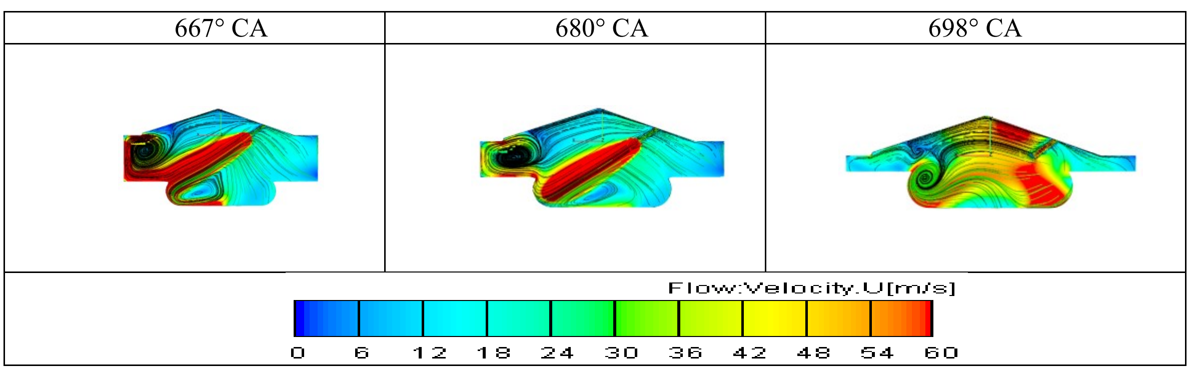


Fig. 5. In-cylinder mixture velocity field distribution at the compression ratio of 18:1

Figure 5 shows the velocity field distribution of the in-cylinder mixture at compression ratio of 18:1. The volume of the combustion chamber reaches its minimum with the increase of compression ratio. With the increase of compression ratio, the turbulence intensity of the mixture in the cylinder also increases continuously. At the same time, the range of influence of the hydrogen jet on the mixture in the cylinder also expands with the increase of compression ratio. As shown in Figure 5, with the increase of compression ratio, the squeezing effect of the bottom of the piston takes effect later than the effect on the mixture in the cylinder at low compression ratio. The vortex effect at the bottom of the cylinder is weaker than the vortex at the top of the cylinder, and the large vortex at the top of the cylinder moves toward the center of the cylinder under the action of the cylinder wall, resulting in an overall increase in the velocity of the mixture in the cylinder. In addition, the increase in the flow rate of the hydrogen jet significantly enhances the turbulent motion inside the cylinder and accelerates the flow velocity of the mixture in the cylinder.

Effect of Compression Ratio on Turbulent Kinetic Energy of In-Cylinder Mixture and Mixture Distribution under Different Operating Conditions

According to the above analysis, it can be seen that the turbulent movement of the mixture in the cylinder will affect the combustion process of the engine. As the compression ratio increases, the turbulent movement in the cylinder becomes more active. From the change process of the velocity field in the cylinder with the crankshaft angle, it can be found that the part of the cylinder with higher gas flow velocity is mainly concentrated in the middle of the cylinder, which is beneficial to the propagation of the flame during the combustion process. In addition, the distribution of the mixture concentration field in the cylinder before combustion starts also has an important influence on the combustion and emission process of the engine. Reasonable mixture distribution is conducive to accelerating the combustion process and reducing emissions.

Turbulent kinetic energy refers to the flow kinetic energy generated by the mixing of fuel and air in the cylinder of a direct injection hydrogen engine due to different mixing degrees and the combustion of fuel during the combustion process [23-24]. The turbulent kinetic energy in the cylinder is an important indicator for evaluating the fuel energy conversion efficiency in the combustion chamber of a direct injection hydrogen engine and the fluidity of the fuel in the engine. Turbulence occurs throughout the entire process of the engine, especially in the mixing stage of the mixture in the cylinder. During the mixing stage of the mixture in the cylinder, the turbulent energy of the turbulent motion in the cylinder directly affects the quality of engine combustion and emissions, and also has an important impact on the engine's output power and the comprehensive utilization rate of fuel. Therefore, studying the turbulent energy of the mixture in the cylinder is of great significance to the comprehensive performance of the direct injection hydrogen engine. In hydrogen engines, due to the extremely high combustibility and diffusion rate of hydrogen fuel, the degree of mixture homogeneity and turbulence intensity play a decisive role in the combustion speed, combustion stability, combustion efficiency, and generation of harmful emissions.

Under different loads, the required amount of fuel is different, and the total amount of fuel required increases with the increase of load. Generally, the hydrogen injection mixing time at medium speed is longer than that at high speed. Therefore, this paper studies the changes in the state of the mixture in the cylinder when the compression ratio changes under different load conditions at 3000 r/min, hydrogen injection flow rate of 0.003 kg/h.

