Review Article

Research progress and challenges of hydrogen-ammonia hybrid fuel engines

ABSTRACT

In this paper, we review the research status of hydrogen and ammonia engines, and discuss the potential of the two fuels as clean energy sources and their challenges. Hydrogen fuel has attracted attention due to its high energy density and zero-emission characteristics, but hydrogen fuel engines have problems such as increased nitrogen oxide emissions, tempering and early ignition. Ammonia fuel, as a carbon-free alternative fuel, has the advantage of being easy to store, but it is inferior to traditional fuels in combustion performance. This paper further analyzes the research progress of hydrogen/ammonia hybrid fuel engines, points out the combustion support effect of hydrogen and the influence of ammonia on combustion rate, and discusses the advantages of hybrid fuel engines in emission control. Finally, this paper summarizes the current development trend of hydrogen/ammonia fuel engine technology and puts forward suggestions for future research directions.

Keywords:Hydrogen Fuel Engines; Ammonia Fuel Engines; Hydrogen/Ammonia Fuel Blends;Combustion Characteristics;Emission Control;Engine Efficiency

Introduction

This paper reviews the research status of hydrogen and ammonia engines, and discusses the potential and challenges of these two fuels as clean energy. Hydrogen fuel has attracted much attention due to its high energy density and zero-emission characteristics, but there are problems such as increased nitrogen oxide emissions, tempering and early ignition in practical applications. Ammonia fuel, as a carbon-free alternative fuel, has the advantage of being easy to store, but it is inferior to traditional fuels in combustion performance. This paper further analyzes the research progress of hydrogen/ammonia hybrid fuel engines, points out the combustion support effect of hydrogen and the influence of ammonia on combustion rate, and discusses the advantages of hybrid fuel engines in emission control. Finally, this paper summarizes the current development trend of hydrogen/ammonia fuel engine technology and puts forward suggestions for future research directions.

1. Research status of hydrogen fuel engines

Hydrogen energy is recognized as a clean energy source, with a wide range of sources, abundant reserves, high energy density, zero emissions, and wide ignition boundaries [1]. Hydrogen's excellent properties have led it to be used by researchers as an alternative to conventional fuels for engines. The research of hydrogen engine has a long history, and researchers have accumulated rich research results through the study of hydrogen engine, which has laid a solid foundation for the subsequent research of hydrogen engine. The use of hydrogen as a fuel in engines dates back to the eighteenth century. Switzerland engineer IsaacRifac successfully developed a single-cylinder hydrogen engine and was granted a France patent on January 30, 1807, becoming the first hydrogen engine patent in the field of automotive products.[2]The development of hydrogen engines has been slow for a period of time after its appearance, and with the intensification of the energy crisis and the greenhouse effect, countries around the world have paid more and more attention to the research of hydrogen engines. Enterprises from all over the world responded positively, competing to develop hydrogen engines and make prototypes for actual testing.

Major international car manufacturers such as Toyota, BMW, and Ford[3][4] have all developed hydrogen engines. In 1990, Musashi Institute of Technology in Japan cooperated with Nissan [5] to successfully develop the "Musashi 8" liquid hydrogen vehicle and exhibited it at the World Hydrogen Energy Conference. In 2001, Ford released its first pure hydrogen engine, which went into production in 2006. In the same year, BMW AG launched the first hydrogen-powered engine with high performance, the BMW Hydrogen 750HL. China's FAW, GAC, Yuchai, Geely and other car factories, although not as early as foreign car manufacturers started research, but also made rich achievements in hydrogen engines. In June 2023, Geely Automobile Power Research Institute officially announced that the thermal efficiency of the 2.0L direct-injection supercharged hydrogen engine independently developed by the institute has been improved to 46.11%, ranking first in the industry. In June of the same year, GAC Group launched the GAC Trumpchi E9 hydrogen hybrid model at the GAC Science and Technology Museum, equipped with a 2L hydrogen engine, and introduced medium and high pressure hydrogen direct injection, a dedicated high-efficiency air intake management system, a high compression ratio and knock suppression technology. In June 2022, FAW Jiefang announced that its first domestic in-cylinder direct-injection hydrogen engine for heavy-duty commercial vehicles independently designed and developed by FAW Jiefang was successfully ignited and operated stably. The engine is a 13-liter heavy-duty model with an operating power of more than 500 horsepower and an indicated thermal efficiency of more than 55%, and has entered the trial production stage of the whole vehicle. In the same month, the YCK16H hydrogen-fired engine launched by Yuchai was also successfully ignited. The engine has a displacement of 15.93 liters and a maximum horsepower of 560 horsepower, making it the largest hydrogen-fired engine in China in terms of displacement and horsepower. According to the research and development of hydrogen engines at home and abroad, hydrogen fuel engines are still a long way from mass production.

