An overview of pre-ignition of hydrogen engine

Abstract:Hydrogen engine has attracted much attention due to its high combustion efficiency , low hydrogen concentration requirement , low environmental pollution and fuel regeneration . But the key issue pre-ignition has hindered the development of hydrogen engines . In order to have a more in-depth understanding of pre-ignition , this paper reviews the mechanism of pre-ignition , the relationship between the nature of hydrogen and pre-ignition , the key factors affecting pre-ignition and the research status of pre-ignition , analyzes the development trend of hydrogen engine and provides a new perspective for the study of inhibiting pre-ignition .

Key words: Hydrogen engine；Pre-ignition;Mechanism；New perspective

1.Introduction

The rapid development of the automobile industry has put tremendous pressure on energy resources and has also created serious environmental pollution problems. Since oil shortages can have a significant negative impact on a country's economy and development, countries around the world are paying particular attention to the exploration of alternative energy sources[1-7]. Hydrogen energy has received widespread attention for its clean, efficient, renewable and sustainable characteristics[8][9]. Hydrogen engine requires low concentration of hydrogen in the combustion process, simple modification and high thermal efficiency, and has great advantages in alleviating the energy crisis and environmental pollution, and scholars from all over the world have high enthusiasm for the research of hydrogen engine[10-13]. However, hydrogen as a fuel has the properties of low ignition energy, wide ignition limit and fast combustion speed, which causes the phenomenon of pre-ignition of combustible mixture in the compression stroke of hydrogen engine, which is a great obstacle to the promotion of hydrogen engine[14-16]. In this paper, we mainly analyze pre-ignition from four aspects, which are as follows: (1) the study of pre-ignition mechanism; (2) the relationship between the special properties of hydrogen and pre-ignition; (3) the factors influencing the occurrence of pre-ignition; (4) the previous studies on pre-ignition.

2.Pre-ignition Mechanisms

Pre-ignition is accidental, discontinuous, and uncontrollable, but it often occurs during the compression stroke. Pre-ignition in a hydrogen engine can be divided into two stages. The first stage is before the inlet valve closes, when the H2-Air mixture in the combustion chamber is ignited prematurely by contact with a localized high-temperature area in the cylinder. In the second stage, after the inlet door is closed and before the spark plug ignites, the H2-Air mixture in the combustion chamber is ignited prematurely by contact with a localized high-temperature area in the cylinder[17-22].

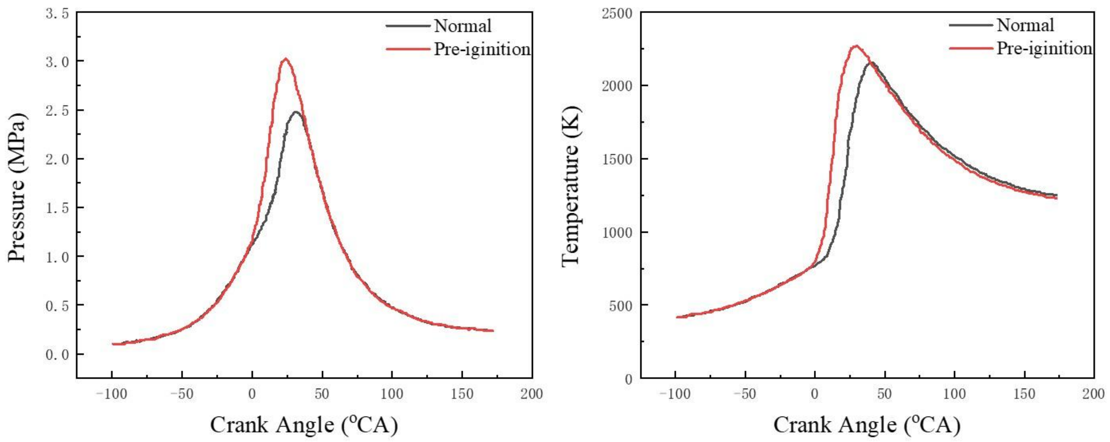

Fig.1.[23] Changes in cylinder temperature and pressure for normal combustion and pre-ignition

