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Core Technologies for Gaseous-Fuel Engines: Current Developments and Future Challenges

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Abstract : In response to the global demand for achieving carbon neutrality, making internal combustion engines more environmentally friendly has become a key priority. This paper reviews the development status and future challenges of core technologies for engines powered by major gaseous fuels such as LPG, CNG, hydrogen, and ammonia. Focusing on fuel supply and injection systems, it comprehensively examines technological advancements, major difficulties, and research directions for each fuel. LPG and CNG engines are enhancing efficiency and reducing CO_2 emissions through the adoption of Liquid/Direct Injection(LPDI/DI) and hydrogen co-combustion, thereby increasing technological maturity. Regarding hydrogen engines, direct injection is a key in backfire prevention and achieving high efficiency, while controlling NOx emissions and ensuring the durability of high-pressure systems continue to present challenges. Despite the advantage of ammonia engines as hydrogen carriers, they face significant hurdles such as poor combustibility and nitrogen-based emissions. Current development efforts are focused on dual-fuel and high-efficiency aftertreatment technologies, particularly for large engine applications. Gaseous-fuel engine technology is evolving through fuel diversification, direct injection, combustion optimization, and aftertreatment advancements. Future progress in advanced combustion technologies, next-generation injection systems, new materials, and optimized control strategies will be essential for gaseous-fuel engines to play a significant role in future eco-friendly power systems.

Key words : Gas engine, Ammonia engine, Hydrogen engine, LPG engine, CNG engine, Fuel injection, Liquid phase injection, Direct injection, Alternative fuels, Hydrogen co-combustion engine, Ammonia dual fuel engine

1. Introduction

As the global response to the climate crisis intensifies and the demand for a carbon-neutral society increases, innovative changes are required throughout the entire energy system. In particular, internal combustion engines, which contribute significantly to energy consumption and greenhouse gas emissions within the transportation and power generation sectors, are now undergoing fundamental technological innovations to ensure sustainability under increasingly stringent environmental regulations. Fully electrified and fuel cell systems are considered ideal alternatives; however, their widespread adoption across all sectors remains challenging in the short term due to technical and economic limitations, as well as infrastructure construction issues. Accordingly, the development of technologies that maximize the efficiency of existing internal combustion engines and utilize clean fuels is emerging as a realistic transitional or complementary solution. In this context, internal combustion engines powered by gaseous fuels are becoming increasingly important as a more environmentally friendly and efficient power system compared to conventional fossil fuel-based technologies.

This review paper covers a range of gaseous fuels, from liquefied petroleum gas(LPG) and compressed natural gas (CNG), which are widely used due to their relatively well-established infrastructure, to hydrogen and ammonia, which are gaining attention as the ultimate eco-friendly, zero-emission fuels when burned. In particular, hydrogen

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and ammonia are expected to serve as key energy carriers and carbon-free fuels for the future hydrogen economy. Along with fuel cell systems, they are expected to serve as key power sources that will lead to decarbonization in the transportation and industrial sectors.[1)]

Although fuel cells have high energy conversion efficiency, hydrogen and ammonia internal combustion engines are actively being researched and developed as important alternative technologies in certain fields (e.g., large ships and long-distance transportation), where application is difficult due to constraints such as cost, durability, and operating conditions.

To unlock the full potential of these diverse gaseous fuels, it is essential to develop core engine technologies tailored to the unique physicochemical properties of each fuel. In particular, fuel supply and injection system technologies that precisely deliver fuel, promote the formation of an ideal mixture with air, and regulate the combustion process are key factors in determining engine performance and exhaust gas characteristics. In addition, combustion control strategies that ensure stability and maximize efficiency, along with post-treatment technologies designed to effectively reduce specific harmful emissions generated during the combustion of each fuel, are also regarded as core technologies.

Therefore, this review paper aims to provide a comprehensive overview of the current development status of core internal combustion engine technologies using major gaseous fuels such as LPG, CNG, hydrogen, and ammonia, with a particular focus on fuel injection systems, while analyzing the major challenges associated with each technology. We examine the technological challenges, as well as research and development trends, to overcome them according to the characteristics of each fuel and propose future directions for the development of gaseous-fuel engine technology.

2. Core Technologies of Gaseous-Fuel Engines

Maximizing the performance and eco-friendliness of gaseous-fuel engines requires a thorough understanding of each fuel's unique characteristics and the application of core technologies tailored to those properties. This chapter compares the physicochemical properties of major gaseous fuels with those of gasoline, and outlines the overall development status and direction of fuel supply and injector technologies, which are central to gaseous-fuel engine technology.

