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The Current State of Hydrogen-Enriched Engine Development

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Authors' contributions

This work was carried out in collaboration among all authors. Author XZ did formal analysis, wrote original draft, reviewed and edited the manuscript. Author JW did formal analysis, wrote, reviewed and edited the manuscript. Author ZL did formal analysis. Authors SS, JM and CZ did data curation. All authors read and approved the final manuscript.

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ABSTRACT

In recent years, with the further strengthening of environmental protection, researchers have paid extensive attention to the hydrogen-enriched engine. hydrogen-enriched mix hydrogen with conventional fuels and are designed to reduce exhaust emissions, improve combustion efficiency and enhance power performance. Proper hydrogen incorporation can reduce carbon emissions and nitrogen oxide emissions, and improve engine power output and combustion efficiency. In this paper, four kinds of hydrogen-enriched engines are introduced comprehensively, and the effects of hydrogen-enriched ratio on combustion and emission performance of engines are analyzed, as well as the effects of different technologies on hydrogen-enriched engines. The research results show that hydrogen-enriched engines have significant advantages in reducing emissions, improving combustion efficiency and enhancing power performance, and become one of the important technologies for the future automotive industry to transition to clean energy.

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1. INTRODUCTION

Carbon dioxide emissions have been increasing since the Industrial Revolution, with a more pronounced increase since 1970. Greenhouse gas emissions have become a global issue, long attracting scientific attention. In 2019 alone, the Asia-Pacific region generated significant energy consumption and carbon emissions. The greenhouse effect has caused serious and irreversible damage to ecosystems, greatly impacting human living environments. For instance, coastal cities like Shanghai and Jakarta are reported to be at risk of sinking due to rising sea levels, forcing local populations to relocate. This serves as a warning for the unsustainable development of other major coastal cities globally. Moreover, traditional industrial burners are difficult to replace worldwide [1]. Nitrogen oxides are precursors to secondary atmospheric pollutants like ozone and acid rain, and can also lead to photochemical smog, harming both human health and the environment. Therefore, finding a clean fuel to replace traditional fossil fuels is crucial. Hydrogen is seen as an ideal fuel for combustion in an environmentally friendly manner. Its high combustion efficiency and water as its only byproduct make it an ideal renewable clean energy source. Hydrogen is widely accessible and can be produced through various methods, including water electrolysis, biomass conversion, and sludge treatment [2]. However, despite its many beneficial properties, widespread adoption of hydrogen faces significant challenges. Hydrogen liquefaction is difficult, requiring extremely low temperatures and high pressures. Hydrogen's low volumetric energy density makes storage and transportation costly and logistically challenging [3]. The infrastructure for hydrogen refueling stations also faces economic barriers, needing substantial initial investments and operational costs. The combustion characteristics of hydrogen also pose safety issues, with its wide ignition range and low ignition energy potentially leading to engine backfire and premature combustion. To address these challenges, while continuing research and innovation in hydrogen engines and related technologies, hydrogen's usage is being expanded. Ammonia as a fuel is difficult to burn and generates a large amount of nitrogen oxides when combusted. Gasoline, natural gas, and alcohols as fuels result in significant carbon dioxide emissions from engines. Mixing hydrogen with ammonia not only increases the combustion speed but also reduces nitrogen oxide emissions [4]. Hydrogen can also reduce the carbon dioxide emissions from the combustion of the other three fuels. This article summarizes and looks forward to the development status of four types of hydrogen-blended engines.

