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Review

A Review of Marine Dual-Fuel Engine New Combustion Technology: Turbulent Jet-Controlled Premixed-Diffusion Multi-Mode Combustion

Jianlin Cao [1,†], Zebang Liu [2,†], Hao Shi [3,*], Dongsheng Dong [4,*], Shuping Kang [2] and Lingxu Bu [1]

[1] Marine Engineering College, Dalian Maritime University, Dalian 116026, China; caojianlin@dlmu.edu.cn (J.C.); blx15114774497@dlmu.edu.cn (L.B.)
[2] School of Engineering, Cardiff University, Queen's Building, Cardiff CF24 3AA, UK; liuz91@cardiff.ac.uk (Z.L.); kangs9@cardiff.ac.uk (S.K.)
[3] Department of Mechanical Engineering, Reactive Flows and Diagnostics, Technical University of Darmstadt, Otto-Berndt-Straße 3, 64287 Darmstadt, Germany
[4] School of Naval Architecture, Ocean and Energy Power Engineering, Wuhan University of Technology, Wuhan 430000, China
* Correspondence: hao.shi@rsm.tu-darmstadt.de (H.S.); dds2020@whut.edu.cn (D.D.)
† These authors contributed equally to this work.

Abstract

Driven by stringent emission regulations, advanced combustion modes utilizing turbulent jet ignition technology are pivotal for enhancing the performance of marine low-speed natural gas dual-fuel engines. This review focuses on three novel combustion modes, yielding key conclusions: (1) Compared to the conventional DJCDC mode, the TJCDC mode exhibits a significantly higher swirl ratio and turbulence kinetic energy in the main chamber during initial combustion. This promotes natural gas jet development and combustion acceleration, leading to shorter ignition delay, reduced combustion duration, and a combustion center (CA50) positioned closer to the Top Dead Center (TDC), alongside higher peak cylinder pressure and a faster early heat release rate. Energetically, while TJCDC incurs higher heat transfer losses, it benefits from lower exhaust energy and irreversible exergy loss, indicating greater potential for useful work extraction, albeit with slightly higher indicated specific NOx emissions. (2) In the high-compression ratio TJCPC mode, the Liquid Pressurized Natural Gas (LPNG) injection parameters critically impact performance. Delaying the start of injection (SOI) or extending the injection duration degrades premixing uniformity and increases unburned methane (CH_4) slip, with the duration effects showing a load dependency. Optimizing both the injection timing and duration is, therefore, essential for emission control. (3) Increasing the excess air ratio delays the combustion phasing in TJCPC (longer ignition delay, extended combustion duration, and retarded CA50). However, this shift positions the heat release more optimally relative to the TDC, resulting in significantly improved indicated thermal efficiency. This work provides a theoretical foundation for optimizing high-efficiency, low-emission combustion strategies in marine dual-fuel engines.

Keywords: turbulent jet ignition; marine dual-fuel engine; turbulent jet-controlled diffusion combustion; high efficiency; low emission; advanced combustion mode; diesel jet-controlled diffusion combustion

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1. Introduction

Maritime transportation serves as a critical enabler of global commerce, accounting for the movement of over 80% of international trade volume. This prominence is largely attributed to its inherent efficiency and cost-effectiveness for the large-scale transport of goods across continents. Powering the vast majority of the world's commercial fleet, internal combustion engines (ICEs) facilitate over 90% of this global seaborne trade and remain the primary propulsion option for modern marine vessels [1,2].

Large-bore, low-speed, two-stroke diesel engines constitute the predominant propulsion systems employed in ocean-going maritime vessels. Despite their operational efficiency, their exhaust emissions represent a significant source of environmental concern. These emissions are typically categorized into two categories: conventional atmospheric pollutants—including sulfur oxides (SOx), nitrogen oxides (NOx), and particulate matter (PM)—which primarily impact local air quality and contribute to regional environmental degradation; and greenhouse gases (GHGs)—notably carbon dioxide (CO_2) and methane (CH_4)—which are widely recognized contributors to global climate change. Illustrating the scale of this challenge, the global shipping industry consumes approximately 300 million tons of fuel oil equivalent annually. Global marine SOx emissions account for approximately 4% of the world's total, NOx emissions for around 7%, and GHG emissions—predominantly CO_2—reach approximately 1 billion tons per year, representing nearly 3% of total global anthropogenic CO_2 emissions. Regionally, shipping activities in major maritime nations like China contribute significantly to national emission inventories, estimated to account for 4–9% of SOx, 15% of NOx, and 2.7% of national CO_2 emissions.

Driven by increasingly stringent regulations governing ship exhaust emissions and greenhouse gas control, marine low-speed engines necessitate significant technological advancement to enhance thermal efficiency and mitigate pollutant emissions. Various technologies have been developed and implemented to enable compliance with the IMO Tier III NOx emission standards [3–5]. These include engine-based measures such as wet combustion techniques [6–11] and exhaust gas recirculation (EGR) [12–17], exhaust aftertreatment systems like selective catalytic reduction (SCR) [18–20], and the adoption of alternative fuels [21–25]. Among these approaches, the utilization of alternative fuels has demonstrated notable effectiveness in achieving substantial NOx reduction [21–24]. Key alternative fuels currently employed for NOx mitigation purposes encompass liquefied natural gas (LNG) [26], liquefied petroleum gas (LPG) [27], and methanol [28]. Figure 1 illustrates the comparative NOx reduction potential of different control strategies applied to marine engines [29]. As depicted in Figure 1, dual-fuel engine concepts utilizing natural gas exhibit the highest potential for NOx emission reduction. Crucially, the implementation of Otto-cycle combustion strategies with natural gas in these dual-fuel engines allows them to achieve IMO Tier III compliance without requiring exhaust gas aftertreatment. This capability is primarily attributed to the premixed combustion characteristics of natural gas, which effectively minimizes the formation of localized high-temperature zones, thereby significantly suppressing thermal NOx formation [30].

In addition to these strategies, recent filtration-based approaches have also shown promise in reducing emissions from marine engines. For instance, a novel non-woven fabric sandwich filter loaded with an activated carbon/polypyrrole nanocomposite has been developed to efficiently remove CO, SO_2, and NOx from gasoline engine emissions. This filter demonstrates high removal efficiencies (up to 99.2% for SO_2) and has the advantages of low cost, high thermal stability, and mechanical durability. Such filtration-based methods offer a complementary approach to traditional emission control techniques and highlight the ongoing efforts to develop more sustainable and efficient solutions for marine engine emissions [31].

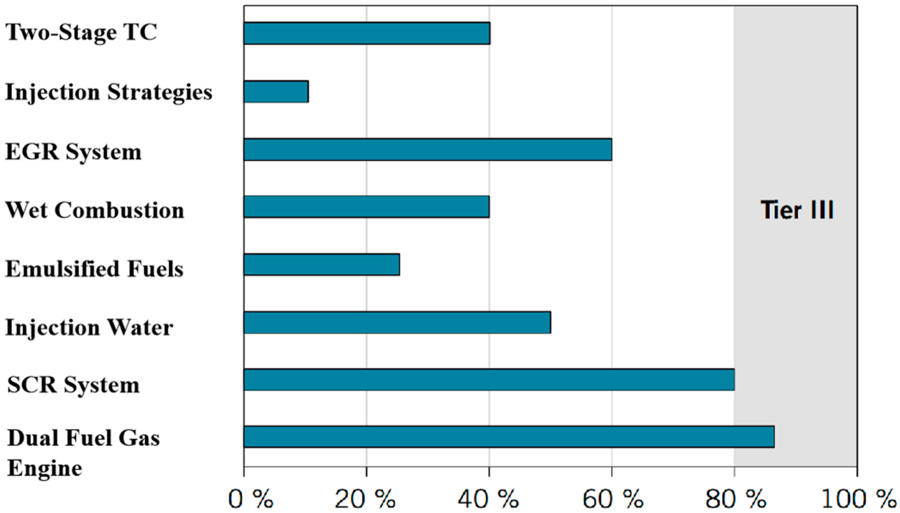

Figure 1. Potential of various NOx reduction technologies [29]. Reprinted with permission.