2.1 Characteristics of Gaseous Fuels

Each gaseous fuel has distinct combustion and physical properties compared to gasoline, which directly affect engine design and operational strategies.

As shown in Table 1, hydrogen (H_2) exhibits an overwhelmingly faster flame propagation speed compared to other fuels, whereas ammonia (NH_3) displays very slow propagation characteristics. This has a significant impact on combustion time, combustion stability, and abnormal combustion (e.g., backfire and knocking) control strategies when designing engines. Ammonia is suitable for large marine engines that operate at relatively slow speeds and do not require fast flame propagation. LPG and CNG exhibit flame speeds similar to gasoline, and possess higher octane numbers than conventional gasoline. This enables the possibility of improving thermal efficiency through higher compression ratios. Since CNG is delivered in a gaseous form, it suffers from reduced volumetric efficiency.

Hydrogen has a very high heating value per mass, a fast combustion rate, and a wide combustion range, which together allow for high-efficiency combustion. However, its remarkably low energy density per volume results in

Table 1 Comparison of key fuel properties

Property	Gasoline	LPG	CNG	Hydrogen (H_2)	Ammonia (NH_3)
LHV (MJ/kg)	~44	~46	~50	~120	~18.6
Boiling pt. (^oC)	35-200	0.5-42	-162	-253	-33
Autoign. temp. (^oC)	230-460	365-470	540-630	500-585	~651
RON	90-98	94-112	120-130	>130	~130
Viscosity (μPa · s)	N/A (gas)	~8	~11	~9	~10
Flame sp. (m/s)	0.4-0.6	~0.4	~0.4	~2.9	~0.07

difficulties in storage and supply, while controlling abnormal combustion due to low ignition energy and fast combustion rate remains a key challenge. Ammonia has no carbon emissions and is easily liquefied, which offers advantages for storage and transportation. Nevertheless, its low heating value, slow combustion rate, and high ignition temperature make securing combustion stability challenging.

2.2 Current Status of Fuel Supply and Injector Technology

Early gaseous-fuel engines mainly used the mixer method, single point injection(SPI), or gaseous-phase port fuel injection(PFI). While these methods have relatively simple structures, they present challenges in precisely controlling the air-fuel ratio and tend to reduce volumetric efficiency, particularly with gaseous fuel injection.

For fuels that can be readily liquefied at room temperature, such as LPG, liquid-phase injection(LPI) technology has been developed to inject the fuel in its liquid state into the intake port. This approach improves volumetric efficiency and fuel metering precision by utilizing the intaking cooling effect caused by the latent heat of vaporization. However, as shown in Fig. 1, technical challenges have emerged, including icing problems caused by the phase change of liquid fuel and the need to ensure the durability of the pump/injector.[1)]

Recent technological developments have been focusing on direct injection(DI) of fuel into the combustion chamber. In CNG engines, this solves volumetric efficiency problems, increases output, and facilitates the application of high compression ratios. The key is the development of high-pressure injectors and the optimization of the nozzle design. In LPG engines, while the advantages of LPI can be inherited, the cooling effect inside the combustion chamber can be maximized, thereby enabling further improvements in efficiency and power output through precise combustion control. Furthermore, both the high-pressure liquid injection and spray control technology are important.

As shown in Fig. 2, it is considered a core technology of hydrogen engines because it effectively addresses the backfire problem, in which the cylinder flame comes out of the intake port, while enabling high volumetric efficiency and precise combustion control.[2)] The primary challenges are achieving an ultra-high pressure injection, addressing material issues (hydrogen embrittlement), and ensuring fast response. In ammonia engines, direct injection is essential for overcoming low combustibility and ensuring combustion stability. Effective flash boiling control and optimal spray formation are important during liquid injection.

Overall, fuel supply and injector technologies for gaseous-fuel engines are evolving from initial gaseous intake port injection to liquid injection and direct injection methods, aimed at improving both efficiency and control precision. In particular, for new fuels (e.g., hydrogen and ammonia), direct injection technology is regarded as a core technology that helps to overcome the inherent challenges of fuel and enhance engine performance. Consequently, the development of high-pressure injectors, pumps, and precision control systems being suitable for the specific properties of each fuel is actively underway. The following chapters will provide a detailed overview of the current status and the challenges of engine technology for each type of fuel.