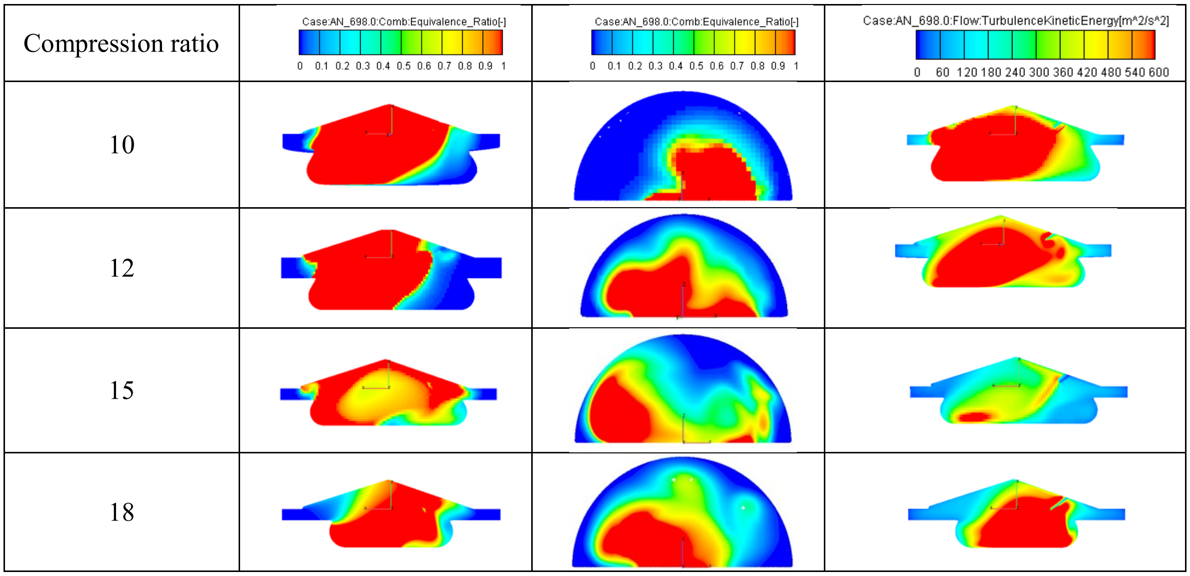


Fig. 6. Mixed gas concentration field and turbulent kinetic energy after hydrogen injection at 3000 rpm and 10% load

Figure 6 shows the concentration field of the mixture and the distribution of the mixture in the cylinder under different compression ratios at the end of the hydrogen injection period at 10% load and 3000 r/min. It can be seen from the figure that after the hydrogen injection stage, the hydrogen in the cylinder is mainly distributed in the left part of the cylinder. And the distribution of hydrogen in the cylinder is more concentrated, forming a fuel plume. The slice in the Y direction of the figure shows the distribution of hydrogen in the cylinder more three-dimensionally. The distribution of hydrogen is mainly concentrated in the center of the cylinder and moves to the right when the compression ratio is 10:1. However, as the compression ratio increases, the distribution of hydrogen in the cylinder gradually moves to the left. This is because when the piston rises during the hydrogen injection process, the hydrogen jet contacts the bowl-shaped structure at the bottom of the cylinder, and is squeezed by the piston and turbulently moves along the cylinder wall. The hydrogen moves to the right along the combustion chamber wall, then to the right, and then to the right. The combustion chamber wall moves to the right. At the end of hydrogen injection, the thicker part of the mixture in the cylinder is mainly distributed in the right part of the combustion chamber. However, with the increase of compression ratio, the depth of the combustion chamber gradually decreases. During the hydrogen injection process, the time when the hydrogen jet contacts the piston is delayed. Finally, at the end of continuous hydrogen injection, the main distribution of hydrogen in the cylinder moves to the left, and the hydrogen concentration in this area increases. According to the turbulent kinetic energy distribution diagram in the cylinder, it can be seen that the flow velocity and turbulent motion of the cylinder mixture in the hydrogen injection area are relatively concentrated after the hydrogen injection is completed. Therefore, the turbulent kinetic energy in the cylinder is relatively high at this time. However, as the compression ratio increases, the turbulent kinetic energy in the cylinder mixture concentration area is weakened by the turbulence in the cylinder.