Fig.1 shows the changes in pressure and temperature in the cylinder between normal combustion and pre-ignition at 1100 r/min. It can be seen from the figure that, compared to normal combustion, pre-ignition will cause the peak pressure and temperature in the cylinder to increase, and the peak phase to advance. Pre-ignition will lead to an increase in negative compression work and a decrease in power; it will also promote an increase in exothermic rate, which will cause the cylinder pressure to rise rapidly, the peak pressure will also rise, the cylinder heat dissipation will also increase, resulting in an increase in the temperature of the cylinder surface, there will be more hot surface, resulting in more serious pre-ignition phenomenon. If the pre-ignition phenomenon is not controlled, it will eventually lead to engine failure.

3. The relationship between hydrogen properties and pre-ignition

Table 1[24]

Physical and Chemical Properties of Hydrogen and Gasoline

Property	Hydrogen	Gasoline
Chemical Formula	H_2	C_8H_{18}
Auto-ignition temperature (℃)	585	434
Boiling point (°C)	20	40-200
Minimum Ignition Energy (MJ)	0.02	0.24
Diffusion coefficient in air (m^2/s)	0.61	0.05
Flame quenching distance (mm)	0.64	2
Low calorific value (MJ/kg)	120	43.5
Ignition limit (%)	4-75	3.5-18
Flame propagation speed (cm/s)	291	37.7

Table 1 shows the physicochemical properties of hydrogen and gasoline as fuels. It can be seen from the table: (1) the auto-ignition temperature of hydrogen is very high and higher than that of gasoline, so it can be used in the ignition type high compression ratio engine; (2) the boiling point of hydrogen is lower than that of gasoline, so both liquid hydrogen and hydrogen can effectively solve the combustion problem caused by local over-concentration or local over-dilution of the mixture; (3) the low calorific value of hydrogen is about 2.7 times that of gasoline, so the same mass of hydrogen can generate more energy than gasoline;(4) The ignition limit of hydrogen is much wider than that of gasoline, and the minimum ignition energy is smaller than that of gasoline, so the engine fueled by hydrogen basically has no stalling problem and is more stable. (5) Hydrogen has no C atom, and the products of combustion as fuel are only water and a certain amount of NOx, no CO, HC, CO_2 and particulate matter, which is the cleanest among the ignition engine fuels. (6) The combustion of hydrogen is carried out according to the chain reaction mechanism, because its flame propagation speed is about 8 times faster than that of gasoline, which means that the combustion of hydrogen engine is closer to the ideal isocapacitive heat cycle, thus effectively improving the thermal efficiency; (7) The diffusion coefficient of hydrogen in the air is large, about 12 times that of gasoline, so it is easier to form a homogeneous mixture[25-29].

Although hydrogen has many advantages as fuel, the probability of pre-ignition in hydrogen engines is higher than in conventional internal combustion engines, especially under high load, and the special properties of hydrogen are the main cause of pre-ignition.

a. Low ignition energy[30]

Under atmospheric conditions, the minimum ignition energy of an H2-Air mixture is 0.013 to 0.020 MJ, which is an order of magnitude lower than the ignition energy of a hydrocarbon air mixture. The small ignition energy allows the hydrogen engine to ignite the thinner gas mixture and ensure immediate ignition. However, having a small ignition energy will increase the likelihood that the H2-Air mixture in the combustion chamber will be ignited by any other source (hot spot) than the spark plug.

b. Short quenching distance[31]

Under certain conditions, the quenching distance of the gas mixture is only 0.64 mm. the shorter the quenching distance, the harder it is to extinguish the flame, which increases the possibility of backfire, and the relationship between pre-ignition, backfire, and knock is mutually reinforcing.