Fig. 1 Icing phenomena of liquid LPG injection

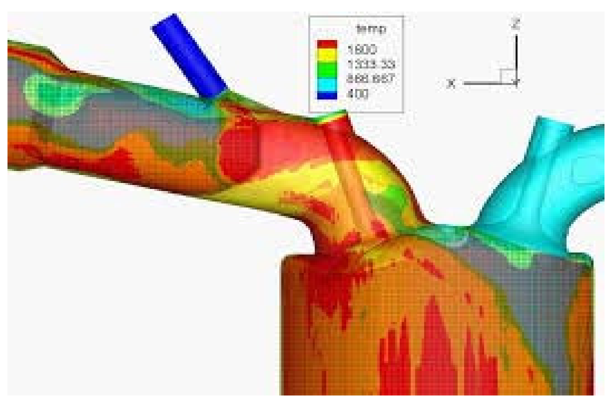


Fig. 2 Backfire in the intake port of a hydrogen engine

3. Ammonia Engine

3.1 Background

Ammonia does not contain carbon, so it does not emit carbon dioxide when burned. Recognized for its potential as an efficient hydrogen storage and transport medium (hydrogen carrier), it is rapidly emerging as a next-generation carbon-free fuel. In particular, ammonia is gaining attention as a practical solution for decarbonizing hard-to-electrify industrial sectors such as shipping, large-scale power generation, and agricultural machinery. As a result, development is underway for internal combustion engine technologies that use ammonia directly as a fuel.

The main purpose of ammonia engine research and development is to contribute to the achievement of greenhouse gas reduction targets, with a focus on ensuring that ammonia-fueled vessels comply with the stringent environmental regulations of the international shipping sector (e.g., IMO 2050).[3,4] Although hydrogen is difficult to produce, store, and transport, ammonia can serve as an effective medium for hydrogen storage and transport due to its ease of liquefaction and high energy density. Another advantage is that the ammonia production and distribution infrastructure is already well established through the existing fertilizer industry and others. The ability to convert it into an eco-friendly fuel while utilizing a significant portion of existing internal combustion engine technology and infrastructure provides advantages in terms of initial investment cost and ease of conversion compared to electrification or fuel cell systems.

The development of ammonia engines and fuel supply systems is being led by large engine manufacturers (e.g., MAN Energy Solutions, Hyundai Heavy Industries, Wärtsilä, IHI Power Systems, and WinGD), especially in the shipping sector, which is facing increasingly stringent carbon emission regulations.[5,6] These companies are either developing the entire fuel supply system, including the fuel injector, as part of the ammonia engine system or collaborating with specialized parts partners.

3.2 Development of Ammonia Injection Technology

As previously discussed, the challenging combustion properties of ammonia, such as low combustion speed and high auto-ignition temperature, make fuel injection and mixture formation technology extremely important for achieving optimal engine performance. Although port injection is theoretically possible, it is not considered to be a major research and development direction because it can lead to uneven mixture formation in the intake port, combustion instability, and reduced efficiency due to low combustion speed, and potential icing problems.

Currently, most research and development efforts on ammonia engines are focused on direct injection into the combustion chamber.[7,8] It is advantageous to improve combustion conditions by directly injecting ammonia along with a pilot fuel (mainly diesel) in a compression ignition (CI) engine to induce stable ignition, and to improve ignition and combustion conditions through stratified combustion in a spark ignition(SI) engine.

In addition, precisely controlling fuel distribution and injection timing in the combustion chamber can increase combustion efficiency and reduce harmful emissions. Active research is underway on the direct injection of ammonia in its liquid state, with the key technology task being the control of the flash boiling phenomenon, as shown in Fig. 3.[9] Flash boiling has the advantage of promoting atomization, but it is difficult to predict and control. Research is in progress to control it through fuel temperature, injection pressure, ambient pressure management, and nozzle design optimization.[10]

As a major research field, active studies are being conducted on simulation and modeling of the ammonia direct injection system,[8,10] investigation of liquid ammonia spray and combustion characteristics, evaluation of the possibility of utilizing GDI injectors, and research on injector characteristics across a wide temperature range, such as those for ships.[7] The effect of ambient pressure on spray characteristics is also an important research topic.[11]

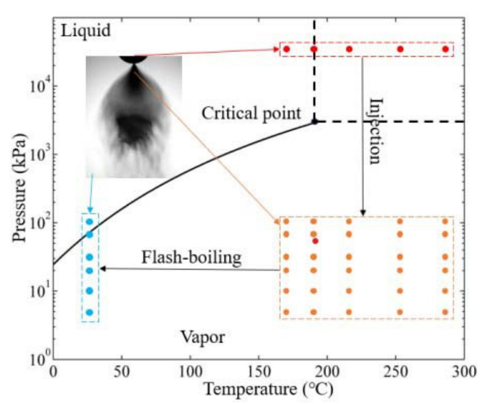


Fig. 3 Flash boiling region of an ammonia engine

3.3 Challenges of Ammonia Engine Technology

Ammonia engines are an important technological alternative for carbon neutrality; however, technical challenges in many areas such as combustion, exhaust gas, fuel supply, and durability must be resolved to ensure commercial viability.