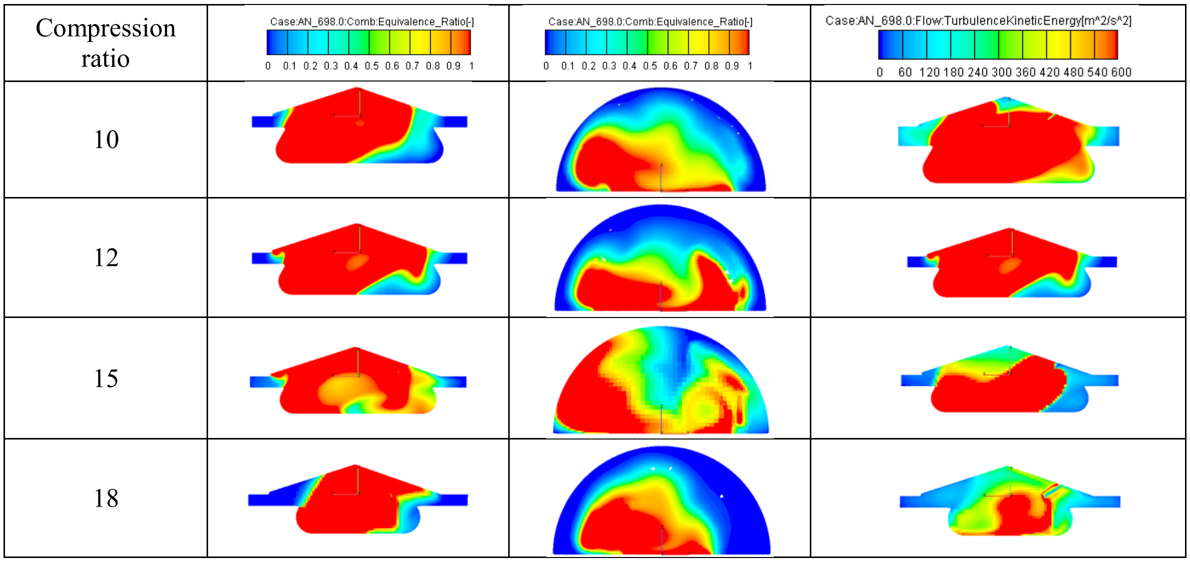


Fig. 7. Mixed gas concentration field and turbulent kinetic energy after hydrogen injection at 3000 rpm and 50% load

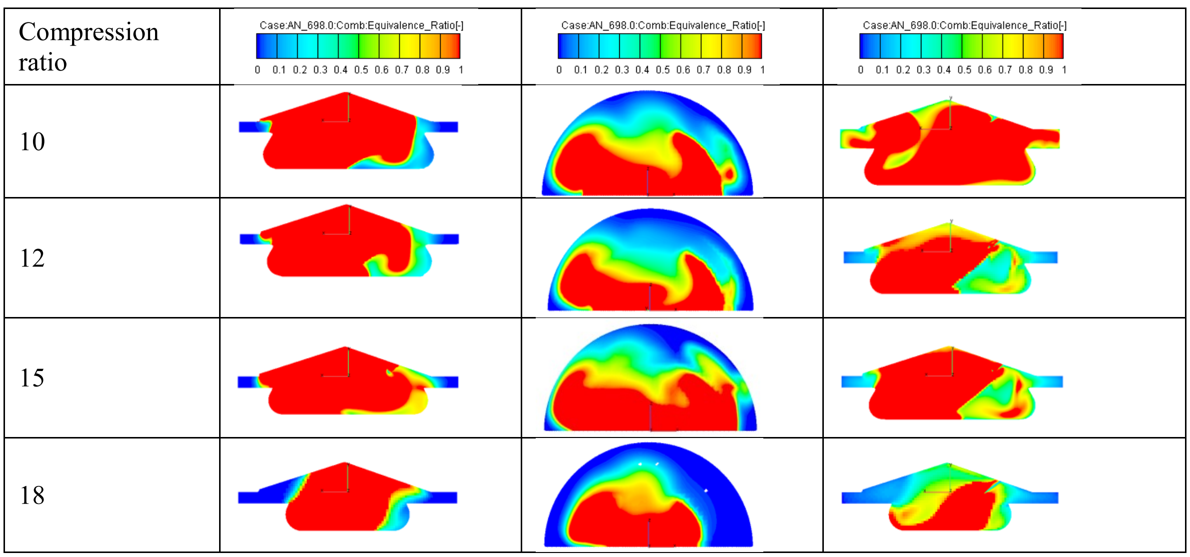


Fig. 8. Mixed gas concentration field and turbulent kinetic energy after hydrogen injection at 3000 rpm and 100% load

Figure 7 shows the distribution of the concentration field and turbulent kinetic energy of the mixture in the cylinder at 3000 r/min and 50% load. It can be seen from the in-cylinder concentration field and the Y-direction slice cloud diagram that when the load increases to 50%, the fuel required by the engine increases. In order to achieve the target equivalence ratio, more hydrogen needs to be injected. Therefore, compared with the area of the combustion chamber occupied by the fuel at low load, the distribution of the in-cylinder concentration field increases. As the area of the combustion chamber increases, the diffusion rate and diffusion range of hydrogen further increase, and an obvious concentration gradient appears. However, with the increase of the compression ratio, the diffusion rate of hydrogen is limited, causing the mixture to gather in the middle of the cylinder. The reason for this phenomenon is that with the increase of the compression ratio, when the piston runs near the top dead center, the back pressure in the combustion chamber at a high compression ratio is higher than the back pressure in the cylinder at a low compression ratio, thereby further limiting the diffusion of fuel in the cylinder. At the same time, as the load increases, the turbulent kinetic energy intensity of the turbulent flow in the cylinder is also increasing. It can be seen that the turbulent intensity in the cylinder at a low compression ratio is significantly higher than that at a high compression ratio.

