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Review

Lean Combustion Enhancement and Decarbonization Technologies for Natural Gas Engines

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Abstract

This study explores key technological challenges and innovative strategies for improving the combustion performance and emission characteristics of low-carbon fuel engines, with a focus on natural gas applications. The core bottlenecks of natural gas combustion, including slow combustion speed and high methane slip under lean burn conditions due to wall quenching, crevice effects, and the long distance of flame propagation from the ignition zone to the whole cylinder, are analyzed. The decarbonization of engines further aggravates these issues. Technological solutions are summarized in four categories, including turbulence enhancement, high-energy ignition, fuel reactivity modification, and fuel synergy with zero-carbon fuels. Geometry modifications of the combustion chamber, dual-fuel operation, pre-chamber ignition, and fuel activation are systematically reviewed and evaluated. A fusion technology integrating diesel pilot ignition with jet flame propagation is analyzed as a new combustion concept, termed induced jet flame combustion. This approach demonstrates significant potential in enhancing both combustion efficiency and stability, especially for lean burn conditions. This work highlights the role of natural gas engines as a transitional technology and a support platform for ultralow-emission and high-efficiency power systems fueled with low/zero-carbon fuels in the context of global decarbonization goals.

Keywords: natural gas; lean burn; diesel pilot; induced flame jet combustion; jet; flame propagation; engine

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1. Introduction

The global imperative to decarbonize the transportation [1] and power generation sectors has catalyzed an urgent shift away from conventional fossil fuels [2,3]. This transition necessitates the development and deployment of high-efficiency, ultralow-emission propulsion systems capable of utilizing sustainable, low/zero-carbon fuels such as hydrogen [4], ammonia [5], and methanol [6]. However, the widespread adoption of these future fuels is impeded by significant combustion-related challenges intrinsic to their physicochemical

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properties [7], most notably difficult ignition [8,9] and slow flame propagation [10] from the ignition zone to the entire combustion chamber under lean burn conditions in the engine cylinder. Hydrogen has an extremely high burning rate; however, in practical engineering applications, it is necessary to adopt a lean combustion operation mode to precisely regulate the hydrogen combustion phase, effectively suppress the formation of nitrogen oxides (NO_x), and avoid abnormal combustion phenomena such as pre-ignition and knock. Under typical lean combustion conditions with an equivalence ratio of $\varphi = 0.5$ and an ambient pressure of 1 atm, the laminar burning velocity of hydrogen will significantly decrease from 110 cm/s at $\varphi = 0.7$ to below 50 cm/s, and the flame propagation capacity is greatly weakened, which also poses a severe challenge to the stability of the combustion process from the ignition zone to the whole cylinder. These bottlenecks are particularly acute in applications demanding high reliability and power density such as large-bore marine [11,12] and stationary power engines.

Decades ago, natural gas [13] emerged as a critical and strategic alternative fuel. Its importance stems not only from its lower carbon percentage [14] compared to traditional liquid fuels but also from a confluence of practical advantages, including abundant global reserves, low cost, mature supply infrastructure, and long-time and well-established engine-employing technologies [15]. Furthermore, the prospect of bio-derived [16] or synthetic methane [17] enhances its sustainability profile. More importantly, natural gas shares fundamental combustion challenges of low laminar flame speed [18] and hard ignition due to high chemical bond energy with many prospective low/zero-carbon fuels [19]. The technological breakthroughs achieved in optimizing [20] the premixed combustion of natural gas directly provide solutions for ammonia and other premixed low/zero-carbon fuels.

Extensive research has been dedicated to overcoming the core limitations of natural gas combustion, including a slow burning velocity and methane slip. The strategies [21] include diesel pilot, geometry optimization of combustion chamber [22], pre-chamber turbulent jet ignition (TJI), and fuel activation via additives or hydrogen. Recent trends indicate a clear paradigm shift from pursuing single-technology optimizations toward the deep integration and synergistic control of multiple physical and chemical processes. An example of this trend is induced jet flame combustion, which synergistically combines the chemical activation of a pilot diesel fuel with the physical enhancement of a turbulent jet flame [23] to create distributed, high-intensity ignition sources and flame jet [24] propagation.

Despite considerable progress, a cohesive framework that systematically links the fundamental physicochemical origins of these combustion bottlenecks to the spectrum of technological solutions and further maps their transferability to future zero-carbon fuels is still lacking in the literature. Most reviews remain confined to either specific technologies or focus on fuel types. This review aims to provide a comprehensive and systematic analysis of the technological pathways for enhancing combustion from the ignition zone to the whole cylinder and reducing emissions in natural gas engines.

Figure 1 shows the conceptual framework of this paper. The challenges in high emissions, low combustion efficiency, knock risks, and related technical optimizations, including enhancements in ignition reliability, acceleration in combustion speed, and stabilization of end-gas combustion, are systematically reviewed in detail. In natural gas engines, the combustion process can be initiated primarily through two distinct ignition modes, spark ignition (SI) [25,26] and compression ignition (CI) [27,28]. Each mode possesses inherent characteristics that influence engine performance, efficiency, and emissions, making their comparative analysis essential for identifying the most suitable approach under specific operating conditions. Therefore, CI and SI for natural gas have been discussed and compared. Then, the landscape of combustion enhancement [29,30] strategies, including turbulence enhancement, high-energy ignition, fuel reactivity modification, and fuel synergy are reviewed and categorized in detail. Furthermore, a fusion technology is proposed, which combines multi-zone ignition [31] and jet flame propagation, named as induced jet flame combustion, to enhance combustion speed under lean burn conditions on large-bore engines. This work will provide a theoretical reference for the development of premixed low/zero-carbon fuel combustion technologies. By establishing this systematic framework, from problems to integrated solutions and future extrapolation, this review aims to serve as a strategic reference for researchers and engineers navigating the complex transition from conventional to sustainable, carbon-neutral premixed combustion systems.

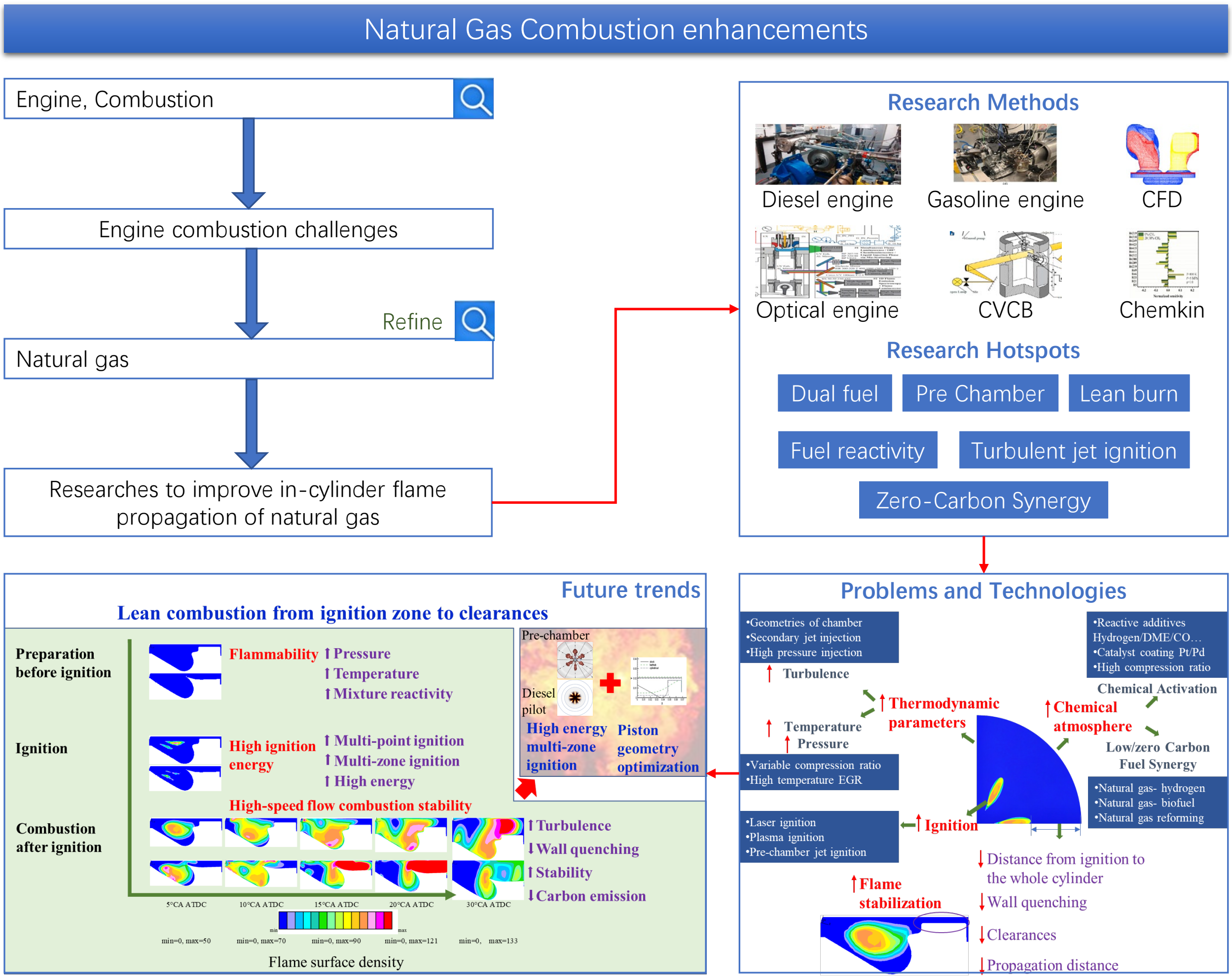

Figure 1. Conceptual framework of this paper.

2. Overall Review of Natural Gas Engine

Figure 2 reveals the natural gas engine temporal evolution of three stages. The early stage is from year 2005 to 2012 [32,33], in which dual-fuel, hydrogen [34], chemical kinetic mechanism [35], and combustion efficiency show sustained bursts, corresponding to the initial application phase of natural gas engines and the need for performance and emission optimization. The mid-stage is from 2013 to 2019 [36–40], in which lean burn, pre-chamber, and combustion instability increase, reflecting a shift in research focus toward high-efficiency combustion modes and their stability challenges. The recent stage is from 2020 to 2026, in which methane oxidation catalysis [41] and ammonia–natural gas blending indicate that research frontiers are extending toward carbon-neutral fuel integration. This transition exacerbates difficulties and challenges in ignition and flame propagation from the ignition zone to the whole cylinder.