2. HYDROGEN-ENRICHED ENGINE

2.1 Hydrogen-Gasoline Engine

Gasoline is a volatile and combustible hydrocarbon mixture liquid that is fractionated and cracked from petroleum, and is the traditional automobile fuel. Burning some hydrogen instead of gasoline can reduce harmful gas emissions. As a fuel, hydrogen has the advantages of cleanliness, high energy density, renewable and as an accelerant. Qide Zhou of Tianjin University [5] has also done research. compared hydrogen-doped gasoline engines with original gasoline engines. The experimental results show that when a small amount of hydrogen is added to the gasoline engine, the ignition delay period is shortened, the combustion propagation speed is accelerated, and the engine is completely burned and thin combustion is realized. Lean combustion is one of the key research directions for efficient and clean combustion technology for gasoline engines.To see how much hydrogen increases the rate of combustion, Bo Zhang [6] proposed “a viable approach to estimate the turbulent burning velocity of gasoline/hydrogen blends in a spark-ignited (SI) engine. This method relied on factors such as the cumulative heat release fraction, engine speed, and engine geometry. The experimental setup involved a naturally-aspirated port-injection gasoline engine that was equipped with a hydrogen injection system. Throughout the experiments, the engine operated at 1400 rpm, varying loads, and different hydrogen volume fractions in the intake gas.The findings revealed that the presence of hydrogen, with its high burning and diffusion velocities, notably influenced the combustion process. Specifically, at 1400 rpm and a manifold absolute pressure of 61.5 kPa under stoichiometric conditions, the peak burning velocity increased as the hydrogen volume fraction in the intake gas rose. For instance, with a hydrogen volume fraction of 0%, the peak burning velocity was recorded at 11.6 m/s. However, as the hydrogen volume fraction increased to 3% and 6%, the peak burning velocity surged to 12.3 m/s and 14.6 m/s, respectively. Additionally, the relevant crank angle for the peak burning velocity advanced from 21.0 degrees to 14.0 degrees and further to 8.6 degrees CA with the increasing hydrogen volume fraction. Moreover, it was observed that the impact of hydrogen addition on enhancing the burning velocity of the gasoline engine was more pronounced at low loads compared to high loads. This indicates that hydrogen blending has a more significant effect on combustion dynamics under lighter engine loads.Overall, these findings underscore the potential of hydrogen blending to improve combustion efficiency and performance in gasoline engines, especially under specific operating conditions".

Fan G [7] studied "the effect of high-energy ignition combined with hydrogen on the combustion stability of a lean-burn gasoline engine through the use of multi-point high-energy ignition and dual direct injection of gasoline/hydrogen. Through the combination of gasoline and hydrogen injection timing, a suitable layered mixture can be formed in the cylinder. Combined with high energy ignition, the fire core can be formed smoothly, and the flame spreads quickly. It is concluded that the introduction of hydrogen increases the concentration of H in the reaction system, enhances the activity of the reaction system, and accelerates the oxidation process of fuel molecules. Compared with pure gasoline engines, the lean combustion limit of hydrogen-doped engines is increased by 66.2% and the indicated thermal efficiency is increased by 6.5%. With the increase of excess air ratio, NO_x emission increases first and then decreases, but when l > 1.6, NOx emission is much lower than the equal ratio condition. Emissions of HC, CO and CO_2 are also lower than in the same proportion".

Fan Junmei [8] of North China University of Water Resources and Electric Power studied the effects of hydrogen mixing on combustion and emission performance of gasoline engines at medium and high rotational speeds. In this study, the combined injection mode of inlet hydrogen injection and in-cylinder direct injection gasoline was used, combined with numerical simulation and theoretical analysis, to explore the effects of different hydrogen mixing ratios on engine combustion and emission performance under medium to high speed and large load conditions. The engine operates at 3500r/min, 4500r/min and 6000r/min at 100%, 90% and 80% load rates, respectively. The proportion of hydrogen mixing is 0%, 5%, 10%, 15% and 20%. The results show that the engine has the best combustion performance at 100% and 90% load rates of 3500r/min and 4500r/min, and the hydrogen blending ratio is 10%. At 80% load rate of 3500r/min, the combustion characteristics are slightly improved when the hydrogen mixing ratio is 10%. When the hydrogen blending ratio is 10% and 15%, the power performance and economy are close to the level of pure gasoline engine. At an 80% load rate of 4500r/min, hydrogen mixing failed to improve engine power and economy. Under the 100% load rate of 6000r/min, the power performance is the best when the hydrogen mixing ratio is 10%. The economy is the best when the hydrogen mixing ratio is 15%. At 90% load rate and 80% load rate, the power performance is best when the hydrogen mixing ratio is 20%. At 80% load rate, the combustion performance is the best when the hydrogen mixture ratio is 10%. The overall CO quality score was low. The mass fraction of CO_2 decreases gradually with the increase of hydrogen mixing ratio. At the 100% and 90% load rates of 3500r/min and the hydrogen blending ratio of 5% and 10%, the NO mass fraction is higher than that of pure gasoline engine. Under the 80% load rate of 3500r/min, the NO mass fraction is higher than that of pure gasoline engine when the hydrogen mixing ratio is 5%, 10% and 15%. Under the loading rate of 90% and 80% of 4500r/min, the NO mass fraction is greater than that of pure gasoline engine when the hydrogen blending ratio is 10%. At 100% and 80% load rates of 6000r/min, with the increase of hydrogen mixing ratio, NO mass fraction increases first and then decreases, but it is always higher than that of pure gasoline engine. In general, under different working conditions, the optimal hydrogen mixing ratio is different, and hydrogen mixing can improve the combustion performance and emission characteristics of the engine in some cases. In addition, under different load and speed conditions, the optimal hydrogen mixing ratio of power performance, economy and emission performance is also different. In the study of the effect of mixed hydrogen on combustion and emission performance of gasoline engines.