Figure 8 shows the distribution of concentration field and turbulent kinetic energy of the mixture in the cylinder at 3000 r/min and 100% load. It can be seen from the cloud diagram that with the further increase of load, the change patterns of the in-cylinder concentration field and turbulent kinetic energy are the same at 100% load and 50% load. However, compared with low load, the area occupied by the in-cylinder concentration field at high load further increases, but the concentration gradient distribution of hydrogen is smaller than at low load, and the diffusion range of hydrogen is further reduced.

Effect of Compression Ratio on Cylinder Pressure and Temperature of Direct-Injection Hydrogen Engine under Different Operating Conditions

This section takes 50% load as an example to show the variation trend of maximum cylinder pressure and temperature with compression ratio at different speeds. Figure 9 shows that under the same load and different speeds, the maximum pressure in the cylinder under each working condition increases with the increase of compression ratio. For example, at 4500 r/min and 0.0036 kg/h, the compression ratio increases from 10 to 18, and the maximum pressure in the cylinder increases from 4.835MPa to 7.453MPa. This is because, under the same other conditions, with the increase of compression ratio, the volume of the combustion chamber gradually decreases before the piston reaches the top dead center of the cylinder. The increase of compression ratio under the same load leads to the increase of pressure and temperature in the cylinder, thereby accelerating the propagation speed of the combustion flame. In addition, with the increase of compression ratio, the vortex inside the cylinder becomes more intense, and the space for vortex in the cylinder continues to increase. At the same time, the squeezing effect between the bottom of the piston and the cylinder head becomes more obvious, and the enhancement of the vortex in the cylinder greatly enhances the combustible mixture. The enhancement of the cylinder eddy current greatly improves the probability of ignition of the combustible mixture molecules, thereby accelerating the reaction process and causing an increase in the maximum cylinder pressure in the cylinder.

Figure 9 also shows that as the engine speed increases, when the speed increases from 3000 r/min to 6000 r/min, the maximum in-cylinder pressure under different working conditions at each compression ratio increases to varying degrees. At low speeds, as the compression ratio increases, the rate of increase in the highest cylinder pressure also increases. The highest cylinder pressure is affected by the compression ratio at low speeds, and as the speed increases, the highest external pressure decreases while the highest internal pressure increases. As the rotational speed increases, the rate of increase in maximum pressure decreases, and the maximum pressure inside the cylinder is less affected by the compression ratio.

