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Dynamics and mitigation strategies of knock in hydrogen-fueled internal combustion engines

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Abstract. In the context of utilizing hydrogen as a fuel for internal combustion engines, it is crucial to address its tendency to induce knock more readily under certain conditions compared to gasoline. Knock not only reduces fuel efficiency but also has the potential to inflict detrimental effects on engine components. It is generally believed that knock is primarily caused by the spontaneous combustion of the end-gas mixture. Current research focuses on the frequency, intensity, and statistical characteristics of knock signals.This study aims to introduce two prevalent and effective methods for mitigating knock: increasing the Exhaust Gas Recirculation (EGR) ratio and water injection into the engine. Experimental observations suggest that at low rotational speeds (n=900 rpm), the amplitude spectra of knock induced by hydrogen and gasoline show similarities. However, at higher speeds (n>3000 rpm), the amplitude of hydrogen-induced knock not only exhibits a greater number of peak values but also intensifies in strength. Notably, the efficacy of increasing the EGR ratio diminishes at high speeds, potentially due to the propensity of methane to also cause knock under high-temperature conditions. In contrast, water injection, while generally effective, may adversely impact the lifespan of engine components.In summary, effective suppression of knock in hydrogen-fueled internal combustion engines is vital for accelerating the adoption of hydrogen in the power sector and making significant contributions to environmental conservation. This paper aims to delve into the analysis of these methods' effectiveness and proposes directions for future research.

Keywords: Hydrogen-Fueled Internal Combustion Engine, Frequency, Intensity

1. Introduction

With the rapid development of hydrogen energy technology, people's interest in applying hydrogen technology in passenger cars has been growing. Utilizing hydrogen as a fuel for conventional internal combustion engines is a convenient method that requires minimal modifications to the vehicle. However, this shift brings new challenges in the application of hydrogen in automobiles, particularly the issue of engine knock caused by hydrogen. Hydrogen-induced knock can negatively affect the engine in several ways, such as overheating leading to lower thermal efficiency, increased dynamic loads causing wear and reduced lifespan of components, and deformation of parts. Therefore, a thorough investigation of the causes and processes of knock is crucial to address these issues in the application of hydrogen internal combustion engines.

Engine knock can generally be categorized into two types: mild knock and severe knock, each with a variety of causes. This article primarily focuses on knock caused by the auto-ignition of the end-gas mixture. It is divided into three main sections discussing engine knock. The first section introduces the causes of knock, with a brief overview of mild knock and a detailed discussion on severe knock. The second section examines the characteristics of knock waves, exploring both the frequency and intensity of these waves. The final section presents two solutions to mitigate knock, followed by a discussion on these methods.

2. Literature Review

In engine knock research, scholars have focused on four key variables and their ranges, as seen in Table 1. To address the problem of engine knock, two main strategies or their combination are primarily adopted, as reviewed by Gao(2022) [1]. The first strategy involves optimizing the structure of the internal combustion engine, including improvements in combustion chamber design and adjustments in spark plug positioning. The second strategy is controlling the combustion process, which involves increasing turbulence kinetic energy, enhancing Exhaust Gas Recirculation (EGR) rates, reducing compression ratios, and using anti-knock additives and water injection. This article focuses on discussing the improvement of the combustion process through the increase of EGR rate and the application of water injection technology.

Table 1. Four key variables of knocking and their range

Variables	**Range when using gasoline**	**Range when using hydrogen**
Rotating speed	1500-2500r/min	Low speed 900r/min High speed over3000r/min
Compression ratio(CR)	CR:8-11	CR: 9-12
Equivalent ratio(ER)	ER: 1.0-1.5	ER: 1-1.5 or over 0.55
Ignition timing(IT)	from 5◦ before top-dead-center (BTDC) to 12◦ after top-dead-center (ATDC)	from 5◦ before BTDC to12◦ ATDC

3. The Review of Engine Knock

3.1. Causes of Engine Knock

As a gaseous fuel, hydrogen has a low octane number sensitivity, and its tendency to cause engine knock is usually measured by its methane number. Hydrogen's low methane number indicates a propensity for knock. Extensive research has been conducted to effectively reduce hydrogen knock. Ye found that the uniformity of the gas mixture significantly impacts knock, with the unburned end-gas mixture's mass directly correlating with knock intensity [2]. Gao (2022) suggests categorizing knock based on its intensity into mild and severe. Mild knock typically arises from unstable combustion, while severe knock is more complex, involving factors like the auto-ignition of the end-gas mixture, and interactions between pressure waves and flames. Under spark-ignition conditions, knock is primarily caused by the auto-ignition of the end-gas mixture. Thus, many researchers typically assume that end-gas auto-ignition is the primary cause of knock in their analyses.