Due to its low combustion speed and high ignition energy requirements, ammonia is susceptible to incomplete and unstable combustion, which in turn leads to low thermal efficiency. To address this issue, the dual-fuel operation method that uses a small amount of highly combustible fuel such as diesel or hydrogen as a pilot fuel to assist the ignition and combustion of ammonia is currently the focus of intensive research.[12)]

In addition, various approaches are being explored, including improving combustion speed and stability by mixing hydrogen generated through the cracking of ammonia or externally supplied hydrogen with ammonia;[13)] enhancing ignition and combustion by increasing the compression ratio of the engine or by supercharging to increase the temperature and pressure in the combustion chamber;[14)] applying advanced ignition systems such as high-energy spark plugs or pre-combustion chambers; and optimizing the combustion chamber shape to promote mixing and combustion by strengthening the swirl and tumble flow in the combustion chamber.[15)]

Since ammonia contains nitrogen in the fuel itself, nitrogen oxides(NOx) are inevitably produced during the combustion process. In the event of incomplete combustion, nitrous oxide(N_2O), a potent greenhouse gas, or unburned ammonia, a harmful substance, may be emitted. To address this issue, combustion control optimization is required to suppress NOx and N_2O production during the combustion process itself through the precise control of the air-fuel ratio and combustion temperature.

Given the current state of technology, the application of a high-efficiency aftertreatment system is considered essential, and the development and integrated application of an ammonia slip catalyst(ASC) to remove ammonia slip along with NOx reduction using urea-based SCR system are being developed as a key technology.[16)] Ammonia has a low heating value and it requires a large-volume fuel supply. It is also corrosive to certain materials, necessitates control of flash boiling when injected in the liquid phase, and raises safety concerns due to its toxicity.

To address these challenges, research and application are being conducted on methods to apply corrosion-resistant materials to fuel lines, pumps, and injectors; develop high-pressure pumps and injectors capable of high-flow injection (e.g., injectors for ships that must operate over a wide temperature range); build systems that precisely control fuel temperature and pressure for flash boiling control; and strengthen safety systems such as dual-pipe structures and leak detection sensors to prevent fuel leakage.[9)]

Durability concerns include the possibility of damage to engine components caused by corrosive fuel environments and ammonia combustion products. Long-term durability is a key requirement, especially for large engines that demand extended service life.

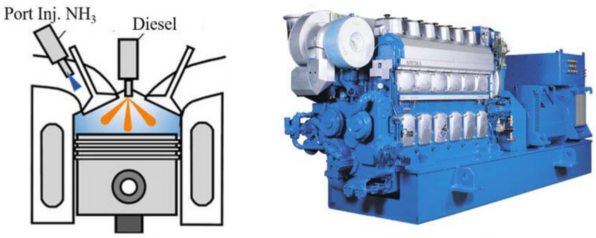
To address this, it is necessary to develop and implement advanced materials with excellent corrosion and wear resistance, optimize lubrication systems suitable for ammonia environments, and develop regular maintenance programs to ensure reliable operation. Currently, the development of ammonia engines is primarily focused on dual-fuel systems and high-efficiency aftertreatment technologies, with intensive research and development efforts aimed at enhancing commercial viability.

3.4 Ammonia Dual-Fuel Engine

3.4.1 Fuel Injection Method

An ammonia dual-fuel engine uses ammonia as the primary fuel, supplemented by a small amount of another fuel(pilot fuel) as an ignition source to promote ammonia combustion. It is often modified based on an existing compression ignition(diesel) engine. Diesel oil, heavy oil, biodiesel, hydrogen, and others can serve as pilot fuels, with the diesel pilot method being the most common.[17)]

As shown in Fig. 4, ammonia is being researched for injection either into the intake port in a gaseous or liquid state, or directly into the combustion chamber in a liquid state, demonstrating advantages in combustion control and efficiency. Pilot fuel is generally injected directly into the combustion chamber, and a small amount is injected at the end of the compression stroke, where it ignites spontaneously from the heat of compression. This process plays a role in starting the combustion of ammonia, the main fuel.