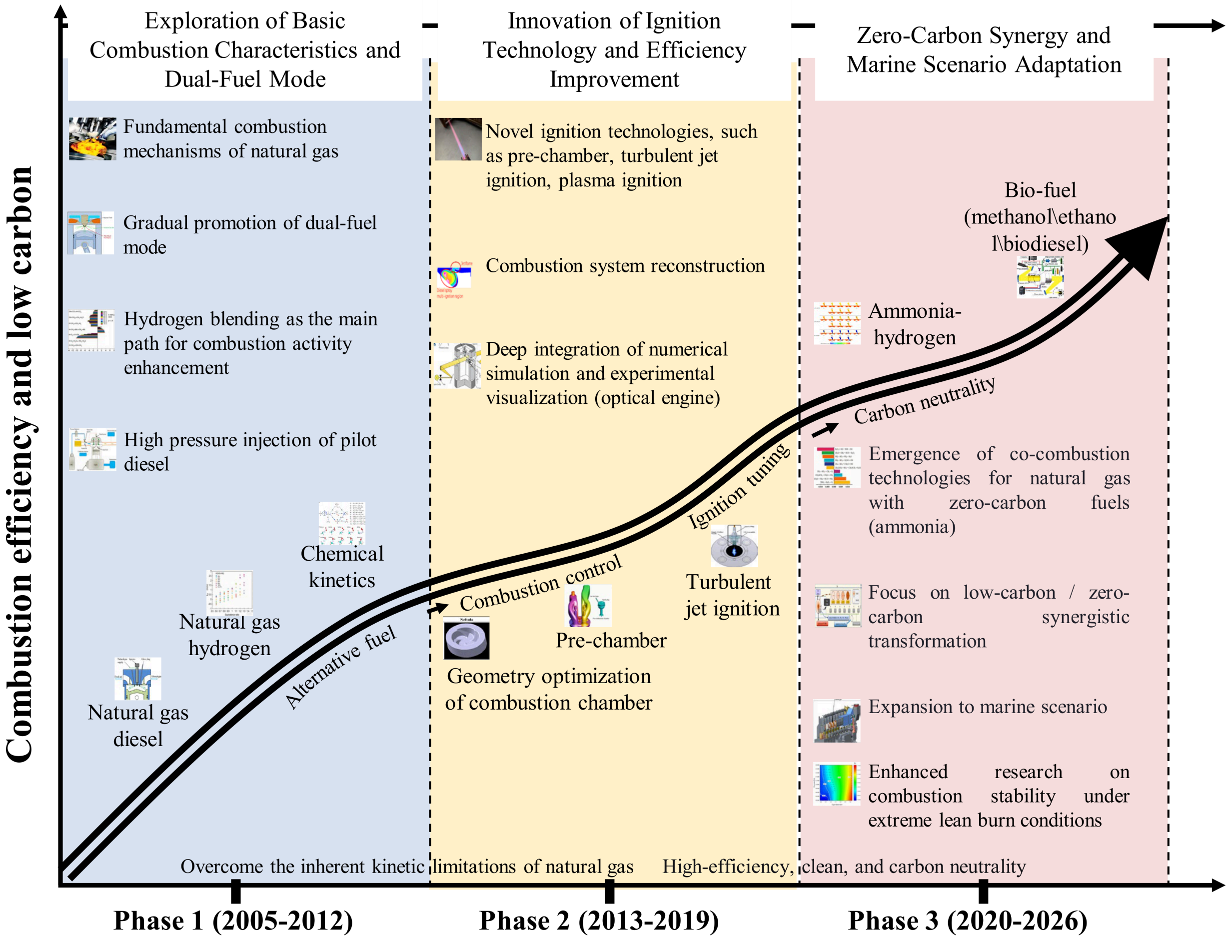

Figure 2. The temporal evolution of natural gas combustion.

Research on natural gas engine combustion has established a knowledge system centered on dual-fuel and lean combustion. These directions collectively signify a paradigm shift in natural gas combustion technology from alternative fuel application to low-carbon intelligent combustion systems, providing scientific support for advancing the critical transitional role of natural gas in achieving the dual carbon goals.

3. Compression Ignition and Spark Ignition of Natural Gas

Natural gas, closely intertwined with other fuels, technologies, research methods, and performance indicators, is a significant low-carbon alternative fuel [42,43] in the current energy transition landscape. Natural gas research is deeply integrated into the existing engine technology system, primarily through diesel and gasoline engines [44], as shown in Table 1. However, the combustion speed of natural gas is slower than that of gasoline and diesel [45], resulting in poor power performance and high methane emissions. The combustion process of natural gas in engines needs to be further optimized. In response, scholars at home and abroad have proposed and developed a series of technologies to enhance the combustion performance [46] of natural gas, including natural gas lean burn [47], pre-chamber ignition [48], dual spark plugs [49], diesel pilot ignition [50], direct injection stratified combustion [51], in-cylinder thermochemical fuel reforming [52], natural gas–hydrogen blending [46], EGR [53], and combinations among these.

One of the mainstream application modes of natural gas is the dual-fuel compression ignition engine. A small amount of diesel serves as the pilot ignition source [44] to ignite the mixture, dominated by natural gas. Diesel pilot ignition technology features a high compression ratio, no throttle loss, minor structural modifications, and excellent combustion and emission performance; hence, it has been widely applied to improve the combustion of methane, ammonia, and methanol. However, diesel-piloted natural gas engines still suffer from problems [54], such as high hydrocarbon emissions, low thermal efficiency under low-load conditions, and knock under high-load conditions, which restrict its application and development process. Optimizing the natural gas combustion process and developing high-efficiency and clean combustion technologies for diesel-piloted natural gas engines are crucial technical approaches to support the large-scale promotion of natural gas-fueled transportation vehicles.

For natural gas in spark ignition engines, the core challenge lies in the contradiction between its high knock resistance and its slow burning velocity. Methane's high octane value (RON $\approx$ 120) permits aggressive compression ratios and extreme lean operation that theoretically lead to high thermal efficiency. However, the inherently low laminar flame speed of methane–air mixtures severely constrains the practical realization of these benefits. Under lean conditions, the combustion duration stretches beyond the optimal crank-angle window, inducing cycle-to-cycle instability, and elevated unburned hydrocarbon emissions. Pre-chamber jet ignition technology emerges as a key breakthrough to accelerate combustion, suppress cycle-by-cycle variation [55], and expand the stable limits under low load conditions.

A pre-chamber [2,48] is a small auxiliary volume located adjacent to the main combustion chamber. It is equipped with a spark plug and communicates with the main chamber through a series of small orifices. In its most basic configuration, the pre-chamber charge is inducted solely from the main chamber during the compression stroke, termed a passive pre-chamber. While structurally simple and widely adopted, the mixture composition of the passive pre-chamber is entirely dictated by the main chamber condition. Under lean- or high-dilution operation, the pre-chamber charge becomes excessively dilute, resulting in weak jet formation and compromised ignition reliability. To overcome this constraint, the active pre-chamber [56] was developed. In this configuration, a dedicated auxiliary fuel supply line provides independent control over the pre-chamber mixture composition, enabling the maintenance of a near-stoichiometric, readily ignitable charge, regardless of the main chamber dilution level. By actively regulating the fuel–air ratio within the pre-chamber, the active design substantially enhances jet vigor, accelerates flame propagation into the main chamber, and extends the stable operating range toward ultra-lean conditions. Despite their differences in charge preparation, both passive and active pre-chambers share the common functional principle that the combustion event within the pre-chamber ejects a high-velocity jet of hot radicals and turbulent flame kernels through the orifices, serving as a distributed ignition source that enlarges the initial flame area and accelerates the overall combustion rate in the main chamber.

Table 1. Comparisons of natural gas integrated into diesel and gasoline engines.

Mainstream Technologies	**Diesel Pilot Ignition [44,50,54,57]**	**Pre-Chamber Jet Ignition [2,48,56]**
Technical Objectives	1. Significantly increase flame propagation speed and shorten combustion duration. 2. Improve lean combustion stability and expand the lean burn limit. 3. Suppress knock tendency at high load conditions.	
Principle	A small amount of diesel, as a highly reactive pilot source, is injected into the cylinder. It auto-ignites, forming multiple high-temperature ignition kernels that ignite the surrounding natural gas–air mixture.	A combustible mixture is formed and ignited within a pre-chamber, generating high-speed, high-temperature turbulent flame jets that are ejected through nozzles into the main combustion chamber, achieving simultaneous multi-point ignition.

Table 1. *Cont.*

Mainstream Technologies	**Diesel Pilot Ignition [44,50,54,57]**	**Pre-Chamber Jet Ignition [2,48,56]**
Characteristics	Multi-zone auto ignition High compression ratio Diesel activation	Multi flame jets and hot radicals High speed flame jets Hydrogen activation
Optimization methods	1. Diesel injection strategy (pressure, timing, pulse width, multi-pulse injection). 2. Optimization of energy substitution ratio between natural gas and diesel. 3. Coupling control with EGR.	1. Optimization of pre-chamber geometry (nozzle design, volume ratio). 2. Pre-chamber mixture formation and control (air-fuel ratio, hydrogen blending ratio). 3. Coordination between jets and main chamber airflow motion.
Applications	Heavy-duty commercial vehicles, marine engines, power generation.	Passenger cars, light commercial vehicles, dedicated natural gas engines.
Development Trends	1. Micro-pilot ignition, extremely low diesel proportion). 2. Integration with EGR and low/zero-carbon pilot fuels (e.g., biodiesel, methanol hydrogen). 3. Combustion phasing optimization.	1. Active pre-chambers, with independent fuel and air supply. 2. Integration with hydrogen for further reactivity enhancement. 3. Integrated electronic control for on-demand adjustment of jet energy.
Performance	NO_x 8.21 g/kWh CH4 1.4 g/kWh ITE 50% Ref [57] L6230ZLC-10 engine, (ZICHAI Power Co., Ltd., Zibo, China) 74.4 L, 796 r/min, 50% load	NO_x 2.28 g/kWh CH4 0.81 g/kWh BTEmax 35.5% Ref [48] S320 ER by ANDORIA Diesel Engine, Andrychow, 1.8 L, 1000 r/min

As shown in Table 1, the ultimate goals and core contradictions of natural gas engine research are pursuing high thermal efficiency and optimizations aimed at reducing carbon dioxide and greenhouse gas (GHG) emissions, as well as nitrogen oxides during lean or high-temperature combustion and methane slip. Particularly, methane and NO_x emissions have a very high global warming potential, posing a severe and unique challenge for natural gas engines. Therefore, research coupled with strategies, like EGR and fuel reforming [58], have been investigated to control NO_x and unburned methane while improving thermal efficiency. CO_2 and NO_x emissions were measured by the emission analyzer, HORIBA MEXA-1500DS under steady-state engine operating conditions in Ref [48].