The researchers studied the combustion of hydrogen premixes. Bang Xiuchao et al. [6][7] studied the spherical expansion flame of hydrogen premixed laminar flow combustion and the laminar combustion velocity of hydrogen/air mixture, and the results showed that the flame velocity and combustion velocity were changed by the existence of flame stretching, and it was also a prerequisite for the instability of flame diffusion,The flame velocity and propagation velocity of hydrogen gas are similar with the fire-to-air ratio, temperature and pressure.

Changes in operating parameters can affect hydrogen engine mixture formation, combustion, and emissions, among other things. Yang Zhenzhong[8]studied the effect of injection timing on the quality of the mixture in the cylinder, and the results showed that the quality of the mixture was better when the hydrogen injection timing was 260 ° CA. Li Yong et al.[9] used simulation methods to study the effects of injection pressure and secondary injection on the formation of cylinder mixture, and the results showed that the injection pressure had the least effect on the formation and combustion of the mixture, and the time and mass fraction of the secondary injection had a significant impact on the tumbling intensity. C. Sopena et al.[10] converted a 1.4-liter gasoline engine into a hydrogen engine, and the throttle was fully opened, and when the excess air coefficient increased, the average effective pressure in the cylinder of the hydrogen engine decreased first and then increased. This is mainly due to the fact that the low density of hydrogen occupies a large cylinder volume, resulting in insufficient air. When the excess air coefficient is 1.6, the engine power decreases more obviously as the rpm increases. At low to medium speeds, hydrogen engines have higher thermal efficiency. Jongtai Lee et al. [11] studied the effects of valve timing and lean pressurization on combustion and emissions of hydrogen engines, and the results showed that hydrogen engines achieved almost emission-free, non-tempering, and high-power operation under the conditions of delayed valve timing and lean pressurization. Ji Changwei et al. [12] studied the influence of ignition advance angle on cold start combustion and emission on a modified 1.6L inlet hydrogen engine, and the results showed that when the ignition advance angle was 15 ° , the engine had the shortest successful start time and the highest peak cylinder pressure in the first cycle. Delaying the ignition advance angle helps to reduce emissions during start-up. In order to optimize the ignition advance angle, the researchers used a variety of algorithms to find the optimal ignition advance angle. Wang et al.[13] used a neural network based on particle swarm optimization to construct an optimization model for the ignition advance angle, and the results showed that the model could accurately obtain the optimal advance angle required for each working condition and improve the performance of the hydrogen engine. Yang Zhenzhong[14]used the fuzzy neural network system to optimize the engine optimization model established by him, and realized the open-closed-loop control of the ignition timing step adjustment, which improved the performance of the hydrogen engine. Dang et al.[15]used the ant colony optimization backpropagation algorithm to study the influence of different speeds and loads on the ignition advance angle, and constructed a nonlinear mapping model from the speed and load of the hydrogen engine to the optimal ignition advance angle, and drew the optimal ignition MAP diagram of the hydrogen engine. Wang et al. [16] studied the effects of direct injection and ignition positions on hydrogen engines, and the results showed that the hydrogen concentration at two characteristic positions away from the nozzle was more stable than that near the spark plug, so the installation of the spark plug away from the nozzle was more conducive to engine ignition and combustion.

The injection strategy also has an impact on the operation of the hydrogen engine. Yang Zhenzhong[17] studied the effects of single-channel injection (SI), two-way symmetrical (SY) distribution and two-way interval (SP) and the nozzle diameter on the formation and combustion performance of PFI engine mixture. Wu Meng [18]studied the effects of nozzle diameter and hydrogen injection pressure on hydrogen engine, and the results showed that large nozzle diameter and hydrogen injection pressure would increase NO emissions, while small nozzle diameter and hydrogen injection pressure would increase the hydrogen residue in the inlet tract and increase the probability of abnormal combustion. In addition, multiple injections [19] and the location of the nozzle hole[20] also affect the combustion and emissions of hydrogen engines.