(a) dual fuel injection concept (b) Wärtsilä DF32 engine

Fig. 4 Ammonia-diesel (pilot injection) dual fuel engine concept and a commercial engine

3.4.2 Engine Operation Strategy and Characteristics

Ammonia energy ratio(AER) refers to the proportion of ammonia in the total fuel energy. As shown in Fig. 5, one of the main goals of the study is to maximize AER to minimize carbon emissions due to pilot fuel combustion. Although some studies have reported achieving high AERs of up to 95–98 %, there are also studies that show that an AER of 60–80 % is appropriate for actual operation in order to optimize efficiency and exhaust gas emissions.[18)]

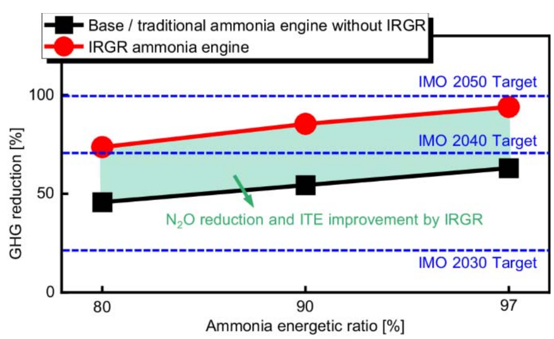


Fig. 5 GHG reduction with AER variation in ammonia engine

It is important to optimize the injection strategy, such as the injection timing and amount of pilot fuel, as well as the injection timing and method of ammonia, according to the engine load and speed requirements. For example, increasing the diesel injection pressure and advancing the injection timing can promote premixing with ammonia, thereby improving combustion and increasing thermal efficiency. In terms of performance, thermal efficiency can be improved or decreased compared to pure diesel operation based on the AER and operating conditions, and the possibility of improving efficiency through optimal control is reported. As the ammonia ratio increases, securing combustion stability can become more difficult, prompting research into methods such as hydrogen mixing.[19)]

4. Hydrogen Engine

4.1 Importance of Hydrogen Engine

Hydrogen, the ultimate carbon-free fuel that produces only water when burned, is gaining attention as a key energy source for solving global warming problems and realizing a carbon-neutral society. In particular, using hydrogen as a fuel in the internal combustion engine sector is regarded as a promising approach to achieving zero carbon emissions while utilizing existing engine technology and infrastructure. Hydrogen engines have high theoretical thermal efficiency potential and fast response, and they may provide advantages in terms of cost and durability compared to fuel cell systems. As a result, their potential applications in various transportation and power generation fields are being actively researched. In particular, in the field of large engines (e.g., ships, power generation, and heavy-duty trucks), their importance is increasingly highlighted as a practical carbon-free power source that can complement the limitations of fuel cell systems.

4.2 Development of Hydrogen Injection Technology

The unique characteristics of hydrogen fuel have necessitated the development of a fuel injection method for engine application. The port injection method was attempted in early hydrogen engine research by injecting hydrogen into the intake port. Although it had the advantage of a relatively simple structure, it faced significant challenges due to the unique characteristics of hydrogen, namely, its gaseous state at room temperature and pressure, extremely low density, broad combustion range, exceptionally low minimum ignition energy, and rapid combustion speed. As shown in Fig. 6, there is a decrease in volumetric efficiency and backfire. Since gaseous hydrogen occupies the intake air space, the amount of air flowing into the engine decreases, thus reducing output and efficiency. In addition, when the intake valve opens, the hydrogen-air mixture in the intake port and manifold can easily be ignited due to residual high-temperature gas, causing the flame to flow back into the intake system. This issue poses a fatal risk that can lead to engine damage and driving instability.[20,21)]

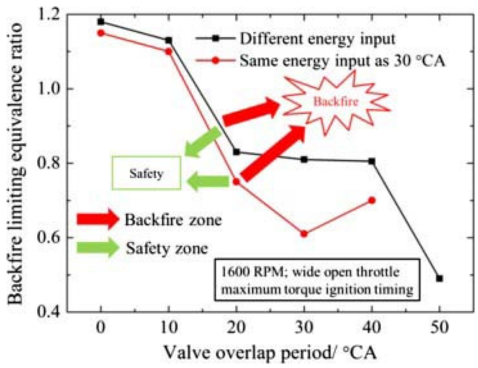


Fig. 6 Backfire zone with valve overlap periods in a hydrogen engine

Hydrogen Direct Injection (H_2DI) is currently the focus of research and development aimed at addressing the fundamental issues of the port injection method, particularly the backfire problem, and at maximizing the performance of hydrogen engines.

