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# Research on Combustion and Emission Characteristics and Performance Optimization Technology of Hydrogen Internal Combustion Engines

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## Abstract

Against the backdrop of the "Dual Carbon" goals and energy transition, hydrogen internal combustion engines have become an important development direction for hydrogen power by virtue of mature industrial chains and low-cost advantages. Nevertheless, backfire, pre-ignition, high $NO_x$ emissions and insufficient thermal efficiency remain bottlenecks restricting their large-scale promotion. Experiments show that $NO_x$ emissions are significantly regulated by the excess air coefficient and reach the peak in the moderate lean-burn range; under cold start conditions, $NO_x$ emissions hit the maximum at $\lambda$=1.41, with an emission reduction rate of 84.4% when $\lambda$ drops to 0.72. The adoption of direct in-cylinder injection can fundamentally avoid intake mixture premixing and suppress backfire and pre-ignition. Matching lean combustion, optimized ignition and hydrogen injection strategies as well as eliminating throttle pumping loss can greatly improve in-cylinder combustion quality and thermal efficiency. Based on domestic and overseas research, this paper reviews relevant technical routes, clarifies key optimization methods and technical deficiencies, and offers theoretical references for the engineering calibration and clean, efficient development of hydrogen internal combustion engines.

## Keywords

hydrogen internal combustion engine, excess air coefficient, nitrogen oxide emission, direct in-cylinder injection, thermal efficiency

## 1. Introduction

Traditional fossil energy is the main power source in the transportation field, and greenhouse gases and pollutants emitted by its combustion continuously aggravate global ecological pollution. Promoting the low-carbon transformation of transportation energy has become an inevitable trend in the industry. As a typical zero-carbon clean fuel, hydrogen only generates water during combustion, without carbon-containing pollutants such as carbon dioxide and hydrocarbons. It also has high energy density and clean renewable properties, making it the most promising alternative energy source for the zero-carbon upgrading of internal combustion engines [1]. Since the Industrial Revolution, the long-term extensive consumption of fossil fuels has continuously intensified the global greenhouse effect. To cope with the climate crisis, China has continuously promoted the green upgrading of the energy structure. Data shows that China's carbon dioxide emissions per ten thousand yuan of gross domestic product decreased by 5.0% year-on-year in 2025, and the power generation of clean energy such as hydropower, nuclear power, wind power and solar energy increased by 14.4% year-on-year, which fully reflects the promotion intensity of China's low-carbon transformation. Against this background, China has put forward the strategic goals of “carbon peaking in 2030 and carbon neutrality in 2060,” and formally incorporated hydrogen energy into the national energy management system in 2024. Hydrogen power technology has become a key research direction in the field of internal combustion engines. At present, hydrogen power is mainly divided into two technical routes: hydrogen fuel cell and hydrogen internal combustion engine. Compared with hydrogen fuel cells with high cost and complex system, hydrogen internal combustion engines rely on the mature industrial chain of traditional internal combustion engines, with small transformation difficulty, low cost and high operation reliability, which are more suitable for popularization and application at the present stage [2]. However, affected by the special physical and chemical properties of hydrogen, there are still three core technical problems: backfire and pre-ignition, high $NO_x$ emissions and low thermal efficiency [3], which seriously restrict large-scale development.

Hydrogen has low ignition energy, strong diffusivity and fast flame propagation speed. The traditional intake port injection structure is extremely prone to abnormal combustion phenomena such as backfire and pre-ignition, resulting in rough engine operation and reduced service life. Ji Changwei et al. found through cold start condition tests that the excess air coefficient has a significant impact on $NO_x$ emissions; the emission reaches the peak when $\lambda=1.41$, and the emission reduction rate can reach 84.4% when adjusted to $\lambda=0.72$ [4]. Jia Bin et al. conducted research on direct in-cylinder injection models and found that when the excess air coefficient changes in the range of 2.1~2.5, the in-cylinder combustion temperature fluctuates between 1800K and 2100K, which significantly changes the $NO_x$ generation and combustion heat release level [5]. Hong Anxin et al. confirmed that direct in-cylinder injection can realize mixture stratification by optimizing injection strategies, avoid the defects of intake port premixing, not only suppress backfire and pre-ignition, but also improve combustion quality and increase the overall thermal efficiency [6]. At the same time, uneven mixture distribution and unreasonable combustion organization are easy to cause insufficient combustion and large energy loss, which further drag down the thermal efficiency performance.