As a marine fuel, natural gas presents several distinct advantages, positioning it as a cleaner alternative to conventional heavy fuel oil. These benefits include its abundant global reserves, relatively high lower heating value (LHV), absence of sulfur compounds, lower emissions of criteria pollutants during combustion, and favorable cost compared to some alternatives [32,33]. Comparative studies highlight the significant environmental benefits, indicating that combustion of natural gas, owing to its lower hydrogen-to-carbon ratio compared to diesel fuel, can reduce CO_2 emissions by approximately 20%, NOx emissions by up to 90%, and virtually eliminate SOx and PM emissions. Reflecting its growing significance, projections by the classification society DNV-GL anticipate that liquefied natural gas (LNG) will constitute approximately 32% of the energy demand for ocean-going vessels by 2050. Consequently, driven by both its inherent advantages and increasing global demand for cleaner energy carriers, engine technologies capable of efficiently utilizing natural gas have garnered substantial research and development focus in recent years [34,35].

However, the practical application of natural gas as a marine fuel also faces several challenges. One of the primary concerns is the storage and handling complexity associated with LNG. Its cryogenic temperature requirements necessitate specialized containment systems and infrastructure, which can be costly and technically demanding. Additionally, the potential for methane leakage during storage, transportation, and bunkering poses both safety and environmental risks. Methane is a potent greenhouse gas, and even small leaks can significantly impact the overall climate benefits of using natural gas as a fuel. Therefore, while natural gas offers substantial environmental advantages, addressing these practical limitations is crucial for its widespread adoption in the maritime industry.

This review focuses on the advanced combustion technologies for marine low-speed dual-fuel engines, specifically targeting the application of turbulent jet ignition (TJI) technology to enhance combustion efficiency and reduce emissions. The scope of this review includes two novel combustion modes: Turbulent Jet-Controlled Premixed Combustion (TJCPC) and Turbulent Jet-Controlled Diffusion Combustion (TJCDC). These modes leverage pre-chamber jet ignition to integrate the advantages of both premixed and diffusion combustion while mitigating their respective drawbacks.

The novelty of this review lies in its comprehensive analysis of these combustion modes, providing detailed insights into their operational principles, combustion characteristics, and emission profiles. Unlike previous reviews that have primarily focused on individual combustion modes or specific fuel types, this work offers a holistic perspective by comparing and contrasting the performance of TJCPC and TJCDC under various operating conditions. Additionally, this review highlights the potential of TJI technology to optimize combustion strategies for marine dual-fuel engines, offering a theoretical foundation for the development of high-efficiency, low-emission propulsion systems..

Existing reviews on marine dual-fuel combustion technologies have predominantly focused on specific fuel types, such as liquefied natural gas (LNG) or methanol, or individual emission control techniques. While these reviews have provided valuable insights into the technical aspects of dual-fuel systems, they often lack a comprehensive analysis of the overall system performance and environmental impact. This review addresses this gap by offering a holistic perspective that encompasses the entire spectrum of marine dual-fuel combustion technologies, from fuel injection systems to exhaust aftertreatment.

Furthermore, this review incorporates the latest advancements in pre-chamber jet ignition technology, hybrid fuel systems, and advanced combustion modeling techniques, which have not been extensively covered in the existing literature. By examining the application of TJI in both premixed and diffusion combustion modes, this work provides a detailed understanding of the combustion characteristics and emission profiles of TJCPC and TJCDC. Additionally, this review highlights the practical challenges and opportunities associated with the implementation of dual-fuel and TJI technologies in marine engines, providing actionable recommendations for future research and development efforts.

Currently, dual-fuel technology represents the predominant propulsion system employed in low-speed marine engines utilizing natural gas for ocean-going vessels. This technology enables flexible operation, permitting seamless transitions between pure diesel and dual-fuel modes. In the dual-fuel mode, natural gas is used as the primary energy source, typically providing over 80% of the total energy input, with a small pilot injection of diesel fuel serving as the ignition source. Based on the combustion mode of natural gas, two primary technological approaches are distinguished for low-speed marine dual-fuel engines. The first approach involves premixed combustion, generally operating on the Otto-cycle principle, where a combustible air–fuel mixture is prepared within the cylinder via low-pressure direct injection (LPDI) of natural gas. The second approach utilizes diffusion combustion, aligning with the Diesel-cycle principle, employing high-pressure direct injection (HPDI) to introduce natural gas directly into the combustion chamber at high pressure, with combustion proceeding as the fuel mixes with the surrounding air.

Turbulent jet ignition (TJI), also known as pre-chamber jet ignition, represents an advanced ignition enhancement technology that has recently garnered significant interest within the marine engine sector due to its superior ignition performance [36–41]. Pre-chamber systems are typically classified into two categories, passive and active, based on whether fuel is directly introduced into the pre-chamber volume [36–42]. Passive pre-chambers do not feature dedicated fuel injection; instead, they are charged with the fuel–air mixture from the main combustion chamber during the compression stroke, a design commonly implemented in spark-ignition (SI) engines. Conversely, active pre-chambers incorporate a dedicated fuel injector and contain both this injected fuel and the mixture drawn from the main chamber, enabling their application in both SI and compression-ignition (CI) engines. For large marine engines with substantial combustion chamber volumes, active pre-chamber systems are generally preferred as they provide sufficient ignition energy and allow for precise control of the ignition timing. While pre-chamber ignition is currently more extensively applied in premixed combustion engine designs [43], research is actively exploring its potential for use in diffusion combustion engines. This expansion is particularly relevant given the increasing interest in alternative fuels with low cetane numbers, which present challenges for ignition via conventional compression-ignition methods.

Research concerning the application of pre-chamber jet ignition systems to premixed combustion in marine engines has seen increasing traction in recent years [44,45]. Leng et al. [46,47] performed simulation studies utilizing a marine medium-speed engine model (320 mm bore) to investigate pre-chamber ignition of premixed methanol and hydrogen-enriched natural gas. Their findings demonstrated that pre-chamber jet ignition facilitates reliable ignition, promotes stable combustion, and yields significant reductions in NOx emissions. Furthermore, this technology was shown to effectively extend the engine's lean burn limit. Complementary work by Li et al. [48] involved three-dimensional numerical simulations on a 320 mm bore marine natural gas engine, specifically examining the impact of pre-chamber orifice geometry and distribution strategies. As illustrated in Figure 2, the optimized design of the pre-chamber channels resulted in improved main chamber combustion efficiency, leading to a higher indicated power output and decreased NOx emissions.

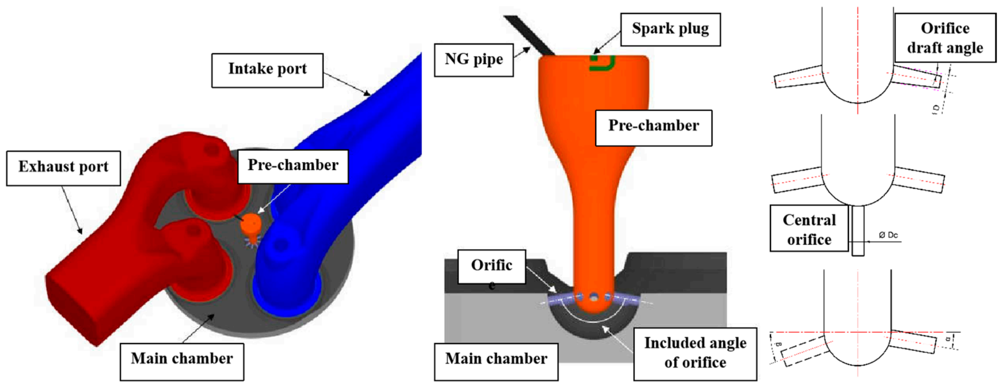

Figure 2. Example pre-chamber design for a marine medium-speed natural gas engine [48]. Reprinted with permission.

For marine low-speed engines, pre-chamber ignition technology has been successfully applied for igniting premixed natural gas–air mixtures [43–49]. These engines typically operate under ultra-lean premixed combustion conditions to achieve significantly reduced NOx emissions due to inherently lower combustion temperatures. However, a key challenge for gas premixed combustion in marine engines is its relatively narrow stable operating range. At the rich limit, the mixture is susceptible to pre-ignition and knocking, potentially leading to destructive detonation [50–52]. Conversely, operating too lean can result in misfire and combustion instability [53]. Pre-chamber ignition addresses the limitations at the lean limit by providing high ignition energy and robust ignition reliability, thereby effectively extending the lean burn capability of marine natural gas engines. Moreover, this technology enhances flame kernel development and propagation in ultra-lean mixtures while simultaneously mitigating abnormal combustion events such as end-gas autoignition [54]. The advantages offered by pre-chamber technology suggest significant market potential for low-speed marine natural gas engines, prompting increasing research attention in this area.