Conventional engine technology is also being used in hydrogen engines. Qing-he Luo et al.[21] studied the effect of the equivalent ratio on its performance at low rpm on a 2.3L turbocharged PFI hydrogen engine, and the results showed that with the increase of the equivalent ratio, the power of 1500r/min and 2000r/min increased from 6.4KW and 6.8KW to 16.5kW and 21KW, respectively, indicating that the average effective pressure covariance (COVimep) was less than 1.5% at low engine speed. Combustion stability increases with increasing equivalent ratio. Nguyen et al.[22] investigated the effect of using a supercharger on the power of a hydrogen engine (PFI) and compared the supercharger with the turbocharger and showed that the supercharger resulted in lower pumping losses and a higher indicated average pressure.

Hydrogen engines have the problem of higher nitrogen oxide emissions compared to conventional fuel engines. Hari Ganesh et al. [23] converted a single-cylinder conventional spark-ignition engine to a hydrogen engine using timed intake manifold injection and compared its performance with that of a gasoline engine, and the results showed that NOx emissions were four times higher than that of gasoline engines at full load. Jayakrishnan et al. [24] conducted a study on a single-cylinder engine that could switch between gasoline and hydrogen, and showed that the high-temperature combustion process in the cylinder resulted in higher NOx emissions in hydrogen engines, which were as high as 5.6 g/kWh compared to 0.6 g/kWh in gasoline engines under the same operating conditions. To curb nitrogen oxide emissions from hydrogen engines, the researchers used a variety of methods. Guo Pengxiang[25]studied the effects of EGR rate and multiple injections on the performance of hydrogen engines, and the results showed that after coupling multiple injections with EGR, the NOx emission reduction effect was more obvious than that of a single injection under different loads, and the improvement was more obvious under low speed conditions. Vipin Dhyani et al. [26] proposed a combination of EGR and water injection to reduce NOx emissions, and the results showed that NOX emissions decreased with the increase of EGR and water-to-hydrogen ratio (WHR), NOx emissions decreased by 57% at EGR of 25%, and 97% at WHR of 7.5%, and water injection technology can achieve ultra-low NOX emissions without affecting engine performance.

Due to the nature of hydrogen, hydrogen engines also have abnormal combustion problems such as tempering and early ignition, and researchers have used a variety of methods to suppress abnormal combustion. Vipin Dhyani [26] proposed a method that combines water injection and EGR, which can be controlled by adjusting EGR and water injection. In addition, changing the valve overlap period and delayed ignition time can control the tempering of hydrogen-fueled ignition engines[27]. Wang et al. [28] studied the effects of different hydrogen injection parameters on the formation process of hydrogen/air mixture, and the results showed that when the hydrogen injection timing was 410-430 ° CA, the residual hydrogen in the inlet tract was less, and the mixture concentration in the inlet valve was low, which inhibited early ignition and tempering. Yang Zhenzhong[29] studied the inhibitory effect of delayed ignition time and water injection on abnormal combustion of hydrogen engines, established the relationship between the degree of early ignition inhibition and ignition time, and the relationship between the degree of tempering inhibition and the water injection rate, and proposed a control method to reduce the possibility of tempering while maintaining the power output of the engine.

2. Research status of ammonia fuel engines

Ammonia (NH3) is composed of nitrogen and hydrogen in terms of chemical formula, and is a carbon-free, colorless, pungent odor combustible gas that does not produce carbon dioxide after combustion, and the hydrogen content of ammonia can be as high as 17.7% by mass[30]. Compared with hydrogen, ammonia has a higher boiling point, is easier to liquefy and store, and has a narrow explosion limit [31]. According to statistics, the cost of producing ammonia is about one-third of that of hydrogen[32]. In today's increasingly focused carbon footprint, ammonia is a strong competitor to hydrogen. Researchers have long been looking at ammonia as a potential fuel alternative to hydrocarbon fuels.