c. Wide ignition limite[32]

When the gas mixture is too concentrated or too dilute, it does not form the center of the flame after the spark is discharged, and producing flame propagation. The spark first ignites a small portion of the combustible gas mixture in the gap between the electrodes, so that the heat emitted which is greater than the heat dissipated to the surrounding gas mixture before the flame spreads and develops; otherwise, it will be extinguished. Mixture is too concentrated will emit less heat due to incomplete combustion, while mixture that is too dilute will not catch fire due to its low calorific value that make the small amount of heat emitted. These two limits of gas mixture concentration are called ignition limits. The ignition limit for H2-Air mixtures is 4.1% to 75%, which is much wider than that of other fuel mixtures such as gasoline and diesel, showing that they can be ignited in either the concentrated or diluted state.

4. Factors affecting pre-ignition

4.1 The high-temperature area[33]

The source of the ignition mixture in the combustion chamber before ignition timing can be called the high-temperature area, which is mainly composed of high-temperature hot spots, high-temperature exhaust gases and afterburning mixture. High-temperature area is mainly divided into two categories, one is the spark plug or spark electrode, intake and exhaust valves, cylinder or piston surface deposits, the decomposition of the lubricating oil, carbon particles and the air into the cylinder magazine with the air through the high temperature heating to form a hot spot; the other is the high-temperature exhaust gas and afterburning mixture remaining in the small gap in the combustion chamber;The relationship between pre-ignition and high-temperature area, average temperature and high temperature duration is close.The hydrogen-air mixture requires less ignition energy, and the surface area in the high-temperature region of the cylinder is smaller for pre-ignition to occur. The spontaneous combustion temperature of hydrogen in air is 858 K,that decreases as the pressure increases, so it can be inferred that the ignition temperature of hydrogen-air mixture in the cylinder is slightly lower than 858K. Meanwhile, the longer the duration of the high temperature area, the more likely it is that pre-ignition will occur. Any operating and structural parameters that increase the area, temperature, and duration of the high-temperature area will increase the likelihood of pre-ignition.

4.2 Equivalent ratios

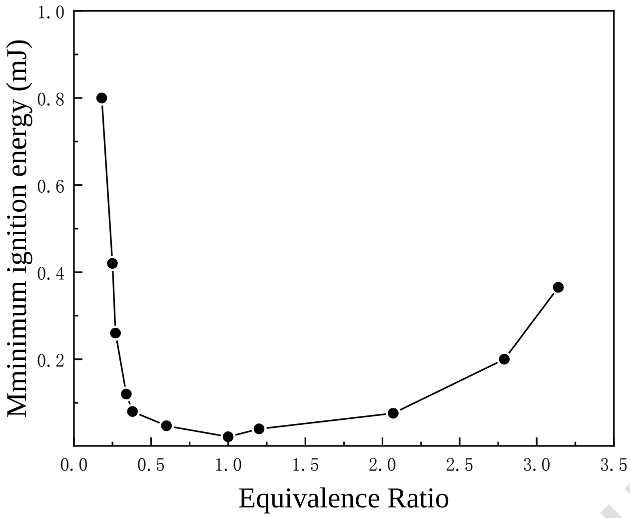

Fig.2.[34] The relationship between the equivalence ratio and the minimum ignition energy.

Figure 2 shows the minimum ignition energy of a hydrogen mixture at different equivalence ratios. It can be seen that the minimum ignition energy decreases rapidly in the range of 0-0.6 as the equivalence ratio increases; in the range of 0.6-1.2, the minimum ignition energy decreases first and then increases, and is at the minimum value at about 1.0; in the range of 1.2-3.5, the minimum ignition energy increases significantly. The smaller the ignition energy is, the easier the mixture is to ignite and the higher the probability of pre-ignition. It has been shown that when the equivalent ratio of hydrogen fuel is less than 0.4 or more than 1.2, the probability of pre-ignition is small. Therefore, all factors that can affect the equivalency ratio can have an indirect effect on pre-ignition[35].