In addition to its established role in igniting premixed combustion engines, TJI technology has recently attracted increasing research interest for its application in diffusion combustion engines. This is particularly relevant for fuels with low cetane numbers, which exhibit limited auto-ignition capability under compression and, therefore, require an external ignition source. Conventionally, ignition in such diffusion combustion dual-fuel scenarios is achieved through a direct micro-pilot injection of diesel fuel. Compared to conventional diesel pilot-ignition methods, the application of pre-chamber jet ignition in diffusion combustion offers several key advantages:

(1) The high-velocity turbulent jets ejected from the pre-chamber significantly enhance the mixing of the main fuel (typically injected into the main chamber) with air, thereby improving the overall combustion rate and potentially increasing engine thermal efficiency.
(2) The physical separation afforded by the pre-chamber design allows for independent control over the combustion characteristics of the small amount of ignition fuel and the bulk of the main fuel combusting in the main chamber, minimizing mutual interference.
(3) Utilizing a pre-chamber ignition system can enable a significantly higher substitution rate of the main fuel compared to main-chamber micro-pilot diesel ignition. This increased substitution of fossil liquid fuel often leads to a reduction in engine-out emissions, including PM, SOx, and CO_2.

The pre-chamber jet-ignition diffusion combustion concept, termed Pre-chamber-Ignited High-Pressure Direct Injection (PI-HPDI), was first proposed and experimentally validated by Kammel et al. in 2019 [55], building upon existing HPDI technology for natural gas. This concept was experimentally verified on a high-speed, large-bore natural gas engine. As depicted in Figure 3, the PI-HPDI configuration features an integrated design wherein the HPDI natural gas injector is embedded within the pre-chamber volume, optimized for spatial arrangement and ignition performance. Unlike conventional diesel-ignited natural gas diffusion combustion engines, the PI-HPDI system operates exclusively on natural gas, without the need for a diesel pilot. The pre-chamber is equipped with a spark plug and a natural gas injector, while the main combustion chamber receives the primary natural gas charge via the integrated HPDI injector. Combustion is initiated by the flame jets ejected from the pre-chamber, which directly ignite the high-pressure injected natural gas in the main chamber. This process is characteristic of diffusion combustion, where fuel–air mixing and combustion occur simultaneously, and is not characterized by a distinct flame front propagating across the main chamber. This combustion mode facilitates the use of a high compression ratio without incurring knocking. Research indicates that PI-HPDI can achieve combustion characteristics comparable to those of diesel engines. Stable operation, however, is contingent upon sufficient momentum of the pre-chamber flame jets and precise ignition timing. These parameters are closely influenced by the structural design of the pre-chamber, the timing of fuel injection and ignition events within the pre-chamber, and the overall excess air ratio.

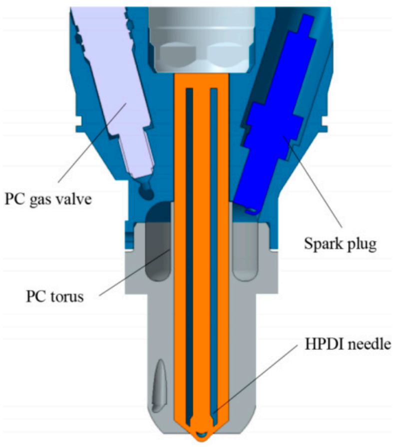

Figure 3. System layout of PI-HPDI [55]. Reprinted with permission.

Extending the foundational work by Kammel et al. [55], Zelenka et al. [56] performed a series of full-engine experimental investigations on the PI-HPDI concept. Their findings demonstrated that PI-HPDI is capable of achieving thermal efficiency comparable to that of conventional diesel engines, while enabling precise control over combustion phasing and the heat release rate. Furthermore, they reported a significant reduction in NOx emissions compared to diesel operation; however, this was accompanied by an increase in carbon monoxide (CO) and unburned hydrocarbon (UHC) emissions by a factor of 2 to 3. In a separate but related comparative study, Nsaif et al. [57] evaluated pre-chamber jet ignition applied to both natural gas premixed and diffusion combustion modes. The results of this investigation revealed that operating in the diffusion combustion mode drastically reduced methane slip (natural gas slip), reporting a reduction exceeding an order of magnitude, albeit at the cost of elevated NOx emissions.

Extending the investigation beyond gaseous fuels, Dempsey et al. [58,59] posited that liquid fuels—due to their potential for higher injection pressures and more flexible control—could particularly benefit from a pre-chamber-ignited high-pressure direct injection concept; consequently, they proposed a novel combustion concept, Pre-chamber-Enabled Mixing-Controlled Combustion (PC-MCC), and conducted experimental studies using methanol and ethanol. By varying the pre-chamber ignition timing, two distinct PC-MCC operating modes were identified: one characterized by direct ignition of the main liquid fuel jets by pre-chamber flame jets, and another where earlier pre-chamber ignition primarily serves to preheat the main combustion chamber charge. PC-MCC was also found to exhibit stable combustion characteristics, showing relative insensitivity to intake temperature and operational parameters. When fueled with ethanol, PC-MCC achieved a substantial 40% reduction in NOx emissions compared to diesel engines at the equivalent indicated thermal efficiency, highlighting its potential for efficient and clean combustion. Building upon this foundation, Zeman et al. [60,61] further explored PC-MCC by modifying the integrated injector–pre-chamber design into a split configuration where the main injector and pre-chamber are physically separated, as illustrated in Figure 4. Their research, employing ethanol and its blends, concentrated on the influence of pre-chamber placement and structural characteristics. The results underscored the critical role of pre-chamber orifice diameter in PC-MCC performance; larger orifices increased jet momentum, enabling flame jets to penetrate effectively towards the vicinity of the high-pressure direct injector and thereby enhancing ignition effectiveness. Comparing pre-chamber placement options, the side-mounted configuration demonstrated superior ignition stability and presented fewer challenges for cylinder head design compared to the center-mounted design, which proved more sensitive to ignition timing and required substantial structural modifications. The study additionally corroborated PC-MCC's robust fuel adaptability, noting that variations in fuel composition and reactivity had minimal detrimental impact on overall engine performance.

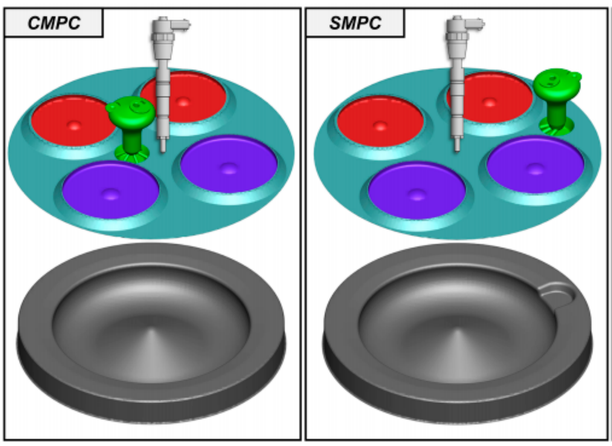

Figure 4. System layout of PC-MCC for split design [60]. Reprinted with permission.

Complementing engine-based investigations, the fundamental combustion characteristics of jet-initiated diffusion combustion have been explored using optical diagnostic techniques. Tudela et al. [62,63] utilized an optical engine platform to compare the combustion behavior of natural gas as the main fuel under three distinct ignition strategies: conventional diesel micro-pilot ignition, glow-plug-assisted ignition, and pre-chamber jet ignition applied to diffusion combustion. The experimental setup is depicted in Figure 5. Evaluation based on in-cylinder peak pressure and cycle-to-cycle variation metrics indicated that pre-chamber jet ignition exhibited superior combustion stability and performance. This enhanced performance was primarily ascribed to the energetic turbulent jets emanating from the pre-chamber, which facilitated improved mixing and accelerated combustion upon interaction with the directly injected natural gas jet. Furthermore, this ignition strategy was found to maintain stable combustion across a broad spectrum of operating conditions.