Starkman et al. [33] showed that ammonia-fueled ignition engines are feasible when ammonia enters as vapor and partially cracks into hydrogen and nitrogen, and the hydrogen gas credit number should not be less than 5%. In the sixties of the last century, United States General Motors Company[34] studied the application of ammonia fuel in the engine, and the results showed that the combustion performance of ammonia was significantly inferior to that of gasoline, and its maximum power was only 17.5% of gasoline, and the maximum thermal efficiency was only 38% of gasoline. Increase the compression ratio and add a small amount of hydrogen to the ammonia. Samuelsen[35]studied the propagation velocity of ammonia/air flame using a cooperative fuel study spark ignition engine, and compared it with isooctane fuel, the ammonia flame propagation velocity was slower and the average kernel development time was longer. Starkman et al. [33] studied the application of ammonia fuel in compression-ignition (CI) engines, and the results showed that due to the high autoignition temperature of ammonia, continuous compression ignition could not be achieved even at a compression ratio of 30:1 and a speed of more than 1200 r/min, and spark ignition was required to start the engine normally at the standard compression ratio of the engine [36]. Gray et al. [37] also studied the application of ammonia fuel to CI engines, and the results showed that for CI ammonia engines to operate normally, it is necessary to increase the inlet temperature and compression ratio to 35:1.

The minimum ignition energy required for ammonia is 8 mJ, and it can only be burned when the volume fraction in air is in the range of 15.0%~28.0%, and the combustion range is narrow[38][39]. During combustion, ammonia is characterized by a low laminar combustion rate. HAYAKAWA et al.[40] studied the laminar combustion rate of ammonia under different injection pressures, and the maximum laminar combustion rate was 7 cm/s. The propagation rates of hydrogen and methane are 300 cm/s and 40 cm/s, respectively, and ammonia is much lower than that of hydrogen and methane [41]. Mei B et al. [42] investigated the effects of oxygen-rich and high-pressure conditions on the laminar flame propagation velocity of ammonia in combustion vessels, and the results showed that the laminar combustion velocity increased with increasing oxygen content, but decreased with increasing initial pressure.

Due to the difficulty of burning ammonia engines and increasingly stringent emission regulations, researchers began to explore ammonia blending with other fuels while studying ammonia engines. Compared with ammonia, hydrocarbon fuels such as methane, hydrogen, and diesel have a higher laminar combustion rate, and they are mixed with ammonia to effectively increase the laminar combustion rate of ammonia [43]. Hydrocarbon fuels mixed with ammonia can reduce greenhouse gas emissions when burned.

3 Research status of hydrogen/ammonia fuel engines

Hydrogen has a high combustion rate and is prone to abnormal combustion when used as engine fuel, while ammonia has a low combustion rate and is difficult to burn when used as engine fuel. The researchers combined the physicochemical properties of the two fuels to study the hydrogen/ammonia engine. Pochet et al. [44]converted a homogeneous supercharged diesel engine into a hydrogen/ammonia engine and studied its performance, and the results showed that the indicated average effective pressure (IMEP) increased with the increase of ammonia content in the blend. During the transition from pure H2 to 95% volume of NH3, a 67% increase in IMEP was observed. An increase in the proportion of ammonia in the fuel mixture can delay the combustion process, leading to a decrease in temperature and pressure. Lhuillier et al. [45]investigated the laminar and turbulent flame characteristics of ammonia combustion in engines. The results showed that an increase in the proportion of H2 led to a faster increase in HRR.

H2 plays the role of an accelerant in H2/NH3/air combustion, and NH3 has a great influence on the maximum combustion rate of the mixture. Li et al. [46]studied the combustion characteristics and NOX formation of hydrogen/ammonia at different air-fuel ratios and initial concentrations of H2, and the results showed that NH3 affects the maximum combustion rate of the mixture, H2 promotes the combustion of the mixture, and the thermal NOx in the combustion of the hydrogen/ammonia mixture is reduced compared with the combustion of pure hydrogen.