Diesel pilot ignition is essentially a fuel chemical reactivity compensation strategy with a high compression ratio, introducing a highly reactive fuel to overcome the difficulty of natural gas auto-ignition and improve its thermal efficiency [59]. Pre-chamber jet ignition [60] is fundamentally a combustion physical process intensification strategy, creating high-intensity turbulence and multiple ignition kernels to accelerate combustion. Its strengths are its high potential for combustion speed and stability improvement [61]. In the future, driven by the pursuit of ultimate efficiency and ultralow emissions, diesel pilot ignition combined with jet ignition could achieve faster, more stable, and cleaner combustion on a compression ignition platform.

4. Core Technological Pathways for Optimizing Natural Gas Combustion and Emissions

Natural gas is primarily composed of CH_4 with a low carbon-to-hydrogen ratio, resulting in lower CO_2 emissions and clean combustion with extremely low particulate emissions. However, the stable molecular structure of CH_4 leads to a laminar flame speed significantly lower than that of gasoline and hydrogen, resulting in prolonged combustion duration [62].

Stable molecular structures and low reactivity, due to the high chemical bond energy, is a common issue for low/zero-carbon fuels, facing challenges of slow combustion speed, difficulty in ignition [56], and poor flame stability. In addition, wall quenching, crevice effects, and distance from the ignition zone to the whole cylinder further intensify the challenges in the combustion of low/zero-carbon fuels. Therefore, enhancing thermodynamic conditions, chemical reactivity, and ignition energy to ensure combustion stability are of paramount importance to improve the thermal efficiency, power density, and ultralow emissions of low/zero-carbon lean combustion engines. In addition, it is essential to optimize the flame propagation process from the ignition zone to the entire cylinder. Enhancing in-cylinder turbulence, improving premixed mixture activity, expanding ignition area, and increasing ignition energy can accelerate flame propagation and ensure combustion stability. Meanwhile, tailored combustion optimization and low-carbon fuel adaptation should be implemented to meet carbon neutrality goals. The methods to accelerate natural gas combustion have been summarized in Figure 3. The main technological solutions are summarized in four categories, including turbulence enhancement, high-energy ignition, fuel reactivity modification, and fuel synergy with zero-carbon fuels.

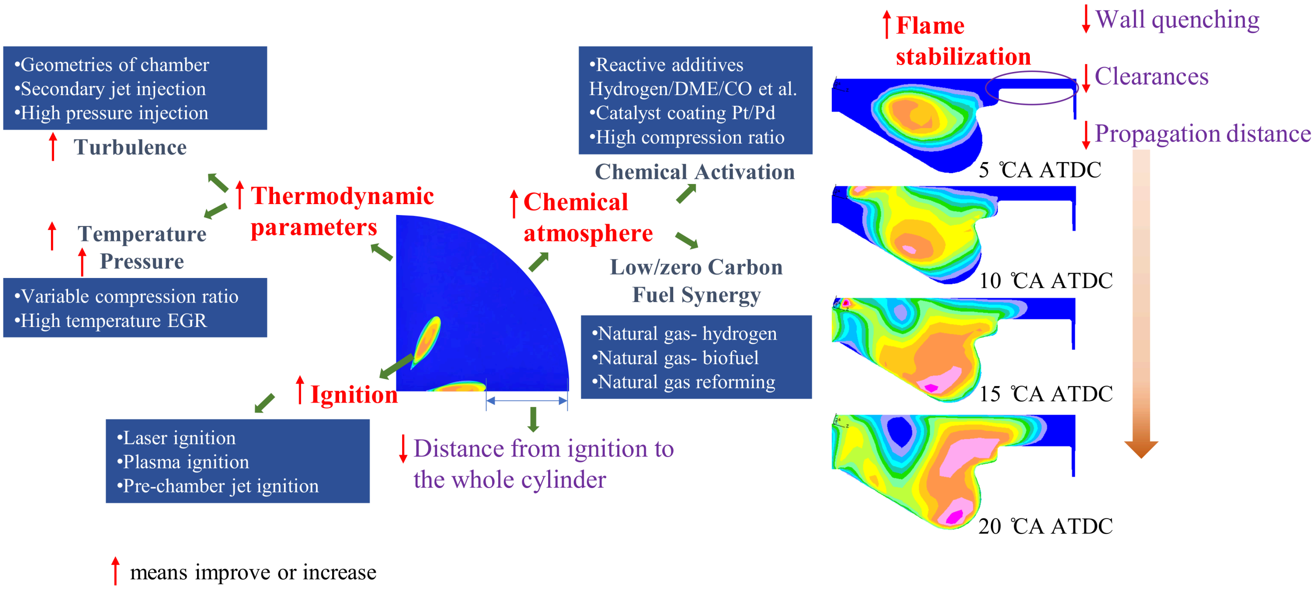

Figure 3. Methods to optimize natural gas combustion and emissions.

4.1. Turbulence Enhancement

The development of novel high turbulence intensity combustion chambers, such as designs with aggressive squish surfaces and high tumble ratios, is a progressing method with which to enhance natural gas combustion by generating ultra-strong turbulence. As shown in Table 2, enhancements of turbulence realized by modifying the piston geometry have been widely validated; the chamber shape is paramount to reducing the combustion duration of natural gas, boost engine efficiency, and decrease methane and NO_x emissions.

The inherent limitations of natural gas, such as low laminar flame speed and prolonged combustion duration, pose significant challenges to the efficiency and emission performance of natural gas-fueled engines. To address these issues, extensive research has focused on optimizing the piston geometry in combustion chambers, as it directly governs in-cylinder fluid flow, turbulent kinetic energy (TKE) distribution, and fuel–air mixing uniformity, key factors that accelerate natural gas combustion.

The shape of the piston bowl is a core element of combustion chamber design; different structural configurations exhibit distinct advantages in regulating combustion processes, as shown in Table 3. Sechul and coworkers [63] conducted experimental studies on a natural gas–diesel dual-fuel reactivity-controlled compression ignition (RCCI) engine with various piston shapes. Their results indicated that, compared to re-entrant bowl pistons, bathtub surface pistons achieved lower incomplete combustion due to the active reaction of natural gas in the squish volume. Additionally, shallow bowl piston geometries, characterized by a lower surface-to-volume ratio, effectively reduce heat transfer, thereby yielding higher thermal efficiencies than re-entrant bowl designs. However, the trade-off is that shallow bowl pistons diminish natural thermal stratification, leading to faster combustion and more severe engine knock under the same operating conditions; this was also further supported by Gainey and coworkers [64] in their research.

Kakaee and coworkers [65] specifically investigated the impact of piston bowl geometry on natural gas/diesel RCCI combustion. They selected three piston bowl types, stock, bathtub, and cylindrical, with a constant compression ratio of 16.1:1, and adopted a double-injection strategy. Their findings revealed that increasing bowl depth led to elevated in-cylinder pressure and temperature, which in turn intensified the combustion reaction. Liu and coworkers [66] optimized the combination of injection parameters and combustion chamber geometries to pursue low fuel consumption and low pollutant emissions. Their research concluded that straight combustion chambers result in significantly lower CH_4 emissions compared to re-entrant combustion chambers, achieving an indicated thermal efficiency of 50.2%.

For specialized combustion demands, innovative piston bowl designs have been developed. Li and coworker [67] developed three bowl geometries, the omega combustion chamber (OCC), the shallow-depth combustion chamber (SCC), and the hemispherical combustion chamber (HCC), and found that SCC enables better combustion performance while maintaining relatively low CO, NO_x, and soot emissions in gasoline–biodiesel-fueled RCCI engines. Tay and coworkers [68] compared three combustion bowl geometries: OCC, SCC, and the shallow-depth re-entrant combustion chamber (SRCC). Among these, the SRCC geometry exhibited the shortest throat length, the highest turbulent kinetic energy, and the shortest combustion duration, demonstrating superior performance in accelerating combustion.

Table 2. Piston core geometric characteristics and performance of multi-type combustion chambers.

Combustion Chamber Type	Core Piston Geometric Characteristics	Key Performance Advantages	Research Validation Scenarios
Hemispherical Combustion Chamber (HCC)	Hemispherical piston top with smooth surface	Uniform flow-field distribution, suitable for baseline combustion modes	Used as a comparative baseline by Li et al. [67] in gasoline–biodiesel RCCI engines
Shallow-Depth Combustion Chamber (SCC)	Shallow and open piston bowl with smooth transitions	Excellent combustion performance, low CO, NO_x, and soot emissions	Verified by Li et al. [67] in gasoline–biodiesel RCCI engines, suitable for high-speed operating conditions
Omega Combustion Chamber (OCC)	Ω-shaped piston bowl with optimized throat and bowl bottom curvature	Strong multi-fuel adaptability, good coordination between turbulence and combustion	Compared with SRCC and SCC by Tay et al. [68] in kerosene–diesel direct injection compression ignition engines
Bowl-in-Piston Chamber	Piston top integrated with a bowl-shaped structure, connected squish region and bowl	High turbulence intensity generated in the squish region, promoting rapid flame propagation	Studied by Liu et al. [66] in heavy-duty natural gas spark ignition engines; fast-propagating flames can be formed even under extremely lean operating conditions

Table 2. *Cont.*

Combustion Chamber Type	Core Piston Geometric Characteristics	Key Performance Advantages	Research Validation Scenarios
Two-Stroke Rod-Less Opposed-Piston Combustion Chamber	Three piston designs: 1. Pancake piston (flat spherical arc structure) 2. Pit piston (top concave type) 3. Pit-guided piston (guided concave type)	1. Pancake: Excellent maintenance of intake swirl intensity 2. Pit: Average turbulent kinetic energy increased by 25%, combustion duration shortened by 13.1%, reduced knock tendency 3. Pit-guided: good maintenance of tumble intensity	Verified by Zhu et al. [69] in two-stroke rodless opposed-piston spark ignition engines, suitable for different flow-field requirements

Nayak and coworkers [70] modified the combustion chamber geometry from a baseline hemispherical combustion chamber (HCC) to toroidal combustion chamber (TCC), SCC, SRCC, and toroidal re-entrant combustion chamber (TrCC) while maintaining a consistent compression ratio. The results showed that the TrCC geometry improved BTE by 6.4% compared to the original diesel baseline.