3.2. Characteristics of Engine Knock

Please ensure that affiliations are as full and complete as possible and include the country. The addresses Engine knock is essentially a phenomenon of pressure waves. In studying engine knock, researchers typically focus on two key aspects: the intensity and frequency of these waves. This article specifically investigates the knock characteristics of hydrogen under various rotational speed conditions, particularly at low and high speeds.

3.2.1. Frequency of Knock. In 2007, SZwaja [3] compared the knock frequencies of hydrogen and gasoline under low-speed conditions (n=900r/min, equivalence ratio=1, compression ratio=12, ignition timing: 5-12°). To achieve this, he used a 4kHz high-pass filter to eliminate the low-frequency and DC components produced by cyclic compression and normal combustion, followed by a Fast Fourier Transform analysis. The study found that the primary mode frequency for hydrogen was at 6.4kHz, while for gasoline, it was 5.7kHz. The amplitude spectra of both were similar, predominantly concentrated around their respective primary mode frequencies. This difference can be explained by a formula proposed by B. Bäuerle:

$$f = \frac{\mathrm{C\rho}}{\pi \mathrm{B}} \tag{1}$$

This formula takes into account the effects of fuel density and combustion temperature on local sound speed, thereby influencing the frequency of knock. Continuing the translation: Luo (2016) [4] focused on high-speed conditions (n>3000r/min, equivalence ratio>0.55, compression ratio=10, ignition timing: BTDC to maximum braking torque). Using experimental methods similar to SZwaja, Luo found that under severe knock conditions with KI=20.9, the amplitude spectrum was different from SZwaja's findings at lower speeds. Luo noted that the amplitude spectrum mainly concentrated around four frequency points with approximately equal intervals between them. This indicates that under high-speed conditions, the combustion situation becomes more complex, likely caused by multiple factors.

3.2.2. Intensity of Knock. Waves SZwaja defined a pressure intensity index (PI) for knock waves and recorded the pressure fluctuations during the combustion of hydrogen and gasoline using sensors. In analyzing high-level knock data, he found that the skewness of the data distribution for both hydrogen and gasoline was small and negligible. Thus, he used a normal distribution model to fit the probability density function of knock intensity. The fit was evaluated using the coefficient of multiple determination (CoMD), with hydrogen's CoMD value being 0.96 and gasoline's 0.89. According to the fitted normal distribution curve, the average intensity and variance of hydrogen knock were lower than those of gasoline, indicating that at low speeds, hydrogen knock is less intense and relatively easier to control. This may be related to the low sensitivity of hydrogen's methane number and its higher sensitivity to octane number. Luo's study indicates that at high speeds (n>3000r/min), hydrogen's knock intensity surpasses that of gasoline. This knock primarily results from high thermal load causing hot spots in components like exhaust valves and spark plugs, where temperatures significantly exceed the average. Temperature gradients exceeding 30K may trigger combustion knock, not attributed to temperature rises from cylinder compression. Furthermore, at speeds over 3000r/min, increased engine speed intensifies knock wave oscillations, making hydrogen knock control more challenging.

3.3. Solution to knocking

To address engine knock, researchers have developed various approaches, such as enhancing turbulence, refining combustion chamber design and spark plug placement, lowering compression ratios or end-gas temperatures, and integrating anti-knock additives and water injection. This article specifically discusses two prominent strategies for knock suppression: using hydrogen and methane in Exhaust Gas Recirculation (EGR) mixtures, and injecting water into engines. These techniques have shown potential in effectively managing knock occurrences.

3.3.1. Mixing of hydrogen and EGR. In his 2019 study, SZwaja [5] examined the effects of hydrogen and methane-dominated EGR mixtures on engine knock under specific conditions, including a speed of 1500r/min, a compression ratio of 9, an equivalence ratio between 1 and 1.5, and ignition timing set at 0 (TDC) or 5CA degrees before top dead center (BTDC). Utilizing the maximum peak values of high-frequency in-cylinder pressure oscillations, the study assessed the engine's knock intensity. Results showed a significant linear decrease in hydrogen knock intensity with increased EGR rates. For instance, at a 20% EGR, the Knock Intensity (KI) dropped from 40Kpa to 20Kpa.

Incorporating methane as a fuel in internal combustion engines chiefly aims to raise the methane number, thereby mitigating the knock phenomena associated with hydrogen-rich mixtures. Given the severe knock tendencies of pure hydrogen fuel, engines solely dependent on it are becoming less prevalent. In contrast, integrating hydrogen with Exhaust Gas Recirculation (EGR) technology is emerging as a mainstream solution. This method not only effectively manages knock but also optimizes combustion efficiency.

However, SZwaja's (2009) [6] research indicates that at higher temperatures, the methane added through EGR technology may not effectively reduce knock caused by hydrogen fuel, potentially leading to knock levels similar to pure hydrogen combustion. The experiment considered engine speeds of only 1500 rpm, lower than typical operational speeds, suggesting in-cylinder temperatures might be below real-world conditions. This implies that in practical applications, controlling knock through methane-EGR mixtures might not be as effective.