Since direct injection does not have a fuel-air mixture in the intake system, it can effectively prevent backfire. In addition, it can secure high volumetric efficiency without reducing intake efficiency, and offers advantages in achieving high output when combined with supercharging. As shown in Fig. 7, the injection timing of hydrogen in the cylinder can be precisely controlled to adjust the mixture distribution, whether homogeneous or stratified, within the combustion chamber, thereby optimizing the combustion process. This contributes to improved efficiency and increased output. Fuel injection timing can be delayed to the latter part of the compression stroke, which can reduce the risk of pre-ignition.[22-24)]

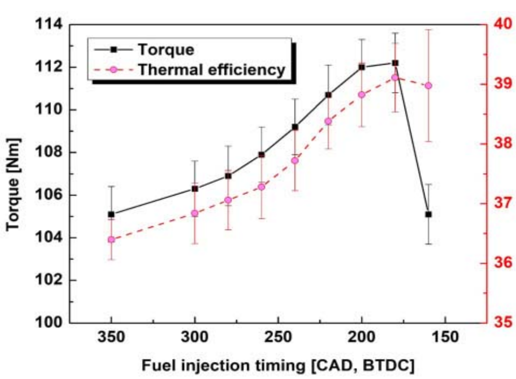


Fig. 7 Effect of injection timing on performances in a hydrogen direct injection engine

4.3 Challenges of Hydrogen Engine Technology

Hydrogen engines present a promising alternative for producing power without carbon emissions by utilizing the existing engine infrastructure. However, there are several technical challenges that must be addressed to achieve commercial viability. These challenges are particularly evident in the development of direct injection engines, including the following specific technical difficulties.

First, controlling NOx emission remains a significant challenge. While hydrogen combustion itself does not emit carbon, the high combustion temperatures can cause nitrogen in the air to oxidize, leading to the formation of NOx. Solutions include lowering the combustion temperature by operating with a very lean air-fuel ratio by utilizing the wide combustion limit of hydrogen; controlling the combustion temperature through exhaust gas recirculation (EGR), as shown in Fig. 8;[25)] controlling the combustion temperature through water injection, etc.;[26)] suppressing the creation of local high-temperature areas by optimizing the injection timing and strategy;[24)] and applying a high-efficiency aftertreatment system such as SCR.[27)]

Second, it is essential to control abnormal combustion and ensure stable combustion. The high flame speed and low minimum ignition energy of hydrogen increase the likelihood of abnormal combustion events, such as pre-ignition and knocking. Effective control of the rapid heat release rate is particularly critical in large engines.[28,29)] Solutions include precise injection control (e.g., timing, number of times, and pressure) via direct hydrogen injection,[30,31)] ensuring combustion stability through the optimization of the combustion chamber and piston shape,[32)] and applying an appropriate ignition system (e.g., optimizing

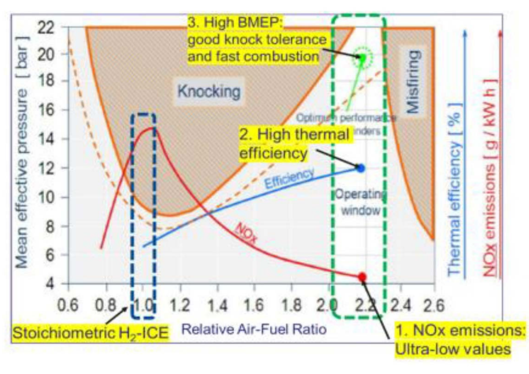


Fig. 8 NOx reduction with lean burn and high EGR in hydrogen engine

spark plug position and energy).[33] Research on hydrogen auto-ignition characteristics is also important for establishing combustion control strategies.

Third, it is necessary to achieve technological maturity in high-pressure hydrogen direct injection fuel systems. It is essential to develop injectors and fuel pumps capable of ultra-high-pressure and high-flow-rate injection at pressures exceeding several hundred bar, select materials resistant to hydrogen embrittlement, and implement precise flow control and leak prevention technologies under extreme pressure conditions.[34-36] To this end, major parts manufacturers, such as Bosch,[37] Phinia,[38] and Liebherr,[39] are participating in the development of hydrogen-only injectors and systems, and there is active research on design methodologies, including computational fluid dynamics(CFD) analysis, to optimize injector sizing.