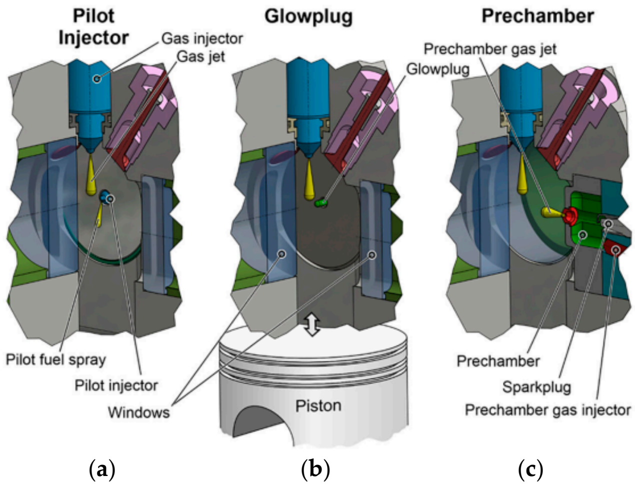

Figure 5. Installation diagrams of natural gas ignition methods: (**a**) diesel micro-injection; (**b**) glow-plug-assisted ignition; and (**c**) pre-chamber jet ignition [62]. Reprinted with permission.

Wei and Zhou [64,65] proposed the Turbulent Jet Ignition–High-Pressure Direct Injection (TJI-HPDI) combustion concept and conducted investigations into its fundamental ignition and combustion mechanism using a constant-volume chamber with high-pressure direct-injected natural gas. As depicted in Figure 6, their results demonstrate that varying the jet-to-ignition timing interval leads to the emergence of three distinct combustion modes: one where the presence of natural gas suppresses combustion, a second where natural gas initially suppresses and subsequently promotes combustion, and a third where natural gas is directly ignited and promotes combustion. Their study identified the existence of an optimal jet-to-ignition interval that correlates with the most favorable combustion performance. Furthermore, they mapped regions of successful ignition and ignition failure as a function of the jet-to-ignition timing and the pulse width of the main natural gas injection. The authors concluded that TJI-HPDI is capable of enabling stable and efficient combustion, with performance primarily governed by the interplay of fuel stratification and turbulence within the chamber.

Diesel pre-chamber turbulent jets, characterized by high temperature and velocity, offer robust ignition capability for low-speed dual-fuel engines compared to conventional diesel spray ignition. The inherent trade-offs associated with the two primary natural gas combustion modes—premixed combustion yielding significantly reduced NOx emissions but suffering from limited thermal efficiency and a narrow power output range, and diffusion combustion providing higher thermal efficiency and greater power output but at the cost of elevated NOx emissions—mean that low-speed dual-fuel engines constrained to single-mode operation face significant challenges in simultaneously optimizing both performance and emission characteristics. Addressing this challenge, the Turbulent Jet-Controlled Premixed-Diffusion Multi-Mode Combustion (TJC-PDMC) strategy, based on diesel pre-chamber turbulent jets, is proposed as an approach that integrates the advantages of both combustion modes while mitigating their respective drawbacks. Given the limited systematic review coverage of this emerging technology in the existing literature, this paper provides a summary of the research progress concerning TJC-PDMC technology for low-speed dual-fuel engines employing diesel pre-chamber turbulent jets. Furthermore, to facilitate a comprehensive understanding of this research domain, this review proposes a detailed classification into two distinct combustion modes: Turbulent Jet-Controlled Premixed Combustion (TJCPC) and Turbulent Jet-Controlled Diffusion Combustion (TJCDC). These proposed combustion modes represent novel pathways toward achieving high-efficiency and low-emission performance in large-bore two-stroke marine natural gas/diesel engines.

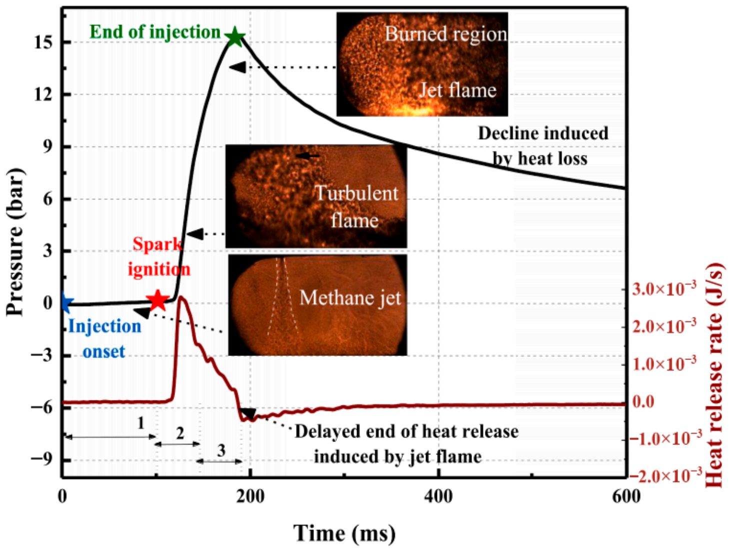

Figure 6. Stages of natural gas combustion ignited by pre-chamber jet ignition [64]. Reprinted with permission.

This paper is organized into four main sections: Section 1 provides an introduction outlining the background and motivation for this review; Section 2 reviews the research specifically on the TJCDC mode; Section 3 examines the body of work concerning the TJCPC mode; and finally, Section 4 presents the conclusions drawn from this review and discusses future research prospects.

2. Turbulent Jet-Controlled Diffusion Combustion (TJCDC) Mode

2.1. Operating Process of the TJCDC Mode

The traditional Diesel Jet-Controlled Diffusion Combustion (DJCDC) mode operates based on the following principle: A small quantity of diesel fuel is injected directly into the main combustion chamber near the Top Dead Center (TDC). This pilot injection undergoes autoignition, forming a flame kernel. Subsequently, natural gas is injected at high pressure into the vicinity of this diesel flame kernel, where it is ignited and combusts primarily via diffusion. For reliable ignition, the energy contribution from the diesel pilot typically exceeds 5%. However, the use of a significant diesel pilot injection inherently presents several drawbacks. Diesel, being composed of larger hydrocarbon molecules with longer carbon chains, is prone to forming soot particles during combustion. Furthermore, its higher carbon-to-hydrogen ratio results in elevated CO_2 emissions compared to cleaner fuels. Additionally, the relatively lower injection velocity of the diesel pilot jet provides limited assistance in promoting the mixing and development of the high-pressure natural gas jets.

Aiming to minimize the required pilot diesel fuel quantity while simultaneously ensuring effective ignition and promoting the development and mixing of the main natural gas jets, this review proposes a TJCDC mode for low-speed dual-fuel engines based on pre-chamber jet ignition technology. This proposed combustion mode utilizes two opposed pre-chambers strategically installed on the cylinder head. The operational principle involves injecting diesel fuel into these pre-chambers near the TDC, leading to its ignition. The subsequent combustion within the pre-chambers generates high-temperature, high-pressure gases that are then discharged through the pre-chamber orifices, forming high-speed, high-temperature turbulent jets in the main combustion chamber. Upon interaction with the simultaneously injected natural gas jets, the natural gas is rapidly ignited and undergoes diffusion combustion. Figure 7 illustrates the operating principle of the TJCDC mode.

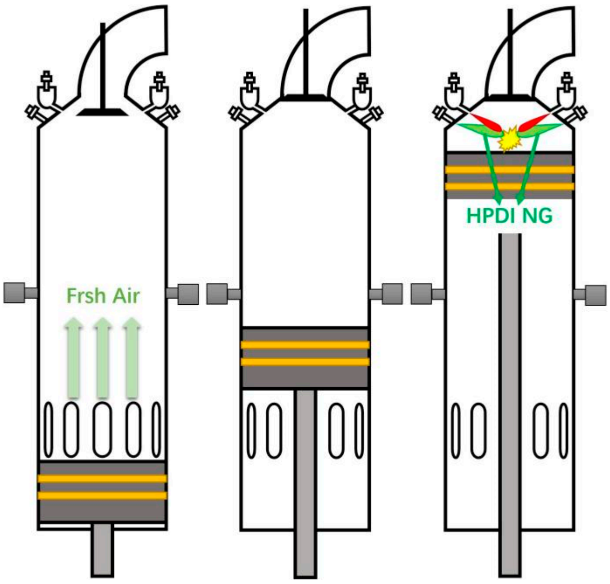

Figure 7. Operational schematic of the TJCDC mode.