Changes in ammonia doping ratios and operating parameters affect the emissions of hydrogen/ammonia engines. Fredrik R. Westlye et al. [47]conducted experiments on a 0.6L displacement CFR engine, and studied the NOx emissions of hydrogen/ammonia engines with compression ratios of 7, 11, and 15 under the fuel composition of 80% vol% ammonia and 20vol% hydrogen. The later the ignition time, the higher the temperature in the cylinder, and the increase of N2O generation. Rocha RC et al.[48] investigated the chemical kinetic models of hydrogen/ammonia ignition, flame propagation, and NO emissions, and the results showed that the addition of H2 to NH3 resulted in an increasing trend in flame velocity and NOx emissions.

Conclusion

This paper reviews the research status of hydrogen and ammonia engines, and discusses the potential and challenges of these two fuels as clean energy. Hydrogen fuel has attracted attention due to its high energy density and zero-emission characteristics, but hydrogen fuel engines have problems such as increased nitrogen oxide emissions, tempering and early ignition. Ammonia fuel, as a carbon-free alternative fuel, has the advantage of being easy to store, but it is inferior to traditional fuels in combustion performance.

The research of hydrogen fuel engines has a long history, from the earliest hydrogen engine patents to the present, it has gone through the process from theory to practice. In recent years, with the intensification of the energy crisis and the greenhouse effect, the research of hydrogen fuel engines has received more attention. Major international car manufacturers such as Toyota, BMW, Ford, etc., as well as domestic companies such as Geely, GAC, Yuchai and other enterprises, have made significant progress in the research and development of hydrogen fuel engines, especially in improving engine thermal efficiency and reducing emissions.

Ammonia-fueled engines are considered an important direction for alternative fuels in the future due to their carbon-free nature. Although ammonia fuel has a disadvantage in terms of combustion rate, its high hydrogen content and ease of storage make it an ideal complement to hydrogen fuel. Researchers blended hydrogen and ammonia to improve combustion performance, increase combustion speed, and reduce emissions.

Studies of hydrogen/ammonia hybrid fuel engines have shown that the combustion effect of hydrogen and the effect of ammonia on the combustion rate make this hybrid fuel advantageous in terms of emission control. By adjusting the fuel mixing ratio and optimizing the injection strategy, the combustion process can be effectively improved, the engine performance can be improved, and the emission of harmful substances such as nitrogen oxides can be reduced.

Although hydrogen/ammonia hybrid fuel engines have many advantages in theory, they still face many challenges in practical applications, including issues of technical maturity, cost-effectiveness, and safety. Future research needs to further optimize the combustion process, solve abnormal combustion problems such as early ignition and tempering, and improve fuel utilization and overall engine performance.

In conclusion, hydrogen/ammonia hybrid fuel engines show broad application prospects as a clean and efficient alternative energy solution. However, in order to achieve its commercial application, it is necessary to overcome technical bottlenecks and improve the reliability and economy of the fuel. Future research should continue to focus on technological innovation and explore more optimization pathways to accelerate the practical application of hydrogen/ammonia hybrid fuel engines.

Reference

[1] Liu J, Zhang M, Tang Q, et al. Supra hydrolytic catalysis of Ni3Fe/rGO for hydrogen generation[J]. Advanced Science, 2022, 9(21): 2201428.

[2] Rao Guanglong. Performance research and improvement of hydrogen energy vehicle power system[D].Shanghai Jiao Tong University,2013.

[3] Yang L, Li J, Wang L, et al. Application of hydrogen in vehicle engine[J].Automotive Technology,2006(12):1-5.

[4] Wang Lei. Experimental study of pure hydrogen and natural gas hydrogen-blended fuel engine[D].Shanghai Jiao Tong University,2013.

[5] Guo Zhidong. Public test run of hydrogen-fueled vehicle "Musashi 8"[J]. Friends of Automobile, 1991 (2): 17-18.

[6] Bang Xiuchao, Liu Fushui, Liu Xinghua. Tensile study on spherical expansion flame of hydrogen premixed laminar flow combustion[J].Combustion Science and Technology,2011,17(03):237-242.).

[7] Bang Xiuchao, Liu Fushui. Experimental measurement and simulation calculation of laminar combustion velocity of hydrogen/air mixture[J].Combustion Science and Technology,2011,17(05):407-413.).

[8] Zhenzhong Y, Aiguo S, Fei W, et al. Research into the formation process of hydrogen–air mixture in hydrogen fueled engines based on CFD[J]. International Journal of Hydrogen Energy 2010, 35:3051-3057.