Based on the aforementioned study, we understand that the octane number is an appropriate metric for measuring the detonation intensity of hydrogen at low speeds (n=900), while the methane number is more suitable for assessing hydrogen detonation at medium speeds (n=1500). However, at high speeds (n=3000), there is currently a lack of an effective standard for evaluating the detonation characteristics of hydrogen. Therefore, finding a fuel that maintains good resistance to detonation even under high-temperature conditions is crucial. If such a fuel is found, it could not only help us more accurately assess the detonation characteristics of hydrogen at high temperatures but also potentially enhance the control of hydrogen detonation by replacing methane in a mixed combustion with hydrogen.

3.3.2. Water Injection in Engines. In his 2019 study, Brusca [7] advanced a water injection strategy for hydrogen-fueled internal combustion engines, inspired by historical applications of water injection in aircraft engines. Water injection, serving as an efficacious cooling approach, primarily aims to diminish temperatures within the combustion chamber and the exhaust gases. This methodology not only reduces the mean temperature of gases within the engine but also attenuates the temperature gradient proximate to thermal hotspots. Consequently, it can be postulated that the introduction of water injection facilitates enhanced control over the combustion process of hydrogen. Beyond ameliorating detonation concerns, the implementation of water injection technology also curtails emissions of NO_x and augments the engine's compression ratio and power density, thereby substantially elevating the engine's overall efficacy.

This is attributed to the fact that in spark-ignition engines, severe detonation is commonly induced by excessively high temperatures of the end-gas mixture, precipitating a premature combustion process. Water injection technology mitigates detonation phenomena by lowering the temperatures within the combustion chamber. This implies that under water injection conditions, even higher compression ratios and power densities, which might otherwise lead to elevated temperatures, become feasible. Concurrently, the issue of NO_x emissions caused by high temperatures can also be effectively reduced through water injection.

However, this water injection solution also presents certain long-term challenges. Firstly, the use of water may lead to corrosion of metal components, thereby shortening the lifespan of the engine. Secondly, water injection can cause emulsification of the lubricating oil, which diminishes its fluidity and consequently impacts the engine's normal oil supply. Emulsified lubricating oil may also reduce its lubricating efficiency, increasing friction and wear, and further reducing the engine's longevity.

While the water injection method entails the aforementioned drawbacks, these issues are not insurmountable. In addressing the corrosion problem in engines, utilizing materials with enhanced corrosion resistance is an effective solution. For instance, the use of steel alloyed with chromium can significantly augment the material's corrosion resistance, thereby decelerating engine corrosion. Additionally, to counteract the issue of lubricating oil emulsification, employing lubricants with higher resistance to emulsification can enhance the lubrication effectiveness and stability of the engine.

4. Conclusion

1. Severe detonations are primarily caused by the auto-ignition of the hydrogen end-gas mixture.

2. The frequency characteristics of detonation waves suggest that under conditions of high speed and lean equivalence ratios, the detonation frequency of hydrogen is higher than that of gasoline. Conversely,

at low speeds and stoichiometric ratios, the detonation frequency of hydrogen is comparable to that of gasoline, albeit slightly elevated.

3. In terms of detonation wave intensity, under low-speed and stoichiometric conditions, hydrogen exhibits a lower and more concentrated average amplitude compared to gasoline.

4. At low speeds, the octane number serves as an appropriate metric for assessing the detonation degree of hydrogen.

5. Increasing the EGR (Exhaust Gas Recirculation) rate can reduce hydrogen detonation at medium speeds. However, under conditions of excessive speed and high temperature, methane present in the EGR may participate in detonation, thereby diminishing its effectiveness.

6. Water injection in the combustion chamber can attenuate detonation by lowering temperatures. Nonetheless, this approach may lead to issues such as corrosion of engine metal components and emulsification of lubricating oil.

Hydrogen energy, as an exceedingly clean energy source, is progressively becoming a pivotal energy form sought after in the context of global energy transformation and sustainable development. Utilizing hydrogen gas directly as a vehicle fuel represents a method with relatively minimal impact on the existing automotive market. However, due to the characteristics of hydrogen, it is prone to detonation issues within the operational speed range of automobile engines. Currently, the trend in the application of hydrogen in automotive internal combustion engines is to mix it with other gases. Although this approach contributes to the goal of energy conservation and emission reduction, it is not a flawless solution. The authors of this paper posit that using hydrogen as a component of internal combustion engine fuel may only be a transitional measure. In the future, hydrogen fuel cell technology, owing to its efficiency and eco-friendliness, is likely to supplant existing hydrogen internal combustion engine technology.

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