2.2. Combustion and Emission Characteristics of the TJCDC Mode

2.2.1. Combustion Characteristics of the TJCDC Mode

Figure 8 shows a three-dimensional model of the DJCDC and TJCDC combustion modes and their components, while Figure 9 shows the locations of the DJCDC and TJCDC diesel and natural gas injectors on the cylinder head. Figure 10 presents a comparison of the flame development process for the DJCDC and TJCDC combustion modes. Figure 10a employs an equivalence ratio iso-surface of 0.5 to delineate the fuel jet contour, representing primarily natural gas after 3 °CA ATDC, while a 1700 K iso-surface is utilized to indicate the flame front contour. Figure 10b illustrates the temporal evolution of the areas corresponding to these iso-surfaces. As evident from Figure 10a, the geometry of the natural gas diffusion flame front generally conforms to the contour of the fuel jet, signifying that the development of the main natural gas jet directly governs the diffusion combustion area and, consequently, dictates the heat release rate. Under the influence of the energetic turbulent jets generated in the TJCDC mode, the natural gas jet exhibits enhanced penetration, extending farther into the combustion chamber and presenting a larger jet area compared to the DJCDC mode. Consistent with this observation, Figure 10b shows that during the initial jet development phase, the natural gas jet area in TJCDC is consistently larger than in DJCDC. This larger jet area translates to a greater flame area during the early stages of flame development under

TJCDC. However, in the interval between 6 and 10 °CA ATDC, the flame area in the TJCDC mode becomes smaller than that in the DJCDC mode. This phenomenon is attributed to the earlier impingement of the rapidly developing natural gas jet onto the cylinder wall in the TJCDC mode, particularly evident after 6 °CA ATDC, where a substantial portion of the jet undergoes wall collision. This interaction at the wall surface disrupts flame propagation along the jet periphery, leading to a decelerated rate of flame area increase compared to the DJCDC mode.

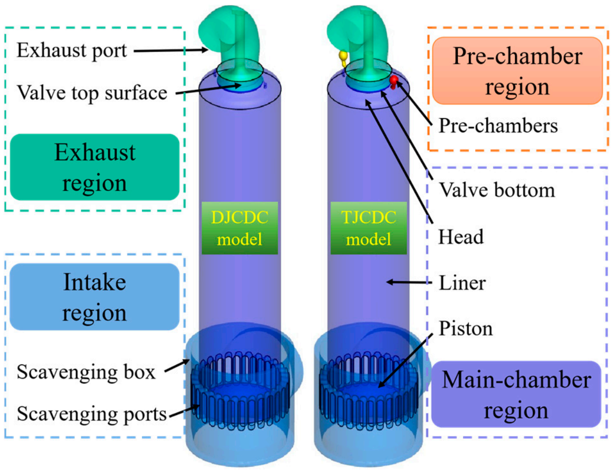

Figure 8. Three-dimensional models and component diagrams of the DJCDC and TJCDC modes.

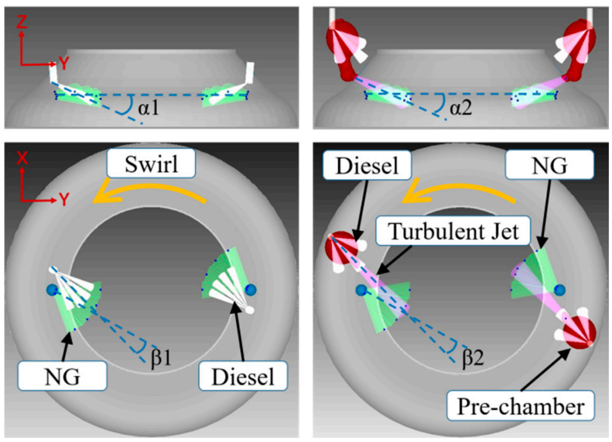

Figure 9. Fuel injection system layouts for the DJCDC and TJCDC modes.

2.2.2. Emission Characteristics of the TJCDC Mode

Figure 11 illustrates the indicated specific emissions of greenhouse gases (specifically CO_2) and NOx for the DJCDC and TJCDC modes. Figure 11a shows that the equivalent indicated CO_2-specific emission of the TJCDC mode is 3.7 g/kWh lower than the DJCDC mode. Several factors contribute to this reduction. Firstly, the lower pilot diesel proportion in TJCDC (2% vs. 4.8% in DJCDC) results in a higher overall hydrogen-to-carbon (H/C) ratio of the fuel mixture. As demonstrated by using n-heptane (C7H16) (H/C = 2.3) and methane (CH_4) (H/C = 4) as surrogates, fuels with higher H/C ratios yield less CO_2 per unit energy. Secondly, reduced afterburning in TJCDC contributes to lower unburned CH_4 emissions. Thirdly, the higher thermal efficiency of TJCDC means more power is generated per unit fuel energy, thus lowering specific CO_2 emissions. Conversely, Figure 11b reveals that NOx emissions—which correlate strongly with the maximum mean temperature (MMT)—are higher in the TJCDC mode, measuring 0.8 g/kWh more than DJCDC. This increase is attributed to the faster heat release rate in TJCDC, leading to higher in-cylinder temperatures and enhanced thermal NOx formation.

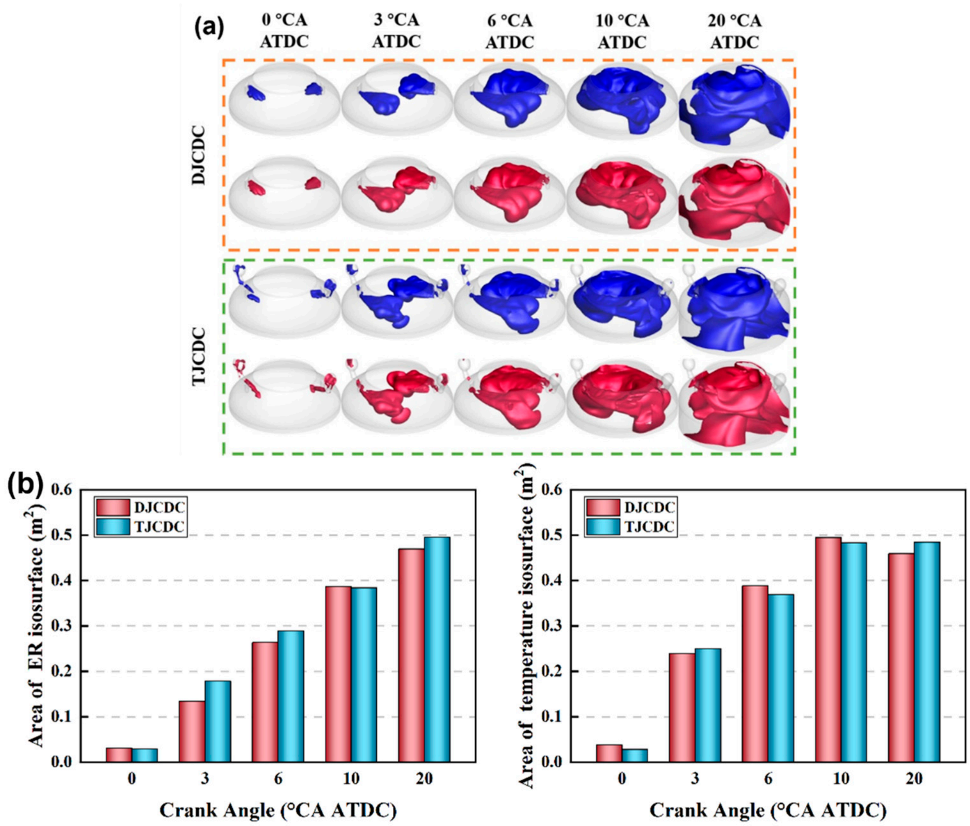

Figure 10. Comparison of flame development process in DJCDC and TJCDC modes: (**a**) evolution of equivalence ratio (ϕ = 0.5) and temperature (1700 K) iso-surfaces versus crank angle; (**b**) area of the 1700 K temperature iso-surface versus crank angle.