In addition to piston bowl shape optimization, innovations in the overall piston contour have been tailored to meet the operational requirements of specialized engine structures, further enhancing combustion acceleration effects. Zhu and coworkers [69] conducted research on a two-stroke rodless spark ignition opposed-pistons engine and analyzed three piston types: pancake piston, pit piston, and pit-guided piston. The pancake piston, with its simple and smooth spherical arc structure, is beneficial for maintaining intake swirl strength. In contrast, the swirl strength of the pit and pit-guided pistons decreases significantly, while their tumble strength is well-preserved. Compared to the pancake and pit-guided pistons, the pit piston increases average TKE by approximately 25%, with a more concentrated distribution at spark timing. Although the pit piston exhibits a 0.3% reduction in indicated thermal efficiency, it shortens combustion duration by 13.1%, thereby reducing knock tendency.

Benajes and coworker [71] demonstrated that a reduced piston surface area and diminished charge motion are key factors for improving gross indicated efficiency across different engine loads. Specifically, a shallow piston geometry with a smooth transition from the center to the squish region, featuring a 16% reduced surface area, significantly enhances gross work at low loads. However, this advantage diminishes at higher loads, due to increased combustion losses.

The effectiveness of piston geometry optimization in accelerating natural gas combustion relies on synergistic matching with other key engine parameters. Stocchi and coworkers [72] used multi-dimensional CFD code AVL FIRE to simulate the combustion process and fluid flow in spark ignition natural gas engines with three different combustion chamber designs. Their results indicated that turbulence intensity has almost no influence on the combustion process during the flame kernel development phase. However, appropriately enlarging the squish area can increase inverse extrusion flow, improve in-cylinder TKE, and thereby promote flame propagation. Wu and coworkers [73] further supplemented this finding by noting that, while turbulence intensity has little effect during flame kernel development, it directly and significantly influences flame propagation velocity during the rapid combustion period. This highlights that the synergistic optimization of piston geometry, squish area design, and turbulence intensity regulation is critical for accelerating combustion.

The optimization of high-pressure direct injection (HPDI) technology, when combined with piston geometry optimization, further enhances combustion acceleration. HPDI enables late injection and faster fuel–air mixing; when paired with diesel pilot ignition, it achieves both high speed and efficiency. Multiple injections during the intake and compression strokes create a reactivity-stratified chemical atmosphere within the cylinder, enabling rapid and controllable combustion. This technical combination fully leverages the advantages of piston geometry in organizing in-cylinder flow, forming a synergistic effect that accelerates natural gas combustion.

Yan and coworkers [74] investigated three representative chamber geometries through experiments and simulations, providing additional data support for the synergistic optimization of piston geometry and combustion systems. Lim and Reitz [75] developed a chamfered piston crown design to reduce unburned hydrocarbon (UHC) emissions from ring-pack crevices, achieving a 17–41% reduction in crevice-borne UHC emissions compared to conventional piston designs. This optimization of the piston crown contour [76,77] improved combustion completeness, indirectly contributing to combustion acceleration.

Liu and coworkers [78,79] focused on heavy-duty spark-ignited natural gas engines with bowl-in-piston chambers. Their research highlighted that increasing natural gas utilization in heavy-duty engines helps to reduce greenhouse gas emissions from power generation and transportation. However, retrofitting compression ignition engines to natural gas spark ignition operation can increase methane emissions without expensive aftertreatment. A key reason for the low combustion efficiency in retrofitted engines is the low laminar flame speed of natural gas, coupled with the larger bowl size of diesel engines as compared to traditional gasoline engines; it increases flame travel length and extends combustion duration. Optical measurements in their study showed that fast-propagating flames can be formed even under extremely lean operating conditions, as the squish region of the bowl-in-piston chamber generates high turbulence intensity inside the bowl. Nevertheless, the flame propagation speed decreases by 55% when transitioning from the bowl to the squish region, due to a significant reduction in turbulence intensity in the squish region. Furthermore, the squish volume traps a substantial fuel fraction, which undergoes slow and inefficient combustion during the expansion stroke. These results emphasize the paramount importance of optimizing chamber shape to improve engine efficiency and reduce emissions. Overall, piston geometry optimization achieves accelerated natural gas combustion by regulating in-cylinder flow-field structure, enhancing turbulent kinetic energy, and improving fuel–air mixing uniformity. The research findings confirm that reasonable piston geometry design, whether through bowl shape modification, overall contour innovation, or synergistic matching with injection parameters, can effectively address the inherent limitations of natural gas combustion, providing valuable technical references for the development of high-efficiency, low-emission natural gas engines.

Table 3. Piston geometries to enhance natural gas combustion.

Combustion Chamber Type	Reference	Key Performance Advantages
Shallow/re-entrant piston	[63]	Lower incomplete combustion compared to the re-entrained shape due to active reaction of natural gas in the squish volume
Shallow/re-entrant piston	[64]	Lower surface-to-volume ratio of the shallow bowl piston geometry is effective at reducing heat transfer, resulting in higher thermal efficiencies than the re-entrant bowl piston geometry, but prone to knock
Hemi-Spherical/Toroidal/Toroidal re-entrant/Shallow-depth/Shallow-depth re-entrant piston	[70]	With SCC, better combustion and performance can be achieved while maintaining relatively lower CO, NO and soot emissions; TrCC geometry obtained an improvement of the BTE by 6.4% compared to original diesel baseline

Table 3. *Cont.*

Combustion Chamber Type	Reference	Key Performance Advantages
OCC/SCC/SRCC piston	[68]	SRCC geometry obtained the shortest throat length, the highest turbulence kinetic energy and short combustion duration
Reentrant pistons with different radius	[66]	CH4 emissions are significantly lower when using the straight combustion chamber compared with using the re-entrant combustion chamber and obtained the indicated thermal efficiency of 50.2%
Stock/Cylindrical/Bathtub piston	[65]	By increasing bowl depth, in-cylinder pressure and temperature were increased
Stock/Steped/Bathtub piston	[71]	Reduced piston surface area and reduced charge motion are the key factors to improve the gross indicated efficiency over the different engine loads. Moreover, it is found that a shallow piston geometry with a smooth transition from the center to the squish region, with a 16% reduced surface area, strongly improves the gross work at low loads
Straight/re-entrant/shaped cross rib piston	[73]	A combustion chamber with a proper shape can make the appropriate mixture flow; appropriate intensity of turbulence and crowded flow is conducive to the spread of flames
Cylinderical/Nebula/Cross/Reentrant piston	[74]	The reentrant chamber has the highest turbulence intensity before top dead center (TDC), and, hence, a higher flame surface density
Pancake/Pit/Pit-guided pistion	[69]	Compared to pancake and pit-guided pistons, the average TKE for the pit piston increased by approximately 25%, with a more concentrated distribution at the spark timing; the pit piston has a 0.3% decrease in the indicated thermal efficiency, but a 13.1% decrease in combustion duration
chamfered piston	[75]	Compared to the conventional piston design, the chamfered piston showed 17–41% reduction in the crevice-borne UHC emission

While considerable research has been devoted to optimizing combustion chamber geometry for enhanced in-cylinder turbulence, most efforts remain focused on the intensification of flow motion within the piston bowl region. In premixed lean burn natural gas engines, however, the flame propagation pathway extends well beyond the bowl from the ignition zone across the entire cylinder to the liner walls and crevice regions. Effective combustion optimization must, therefore, adopt a full-cylinder, full-pathway perspective. During the propagation phase, excessive clearance distances between the ignition zone and distant cylinder regions delay flame arrival and increase knock propensity, while cold-wall quenching extinguishes the flame at all solid boundaries, regardless of in-cylinder turbulence levels. Addressing these challenges requires integrated strategies that combine ignition system designs such as pre-chamber or jet targeting.

4.2. Chemical Activation

Fuel activation [80] significantly increases flame speed [81] using highly reactive additives [82] blended with the main fuel, and catalytic/non catalytic additives [83], such as formaldehyde (CH_2O) radical precursors or hydrogen, shorten CH_4 ignition delay [84] and flame propagation. The validation and simplification of detailed CH_4 reaction mechanisms [85,86] under high-pressure and lean burn conditions provide accurate models for combustion system design. The exploration of surface catalytic combustion by coating catalysts [87] on combustion chamber walls or specialized substrates is needed to achieve low-temperature, flameless, rapid oxidation of CH_4.

To address natural gas's inherent limitations of low laminar flame speed and combustion inefficiency, improving fuel reactivity has emerged as a key strategy for enhancing its combustion performance. Hydrogen [88], as a clean fuel, enables lean premixed combustion to curb NO_x emissions, yet faces significant challenges in pre-ignition control and stable combustion management in practical engines. Non-thermal plasma [89], the reforming of methane to generate hydrogen–methane blends, significantly boosts laminar flame speed due to additional reaction kinetics from long-lived species or altered energy levels, outperforming bottled hydrogen–methane blends [90], while reducing pure hydrogen demand [89]. For composite propellant-related combustion systems, a Cl_2 addition modifies DME/N_2O reaction [91] pathways and flux distribution without changing ignition activation energy, offering insights into reactivity regulation [92]. Meanwhile, kinetic models critically impact super-knock [93,94] prediction in high-compression natural gas engines, as discrepancies among models lead to varying detonation [95] regime predictions, highlighting the need for validated mechanisms tailored to engine conditions. Collectively, fuel reactivity improvement via hydrogen blending, plasma reforming, additive modulation, and kinetic model optimization effectively addresses natural gas combustion challenges, enabling efficient, low-emission operation. Table 4 shows the main additives employed in internal combustion.

Table 4. Additives employed in references.