At present, there are many domestic and foreign studies on the combustion mechanism and optimization of hydrogen internal combustion engines, but systematic reviews focusing on the three problems of backfire and pre-ignition suppression, $NO_x$ emission reduction and collaborative improvement of thermal efficiency are still insufficient. Based on the existing research results, this paper systematically sorts out the combustion characteristics and key influencing mechanisms of hydrogen internal combustion engines, focuses on analyzing the application paths of technologies such as direct in-cylinder injection and parameter matching, clarifies the current technical bottlenecks and prospects the development trend, aiming to provide theoretical reference for the clean and efficient development of hydrogen internal combustion engines.

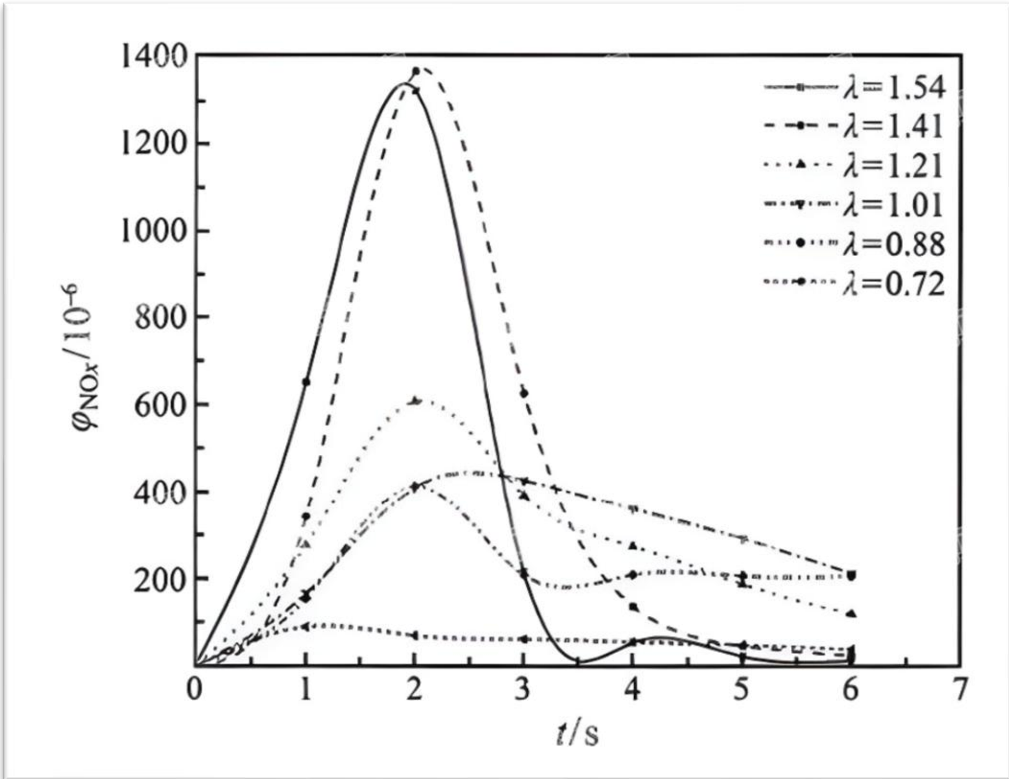
## 2. Influence of Excess Air Coefficient on Emissions and Thermal Efficiency

Hydrogen internal combustion engines use hydrogen as fuel, and the combustion process does not contain carbon elements, which fundamentally eliminates conventional emissions such as CO, HC and particulate matter. Nitrogen oxides ($NO_x$) become the main harmful emissions [6,7]. In the combustion process of hydrogen fuel, $NO_x$ completely follows the high-temperature thermal generation mechanism, that is, $N_2$ and $O_2$ in the air undergo oxidation reactions under high-temperature and oxygen-rich conditions in the cylinder, and its generation rate is highly dependent on three core factors: peak in-cylinder temperature, local oxygen concentration and high-temperature duration [5]. Due to the fast flame propagation speed, wide lean-burn limit and extremely low ignition energy of hydrogen, tiny changes in mixture concentration will significantly change the combustion rate and in-cylinder temperature distribution [7]. Therefore, the excess air coefficient $\lambda$ has become the most direct and key operating parameter to regulate $NO_x$ generation.