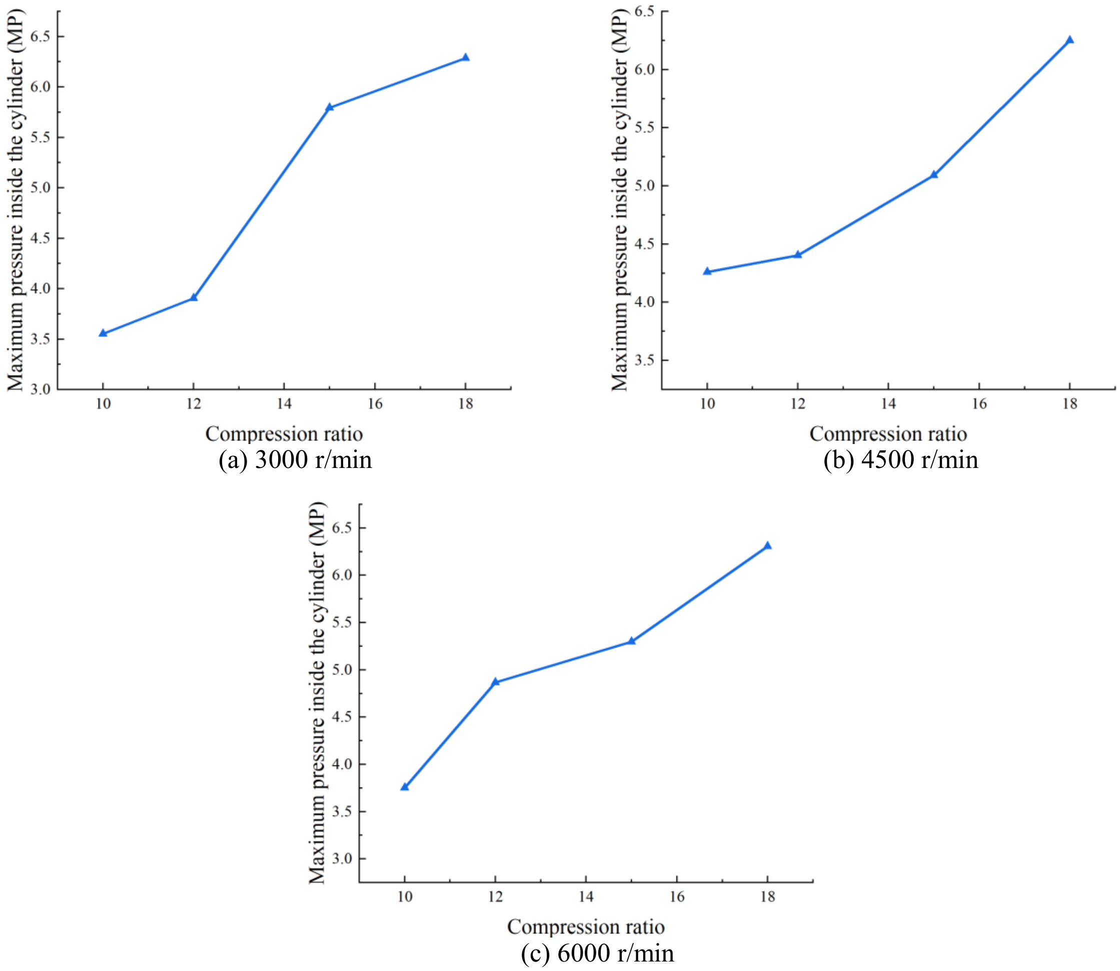


Fig. 9. The influence of the change of compression ratio at different speeds on the maximum pressure in the cylinder

As can be seen from Figure 10, under different working conditions of 50% load and different speeds, the maximum combustion temperature in the cylinder shows a positive correlation with the compression ratio, that is, as the compression ratio increases, the peak temperature that can be achieved in the cylinder rises synchronously. This shows that the increase in compression ratio improves the combustion quality of the mixture in the cylinder, speeds up the reaction speed of the mixture, and can increase the combustion heat in the cylinder, thereby increasing the maximum temperature in the cylinder. Figure 10a shows that at low speed and the same load, the maximum temperature in the cylinder is slightly higher than the peak temperature at high speed. This is because at low speed and the same load, the combustion duration of the mixture in the cylinder is longer and the heat release combustion is more complete. In addition, at low speed, the cylinder temperature of the mixture combustion is smaller than the combustion chamber structure, and the heat transfer loss is reduced, which increases the peak temperature in the cylinder. When the speed increases to 4500 r/min and 6000 r/min (Figures 10b,c), the peak temperature in the cylinder decreases. On the one hand, as the speed increases, the time of each cycle becomes shorter, and the heat transfer loss of the engine increases. On the other hand, as the speed increases, the combustion duration shortens, the combustion time of the mixture in the cylinder is relatively reduced, and the mixture cannot release the heat in the cylinder in a timely and complete manner. But overall, the increase in compression ratio is beneficial to speeding up the combustion speed of the mixture in the cylinder, promoting combustion stability, and accelerating the heat release rate of the fuel.