[9] Li Y, Gao W, Zhang P, et al. Effects study of injection strategies on hydrogen-air formation and performance of hydrogen direct injection internal combustion engine[J]. International Journal of Hydrogen Energy, 2019, 44(47): 26000-26011.

[10] CSopena C, Diéguez P M, Sáinz D, et al. Conversion of a commercial spark ignition engine to run on hydrogen: Performance comparison using hydrogen and gasoline[J]. international journal of hydrogen energy, 2010, 35(3): 1420-1429.

[11] Lee J, Lee K, Lee J, et al. High power performance with zero NOx emission in a hydrogen-fueled spark ignition engine by valve timing and lean boosting[J]. Fuel, 2014, 128: 381-389.

[12] Ji Changwei, Bai Xiaoxin, Wang Shuofeng, et al. Effect of ignition angle on cold start combustion and emission characteristics of hydrogen engine[J].Journal of Beijing University of Technology,2019,45(09):911-917.).

[13] Wang Lijun, Yang Zhenzhong, Zhang Qingbo, et al. Optimization of ignition advance angle of hydrogen engine based on particle swarm neural network[J].Small Engine & Motorcycle,2010,39(04):61-64.).

[14] Yang Z, Wang L, Xiong S, et al. Research on the optimizing control technology based on fuzzy-neural network for hydrogen-fueled engines[J]. International journal of hydrogen energy, 2006, 31(15): 2370-2377.

[15] Dang J, Wang L. Optimization control of hydrogen engine ignition system based on ACO-BP[J]. International journal of hydrogen energy, 2021, 46(78): 38903-38912.

[16] Wang Changyuan, Liu Fushui. Journal of Engine Engines,2010,28(06): 519-524.

[17] Yang Z, Zhang F, Wang L, et al. Effects of injection mode on the mixture formation and combustion performance of the hydrogen internal combustion engine[J]. Energy, 2018, 147: 715-728.

[18] Wu Meng. Effect of nozzle area and hydrogen injection pressure on the formation and combustion of PFI hydrogen engine mixture[D]. North China University of Water Resources and Hydropower, 2016.

[19] Zhang Wei. Numerical simulation study on the effect of multiple injections on inlet tract injection hydrogen engine[D]. North China University of Water Resources and Hydropower, 2016.

[20] Huang Yan. Effect of hydrogen injection time and nozzle hole position on the formation and combustion performance of PFI hydrogen engine mixture[D]. North China University of Water Resources and Hydropower, 2015.

[21] Luo Q, Hu J B, Sun B, et al. Effect of equivalence ratios on the power, combustion stability and NOx controlling strategy for the turbocharged hydrogen engine at low engine speeds[J]. international journal of hydrogen energy, 2019, 44(31): 17095-17102.

[22] Nguyen D, Choi Y, Park C, et al. Effect of supercharger system on power enhancement of hydrogen-fueled spark-ignition engine under low-load condition[J]. International Journal of Hydrogen Energy, 2021, 46(9): 6928-6936.

[23] Ganesh R H, Subramanian V, Balasubramanian V, et al. Hydrogen fueled spark ignition engine with electronically controlled manifold injection: An experimental study[J]. Renewable energy, 2008, 33(6): 1324-1333.

[24] Unni J K, Govindappa P, Das L M. Development of hydrogen fuelled transport engine and field tests on vehicles[J]. International Journal of Hydrogen Energy, 2017, 42(1): 643-651.

[25] Guo Pengxiang. Research on EGR and multi-injection coupling electronic control system of hydrogen engine[D].North China University of Water Resources and Hydropower,2020.

[26] Dhyani V, Subramanian K A. Control of backfire and NOx emission reduction in a hydrogen fueled multi-cylinder spark ignition engine using cooled EGR and water injection strategies[J]. International journal of hydrogen energy, 2019, 44(12): 6287-6298.

[27] Verhelst S, Demuynck J, et al. Impact of variable valve timing on power, emissions and backfire of a bi-fuel hydrogen/gasoline engine. Int J Hydrog Energy 2010;35:4399–408.