Liu Jiahui [9] also from North China University of Water Resources and Electric Power, has done research on the effects of ignition timing and hydrogen injection pressure on the performance of hydrogen-doped gasoline engines. In the selected ignition timing range, with the increase of ignition advance Angle, the indicated power and indicated thermal efficiency of the engine show a trend of first rising and then decreasing. All the above mentioned are the studies of external influences on hydrogen-doped engines at medium and high speeds, and the lack of studies on medium and low speeds, so the influence of hydrogen doped engines at medium and low speeds is another direction of future research.

Li Runzeng [10] from Jilin University studied the impact of exhaust gas recirculation on combustion and emission of in-cylinder hydrogen gasoline engine. The addition of EGR can control combustion temperature, reduce NO_X emission, and reduce pump gas loss, but it also has a hindrant effect on combustion. Gu Jiaqi [11] and Zhang Ya [12] also at Jilin University, have both done relevant research on the impact of EGR on hydrogen-doped engines and also concluded that EGR can reduce emissions. Using new materials and advanced technologies, such as catalysts and fuel cell technology, the performance and efficiency of hydrogen-gasoline hybrid engines can be further improved. In general, hydrogen-gasoline hybrid engines have great prospects for development as a potential clean energy solution. Future research should continue to explore its technical and application potential in depth to promote its wide application and promotion in the automotive industry.

2.2 Hydrogen-Natural Gas Engine

Natural gas is stored in underground porous rock formations, including oil field gas, gas field gas, coal bed gas, mud volcano gas and biological gas, and a small amount of coal seam. It is a high quality fuel and chemical raw material. The exhaust gas produced by burning natural gas is cleaner than that of traditional fuels such as coal and oil. It almost does not contain harmful substances such as sulfur and nitrogen oxides, while the amount of carbon dioxide emitted is also low, and the pollution of the atmospheric environment is smaller. For hydrogen-doped natural gas engines, Ma Fanhua [13] of the State Key Laboratory of Automotive Safety and Energy Conservation, Tsinghua University, conducted experiments on the effect of hydrogen mixing on engine load change on a six-cylinder inlet jet supercharged washing and dyeing natural gas engine. The test results show that hydrogen blending can effectively reduce the maximum pressure cycle variation and average indicated pressure variation of the engine, and the effect is more obvious in the case of tin. Effect on combustion process and performance of hydrogen-doped natural gas engine. A lot of researchers have done this.

Dong Shaoyi [14] of Hunan University systematically investigated the basic law of in-cylinder combustion parameters changing with hydrogen mixing ratio through in-depth study of the bench test of natural gas engine. In addition, he carried out bench tests on hydrogen-doped high-compression ratio, supercharged premixed natural gas engines, obtaining detailed performance, operation and combustion parameters. In particular, he focused on how key combustion parameters, including the 50% combustion point location and the 10% to 90% combustion duration, evolve with the hydrogen energy ratio. On this basis, by analyzing the effect of hydrogen blending on the equivalent specific gas consumption, NO_X, HC and CO_2 emissions of natural gas engines, the corresponding standard digital model of natural gas hydrogen blending engines is established, which can be used to predict the performance parameters of similar engines reliably.