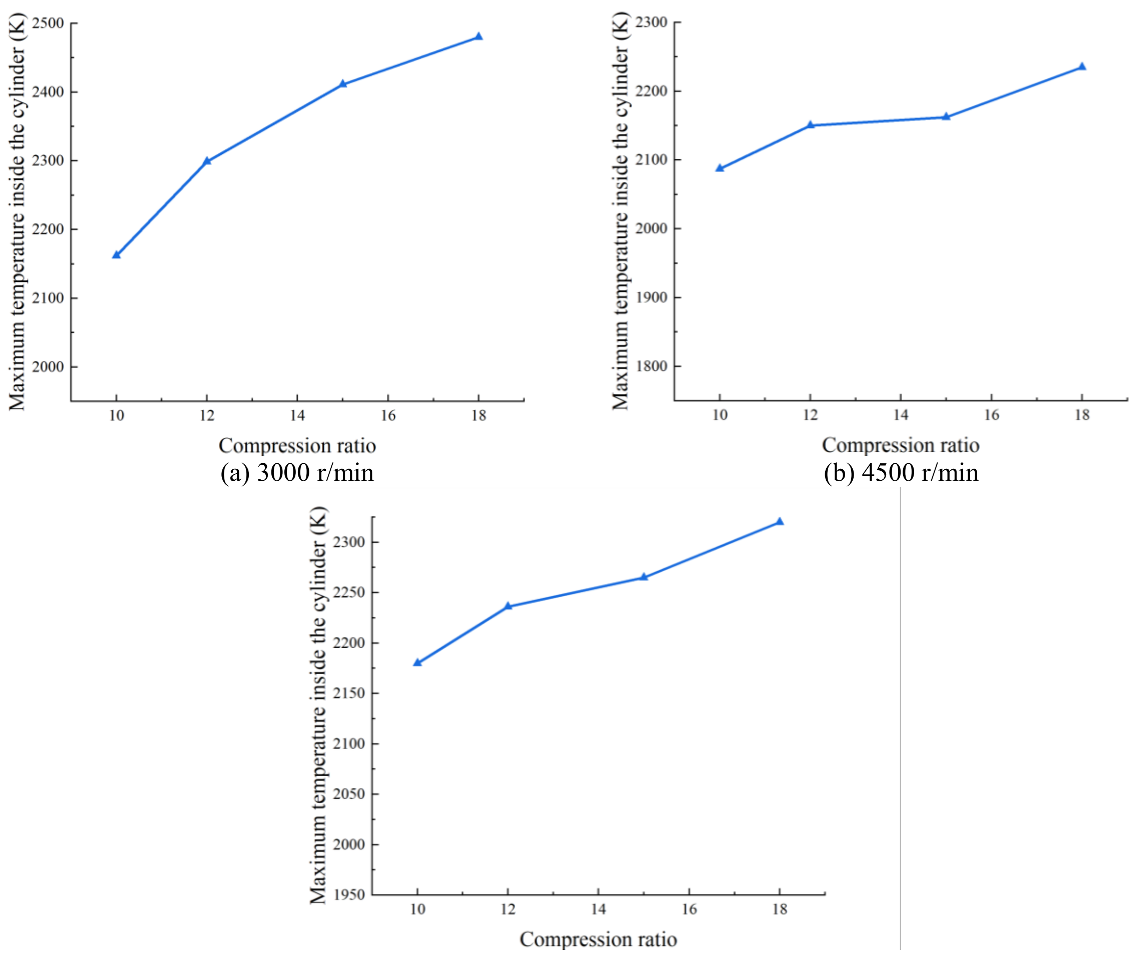


Fig. 10. The influence of the change of compression ratio on the maximum temperature in the cylinder at different speeds.

Effect of Compression Ratio on the Dynamics of Direct Injection Hydrogen Engines under Different Operating Conditions

As can be seen from Figure 11, taking 6000 r/min and 0.0041 kg/s as an example, when the compression ratio increases from 10:1 to 18:1, the indicated power of the engine increases from 26.4kW to 33.2kW. And at 50% load, the maximum indicated power at different speeds increases with the increase of rotational speed. This is because under the same conditions, as the compression ratio increases, the higher the compression ratio, the smaller the combustion chamber volume. Before the piston moves to the upper end point, the turbulent motion of the working material in the combustion chamber in the cylinder becomes more intense, which can be improved, effectively shortening the flame development period and accelerating the spread of the flame. At the same time, the increase in compression ratio reduces the combustion chamber volume, increases the back pressure in the cylinder, and can inhibit the diffusion of the mixture, thereby increasing the indicated power of the engine.

By analyzing the effect of compression ratio on engine indicated power under different working conditions, it can be seen that the trend of indicated power of hydrogen engine under various working conditions is roughly the same as that of the highest pressure in the cylinder. The change of combustion pressure in the cylinder can indicate the ability of the fuel to convert chemical energy into heat 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. Under the same conditions, increasing the compression ratio can significantly improve the power loss of hydrogen engines caused by lean combustion. Therefore, by increasing the compression ratio, the overall indicated power of the engine can be significantly improved.