Additives	Reference	Characters
DME	[96–105]	A promising propellant because of its high energy content and combustion properties.
Cl-2	[106]	The addition of Cl-2 reduces the activity of the fuel mixture system. However, the ignition activation energy required for ignition is not changed.
Methanol	[107]	The prolonged crank angle (CA 0–10) and (CA 10–90) could be shortened via the addition of methanol. Brake thermal efficiency increased with an increase in lambda and the methanol energy substitution ratio.
Natural antioxidant additive	[108]	Natural antioxidant additive Melia Azedarach (MA) of 1000 ppm is added; it was found that the addition of MA shows an improvement of BTE 2.17% higher than that without the additive; the NO_x emission with additive is 1079 ppm, which is 21.9% lower than that without additives.
Hythane	[80]	Hythane is generated from non-thermal plasma reforming of methane using a dielectric barrier discharge reactor. The enhanced flame speed can neither be addressed based on thermal effects nor due to the presence of neutral intermediate species. Hythane potentially results in additional reaction kinetics influences, which accelerate the combustion process.
CO, N_2, H_2O, and CO_2	[82]	Cho and coworkers investigated the effects of gas additives (H_2, CO, N_2, H_2O, and CO_2) on the uncatalyzed partial oxidation of methane in a spark ignition engine. The dilution components (N_2, H_2O, and CO_2) impeded methane combustion owing to their thermal effects, with CO_2 exhibiting the most pronounced delay in combustion. Fuel additives (H_2 and CO) enhanced combustion by increasing the flame initiation and propagation speed, whereas NO_x emissions increased significantly in the CO additive experiments, which was attributed to accelerated NO_x formation reactions.
Furan-based derivatives	[109]	Directly used in internal combustion engines as alternative fuels or as additives to conventional fuels.
Hydrogen	[43,110–122]	Hydrogen addition reduces flame distortion and enhances crevices combustion. Higher hydrogen concentration promotes flame-front wrinkling. Reduction in NO_x emissions for lean burn conditions. Abnormal combustion phenomena, such as backfire, often occur in the port fuel-injected engine.

Accurate chemical reaction mechanisms serve as the theoretical foundation and optimization prerequisite for achieving high-efficiency and clean combustion. Fakhari and coworkers [123] developed a reduced mechanism comprising 60 species and 372 reactions, which improved the prediction accuracy of ignition delay time for natural gas–diesel dual fuel by 20% and reduced the simulation error to 0.2 milliseconds. Additionally, the physicochemical properties of the fuel itself are crucial. Lou and coworkers [124] conducted experiments using a constant-volume combustion bomb and found that the proportion of ethane (C_2H_6) in natural gas significantly impacts its laminar flame speed. For every 2.5% increase in ethane content, the laminar flame speed increased by approximately 5.1% on average. This indicates that optimizing the chemical composition and reaction kinetics of the fuel forms the basis for enhancing combustion rate and stability.

Lean combustion [125] is a key pathway to improving thermal efficiency. However, the inherently slow flame speed of natural gas makes it prone to combustion instability and cyclic variations under lean conditions. Zhang and coworkers [126] provided a solution to this problem. They found that using high ignition energy (150–200 mJ) combined with a large spark plug gap could extend the lean combustion limit of methane to an excess air ratio (λ) of 1.55, primarily due to the enlargement of the initial flame kernel. However, while high exhaust gas recirculation (EGR) rates help to reduce NO_x emissions, they often deteriorate flame stability. Camacho and coworkers [127] revealed the opposing effects of EGR and H_2 on flame stability: high EGR worsens flame stability, whereas increasing H_2 improves it. This provides a strategy for synergistic control, leveraging the chemical activation effect of hydrogen to counteract the negative impacts of high EGR, thereby maintaining stable operation under lean conditions without significantly increasing CO_2 emissions.

The utilization of hydrogen blending is currently one of the most active directions for improving natural gas combustion. Its effects manifest across multiple levels, from macroscopic power enhancement to microscopic chemical reaction promotion. Kim and coworkers [128] demonstrated that, for a hydrogen-fueled spark ignition engine under lean conditions with $\lambda = 1.4$ using port fuel injection and a high compression ratio of 14, a brake power of 14.7 kW could be achieved. By switching to direct injection, the power could be further increased to 21.1 kW, while maintaining the same thermal efficiency. Ayad and coworkers [120] employed optical engine studies and found that even trace amounts of hydrogen (as low as 0.42 mg/s) could promote the formation of OH* radicals, leading to more uniform flames and better radical distribution. This enhancement improved all combustion phases, including the post-combustion period, providing empirical support for onboard hydrogen production as a transitional strategy. However, abnormal combustion phenomena, such as backfire, often occur in the port fuel-injected engine. Tyrewala and coworkers [129] found that adding hydrogen to methane (with hydrogen energy shares ranging from 0% to 20%) under constant intake pressure, combined with EGR, effectively reduced emissions of unburned hydrocarbons, carbon monoxide, and nitric oxide. They attributed the more-than-linear decay rates of CH_4 and H_2 to the chemical synergistic effects of hydrogen addition and EGR. To achieve more precise control over the combustion process, researchers have explored physical activation based on fuel stratification [130] and advanced ignition technologies. Chen and coworkers [125] pointed out that, under lean conditions, delayed hydrogen injection reduces mixture inhomogeneity, offering an effective pathway for efficient stratified combustion [131] that simultaneously achieves high thermal efficiency and low emissions.

Chemical activation serves as a core technological pathway for enabling high-efficiency, low-emission combustion in natural gas engines. Its essence lies in accelerating reaction kinetics and reducing ignition energy barriers through the introduction of additives, such as hydrogen, thereby achieving precise control over the combustion process. However, this must be integrated with other control measures, such as stratified combustion and high-energy ignition, to enable more accurate spatiotemporal regulation of combustion. Such integration extends the lean combustion limit, suppresses knock tendency, and reduces methane slip, ultimately achieving synergistic optimization of thermal efficiency improvement and pollutant emission control.

4.3. Advanced Ignition

Advanced ignition technologies have evolved to address the persistent challenges of slow flame propagation, narrow lean burn limits, and combustion instability in natural gas engines. On the one hand, high energy-density ignition methods, such as laser ignition, microwave ignition, and plasma-assisted ignition, promote rapid ignition and initial flame kernel development in natural gas/air mixtures through localized high energy flux, and have been widely studied in internal combustion engines. On the other hand, multi-point or jet ignition technologies have developed rapidly, utilizing high-temperature jet flames generated from one or more pre-chambers as distributed ignition sources. These simultaneously ignite multiple regions in the main combustion chamber, drastically increasing the combustion surface area and significantly shortening the combustion duration. Complementing these ignition advances, variable compression ratio (VCR) systems integrated with intelligent thermal management have been proposed. This approach allows for reduced compression ratios under high loads to prevent knock, while increasing compression ratios and synergistically raising intake temperatures under low loads to ensure rapid and stable ignition. Table 5 summarizes advanced ignition technologies.

Further mechanistic insights into jet ignition have been gained through detailed investigations. Sun et al. [132] revealed how a pre-chamber flame propagates through a small-diameter nozzle into the main chamber without extinguishing, with the key being the maintenance of distance between the flame core and the wall to preserve temperature and free radicals. Zhong and coworkers [60] investigated the mechanism of pre-chamber TJI for high-pressure direct-injection methane jets. They found that TJI significantly expands the lean burn limit and improves combustion characteristics compared to homogeneous premixed combustion, primarily through mixture stratification [133] and turbulence effects. Hydrogen enrichment in the pre-chamber can further enhance jet intensity and energy. Extending the applicability of this concept, Zhong and coworkers [134] applied TJI to liquid ammonia spray combustion, revealing a three-stage process (pre-chamber combustion, partially premixed combustion, and mixing-controlled combustion), thus offering a novel ignition approach for ammonia engines. The practical effectiveness of such systems has been demonstrated by Gürbü and coworkers [135], who applied hydrogen-assisted jet ignition (HAJI) in a direct-injection spark ignition engine. Under lean conditions, this approach achieved substantial improvements in pressure rise rate, heat release rate, combustion duration, and cycle-to-cycle variability, demonstrating its effectiveness in enhancing performance and reducing HC emissions. Beyond jet-based methods, Zhang and coworkers [136] conducted breakthrough research using transient plasma ignition to combust hydrogen in a retrofitted natural gas engine under ultra-lean conditions (λ up to 5). This resulted in a two-fold improvement in engine stability, a four-fold reduction in NO_x emissions, and a 175% increase in maximum mechanical power. The enhancement mechanisms are attributed to the hydrodynamic effects of ionic wind and chemical activation generated by the plasma. Compared with conventional spark ignition, plasma ignition provides higher energy, larger ignition volume, and more active radicals, enabling reliable ignition under high-speed flow and lean conditions.

Optimizing ignition also involves understanding and controlling its interaction with in-cylinder flows and fuel injection. Zhang and coworkers [137] systematically studied the ignition characteristics of premixed methane jets impinging on walls. They identified two ignition modes and found that ignition performance is significantly influenced by the dimensionless impingement distance (H/D) and wall shape, noting that optimizing wall geometry can minimize high-turbulent kinetic energy stagnation zones, thereby promoting ignition. Qiu and coworkers [138] investigated the interaction between high-pressure methane jets and premixed flames, revealing a shift in the dominant combustion mode from premixed flame surfaces to diffusion flame surfaces within the main chamber. Relatedly, research on hydrogen jet cold ignition of coalbed methane [139] demonstrated that the interval between ignition and hydrogen injection decisively affects combustion duration and flame morphology transition, with earlier hydrogen involvement accelerating combustion speed.

Finally, the synergy between fuel composition and ignition systems presents another avenue for improvement. Pan and coworkers [140] conducted simulation studies showing that blending 10–30% hydrogen into methane significantly reduces the ignition delay of glow plug ignition and allows for reliable ignition at lower glow plug operating temperatures, thereby extending component life. Supporting this integrated view, Arutyunov and coworkers [141] emphasized, in their review, that for hydrogen-enriched natural gas mixtures, ignition kinetics may undergo significant changes at temperatures below 1000 K (relevant to engine operating conditions). This challenges existing knock-resistance evaluation criteria and underscores the potential of co-optimizing fuel composition and ignition strategies to improve overall combustion characteristics.

Together, these advances illustrate a multi-faceted approach where next-generation ignition technologies, synergistic control of in-cylinder processes, and tailored fuel formulations are being integrated to push the boundaries of efficiency, stability, and cleanliness in natural gas combustion.

Table 5. Advance ignition technologies.