Fourth, securing long-term durability and reliability is important. Material deterioration due to hydrogen embrittlement, wear of high-pressure operating parts, and lubrication problems can affect long-term durability. To address these issues, it is necessary to develop hydrogen-resistant materials and coating technologies, apply innovative designs (e.g., Bosch's lubrication-free injectors), develop lubrication systems suitable for hydrogen environments, and secure maintenance technologies.

Despite these challenges, research and development of hydrogen engines centered on hydrogen direct injection technology is ongoing, and by solving technical difficulties, the potential of hydrogen as a carbon-free power source is increasing.

5. LPG/CNG Engine

5.1 Characteristics

LPG and CNG have long been used as alternative fuels for internal combustion engines and are widely used globally, thanks to their relatively well-established fuel supply infrastructure. Compared to gasoline or diesel, these fuels offer environmentally friendly advantages with almost no sulfur oxides(SOx) and particulate matter(PM) emissions when burned. These fuels are also advantageous in reducing carbon monoxide(CO) and hydrocarbon(HC) emissions. In addition, a high octane number allows for an increased engine compression ratio, which, in turn, enhances thermal efficiency.

However, LPG and CNG are hydrocarbon-based fuels, so they have the fundamental limitation of emitting carbon dioxide when burned. This limitation prevents the achievement of the carbon neutrality goal pursued through the use of carbon-free fuels such as hydrogen and ammonia. Nevertheless, they remain important eco-friendly fuel options in the short and medium term due to their compatibility with existing internal combustion engine systems, economic efficiency, and relatively easy emission reduction characteristics.

5.2 Development of LPG Engine Technology

LPG engine technology has steadily advanced to improve efficiency and eco-friendliness, with the development of fuel injection methods playing an important role. Gaseous port injection(gaseous PFI), which involves injecting LPG in a gaseous state into the intake port, is a method widely used in both initial and retrofit markets. Although the structure is simple, it has the drawback of reduced power output caused by a decrease in volumetric efficiency.

Liquid port injection(LPI) addresses the problem of reduced volumetric efficiency by injecting LPG in its liquid form into the intake port,[40] while also boosting output through the intake cooling effect created by the latent heat of vaporization.[41,42] Theoretical and experimental studies have been conducted on the characteristics of injector durability, exhaust gas, and liquid injection systems.[43] There is a possibility of icing problems due to rapid vaporization, so measures such as injector heating are necessary,[44] and securing the durability of the fuel pump is also a technical challenge due to the characteristics of low-viscosity fuel.[45] Hyundai KEFICO and other companies have developed and commercialized injectors and pumps for LPI systems.

Liquid phase direct injection(LPDI) is a cutting-edge technology that directly injects liquid LPG into the combustion chamber, similar to the gasoline direct injection (GDI) technology. Building on the advantages of LPI, this technology can further enhance thermal efficiency and power output by maximizing the combustion chamber cooling effect, increasing the compression ratio, and providing precise combustion control.[46] Studies have been conducted on the spray characteristics of LPG using GDI-type injectors, and key challenges include the development of high-pressure injection technology and ensuring the durability of injectors and pumps. Recently, the development of a T-LPDI engine combined with a turbocharger and its commercialization application to 1-ton trucks has increased technological maturity.[47)]

5.3 Development of CNG Engine Technology

CNG engine technology has also improved its performance and efficiency by transitioning from the port injection method to the direct injection method. At present, various technologies are being applied to improve efficiency and reduce exhaust gas, especially in the large engine sector. The port injection method, which injects gaseous CNG into the intake port, is the most common method. Reduced volumetric efficiency has remained a challenge, and multi-hole nozzle injectors have been studied to secure mixture uniformity.[48-50)] Several companies, including Bosch, are manufacturing related systems and parts.

The direct injection method solves the volumetric efficiency problem, increases output, and enables precise combustion control through direct injection within the combustion chamber.[51)] Research is actively being conducted on the effects of high-pressure injection characteristics and nozzle design on exhaust gas, including PM, and combustion. Companies like Westport have commercialized high-pressure direct injection systems for large engines.[52)]

An in-depth study is underway on the strategy of increasing the compression ratio to maximize engine efficiency by utilizing the high octane number of CNG. This is achieved through the unique high knocking resistance of CNG, the application of direct injection technology that is advantageous for knock suppression, the lean combustion operation that contributes to NOx reduction and efficiency improvement, and the application of the Miller Cycle that increases the expansion ratio in combination with a high geometric compression ratio.[53)]

5.4 Technological Development Using Hydrogen Co-Combustion

LPG and CNG engines have a fundamental limitation in carbon dioxide emission, so the development of technology to mix and use hydrogen is being sought as an important technological development to reduce these emissions and further improve engine efficiency.