From the perspective of generation mechanism, when the in-cylinder temperature exceeds 1800 K, the thermal $NO_x$ generation rate rises exponentially [6]; the higher the oxygen concentration and the longer the high-temperature residence time, the greater the cumulative $NO_x$ generation. By changing oxygen concentration and combustion temperature at the same time, the excess air coefficient presents a typical nonlinear influence law on $NO_x$ emissions. In the medium lean-burn range, the oxygen in the cylinder is sufficient and the combustion temperature remains at a high level, the flame development period and rapid combustion duration are significantly prolonged, and the high-temperature residence time increases, which provides the optimal conditions for $NO_x$ generation, resulting in the peak of $NO_x$ emissions [5]. With the further increase of the excess air coefficient, the mixture is excessively diluted, the combustion temperature drops rapidly, and the $NO_x$ generation is inhibited; when the excess air coefficient decreases and the mixture shifts to a rich mixture, the oxygen concentration drops sharply. Although the local combustion temperature rises slightly, the oxygen-deficient environment and faster combustion rate jointly shorten the high-temperature duration, and the $NO_x$ generation will decrease rapidly [8].

A large number of tests and simulation results have confirmed the above laws [5-8]. Figure 1 shows the variation law of $NO_x$ emissions with time under different excess air coefficients [7]. Under the cold start condition of intake port injection hydrogen internal combustion engine, when the excess air coefficient decreases from 1.54 to 0.72, $NO_x$ emissions first rise slightly and then decrease significantly, reaching the emission peak at $\lambda$=1.41; when $\lambda$=0.72, the average $NO_x$ emissions within the first 6 seconds of cold start are reduced by 84.4% compared with the lean-burn condition [7]. Under the steady-state working conditions of direct in-cylinder injection hydrogen internal combustion engines, when $\lambda$ decreases from 2.5 to 2.1, the average in-cylinder temperature rises from 1800 K to 2100 K, the oxygen concentration is relatively sufficient, and $NO_x$ emissions continue to rise as the mixture becomes richer [5]. This shows that $NO_x$ emissions in the lean-burn range are mainly controlled by combustion temperature, while $NO_x$ emissions in the rich-burn range are mainly controlled by oxygen concentration, and the medium excess air coefficient range is a high-risk area for $NO_x$ emissions [7,8].

*Figure 1: Variation of $NO_x$ Emissions with Time under Different Excess Air Coefficients [7]*




In conclusion, the excess air coefficient $\lambda$ is a key operating parameter affecting $NO_x$ generation and emissions of hydrogen internal combustion engines through the collaborative regulation of in-cylinder combustion temperature, oxygen concentration and high-temperature residence time [6]. In the medium excess air coefficient range, both temperature and oxygen concentration are at appropriate levels, the $NO_x$ generation rate is the fastest and the cumulative amount is the largest, forming a high-emission risk area; after entering the ultra-lean combustion range, the oxygen concentration is always sufficient, and $NO_x$ generation increases significantly with the rise of combustion temperature, showing temperature-dominated control; while in the rich-burn range, although the local combustion temperature rises slightly, the sharp drop of oxygen concentration becomes the main limiting factor, and $NO_x$ generation is significantly inhibited.

At the same time, the excess air coefficient is also the core parameter determining the thermal efficiency of hydrogen internal combustion engines. It significantly regulates the overall energy utilization by changing mixture concentration, combustion temperature and flame propagation rate. The appropriate lean-burn range can reduce in-cylinder heat transfer loss, promote complete combustion of hydrogen, and reduce post-combustion and energy loss; excessively high excess air coefficients will cause excessive dilution of the mixture, slow flame propagation, lag combustion phase, aggravate incomplete combustion, and thermal efficiency will decline; while excessively rich mixtures will cause oxygen-deficient combustion in the cylinder, increase combustion loss, and also restrict the improvement of thermal efficiency. Relevant studies show that direct in-cylinder injection hydrogen internal combustion engines have good thermal efficiency potential in the range of $\lambda$=2.1~2.5. Moderately reducing the excess air coefficient can accelerate flame propagation and improve the in-cylinder combustion work capacity, laying a foundation for thermal efficiency optimization [5]. Therefore, in the actual operation control of hydrogen internal combustion engines, the high-emission range of medium excess air coefficients should be actively avoided, the emission characteristics and thermal efficiency should be coordinated and optimized, and rich-burn emission suppression or precise lean-burn temperature control strategies should be adopted combined with working conditions. On the premise of ensuring combustion stability and power output, efficient in-cylinder control of $NO_x$ emissions and synchronous improvement of thermal efficiency can be realized, which provides an important theoretical basis for low-emission and high-efficiency operation and calibration optimization of hydrogen internal combustion engines [7].