Ignition Method	Core Mechanism	Key Advantages	Typical Conditions and Effects	Reference
Plasma Ignition	Generates high-energy active free radicals (H,·OH) to reduce reaction activation energy; ionic wind.	Short ignition delay, strong lean burn stability, low NO_x emissions.	λ = 1.6–5, Engine stability improved by 2 times at an engine speed of 1500 r/min, NO_x emissions reduced by 4 times, maximum mechanical power increased by 175% under the condition of 0.2 kW at an engine speed of 1100 r/min.	[136]
Hot Surface Ignition (Glow Plug, GP)	The high-temperature surface transfers energy continuously to the natural gas-air mixture through heat conduction.	Stable ignition, simple structure, suitable for modified natural gas fuels.	Adding 10–30% hydrogen reduces IDT by 9% and IDP by 27%; reliable ignition is maintained for 20% hydrogen-blended fuel even when the glow plug temperature is reduced by 100 K at the speed of 3200 r/min.	[140]
Pre-Chamber Turbulent Jet Ignition (TJI)	Pre-chamber jet provides distributed high-temperature ignition sources, enhancing turbulence and mixing in the main combustion chamber.	Large combustion area, short combustion cycle, suitable for lean burn/high-pressure conditions.	Combustion duration shortened by 33.3%, lean burn limit expanded λ = 1.4–3.3, replacing diesel pilot injection to simplify injection strategy.	[60,132,138,141]
Multi-Point Ignition/Twin Spark Plugs	Simultaneous ignition from multiple sources shortens flame propagation distance.	High combustion efficiency, strong stability, suitable for large-volume combustion chambers.	λ = 1–1.5, Combustion efficiency improved by 4–8%, flame propagation speed accelerated, unburned HC emissions reduced.	[142]

Table 5. *Cont.*

Ignition Method	Core Mechanism	Key Advantages	Typical Conditions and Effects	Reference
Hydrogen Jet Assisted Ignition	Hydrogen's high reactivity lowers the ignition threshold; optimized jet timing enhances flame transition and propagation.	Suitable for low-concentration natural gas/lean burn, high ignition reliability.	λ = 0.8–1.2, at an engine speed of 2300 r/min. For λ = 1.2 lean mixture, hydrogen injection increases Pmax by 62.3%, thermal efficiency by 3.08 units; and reduces combustion duration.	[135,139]
Diesel Secondary Injection	Supplementary diesel injection after main injection forms secondary ignition sources/enhances local mixing.	Suitable for natural gas–diesel dual-fuel systems.	Reduces NO_x–soot emission trade-off, unburned HC/methane emissions reduced by 15–25%; combustion efficiency improved by 3–5%.	-
Wall-Impinging Passive Jet Ignition	Jet–wall interaction forms different ignition modes; stagnation effect and turbulence intensity jointly affect ignition efficiency.	Suitable for specific combustion chamber structures, no active fuel supply, low cost.	λ = 1–1.5, ignition delay varies by 3.3–6.6 ms under different H/D M-shaped wall forms.	[137]

4.4. Fuel Synergy

With the acceleration of global carbon-neutrality efforts, carbon-neutral fuels have emerged as a critical research frontier in energy and power sectors. Consequently, the focus of natural gas engine research is shifting decisively from traditional fuel optimization toward deep integration with carbon-neutral fuels such as hydrogen and ammonia. This strategic integration achieves deep decarbonization for internal combustion while simultaneously to improve combustion characteristics. Table 6 lists fuel synergy among natural gas and zero/low-carbon fuels.

Hydrogen, distinguished by its high flame speed, wide flammability limits, and zero-carbon properties, serves as the most direct means to enhance flame propagation of natural gas. Supporting this, Carvalho and coworkers [143] found that adding 33% hydrogen to producer gas yields a flame morphology comparable to pure natural gas. Furthermore, a hydrogen blending ratio of 24–36% provides an optimal performance window for engines originally designed for natural gas, achieving an effective balance between power output and emissions, while notably reducing unburned hydrocarbon (UHC) emissions. In parallel, ammonia (NH_3) is gaining prominence as a practical zero-carbon hydrogen carrier fuel. However, its application faces inherent challenges, including slow combustion speed, difficulty in ignition, and a propensity to generate fuel-borne NO_x. To address these, Wu and coworkers [144] investigated CH_4/NH_3 mixtures by integrating pre-chamber ignition with lean burn technology and developed corresponding combustion mechanisms. Zhang and coworkers [145] studied the oxidation characteristics of NH_3/H_2 and NH_3/CH_4 mixtures in a high-pressure flow reactor, providing essential foundational data for kinetic model development. At the engine application level, Zhu and coworkers [146] conducted a numerical study on an NH_3–H_2 engine, employing secondary hydrogen injection in both the pre-chamber and main chamber. Their results demonstrate that this strategy effectively regulates in-cylinder combustion processes and increases the mean effective pressure. Meanwhile, Fan and coworkers [147] explored an innovative on-board approach using gliding arc plasma for ammonia decomposition to produce hydrogen, subsequently coupling it with an ammonia engine. This method increased brake thermal efficiency by over 3% and significantly improved the combustion stability of pure ammonia.

Beyond hydrogen and ammonia, research is also expanding to include synergistic blends with other renewable fuels. For instance, Zhang and coworkers [148] investigated ammonia–methanol blended fuels, comparing the effects of methanol reforming gas and cracking gas (both containing H_2) on combustion and NO formation. Their findings indicate that reforming gas offers advantages in both the combustion rate and NO control, attributed to its higher hydrogen yield and the dilutive effect of CO_2. Such explorations of ammonia blended with renewable fuels, like biomethanol and biodiesel, pave the way for constructing more flexible, resilient, and sustainable multi-fuel energy systems.

The unique combustion properties of these alternative fuels, particularly their low reactivity, necessitate advanced ignition and combustion management strategies. Pre-chamber TJI has thus emerged as a key technology. As previously noted, TJI has been successfully extended to challenging applications such as liquid ammonia spray combustion (Zhong and coworkers [134]) and ammonia–hydrogen engines (Zhu and coworkers [146]). By generating multiple, distributed ignition sources and enhancing in-cylinder turbulence, TJI effectively overcomes the challenges of difficult ignition and slow flame propagation.

Emission control, especially for ammonia-based fuels, presents a distinct set of challenges and focuses. Ammonia combustion produces significant fuel-borne NO_x, whose formation mechanism fundamentally differs from thermal NO_x. Wei and coworkers [149] elucidated that under lean burn conditions, fuel-borne NO dominates, whereas under stoichiometric conditions, thermal NO prevails. Their work also revealed that the effect of the ammonia blending ratio (XNH_3) on total NO_x emissions exhibits opposite trends under these two combustion regimes. Further insights come from Gain and coworkers [150], who, through combined experiments and simulations, found that ammonia blending alters flame structure and temperature distribution. While it reduces the peak flame temperature, the secondary combustion of hydrogen produced from in situ ammonia decomposition can lead to increased flame height and more uniform heat distribution. To mitigate NO_x emissions, strategies extend beyond advanced ignition. Tu and coworkers [151] demonstrated the effectiveness of air staging in controlling NO emissions from NH_3/CH_4 swirling flames in a model combustor. Additionally, optimizing spark ignition timing (SIT), as studied by Wei and coworkers [149], and carefully calibrating fuel blending ratios, as highlighted by Zhang and coworkers [148], remain crucial for emission control in engines fueled by ammonia blends.

A truly sustainable transition requires a holistic perspective that extends beyond the engine itself. Álvarez and coworkers [152] underscored this by employing a lifecycle assessment methodology to compare the environmental impacts of hydrogen production via various pathways. Their work emphasizes that while global warming potential (GWP) is critical, a comprehensive evaluation of other environmental indicators is equally necessary. This highlights that the "color" of hydrogen (green or not) fundamentally determines its net contribution to carbon neutrality. Therefore, future research must adopt a system-level approach, integrating and co-optimizing fuel production, engine combustion, and aftertreatment systems to genuinely achieve carbon neutrality goals across the entire lifecycle.

Finally, the research landscape is further enriched by comparative and combinatory studies involving a broader spectrum of alternative fuels. Biodiesel, methanol, and ethanol are frequently examined alongside or in blends with natural gas, hydrogen, or ammonia. These studies provide valuable benchmarks, reveal compatibility insights, and help to map out the complex matrix of potential multi-fuel strategies for a diversified, low-carbon future.

Table 6. Fuel synergy among natural gas and zero/low-carbon fuels.

Fuel Synergy	Core Technical Pathways	Reference
Hydrogen–Natural Gas (H_2–NG)	1. Optimization of hydrogen mole fraction (14–62%) 2. Dual-zone hydrogen injection 3. Biomass producer gas–hydrogen–NG blending Renewable energy electrolysis for hydrogen production and NG blending, environmental impact assessment via LCA	[146,152]
Ammonia–Natural Gas (NH_3–NG)	1. Pre-chamber ignition and lean burn 2. Air-staged combustion (regulation of SAR/H/N parameters) 3. High-pressure laminar oxidation kinetics optimization	[144,145,149,151]
Ammonia–Hydrogen–Natural Gas (NH_3–H_2–NG)	1. Secondary hydrogen injection in active pre-chamber + multi-fuel synergy in main combustion chamber 2. characteristics of NH_3–NG premixed jet flames	[146,150]
Ammonia–Methanol–Natural Gas (NH_3–CH_3OH–NG)	1. Methanol reforming (MR)/cracking (MC) for in situ hydrogen production 2. Regulation of fuel ratio and reforming rate	[148]
Ammonia–Natural Gas–Plasma Decomposition Gas	In situ NH_3 decomposition to hydrogen via gliding arc plasma, blended combustion with NG/NH_3	[147]
Biomass Producer Gas–Hydrogen–Natural Gas	Upgrading of biomass producer gas via hydrogen blending, adapted for optical SI engines	[143]

5. Combination of Multi-Technologies

To meet increasingly stringent global emission regulations and carbon neutrality goals, the optimization of combustion for low/zero-carbon fuels has been divided into four distinct technological pathways, including turbulence enhancement, high energy ignition, fuel activation, and zero-carbon fuel synergy, by which, the performance of natural gas engines has been improved significantly. However, natural gas combustion research has expanded from the automotive sector to the marine power market. In the future, marine engines will constitute the main arena for competition in powertrain system technologies [153,154]. Promoting the innovation and application of low/zero-carbon marine engine technologies is of importance. Large-bore and long-duration combustion of marine engine pose greater challenges to low/zero-carbon fuels, such as natural gas and ammonia, because these fuels have stable molecular structures and low reaction activity due to high-energy chemical bonds. Consequently, the integration of existing technologies has become a potential solution to the above problems, as shown in Figure 4.