One promising approach to incorporating hydrogen in LPG engines is the development of on-board reforming technology, which generates hydrogen-rich reformed gas by catalytically reforming a portion of the LPG fuel within the vehicle, eliminating the need for separating hydrogen storage and utilizing the reformed gas for engine combustion, as shown in Fig. 9.[54)]

According to related studies, this method can expand the lean combustion operation range of LPG engines and improve combustion stability with the help of the generated hydrogen.

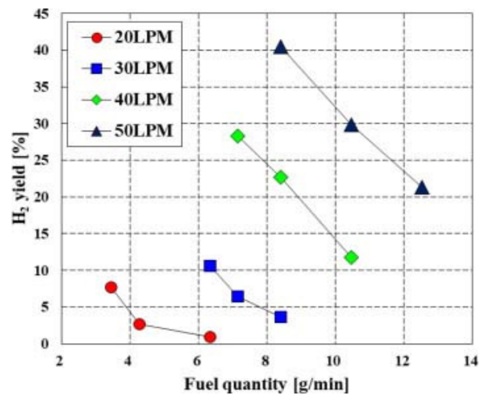


Fig. 9 Hydrogen yield ratio with LPG fuel quantity by on-board reforming

An optimized air-fuel ratio clearly improves fuel efficiency and reduces NOx emissions compared to the existing LPG engine. This shows the potential to enhance both the eco-friendliness and efficiency of the LPG engine by utilizing the combustion promotion effect of hydrogen.[55)]

As a way to utilize hydrogen in a CNG engine, research is actively being conducted on using hydrogen directly mixed in the form of HCNG (Hydrogen-enriched CNG), as shown in Fig. 10.

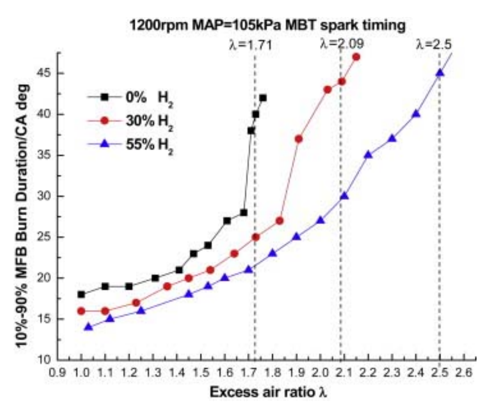


Fig. 10 Mass burn duration reduction with H_2 enrichment in a CNG engine

Adding hydrogen to CNG increases the combustion speed of the fuel mixture and extends the lean combustion limit, leading to improved thermal efficiency and reduced CO and HC emissions. The use of low-carbon hydrogen blends also helps to significantly reduce carbon dioxide emissions.[56-59]

In particular, the low-carbon hydrogen blend ratio can be applied without major changes to the existing CNG engine system. Therefore, it is regarded as a practical approach to gradually reduce carbon emissions during the transitional phase before the full development of the hydrogen infrastructure.

6. Conclusion

This review explores the development status and challenges of key technologies of major gaseous-fuel(LPG, CNG, hydrogen, ammonia) engines, especially fuel injection systems. Gaseous-fuel engine technology is an important alternative to internal combustion engines in the pursuit of carbon neutrality, and continues to evolve through advancements in fuel supply and injection technologies.

Based on advanced technologies and infrastructure, researchers are actively exploring ways for LPG/CNG engines to increase efficiency and reduce carbon dioxide emissions through direct injection and hydrogen co-firing. Hydrogen engines that utilize carbon-free fuels are being studied as core technologies for direct injection that address the backfire issue; however, challenges remain in controlling NOx emissions and ensuring the durability of high-pressure systems/materials. Despite its advantages as a hydrogen carrier, ammonia engines have low flame propagation speed and nitrogen emissions. For this reason, research is focused on the development of dual-fuel and high-efficiency aftertreatment technologies, with particular potential for application in large engines.

Further efforts are needed to address the following key challenges for the ongoing advancement of gaseous-fuel engine technology. It is important to verify eco-friendliness through the development of high-efficiency combustion and next-generation injection systems, securing new materials and durability against hydrogen embrittlement and ammonia corrosion, and developing high-efficiency post-processing technology that matches the characteristics of each fuel's exhaust gas. By overcoming these technical challenges, gaseous-fuel engines are expected to play a key role in achieving carbon neutrality goals, along with fuel cells and electric power systems, as an important axis of future eco-friendly power systems.

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