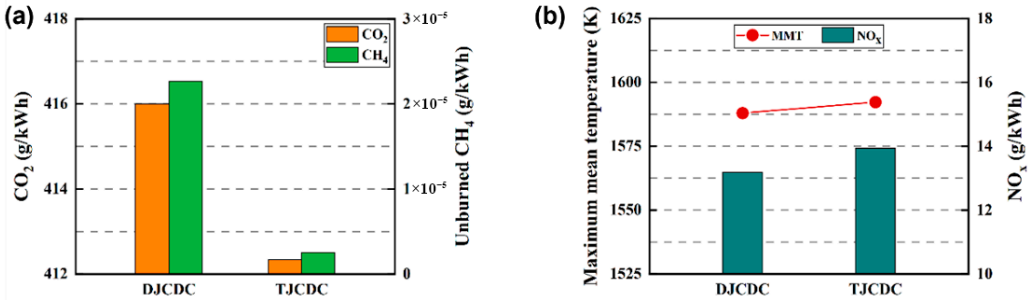

Figure 11. Indicated specific greenhouse gas and NOx emissions in DJCDC and TJCDC modes: (**a**) CO_2 and unburned CH_4 emissions; (**b**) maximum mean temperature and NOx emissions.

As a result of the above study, it can be learned that there are differences in both the DJCDC and TJCDC models in terms of key performance indicator parameters, as shown in Table 1.

Despite the higher NOx emissions in the TJCDC mode compared to DJCDC, several potential strategies can be explored to mitigate this issue. One approach is to optimize the injection timing and quantity of the pilot diesel fuel in the pre-chambers. By carefully controlling the ignition timing, it is possible to reduce the peak in-cylinder temperatures, thereby suppressing thermal NOx formation. Additionally, the use of exhaust gas recirculation (EGR) can be considered to lower the oxygen concentration in the combustion chamber, which in turn reduces NOx emissions. Another promising strategy is the application of selective catalytic reduction (SCR) in the exhaust aftertreatment system. SCR can effectively reduce NOx emissions by converting them into nitrogen and water vapor through the use of a catalyst and a reducing agent, such as ammonia or urea. These strategies, either individually or in combination, could help to achieve a better balance between combustion efficiency and NOx emissions control in the TJCDC mode.

Table 1. Comparison of key performance indicators between DJCDC and TJCDC.

Mode	DJCDC	TJCDC
Ignition delay (°CA)	5.43	4.63
Combustion duration (°CA)	20.8	21.1
Indicated thermal efficiency	52.8%	52.9%
NOx (g/kWh)	13.19	13.94
CO_2 (g/kWh)	416.0	412.3

3. Turbulent Jet-Controlled Premixed Combustion (TJCPC) Mode Study

3.1. Operating Process of the TJCPC Mode

While the combustion rate in natural gas diffusion combustion is primarily governed by the injection rate, limitations in injection technology impose a relatively low upper limit on achievable diffusion combustion rates. In contrast, the combustion rate of premixed natural gas combustion is predominantly determined by the flame propagation speed of the mixture. Under elevated compression ratios, the resultant high in-cylinder pressure and temperature significantly enhance flame propagation speed, leading to a short combustion duration and a high peak in-cylinder pressure, all of which are conducive to improving engine thermal efficiency. Furthermore, lean-burn premixed combustion inherently results in low NOx formation, effectively reducing specific Nox emissions. However, a significant challenge arises under medium- and high-load conditions with high compression ratios, where the premixed combustion rate can become excessively rapid. This can potentially exceed the engine's mechanical limits for peak pressure and pressure rise rate and increase the susceptibility to abnormal combustion phenomena, including pre-ignition and knocking. Therefore, this review proposes the application of a high-compression-ratio TJCPC mode specifically under low-load operating conditions. Under low-load conditions, the inherently lower in-cylinder pressure and temperature levels ensure that, even with a high compression ratio, the premixed combustion rate remains within acceptable mechanical limits, thereby mitigating the risk of abnormal combustion and satisfying mechanical load requirements. Concurrently, employing high-compression-ratio premixed combustion under these conditions facilitates the maximization of thermal efficiency.

Building on the operational characteristics, it is noted that while natural gas diffusion combustion modes are typically compliant with emission standards only outside Emission Control Areas (ECAs), premixed combustion holds the potential for meeting ECA standards directly. However, as discussed, the high-compression-ratio Turbulent Jet-Controlled Premixed Combustion (TJCPC) mode is not suitable for operation at medium and high loads. Consequently, to ensure emission compliance when operating within ECA zones, a low-compression-ratio TJCPC mode is necessary, particularly given that these zones often involve operational profiles encompassing higher engine loads. The feasibility of implementing a low-compression-ratio TJCPC mode is supported by the relatively mature state of variable compression ratio (VCR) technology in marine low-speed engines.

In this section, a three-dimensional simulation model was constructed to investigate the TJCPC mode, based on a 4T50ME-GI engine. Table 2 below shows the detailed parameters of the 4T50ME-GI engine. Modifications to the original 3D engine model included the addition of two opposed low-pressure natural gas injectors on the cylinder liner and the installation of two diesel pre-chambers at the original ignition fuel injector locations on the cylinder head. The operating principle of the TJCPC mode is illustrated in Figure 12. During the piston's upward stroke, typically after scavenge port closure to prevent backflow, natural gas is injected into the cylinder via low-pressure direct injection (LPDI). This gas mixes with air during the compression stroke, forming a relatively homogeneous premixed mixture prior to ignition. Subsequently, pilot diesel fuel is injected into the pre-chambers shortly before TDC. Following diesel autoignition within the pre-chambers, high-temperature, high-speed turbulent jets are ejected into the main combustion chamber. These jets ignite the premixed natural gas–air mixture, leading to rapid premixed combustion of the main charge.

Table 2. Main parameters of 4T50ME-GI engine.

Parameters	Value
Engine Model	4T50ME-GI
Cylinder Bore (mm)	500
Stroke (mm)	2885
Connecting Rod Length (mm)	2200
Geometric Compression Ratio	18.14
Number of Cylinders	4
Number of Pre-Combustion Chambers	-
Pilot Fuel Injector	2
Natural Gas Injection Valve	2
Natural Gas Injection Mode	High-pressure direct injection
Pilot Fuel Maximum Percentage (%)	11.3
Rated Speed (r/min)	123
Rated Power (kW)	7080
Nox Emission Standard	Meets Tier II

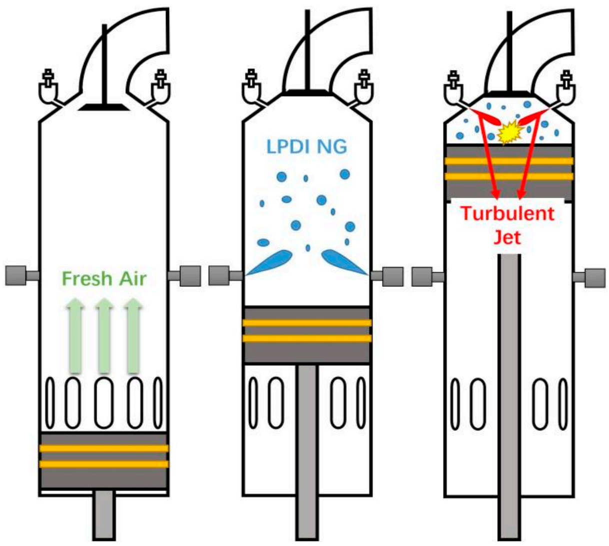

Figure 12. Operation schematic of the TJCPC mode.

3.2. Combustion and Emission Characteristics of the TJCPC Mode

3.2.1. Influence of Natural Gas Injection Parameters on Premixing Performance

The timing of low-pressure natural gas (LPNG) injection exerts a direct influence on the axial distribution of fuel within the cylinder. Variations in injection timing also determine the premixing duration available before ignition, thereby impacting the radial distribution of natural gas. Furthermore, given that the LPNG injection window predominantly occurs during the engine's scavenging and compression strokes, suboptimal timing can result in a significant portion of the natural gas bypassing the cylinder and entering the exhaust system, leading to undesirable methane slip. The homogeneity of the in-cylinder natural gas–air mixture is a critical parameter influencing both combustion efficiency and emission characteristics. Non-uniform premixing gives rise to localized zones of varying equivalence ratio. Locally rich regions are prone to generating excessively high combustion temperatures, resulting in increased Nox formation and a heightened risk of abnormal combustion phenomena like pre-ignition. Conversely, overly lean regions can manifest very low flame propagation speeds, a greater propensity for flame quenching, and substantial emissions of unburned hydrocarbons (UHC) and carbon monoxide (CO), particularly in peripheral combustion zones.