Since combustion chamber geometry can effectively enhance in-cylinder turbulence, it forms a foundational and essential component of any integrated solution. Krieger and coworkers [155] demonstrated that re-entrant and cylindrical piston geometries reduced combustion duration by approximately 40% compared to a baseline design, attributing this improvement to higher post-ignition turbulence intensity, which enhances flame acceleration and stretching. Similarly, Fu and coworkers [156] highlighted the combined effects of piston shape and swirl ratio on combustion and emissions in a diesel pilot natural gas engine. Therefore, by coupling proper piston geometries with advanced ignition methods, more efficient combustion control can be realized.

Current studies in the literature report on two established paradigms of such integration. The first combines diesel multi-zone auto-ignition [157] with a geometry-driven in-cylinder turbulent jet. Here, the high reactivity of diesel ensures reliable multi-point ignition, while a specially designed piston crown geometry transforms the flame momentum into a coherent, annular propagating jet. This organized annular flow rapidly stretches the ignition kernels, significantly accelerating flame propagation.

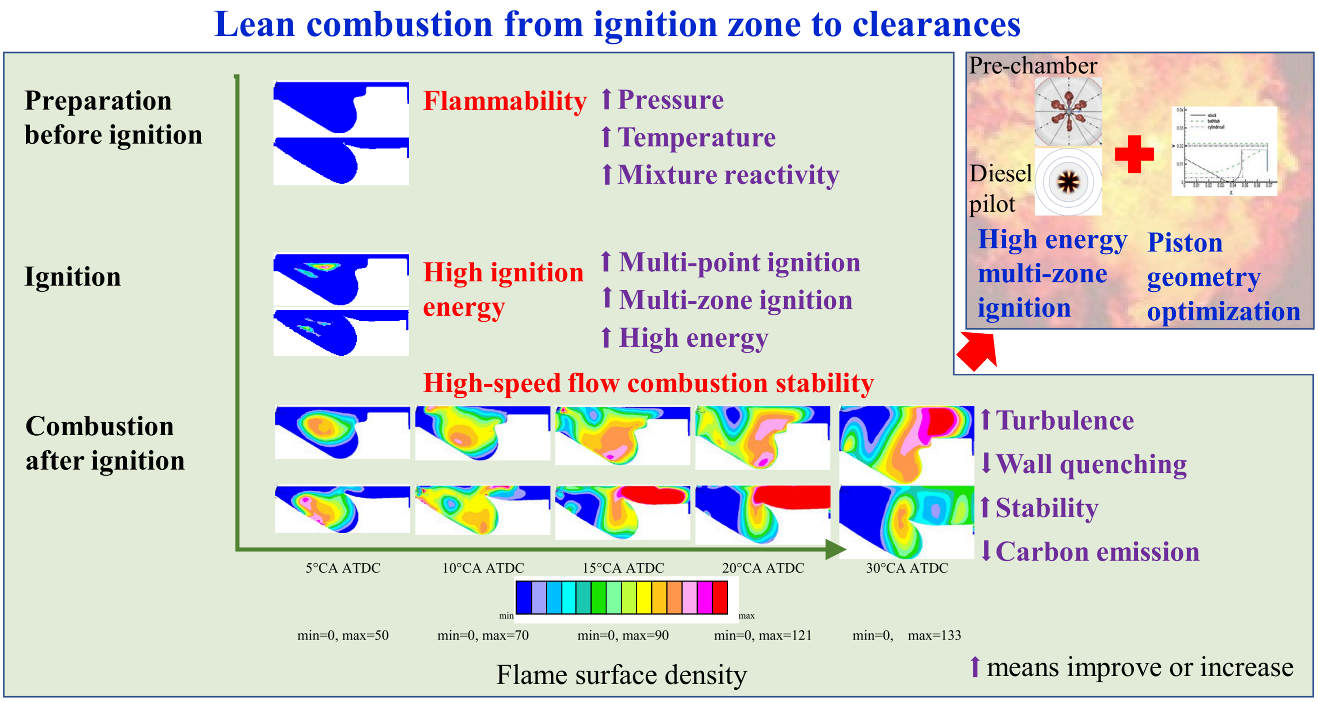

Figure 4. Challenges and solutions of natural gas lean burn combustion from ignition zone to clearances.

The second paradigm integrates a pre-chamber system [158] with geometry-driven in-cylinder turbulence. High-energy combustion within the pre-chamber generates multiple high-velocity, radical-rich turbulent flame jets. These jets interact synergistically with a high-intensity background turbulent field, which is pre-organized by the main chamber geometry, leading to markedly faster flame propagation.

To guide the fusion of existing technologies, four jet generation methods are summarized and compared in Table 7. Aerodynamic jet, energy injection jet, fuel injection jet and acoustic induced jet all have the potential to accelerate the flame propagation of natural gas. For large-bore engines, multi-zone ignition and jet flame are able to support ultra-lean combustion and low/zero-carbon fuels.

Table 7. Jet generation methods that may be integrated in internal combustion engines.

	Aerodynamic Jet	**Energy Injection Jet**	**Fuel Injection Jet**	**Acoustic/Shock-Induced Jet**
Implementation Means	Contraction-expansion structures [159–161]	1. Pre-chamber flame jet [162,163] 2. Plasma jet [164–166]	1. High-pressure direct injection [57,167,168] 2. Secondary injection [169]	1. Pulsed detonation tube 2. Resonant cavity acoustic generator
Jet Temperature	Related to ambient temperature	High	Low	High
Jet Speed	Medium	Fast	Fast	High
Energy Source	Pressure differential	Flame combustion or plasma	Injection pressure	Combustion detonation wave energy or acoustic resonance energy
Jet Intensity	Medium	Strong	Low	High
Main Characteristics	Relies on pressure differential to generate jets or chemical activity depends on the environment	High thermal effect and chemical activity	1. High jet momentum and penetration 2. low chemical activity	1. Extremely high jet intensity 2. Suitable for extreme condition combustion enhancement

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Looking forward, further combustion intensification may be achieved through next-generation fusion concepts, such as coupling plasma jet ignition with geometry-driven in-cylinder flow structures, or by integrating pre-chamber systems with specifically designed annular jet-generating geometries. These advanced syntheses aim to leverage both distributed ignition and macro-flow organization for superior combustion control. However, such integrative approaches remain largely unexplored in the current literature and represent a promising frontier for future research aimed at mastering combustion in next-generation, large-bore, zero-carbon marine engines.

5.1. Fusion of Diesel Pilot Ignition and Geometry Modification

Driven by the pursuit of ultimate efficiency and ultralow emissions, diesel pilot ignition combined with jet flame presents a promising pathway toward faster, more stable, and cleaner combustion on lean burn compression ignition platforms due to multi-zone autoignition realized by pilot diesel and fast flame propagation through jet motion.

Shen and coworkers [157] proposed induced jet flame combustion to enhance natural combustion at low load which realized by combining diesel pilot and jet combustion. An annular jet flame inducing protrusion is designed on the piston, forming a convergent-divergent structure, like a throttling ring, together with the cylinder head along the entire circumferential direction of the cylinder, as shown in Figure 5. This induces a high-speed flame jet from the piston bowl toward the near-wall crevice region, rapidly fills the combustion chamber with the burning flame, and enhances combustion in the distal flammable gas mixture. With the induced jet flame piston, a distinct flame jet appears at 5° CA after the top dead center, achieving a maximum turbulent kinetic energy of 35 m^2/s^2, significantly higher than the results of existing studies on piston structural modifications, with a maximum turbulent kinetic energy of 10 m^2/s^2. In practical combustion devices for hydrocarbon fuels, airflow velocities exceed the maximum possible turbulent flame propagation speeds. This high-speed airflow poses challenges for the stable propagation of flames toward the cylinder wall region. To stabilize the flame within such high-speed flows, the protrusions serve as bluff bodies that stabilize high-speed airflow flames. With this combustion method, the combustion duration of natural gas is reduced from the original 56.2° CA to 35.1° CA. This improvement is achieved without modifying any other engine operating, structural, or control parameters. At a low load condition of 1200 r/min, this method results in a reduction in methane emissions by 61.8%, an increase in IMEP by 14.6%, and a reduction in soot emissions by 51.4%, as shown in Figure 6.

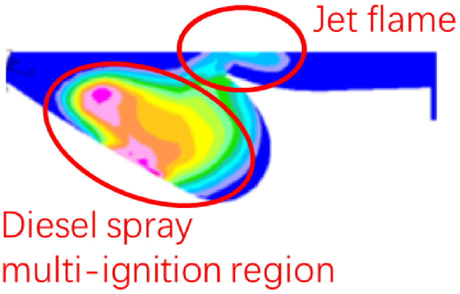


Figure 5. Fusion of multi-zone autoignition and jet flame.

Compared to other combustion chamber structural modifications, the induced jet flame combustion integrates optimizations across multiple aspects, including jet generation, high-speed flame stabilization, and diesel pilot ignition. It simultaneously addresses the requirements of improving ignition efficiency, accelerating flame propagation speed, maintaining flame stability.

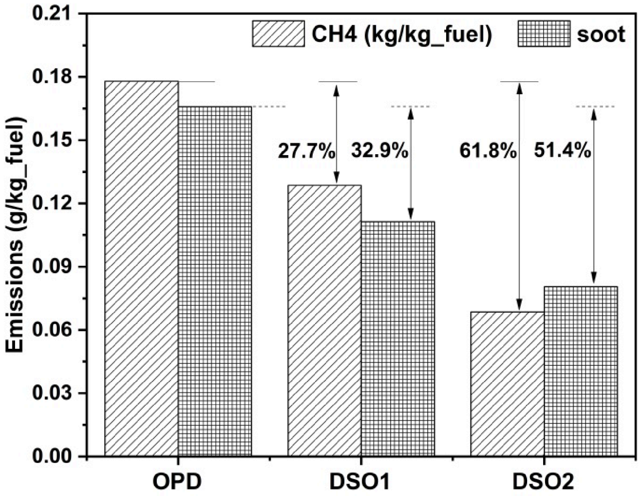


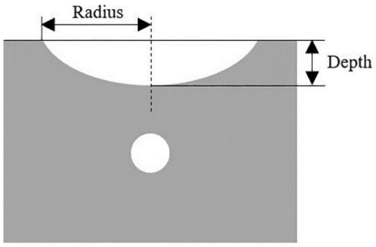
Figure 6. Comparisons of soot and methane emissions among OPD, DSO1, and DSO2.