## 3. Backfire and Pre-ignition Suppression Technology of Direct-in-Cylinder Injection Hydrogen Internal Combustion Engines

Direct in-cylinder injection technology is the core key technology to solve the abnormal combustion of backfire and pre-ignition of hydrogen internal combustion engines, and simultaneously improve thermal efficiency and optimize emissions. Compared with the traditional intake port injection mode, direct in-cylinder injection can inject high-pressure hydrogen directly into the cylinder during the compression stroke, avoid the premixing of hydrogen and air in the intake manifold in advance, and eliminate the inducement of intake pipe backfire from the source; at the same time, it can flexibly adjust the hydrogen injection time, hydrogen injection pressure and injection angle, shorten the residence time of the mixture under a high-temperature environment, effectively suppress the pre-ignition phenomenon caused by hydrogen's low ignition energy and fast flame propagation speed, and greatly improve the problems of rough engine combustion and large cycle fluctuation [8-10].

From the perspective of mixture organization, direct in-cylinder injection can realize stratified combustion and controllable mixture distribution in the cylinder. With the matching of a reasonable combustion chamber flow field, a mixture with an appropriate concentration is formed near the spark plug, and a thin atmosphere is adopted in other areas, which not only ensures ignition stability, but also reduces the local high-temperature and oxygen-rich area in the cylinder and suppresses the generation of thermal $NO_x$ from the mechanism [11]. Combined with literature tests and simulation studies, direct in-cylinder injection can avoid the disadvantages of excessive mixture concentration and incomplete combustion of intake port injection by optimizing the mixture formation law, laying a foundation for the improvement of thermal efficiency [12].

Direct in-cylinder injection has a particularly prominent effect on improving the thermal efficiency of hydrogen internal combustion engines: firstly, the direct injection mode eliminates the hydrogen occupation effect in the intake port, improves the charging efficiency and reduces pumping loss; secondly, by accurately controlling the injection strategy and combustion phase, the heat release process is closer to the ideal thermodynamic cycle, and the compression negative work and post-combustion loss are significantly reduced [8]. At the same time, direct in-cylinder injection can match a larger compression ratio, take advantage of hydrogen's high spontaneous ignition temperature and good anti-knock performance, and further strengthen the heat-work conversion capacity [10]. Relevant studies confirm that after reasonably optimizing hydrogen injection pressure and injection angle, direct injection hydrogen internal combustion engines can effectively reduce in-cylinder heat transfer loss, and the indicated thermal efficiency can be increased by 3%~10.5%

compared with intake port injection, and the optimal model thermal efficiency can reach 46.9% under $\lambda$=2.5 lean-burn condition [11]. In addition, direct in-cylinder injection coupled with lean combustion and coordinated regulation of ignition timing can broaden the lean-burn limit while balancing thermal efficiency and $NO_x$ emissions, avoiding the contradiction that emission improvement is accompanied by thermal efficiency decline in traditional schemes [12].

In summary, direct in-cylinder injection can not only fundamentally solve the abnormal combustion problems such as backfire and pre-ignition of hydrogen internal combustion engines, but also effectively reduce $NO_x$ generation, reduce heat transfer and pumping loss through stratified mixture organization and injection parameter optimization, and significantly improve the overall thermal efficiency and operation stability. It is the core technical path with the most engineering application value for the large-scale popularization of hydrogen internal combustion engines at the present stage.

## 4. Optimizing Engine Load Control Mode to Improve Thermal Efficiency of Hydrogen Internal Combustion Engines

Optimizing the engine load regulation strategy is a key technical path to improve the effective thermal efficiency of hydrogen internal combustion engines. Traditional gasoline engines generally adopt the quantity regulation mode with throttle throttling, and realize load regulation by controlling the intake air volume. Under medium and small load conditions, significant pumping loss will be generated, which can account for a large proportion of the total energy loss of the engine, seriously restricting the improvement of thermal efficiency. Hydrogen has an extremely wide combustible limit, fast flame propagation speed and excellent lean-burn characteristics, which provide ideal conditions for throttle-free quality regulation load control [12,13].

Hydrogen internal combustion engines can completely cancel the throttle structure, abandon the throttling control mode, and turn to the load regulation scheme mainly based on fuel quality regulation. The power output is accurately controlled by directly changing the hydrogen injection volume, fundamentally eliminating the throttling loss and pumping loss brought by the throttle [11]. Studies show that adopting the strategy of full throttle opening and load control by hydrogen injection volume can greatly reduce pumping loss, and the pumping loss reduction range under medium and small load conditions can reach 30%~57%, effectively reducing the additional energy consumption in the intake process and laying a foundation for the improvement of thermal efficiency [13]. Hydrogen does not need atomization and evaporation, and can be quickly mixed with air directly, which also makes the quality regulation control respond faster and the mixture uniformity better, further strengthening the control effect [11].