Zhou Lei [15] of Wuhan Software Engineering Vocational College conducted a study on the effect of hydrogenation ratio on combustion and performance of natural gas engines. In this study, the hydrogenation equipment of a natural gas engine was reformed and the bench test was carried out. The results show that hydrogenation can accelerate the flame propagation speed of mixture, shorten the duration of combustion in cylinder, advance the combustion center of gravity, and further increase the maximum combustion temperature and maximum explosion pressure. However, as the engine load increases, this promoting effect gradually diminishes.

By means of bench test, Wu Changshui [16] from Ocean University of Engineering Technology has conducted a detailed study on the economic and emission characteristics of natural gas hydrogen-doped engines under different loads and ignition advance angles. They used a mixture of natural gas and hydrogen with a hydrogen ratio of 0% to 40% for the test. The results show that with the increase of hydrogen blending ratio, the gas consumption rate shows a decreasing trend, indicating that the economy of the engine has been significantly improved. Under different loads, NO_x and CO emissions increase with the increase of hydrogen blending ratio, while CH_4

emissions decrease. When the hydrogen ratio is constant, the emission of NO_x, CH_4 and CO increases with the increase of ignition advance Angle and hydrogen ratio. The emission performance of natural gas engine can be improved by optimizing the ignition advance Angle.

2.3 Hydrogen-Alcohol Engines

Alcohol fuel refers to a class of liquid fuel with alcohol as the main component, common ethanol, methanol, butanol and so on. These fuels can be produced by fermentation or chemical processes from renewable sources (e.g. crops, wastes), or synthesized from fossil sources (e.g. coal, natural gas). Alcohol fuels play an important role in the modern energy system because of their environmental characteristics and renewability. Main Alcohol fuel Characteristics Ethanol: The most widely used alcohol fuel. It is often produced by the fermentation process of sugar-containing or starchy crops such as corn and sugarcane. It can be used as a pure fuel, and is often used as an additive to gasoline to improve the octane number of gasoline and reduce emissions. Methanol: It can be produced chemically from natural gas, coal or biomass. When used as fuel, it has high efficiency and low emissions. Methanol is highly toxic, so special safety precautions are required when used and stored. Butanol: Butanol has a higher energy density and lower volatility than ethanol and methanol. It can be produced from biomass through the fermentation process and can also be chemically synthesized. Due to its good chemical stability and low vapor pressure, butanol is considered a strong candidate for future automotive fuels.

For the fuel performance and emission characteristics of methanol, ethanol, butanol and hydrogen mixture, Tian Z [17] of Tianjin University, a State Key Laboratory of Engines, established an alcohol-hydrogen engine model through the GT-Power simulation platform for comparison, and concluded. The results show that adding 10% hydrogen to methanol, ethanol or n-butanol can increase the braking torque (BT) by 3.49%, 5.02% and 6.48%, respectively, at 1500 r/min. At 2000 r/min, the increases were 3.14%, 4.74% and 6.62%, respectively. At 1500 r/min, the brake specific fuel consumption (BSFC) was reduced by 31.51%, 24.6% and 21.16%, respectively. At 2000 r/min, they decreased by 31.37%, 24.4% and 21.23%, respectively. HC, CO and CO_2 emissions decreased, but NO_x emissions increased. When the hydrogen ratio is 10%, the CO of the methanol-H2 mixed system is reduced by 48.28% and 65.91%, and the CO_2 is reduced by 14.9% and 24.61%, respectively, compared with the ethanol-H2 and n-butanol-H2 mixed systems at 2000r/min. When a higher proportion of hydrogen is used, BT can be better increased and BSFC and carbon emissions reduced.