Fusion of the diesel pilot ignition and jet flame mentioned for induced jet flame combustion shows significant improvements in the combustion process, with lower combustion duration and methane slip. As proven by existing studies, further integration of diesel pilot ignition and jet flame can be explored in the future to enhance the combustion performance of low-carbon fuels, providing support for the efficient and clean operation of engines.

5.2. Fusion of Pre-Chamber and Geometry Modification

The pursuit of higher combustion efficiency and stability in natural gas engines has driven the development of integrated strategies that combine advanced ignition systems with active in-cylinder flow management. Among these, the coupling of pre-chamber ignition with deliberate turbulence enhancement realized by piston geometry modifications represents a particularly effective pathway to substantially increase the combustion speed of natural gas. While pre-chamber jets introduce turbulence locally and at a specific timing, a well-organized global in-cylinder turbulent flow field is essential to sustain and propagate the flame rapidly throughout the entire chamber.

Xiong and coworkers [158] combined the technologies of prechamber and piston geometry modification to enhance combustion of natural gas based on a 6-cylinder large-bore engine with a cylinder radius of 75 mm. Various geometrical pistons, as shown in Figure 7, have been evaluated; the results indicate that, with a shallower piston bowl, the faster velocity of the flame jet impinges on the piston. Among these four pistons, the best thermal efficiency is obtained with the S7216 piston. The thermal efficiency is higher than that of a flat piston, by 0.9%, as shown in Figure 8. The pre-chamber jets provide the essential ignition energy and distributed flame nuclei within a main chamber that is already filled with a high level of pre-existing, organized turbulence. This turbulence immediately stretches and wrinkles the nascent flame fronts from each jet, significantly increasing their surface area. The global turbulent flow field, now further energized by the jet momentum and the early heat release, ensures that the subsequent flame propagation occurs at a turbulent flame speed that is substantially higher than the laminar flame speed. The enhanced mixing of burned and unburned gases improves heat and mass transfer, further supporting complete and fast combustion.



Name	Radius	Depth
Flat	0 mm	0 mm
S7208	72 mm	8 mm
S7216	72 mm	16 mm
S6016	60 mm	16 mm
S6521	65 mm	21 mm

Figure 7. Piston shapes [158].

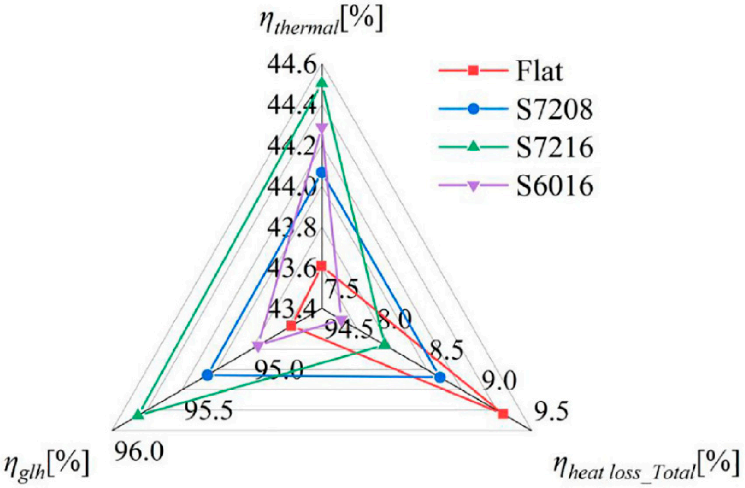


Figure 8. Thermal efficiency, total heat loss, and the degree of constant volume heat release for four pistons [158].

6. Future Outlook

Research on combustion optimization in natural gas/diesel dual-fuel engines has evolved from single-parameter adjustments to a systematic engineering approach integrating multiple technologies. This is driven by the need to address core challenges such as the slow combustion speed of natural gas, poor stability under low loads, and high methane emissions under high loads. Current research focuses on the deep integration of key pathways, including refined combustion chamber design (large squish-area pistons, customized piston bowl geometries [163]), active control of injection [170], ignition strategies (precise pilot diesel timing adjustment [171,172], stratified combustion [173,174], and pre-chamber ignition [175,176]), and diversification of fuel systems (hydrogen blending [177,178], biofuels application [179–181]). In terms of research methodologies, high-fidelity numerical simulations [182] and multi-objective optimization algorithms [183] have become essential tools for investigating mechanisms and supporting system design. Future trends emphasize integrated system-wide optimization [184], fuel-adaptive control [185], and the adoption of zero-carbon fuels, in order to achieve higher efficiency, ultralow emissions, and greater adaptability, thereby playing a crucial role in the ongoing energy transition.

With the goals to reduce carbon emissions and minimize climate changes, the application of low-carbon/zero-carbon fuels, such as natural gas, hydrogen, and ammonia, in engines has become an irreversible trend. However, challenges, such as slow combustion speed, ignition difficulties, and poor flame stability, severely restrict their large-scale application in high-efficiency, low-emission power systems. Based on current research progress and technological bottlenecks, future development in this field will revolve around the deep integration and innovative breakthroughs in three dimensions: fuel reactivity regulation, combustion process enhancement, and system intelligence and synergy.

Future high-efficiency, clean combustion engines will no longer rely on a single technological pathway. Instead, they will intelligently integrate multiple technologies, such as diesel micro-pilot ignition [186], fuel reactivity modification and jet flame propagation [187], to construct adaptive, multi-fuel combustion [188] control platforms. By integrating high-precision in-cylinder sensors to provide real-time feedback on combustion status, jet parameters [189,190], such as trigger timing, duration, intensity, and spatial direction, will be dynamically adjusted to achieve precise matching between jet energy and combustion requirements. Optimizing diesel spray distribution and the spatial guidance of jet flames will form a distributed, gradient-based ignition network within the cylinder. The spatiotemporal synergy of multiple ignition kernels will significantly shorten flame propagation distances and further extend the stability boundaries of ultra-lean combustion. Co-design of fuel and combustion system can be realized by developing dedicated jet structures tailored to the physicochemical properties of zero-carbon fuels, such as hydrogen and ammonia, enabling efficient coupling of fuel chemical energy and jet kinetic energy. The extreme complexity of combustion processes requires research methodologies to evolve from local modeling to full-system, multi-scale coupled simulations. Multi-fuel detailed chemical reaction kinetics, turbulence flame [191] interaction models, and two-phase spray dynamics to build simulation platforms capable of predicting the closed-loop relationships among jets, turbulence, combustion, and emissions, will enable dynamic calibration and optimization of combustion processes, providing a virtual testing environment for adaptive control strategies.

As zero-carbon energy carriers, such as hydrogen, ammonia [192,193], and synthetic fuels, gradually mature, the compatibility between their combustion characteristics and jet technologies will become a focal point of frontier research. The auto-ignition characteristics of hydrogen and the cracking combustion coupling processes of ammonia under high-pressure jet conditions will be explored, as well as the reliable ignition and rapid propagation of zero-carbon fuels through thermodynamic [194] regulation of jets. The inherent high NO_x generation tendency of ammonia combustion [195] will be addressed by developing synergistic emission reduction pathways based on jet mixing intensification, temperature stratification, and chemical inhibition. Multi-fuel compatible jet system design will be developed using versatile jet combustion platforms capable of flexibly switching between natural gas, hydrogen, ammonia, and even liquid synthetic fuels. Through modular nozzle design [196] and control logic reconfiguration, high-efficiency operation with flexible fuel engine will be achieved. Boundary expansion [197] and limit exploration [198] of ultra-lean combustion should be developed to improve thermal efficiency and reduce emissions by utilizing diesel micro-pilot ignition to provide a multi-ignition kernel and combining it with high-intensity turbulent jets [199,200] to accelerate flame propagation. This will explore stable operation ranges for ultra-lean combustion.

7. Conclusions

The core challenges of natural gas combustion are slow combustion speed and high methane slip, which are rooted in its physicochemical properties, and the high sensitivity of flame propagation in the engine cylinder. Strategies, such as combustion chamber geometry optimization (shallow bowl, high squish ratio) and variable swirl/tumble ratios, enhance in-cylinder turbulent kinetic energy and lay the foundation for combustion acceleration.

Multi-point ignition technologies, represented by pre-chamber jet ignition, address both the difficulty of lean ignition and slow flame propagation simultaneously by generating multiple high-energy, radical-rich turbulent jets, demonstrating significant effectiveness.

Fuel activation by blending additives as a combustion promoter into natural gas fundamentally enhances reactivity and extends the lean burn limit. Mixing with zero-carbon fuels, like ammonia, opens new pathways for deep decarbonization. Synergistic design and integrated control among turbulence organization, advanced ignition, and fuel activation are key to future technological breakthroughs.

Based on the trend of technology integration, the concept of induced jet combustion, which combines the chemical activation of diesel, multi-zone pilot ignition with the geometry activation of jet flame, creating a synergistic effect of distributed, high-intensity ignition sources and rapid turbulent flame propagation, holds promise as a transformative solution for enhancing the combustion of not only natural gas but also future fuels like ammonia.

The systematic cognitive framework developed in this study, ranging from problem essence to technological pathways, is applicable not only to natural gas but also provides analytical methods and solution insights for similar combustion challenges faced by future mainstream zero-carbon fuels like ammonia's ignition difficulty and hydrogen's abnormal combustion control. This offers important guidance for promoting the low-carbon transition of powertrain systems.

In summary, the future development of natural gas engine combustion technology will inevitably move towards the deep integration of multi-technology synergy. Through continuous deepening of fundamental research and iterative innovation in engineering technology, natural gas engines will play a crucial role during the energy transition and lay a solid technical foundation for achieving carbon neutrality goals in powertrain systems and marine applications.

Limitations

Current relevant studies mostly rely on simulation analysis and bench-scale experimental tests under ideal and steady operating conditions. Real-road/real-ship dynamic operating conditions, complex variable load environments, and long-term durability performance have not been fully verified. In addition, the collaborative optimization effect and practical adaptability of multi-technology integrated systems still lack sufficient real-world data support. Future research should focus on field validation, long-term operation monitoring, and system-level adaptive optimization to further promote the practical engineering application of relevant combustion technologies.

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