5.Hazards of pre-ignition[36][37]

Pre-ignition will make the engine do negative compression work, reduce the effective output power, research shows that pre-ignition at higher speeds will become more serious, the peak power is reduced by about 50%; but also promote the increase in the exothermic rate that increases will make the cylinder pressure rise rapidly, the peak pressure will also rise, the cylinder heat dissipation will also increase, resulting in the cylinder surface temperature rise, more the high-temperature area appear, causing more severe pre-ignition. If pre-ignition occurs before the intake valve is closed, it can also cause a backfire to occur, where the temperature and pressure of the intake tract increases, preventing fresh charge from entering and causing an engine misfire; severe pre-ignition can also cause knock, which can seriously damage the engine.

Slight pre-ignition will increase the noise and vibration of the hydrogen engine; general pre-ignition will stop the hydrogen engine; severe pre-ignition will cause damage to the components of the hydrogen engine; in addition, the occurrence of pre-ignition will cause the peak temperature increases, thereby increasing NOx emissions.

6. Pre-ignition research[38-43]

Up to now, the research on preventing the pre-ignition of hydrogen internal combustion engines has mainly focused on the level of reducing the temperature in the cylinder, and there is no specific research on the-high temperature area, which is the key factor that causes pre-ignition. In order to suppress the pre-ignition phenomenon of hydrogen engines, predecessors have done the following research. S.Furuhama and others used the method of direct injection mixed combustion in the cylinder to let a certain concentration of H2-Air mixture enter the combustion chamber through the intake manifold, and then to the direction of the spark plug in the combustion chamber before the spark plug is not ignited Directly inject hydrogen at a certain speed, successfully suppressing the occurrence of pre-ignition, and increasing the output power of the hydrogen internal combustion engine and reducing NOX emissions. Kleijn R et al. used thermal dilution methods, such as water injection and exhaust gas recirculation (EGR), to recirculate part of the exhaust gas through the exhaust gas recirculation system back to the intake manifold, and reduce the temperature in the cylinder by introducing exhaust gas. , Thereby reducing the possibility of pre-ignition[38]. Yang et al. used the method of delaying the ignition time and injecting water into the intake manifold, successfully reducing the temperature in the cylinder before ignition, and reducing the possibility of backfire while maintaining engine power output. Jongtai Lee and others used the lean burn method to allow pure air to enter the combustion chamber, and lower the temperature of the combustion chamber before entering the combustible mixture, thereby reducing the possibility of pre-ignition. But this method will limit the power output of the engine. For this lack of power, it can be solved by supercharging.

Pre-ignition is a random event, the time, place, and intensity of which are difficult to determine, and it usually occurs when other abnormal combustion occurs. There are many factors that can cause pre-ignition, and these factors have complex effects on pre-ignition directly or indirectly, and at the same time there is a certain correlation between these factors, which makes the study of pre-ignition difficult. In addition, there is little research on the causes and mechanisms of pre-ignition, which enhances the difficulty of studying pre-ignition in hydrogen engines.

7.Conclusion

The special properties of hydrogen lead to the study of hydrogen internal combustion engine must not bypass the pre-ignition, and the key factors affecting pre-ignition is the high temperature area and the equivalent ratio produced in the compression stroke. The study of the high-temperature area in compression is still in its infancy, and reducing the intensity of the high-temperature area is one of the most effective means to reduce the probability of pre-ignition.

Through the above analysis of pre-ignition, we hope to make the readers have a more comprehensive understanding of pre-ignition, and also hope to promote the scholars in the field of more in-depth research. Although a lot of long-term and difficult work still needs to be done in the process of the practical application of the internal combustion engine, the research will develop rapidly and has a bright future in the context of the hydrogen economy.

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