On this basis, fine optimization of valve timing and intake and exhaust structure can improve the in-cylinder charging efficiency, reduce energy loss in the gas exchange process, and further tap the efficiency potential from the overall matching dimension. By reasonably matching late intake valve closing, early exhaust valve closing or optimizing valve overlap angle, the residual gas coefficient can be reduced, the fresh charge coefficient can be improved, the gas exchange loss can be reduced and the combustion phase can be improved [12]. Relevant simulations and tests confirm that optimizing valve timing can increase the effective thermal efficiency from 40.8% to 41.07%, the power increase range under high-speed working conditions can reach 12.7%, and the fuel gas consumption rate can be effectively reduced at the same time [6]. Collaborative optimization of intake port, exhaust port and valve flow area can reduce intake and exhaust resistance, strengthen in-cylinder tumble and turbulence intensity, not only improve charging efficiency but also accelerate combustion speed, shorten combustion duration, make heat release more concentrated near the top dead center, and improve heat-work conversion efficiency [13].

From the perspective of overall system matching, coupling throttle-free quality regulation, valve timing optimization, intake and exhaust structure improvement with hydrogen direct injection, high compression ratio, ultra-lean combustion and other technologies can realize leapfrog improvement of thermal efficiency of hydrogen internal combustion engines. Studies show that after multi-parameter collaborative optimization, the effective thermal efficiency of a hydrogen fuel direct injection compression ignition engine can reach 51.38%, and the effective thermal efficiency of a conventional direct injection hydrogen internal combustion engine can stably reach 43%~46.9%, which is significantly better than the level of traditional gasoline engines [13]. By canceling the throttle to eliminate pumping loss, optimizing valve distribution and gas exchange to reduce circulation loss, and coordinating the combustion system to improve combustion perfection, the three form a synergy of efficiency increase, and finally realize the overall improvement of effective thermal efficiency of hydrogen internal combustion engines [13].

## 5. Conclusion

Against the background of the global "Dual Carbon" strategy and energy transformation, hydrogen energy, as a zero-carbon fuel, has become an extremely promising alternative energy source in the field of internal combustion engines. Relying on the mature industrial chain foundation and low transformation cost, hydrogen internal combustion engines are regarded as an indispensable link in the hydrogen power technical route. This study systematically reviews the emission characteristics, abnormal combustion suppression, and thermal efficiency improvement technologies of hydrogen internal combustion engines, aiming to provide theoretical reference for the clean and efficient development of hydrogen internal combustion engines.

This paper shows that $NO_x$ is the main emission product of hydrogen internal combustion engines; its generation law is dominated by the excess air coefficient; and the emission peak will appear in the medium lean-burn range, while rich-burn or ultra-lean-burn working conditions can significantly inhibit $NO_x$ generation. Direct in-cylinder injection technology can fundamentally suppress backfire and pre-ignition and greatly improve combustion stability by optimizing the mixture formation mode. In addition, reasonable adoption of lean combustion, optimization of ignition and hydrogen injection timing, and abandonment of throttle throttling control can effectively improve the effective thermal efficiency of hydrogen internal combustion engines from multiple dimensions.

These findings further clarify the core influence of the excess air coefficient, combustion mode and control strategy on the performance of hydrogen internal combustion engines, provide clear optimization paths to solve the three major technical bottlenecks of hydrogen internal combustion engines, namely "high emission, prone to abnormal combustion and insufficient thermal efficiency," and also point out the direction for subsequent engineering calibration and technical improvement.

The relevant conclusions have reference value for researchers engaged in hydrogen power research, technical R&D personnel of internal combustion engine enterprises, and industry practitioners concerned with carbon neutrality policy formulation in the transportation field, helping to promote the industrial application of hydrogen internal combustion engines from laboratories.

With the gradual improvement of hydrogen energy infrastructure and continuous iteration of internal combustion engine technology, hydrogen internal combustion engines are expected to realize large-scale application in commercial vehicles, engineering machinery and other scenarios, contribute key strength to the low-carbon transformation of China's transportation field, and their technological breakthroughs can also provide important support for the promotion of hydrogen energy in more power scenarios.

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## Conflicts of Interest

The authors declare no conflict of interest.

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