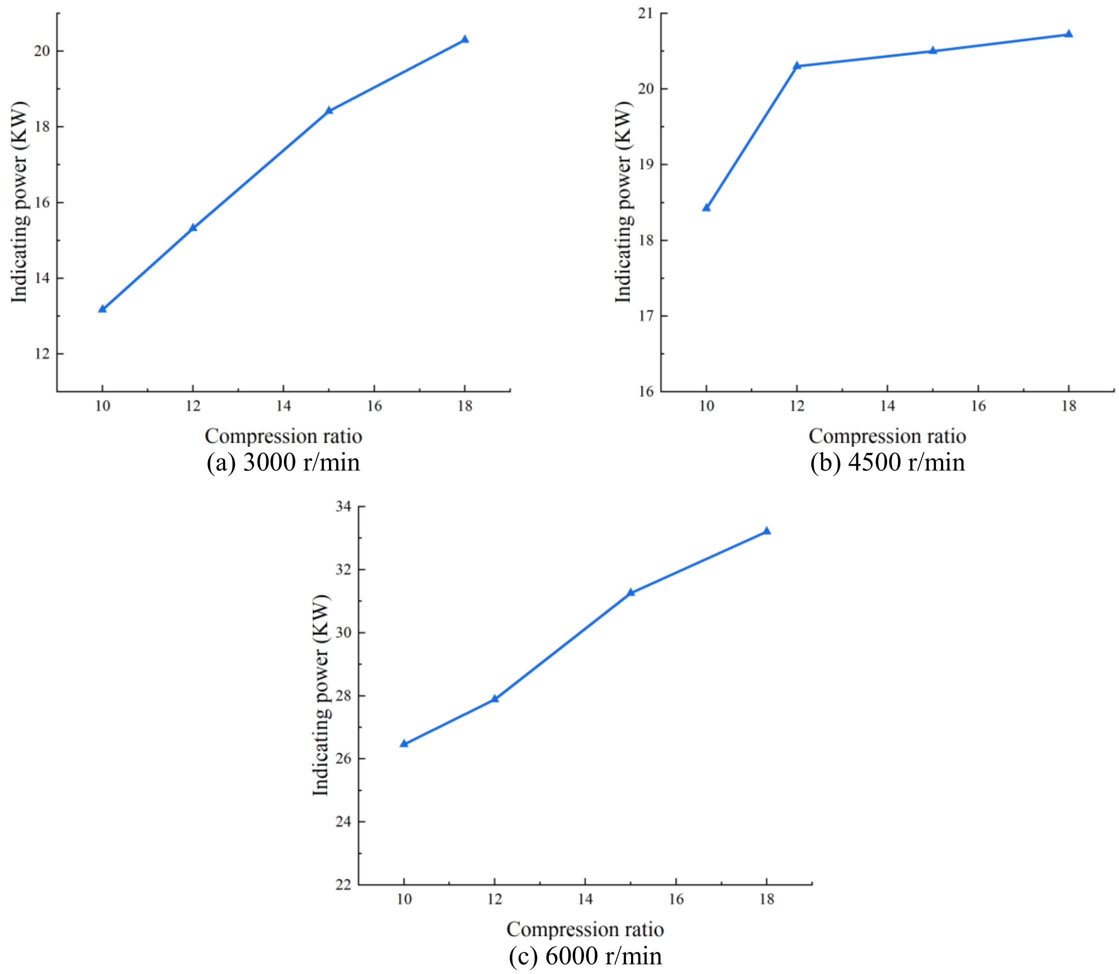


Fig. 11. The influence of compression ratio on the indicated power under different working conditions.

Effect of Compression Ratio on the Economy of Direct Injection Hydrogen Engines under Different Operating Conditions