The team of Professor Yu Xiumin of Jilin University has a deep research on the effect of injection mode on hydrogen-doped alcohol engines. In the study of the effects of secondary hydrogen injection on combustion and emissions of ethanol-based ignition engines, Zheng Tong [18] of the team concluded that under various excess void coefficients, hydrogen mixing can reduce HC and CO emissions. And compared with the single hydrogen injection, the HC and CO emissions of the second hydrogen injection are significantly reduced. However, due to the improvement of the full degree of combustion, NO_x emissions will increase to a certain extent. For compound injection, Hu Zhipeng [19] of the team studied the effects of different direct injection timing on engine combustion and emissions at different hydrogen ratios. The conclusion is as follows: with the increase of hydrogen blending ratio, the flame delay period and rapid combustion period are shortened, and the combustion of the engine is obviously improved The combustion performance and the stability of engine operation are improved. After adding hydrogen, the isovolumetric degree of heat release increased, and the increase was the highest In-cylinder temperature, maximum in-cylinder pressure and IMEP. With the increase of hydrogen mixing ratio, due to the increase of the temperature in the cylinder As a result, NO_x emissions increase, and CO and HC emissions decrease with the increase of hydrogen blending ratio. When $\lambda=1$, the direct injection time is 105°CA and BTDC is the best direct injection time, combustion and HC emission Reach the optimum; When $\lambda=1.3$, it is more appropriate to choose 75°CA BTDC as the direct injection time. As for the above, hydrogen mixing can reduce the emission of CO and HC, but increase the emission of NO_X. Li Yinan [20] studied the combustion and emission characteristics of the hydrogen/n-butanol composite multiple injection engine, and Shang Weiwei [21] again studied the ammonia/n-butanol composite injection based on the direct injection in the hydrogen cylinder. It is concluded that combined injection reduces CO and HC, but increases NO_x. Ding Yunkang [22] of the team studied the influence of hydrogen mixing and EGR on butanol engine, and the EGR rate has a significant impact on the NO_x emission of butanol engine. In the pure butanol combustion, NO_x emission is relatively small, but after the incorporation of hydrogen, the rise of combustion temperature leads to a sharp increase in NO_x emission, especially under the condition of large excess air coefficient. With the increase of EGR rate, NO_x emission decreased significantly, especially under the condition of oxygen-rich combustion. A larger hydrogen blending ratio combined with a larger EGR rate can reduce NO_x emission to a lower level, at which time HC emission is at a moderate level and CO emission is low. However, when the hydrogen blending ratio is larger and the EGR rate is smaller, the NO_x emission is still higher, the HC emission is moderate, and the CO emission is low. A smaller hydrogen blending ratio combined with a larger EGR rate can reduce NO_x emissions to a small level, but HC emissions are relatively high and CO emissions are relatively high at this time. A smaller EGR rate combined with a smaller hydrogen blending ratio can reduce NOx emissions to a lower level, and HC emissions are at a moderate level, while CO emissions are relatively high. Xin G [23] of the School of Energy and Power Engineering, Peking University, proposed a strategy to control the combustion and emission performance of a hydrogen internal combustion engine with intake injection by using ethanol direct injection. The results show that the addition of ethanol can significantly reduce the pressure rise rate of hydrogen engine, and can prolong the critical moments in the combustion process of hydrogen engine, such as CA0-10 and CA10-90, so as to extend the combustion time, improve the combustion efficiency and reduce the generation of incomplete combustion products. It also promotes the power output (BMEP) and fuel efficiency (BTE) of hydrogen engines, which means that ethanol can improve the performance of the engine, improve its power output and fuel utilization efficiency. At the same time, under lean combustion conditions, the addition of ethanol can significantly reduce nitrogen oxide emissions, which is of great significance to reduce the environmental impact of engine emissions, helping to improve air quality and reduce environmental pollution.

Hydrogen-alcohol hybrid engines have the potential to become an important option for clean energy vehicles in the future. Through technological innovation and engineering optimization, the commercial application of this engine type can be achieved and contribute to the sustainable development of the automotive industry.

2.4 Hydrogen-ammonia engine

Ammonia is a colorless gas with an irritating odor and strong corrosiveness. The minimum ignition energy required for ammonia is high, at 8mJ, and it can only burn when its volume fraction in the air is between 15.0% and 28.0%, indicating a relatively narrow combustion range [24,25]. The substances produced by the combustion of ammonia include nitrogen and water vapor, without generating greenhouse gases, while releasing a large amount of heat. However, compared to traditional hydrocarbon fuels, ammonia has unique combustion characteristics. It is difficult to ignite, has a lower combustion rate, leading to significant cycle variations. Direct use of ammonia in engines faces significant challenges due to high emissions of nitrogen oxides (NO_x).