[28] Wang L, Yang Z, et al. The effect of hydrogen injection parameters on the quality of hydrogen–air mixture formation for a PFI hydrogen internal combustion engine. Int J Hydrog Energy 2017;42:23832–45.

[29] Yang Z, Wang L, et al. Research on optimum method to eliminate backfire of hydrogen internal combustion engines based on combining postponing ignition timing with water injection of intake manifold. Int J Hydrog Energy 2012;37:12868–78.

[30] Valera-Medina A, Xiao H, Owen-Jones M, et al. Ammonia for power[J]. Progress in Energy and combustion science, 2018, 69: 63-102.

[31] Gao Zhengping, Tu Anqi, Li Tianxin, et al. Research progress on ammonia combustion technology for zero-carbon power[J].Clean Coal Technology,2022,28(03):173-184.).

[32] Wang S, Ji C, Zhang B. Effects of hydrogen addition and cylinder cutoff on combustion and emissions performance of a spark-ignited gasoline engine under a low operating condition[J]. Energy, 2010, 35(12): 4754-4760.

[33] Starkman E S, Newhall H K, Sutton R, et al. Ammonia as a spark ignition engine fuel: theory and application[J]. Sae Transactions, 1967: 765-784.

[34] Cornelius W, Huellmantel L W, Mitchell H R. Ammonia as an engine fuel[J]. SAE Transactions, 1966: 300-326.

[35] Samuelsen G S, CALIFORNIA UNIV BERKELEY DEPT OF MECHANICAL ENGINEERING. Flame Propagation Rates in the Combustion of Ammonia[J]. 1965.

[36] Pearsall T J, Garabedian C G. Combustion of anhydrous ammonia in diesel engines[J]. SAE Transactions, 1968: 3213-3221.

[37] Gray Jr J T, Dimitroff E, Meckel N T, et al. Ammonia fuel—engine compatibility and combustion[J]. SAE Transactions, 1967: 785-807.

[38] Lesmana H, Zhang Z, Li X, et al. NH3 as a transport fuel in internal combustion engines: a technical review[J]. Journal of Energy Resources Technology, 2019, 141(7): 070703.

[39] Chen D, Li J, Huang H, et al. Chemical Bulletin,2020,83(06):508-515.DOI:10.14159/j.cnki.0441-3776.2020.06.004..

[40] Hayakawa A, Goto T, Mimoto R, et al. Laminar burning velocity and Markstein length of ammonia/air premixed flames at various pressures[J]. Fuel, 2015, 159: 98-106.

[41] Ichikawa A, Hayakawa A, Kitagawa Y, et al. Laminar burning velocity and Markstein length of ammonia/hydrogen/air premixed flames at elevated pressures[J]. International journal of hydrogen energy, 2015, 40(30): 9570-9578.

[42] Mei B, Zhang X, Ma S, et al. Experimental and kinetic modeling investigation on the laminar flame propagation of ammonia under oxygen enrichment and elevated pressure conditions[J]. Combustion and Flame, 2019, 210: 236-246.

[43] Zhou Shangkun, Yang Wenjun, Tan Houzhang, et al. Proceedings of the CSEE,2021,41(12):4164-4182.

[44] Pochet M, Jeanmart H, Contino F. A 22: 1 compression ratio ammonia-hydrogen HCCI engine: combustion, load, and emission performances[J]. Frontiers in Mechanical Engineering, 2020, 6: 43.

[45] Lhuillier C, Brequigny P, Contino F, et al. Experimental investigation on ammonia combustion behavior in a spark-ignition engine by means of laminar and turbulent expanding flames[J]. Proceedings of the Combustion Institute, 2021, 38(4): 5859-5868.

[46] Li J, Huang H, Kobayashi N, et al. Study on using hydrogen and ammonia as fuels: Combustion characteristics and NO_X formation[J]. International journal of energy research, 2014, 38(9): 1214-1223.

[47] Westlye F R, Ivarsson A, Schramm J. Experimental investigation of nitrogen based emissions from an ammonia fueled SI-engine[J]. Fuel, 2013, 111: 239-247.

[48] da Rocha R C, Costa M, Bai X S. Chemical kinetic modelling of ammonia/hydrogen/air ignition, premixed flame propagation and NO emission[J]. Fuel, 2019, 246: 24-33.