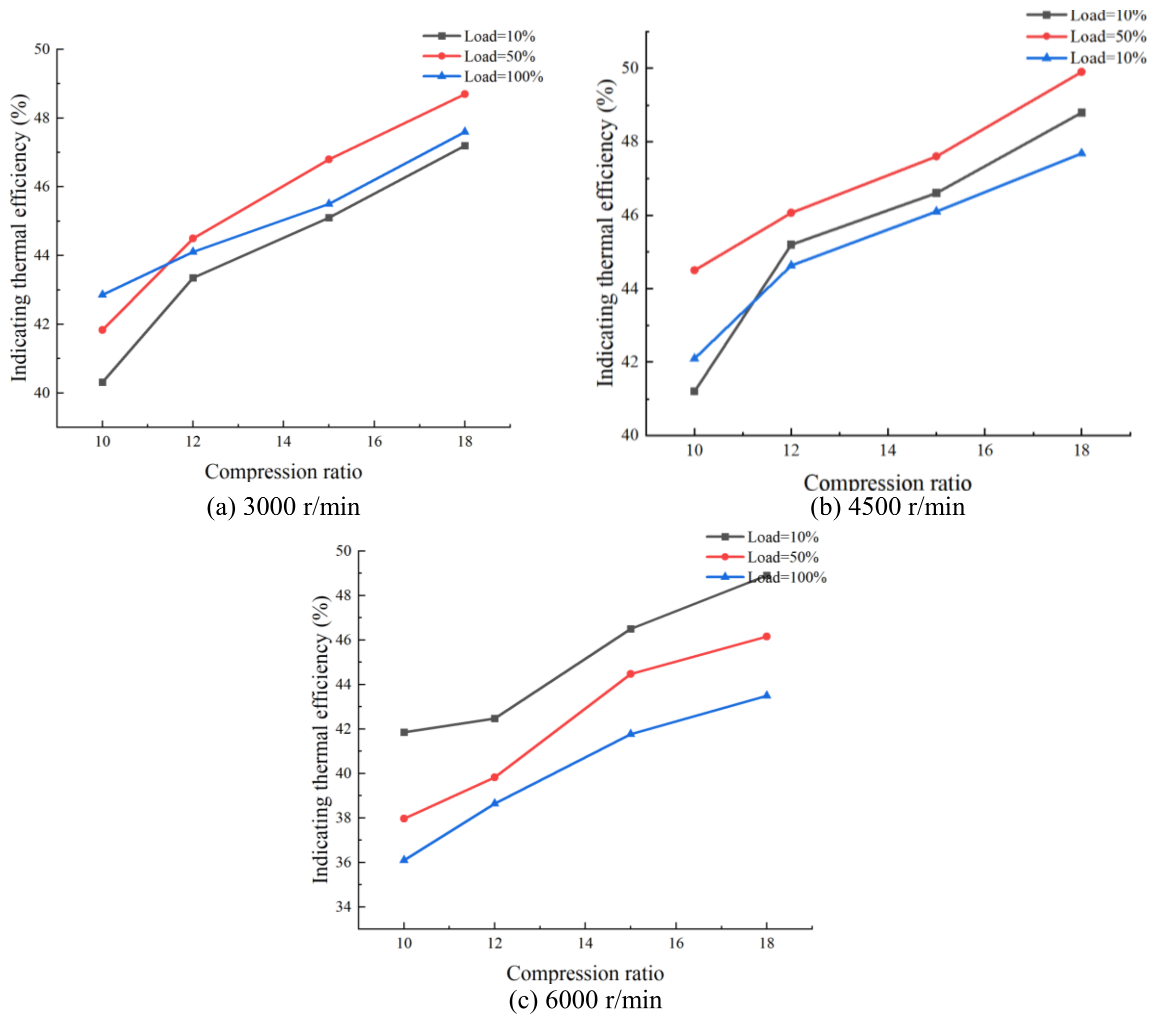


Fig. 12. The effect of compression ratio on indicated thermal efficiency of hydrogen engine under different working loads

Figure 12 shows the changing trend of indicated thermal efficiency with the increase of compression ratio at 3000 r/min, 4500 r/min, and 6000 r/min under some working conditions. This section mainly examines the influence of the single compression ratio factor on the indicated thermal efficiency of the hydrogen engine. Therefore, the compression ratios at 3000 r/min, 4500 r/min, and 6000 r/min are selected to study the influence of compression ratio on the indicated thermal efficiency at different speeds and loads. It can be seen that with the increase of compression ratio, the indicated thermal efficiency of hydrogen engine under different loads also gradually increases, and the economy of the engine gradually improves. This is because under the same conditions, the compression ratio increases, the combustion chamber volume decreases, and the pressure in the cylinder increases during the upward movement of the piston. The increase in cylinder pressure reduces the diffusion degree of the hydrogen jet, forming a high-quality mixture with local enrichment of hydrogen. At the same time, the increase in compression ratio also increases the temperature of the combustion chamber, accelerates the combustion reaction, shortens the combustion duration, and makes the hydrogen combustion more sufficient and complete. Taking 3000 r/min and 50% load as an example, as the compression ratio increases, the best indicated thermal efficiency of the hydrogen engine increases from 41.8% to 48.7%. This shows that increasing the compression ratio is one of the important ways to improve the indicated thermal efficiency of the engine.

From Figure 12, the best indicated thermal efficiency obtained at 50% load, a compression ratio of 18, and 3000 r/min, 4500 r/min and 6000 r/min are 48.7%, 49.5% and 48.7%, respectively. The indicated thermal efficiency at 3000 r/min and 4500 r/min 50% load conditions is significantly higher than that at other conditions. In addition, as the speed increases, the indicated thermal efficiency at 6000 r/min 10% load condition is the best. This is because increasing the target equivalence ratio of load-corresponding combustion increases the pressure and temperature of the combustion process, thereby improving the overall indicated thermal efficiency. However, with the increase in speed and load, the maximum temperature of the in-cylinder reaction in the high load conditions greatly increased, increasing the heat transfer loss of the cylinder wall and other walls. In addition, a fixed ignition timing was used during the experimental simulation, and the turbulent motion in the cylinder was more intense under high-speed and high-load conditions, which accelerated the flame propagation speed and increased the actual compression negative work of the engine. This reduces the indicated thermal efficiency of the hydrogen engine under high load conditions.

Conclusions

(1) With the increase of compression ratio, during the upward movement of the piston, the in-cylinder mixture is enhanced by the squeezing effect of the bottom surface of the piston and the cylinder wall, which promotes the turbulence movement of the in-cylinder mixture and the expansion of the in-cylinder vortex distribution range. In addition, with the continuous increase of the hydrogen injection flow rate, it increases the initial velocity of the hydrogen jet, which accelerates the in-cylinder mixture flow rate and enhances the enhancement of the in-cylinder vortex.

(2) As the compression ratio increases, the main distribution center of hydrogen in the cylinder gradually moves toward the center. When the compression ratio is 18:1, the hydrogen concentration in the middle of the cylinder is higher, and obvious stratification occurs at low load. This is because the increase in compression ratio is affected by the crowded flow on the cylinder wall and the vortex in the cylinder, causing the main distribution of hydrogen in the cylinder to move toward the center of the cylinder. Due to the increase in compression ratio, the background pressure in the cylinder increases, which inhibits the diffusion of hydrogen and causes more hydrogen to diffuse toward the center of the cylinder. As the load increases, the cylinder area occupied by hydrogen fuel gradually increases, and obvious stratification occurs at low loads. The hydrogen concentration gradient decreases under medium and high load conditions.

(3) The increase of compression ratio under different working conditions has a significant effect on the maximum pressure and temperature in the cylinder. On the one hand, the increase of compression ratio enhances the turbulence movement in the cylinder, optimizes the distribution of hydrogen in the cylinder and increases the chance of ignition of the combustible mixture. On the other hand, it helps accelerate the

combustion speed of the mixture in the cylinder, promotes the stability of the combustion, and accelerates the heat release rate of the fuel.

CONFLICTS OF INTEREST

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

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