Researchers have investigated the acceleration of ammonia combustion by using multiple spark plugs, and findings indicate that utilizing multiple spark plugs can indeed speed up the combustion process of ammonia. However, using multiple spark plugs is generally more complex than traditional single spark plug systems, as it necessitates additional hardware and electronic control units to manage the ignition timing and energy output for multiple spark plugs. Furthermore, the cost of multi-spark plug ignition systems is typically higher, and maintenance is significantly challenging [26,27]. Therefore, researchers have turned their attention to hydrogen-ammonia fuel mixtures. The high combustion rate of hydrogen can maximize the combustion efficiency of ammonia. Simultaneously, hydrogen and ammonia are clean energy sources, which do not contribute to environmental pollution. For the combustive effect of hydrogen. Frigo S [28] with a 4-stroke twin-cylinder SI engine of 505 cm3 fuelled ammonia-plus-hydrogen. As a test subject, The experimental findings validate the need for adding hydrogen to the air-ammonia mixture to enhance ignition and augment combustion speed. The optimal ratio primarily hinges on the load rather than the engine speed.

Not only does hydrogen have a combustion-supporting effect on ammonia, but also ammonia can affect the combustion properties of hydrogen.

Xin G [29] of the School of Energy and Power Engineering at Beijing University of Technology studied the combustion and emissions of hydrogen-ammonia engines under partial load conditions. As the volume fraction of added ammonia rises, both the flame development period and flame propagation period are extended, leading to a decrease in the peak heat release rate. Engine power increases with ammonia addition, while indicated thermal efficiency decreases. However, at the ignition timing corresponding to maximum braking torque, increasing the volume fraction of added ammonia results in higher indicated mean effective pressure and indicated thermal efficiency. The addition of ammonia volume fraction minimally affects nitrogen oxides (NO_x) emissions, with NO_x emissions gradually increasing as ignition timing is delayed. For the interaction between hydrogen and ammonia, College of Power and Energy Engineering, Harbin Engineering University Wang Y [30] studied the ignition process under the condition of high pressure direct injection engine. It conducted that IDT could be effectively reduced when adding 10-50% hydrogen to ammonia. Then, after sensitivity analysis of NH_3/H_2 mixtures, the key equations and free radicals affecting combustion characteristics were found. The rate of production (ROP) of the key radicals were carried out. It was found that the hydrogen provided the initial concentration of H radical before the start fire, which greatly improved the ROP of OH radical of R1($H+O_2=O+OH$) compared to the original H needed to break the Ne H chemical bond in pure ammonia. And the OH radical was related to the consumption of NH_3 by R31($NH_3+OH=NH_2+H_2O$). While the ammonia-doped hydrogen fuel engine is still in the research and development stage, with further research and development of ammonia-blended hydrogen engine and ammonia decomposition hydrogen production technology, ammonia fuel will gradually be widely developed and applied as a new, clean, renewable, and reliable alternative fuel in the future, improving the current carbon emission problem and promoting the development of the energy industry.

3. CONCLUSION

Numerous experimental studies have explored the impact of blending hydrogen with traditional fuels on engine performance and emissions. Computer simulations have aided researchers in understanding the effects of hydrogen-fuel mixtures on the combustion process and in guiding how to maximize their benefits. Well-controlled hydrogen enrichment can reduce exhaust emissions, including carbon emissions and nitrogen oxides. The high combustion speed and low auto-ignition temperature of hydrogen contribute to improved combustion efficiency, reduced incomplete combustion, and fuel consumption. Hydrogen's high flammability limit and low ignition delay enhance the engine's dynamic performance and responsiveness. Currently, using hydrogen as a fuel presents challenges; the storage and supply of hydrogen remain problematic, with issues such as storage pressure, safety, and cost needing resolution. Determining the correct hydrogen blending ratio is critical, as too much or too little hydrogen can affect engine performance. Engine components and fuel system materials must be compatible with hydrogen to avoid corrosion and safety issues. For future development, further research into the impact of hydrogen enrichment on engine performance and emissions, development and improvement of hydrogen-enriched combustion systems, and hydrogen storage technologies are viable paths. Policy support and investment from government and industrial sectors will drive the development and commercial application of hydrogen blending technologies. Interdisciplinary cooperation, involving material science, chemical engineering, and mechanical engineering, will be key to advancing hydrogen-enriched engine technologies. Overall, hydrogen enrichment in engines offers advantages in reducing emissions, improving efficiency, and enhancing power performance, but still faces challenges and limitations. Future research will focus on technological improvements and interdisciplinary cooperation.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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