Figure 13 shows the effect of LPNG injection timing on Nox and unburned CH_4 emissions under various load conditions. As can be seen from Figure 13, Under various load conditions, delaying the LPNG injection generally leads to an increase in the mass of unburned methane. Furthermore, beyond a certain threshold of delay, the unburned CH_4 mass escalates sharply. This phenomenon is attributed to late injection, resulting in the natural gas being predominantly located near the top of the combustion chamber at the point of ignition, particularly within narrow crevices such as the volume between the exhaust valve and the cylinder head. These regions are highly susceptible to flame quenching, thereby increasing the level of unburned CH_4 emissions. Regarding Nox formation, its concentration is influenced by both the local equivalence ratio and the spatial distribution of rich mixture zones within the combustion chamber. Higher equivalence ratios in these rich zones are generally conducive to increased Nox formation. Additionally, the spatial positioning of these zones can impact the global flame propagation speed of the premixed charge, consequently influencing in-cylinder temperature profiles and contributing to variations in overall Nox emissions.

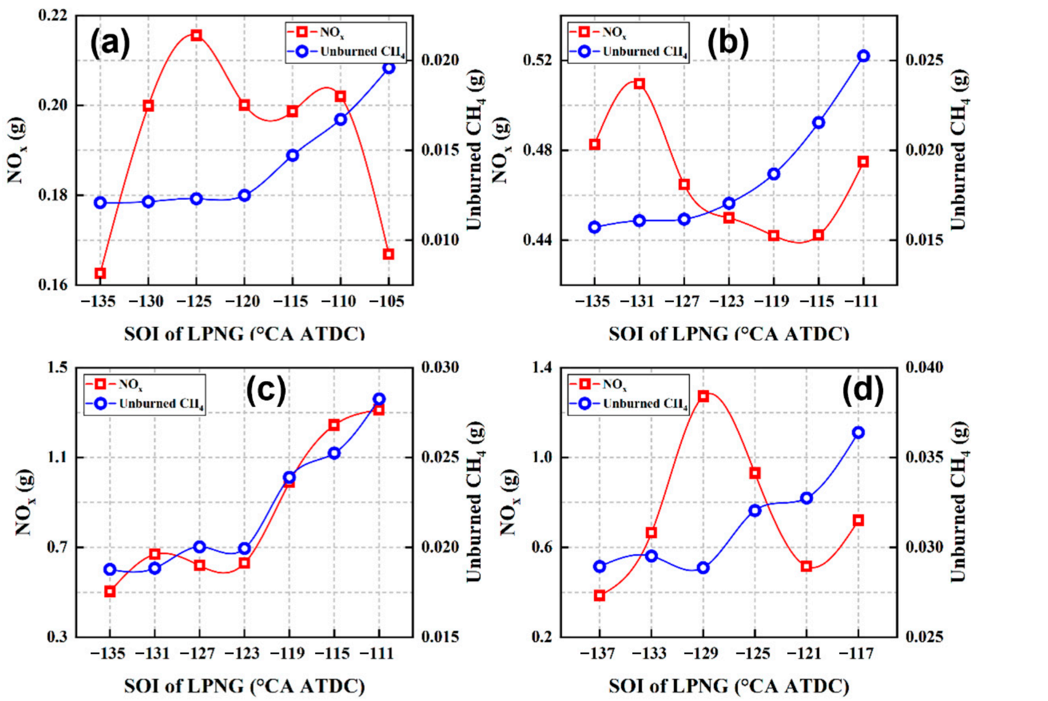

Figure 13. Effect of injection timing of LPNG on NOx and unburned CH_4 emissions: (**a**) 25% load; (**b**) 50% load; (**c**) 75% load; (**d**) 100% load.

Regarding the experimental validation of the TJCPC mode, it is worth noting that Wärtsilä GD engines have largely adopted the TJCPC mode. Therefore, this mode has demonstrated applicability under real marine engine conditions. The extensive application of TJCPC mode in Wärtsilä GD engines indicates that it has undergone rigorous testing and validation, ensuring its reliability and efficiency in practical marine operations. This real-world application provides strong evidence of the mode's effectiveness and suitability for marine engines, supporting the simulation results and highlighting its potential for broader adoption in the industry.

In addition to injection timing, the duration of LPNG injection significantly influences the homogeneity of the in-cylinder premixed charge. While a shorter injection duration is typically associated with higher injection pressure, potentially enhancing initial mixing and increasing the effective mixing time before ignition, it also results in a more spatially concentrated natural gas distribution within the cylinder. This increased concentration elevates the likelihood of forming locally rich zones. Such rich zones can lead to excessively rapid local combustion rates, a pronounced increase in NOx formation, and a higher susceptibility to abnormal combustion phenomena, including pre-ignition and knocking. Consequently, selecting an appropriate LPNG injection duration is crucial for optimizing combustion performance and emissions.

Figure 14 illustrates the influence of LPNG injection duration on the homogeneity of the premixed natural gas–air mixture and unburned methane across various engine load conditions. The LPNG injection duration schemes are such that, for each load, the injection centroid (defined as the crank angle at the midpoint of the injection duration) was maintained constant, while the injection start and end points were symmetrically adjusted to vary the duration. As depicted in Figure 14, unburned CH_4 emissions are observed to increase progressively with the extension of injection duration. This trend is attributable to the earlier injection start associated with longer durations (at a fixed centroid), which facilitates earlier entry of natural gas into the cylinder and provides an extended period for diffusion and potential short-circuiting into the exhaust port. Notably, under 75% and 100% load conditions, the slip CH_4 emissions exceed the permissible limit when the injection duration surpasses 27 °CA. Furthermore, the premixing uniformity exhibits load-dependent behavior; at 25%, 50%, and 75% loads, uniformity initially improves and subsequently deteriorates with increasing injection duration, whereas at 100% load, uniformity continuously deteriorates as the injection duration lengthens.

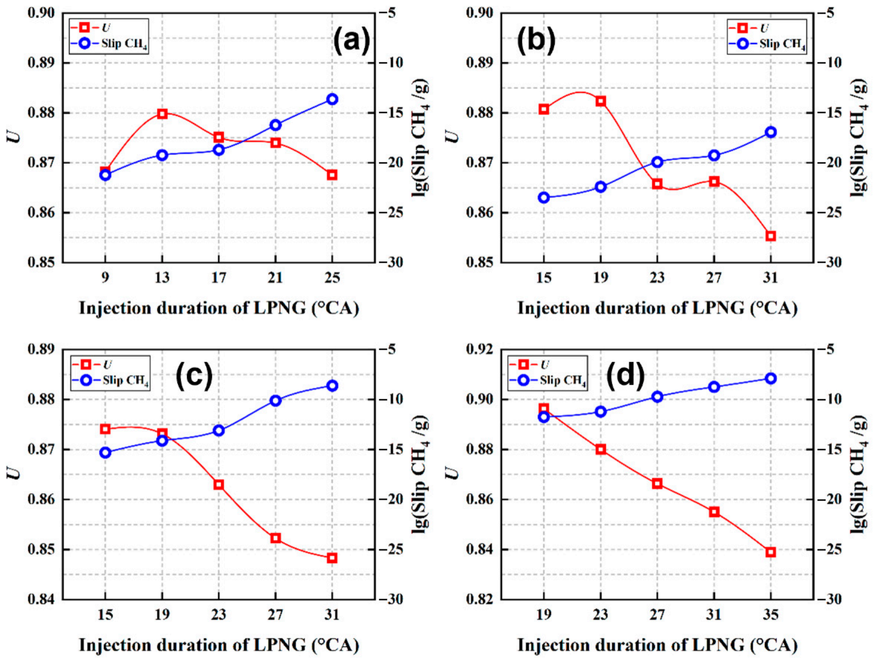

Figure 14. Effect of LPNG injection duration on premixing uniformity and slip CH_4 emissions: (**a**) 25% load; (**b**) 50% load; (**c**) 75% load; (**d**) 100% load.

As a result of the above study, the optimum injection parameters of LPNG in the TJCPC mode at each load condition can be known as shown in Table 3.

Table 3. Optimal injection parameters for natural gas in TJCPC mode.

Load	Injection Timing (°CA ATDC)	Injection Duration (°CA)
25%	−120	13
50%	−123	19
75%	−131	23
100%	−121	27

3.2.2. Effect of Excess Air Ratio Under High Compression Ratio

For the high-compression-ratio TJCPC mode, operation under high-load conditions results in an excessive peak in-cylinder pressure and pressure rise rate, leading to a significantly elevated risk of knocking. However, at low- and medium-load conditions, a high compression ratio can be successfully employed as the peak pressure and pressure rise rate remain within acceptable mechanical limits. This allows for maintaining a low knocking risk while substantially enhancing thermal efficiency. The excess air ratio (λ) exerts a significant influence on the combustion characteristics of natural gas premixed modes, directly impacting engine performance. In the following, different excess air coefficients are realized by keeping the fuel quantity constant and setting different sweep pressures, as shown in Table 4, where the baseline is the original machine scheme. Figure 15 clearly illustrates the influence of λ on the combustion phasing and thermal efficiency for the high-compression-ratio TJCPC mode. Figure 15a shows that an increase in λ prolongs both the ignition delay (SOI–CA10) and the combustion duration (CA10–CA90), causing the combustion centroid (CA50) to shift toward later crank angles. As shown in Figure 15b, higher values of λ correlate with improved combustion efficiency, consequently leading to enhanced thermodynamic and indicated thermal efficiencies. Although increasing λ extends the combustion duration, the accompanying later shift in CA50—particularly towards the optimal timing for work extraction relative to TDC—minimizes compression-negative work and maximizes expansion work output, thus enhancing both thermodynamic and indicated thermal efficiencies.

Table 4. Excess air coefficient scheme at 25% load in TJCPC mode with high compression ratio.

Scheme	Baseline	SP-1	SP-2	SP-3	SP-4	SP-5	SP-6	SP-7	SP-8
Scavenging pressure (bar)	1.60	1.65	1.70	1.75	1.80	1.85	1.90	1.95	2.00
λ	1.97	2.04	2.11	2.17	2.24	2.30	2.37	2.43	2.50

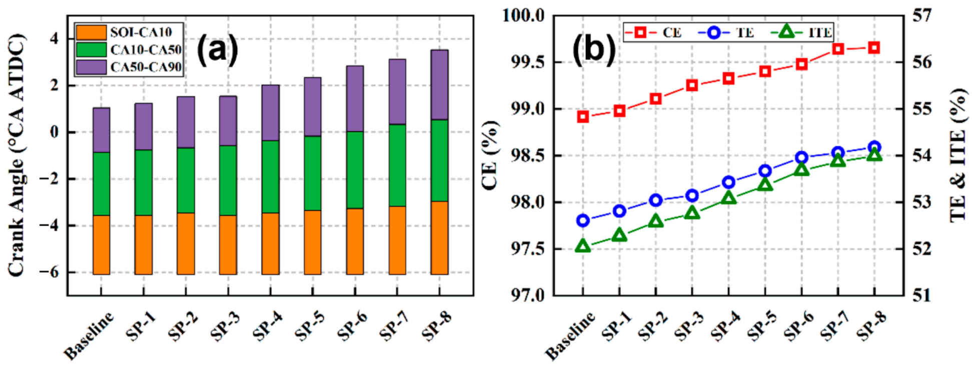

Figure 15. Effect of excess air ratio (λ) on combustion phasing (**a**) and engine efficiencies (**b**) in TJCPC mode with high compression ratios.

For the 4T50ME-GI engine, the compression and peak pressures at full load are 15.3 MPa and 17.4 MPa, respectively. According to the Wärtsilä low-speed engine design standard, the peak pressure should not exceed 1.25 times the compression pressure. Therefore, the peak pressure limit for the engine simulation in this study was set at 18.0 MPa with an allowable pressure fluctuation of $\pm$0.5 MPa around this limit.

While the role of the excess air ratio (λ) and its relationship to efficiency was explained, the risk of ultra-low-purity mixtures to combustion stability was not addressed. A brief discussion of the potential trade-offs between efficiency and misfire propensity follows. Increasing λ to achieve ultra-lean mixtures can significantly improve thermal efficiency and reduce emissions but also poses risks associated with combustion stability. Specifically, ultra-dilute mixtures are more prone to misfire, which occurs when the air–fuel mixture is too lean to sustain combustion. Misfires can lead to incomplete combustion, which can increase emissions of unburned hydrocarbons (UHC) and carbon monoxide (CO). In addition, a misfire can cause significant fluctuations in engine performance, reducing overall efficiency and potentially leading to mechanical failure. Therefore, while λ is optimized for efficiency, combustion stability must be balanced to ensure reliable engine operation.

Figure 16 illustrates the effect of the excess air ratio (λ) on indicated specific greenhouse gas emissions (specifically CO_2 and equivalent CO_2, ECO2, from unburned CH_4, calculated as the mass of $CH_4 \times 28$) and NOx emissions in the high-compression-ratio TJCPC mode. As depicted in Figure 16a, increasing λ results in a decrease in indicated specific CO_2 emissions while simultaneously causing a progressive increase in ECO2 emissions. The reduction in indicated specific CO_2 is primarily attributed to the enhanced thermal efficiency achieved at higher λ, which yields a greater work output per unit of fuel energy input. Additionally, operating with higher λ means less fuel (and carbon) is introduced per cycle volume, contributing to lower gross CO_2 formation per cycle. Conversely, the increase in ECO_2 emissions directly correlates with a rise in unburned CH_4 mass at a higher λ, indicative of decreased combustion completeness as the mixture becomes excessively lean, leading to increased unburned hydrocarbon emissions. As shown in Figure 16b, indicated specific NOx emissions decrease significantly with increasing λ. This reduction is mainly due to the lower peak in-cylinder temperatures associated with leaner combustion, which suppresses thermal NOx formation. The concurrent improvement in thermal efficiency also contributes to lower NOx emissions on a specific basis.

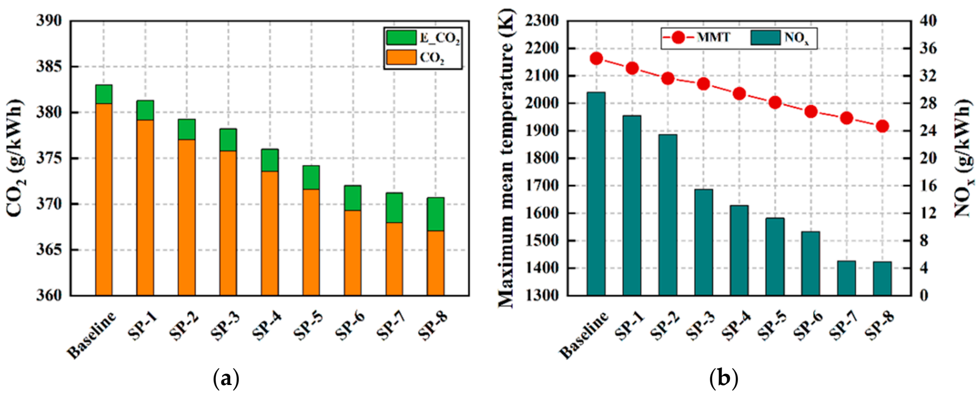

Figure 16. Effect of excess air ratio (λ) on emissions of greenhouse gases (**a**) and NOx (**b**) in TJCPC mode with high compression ratios.

3.3. Future Research Directions and Recommendations

Given the increasing interest in alternative fuels like methanol, ethanol, and ammonia for marine applications, it is valuable to explore how the TJI concepts might adapt to these low-CN or alcohol-based fuels. Preliminary assessments suggest that the high reactivity of alcohol fuels could enhance combustion stability in the TJCPC mode. However, detailed studies are needed to confirm the operational feasibility, including the impact on engine performance and emissions. Additionally, the adaptability of TJI systems to ammonia, considering their unique combustion characteristics, merits further investigation.

Future research should prioritize empirical validation of TJI concepts with various fuels through comprehensive engine testing. It is essential to evaluate the real-world performance and emission profiles of these combustion modes under practical marine operating conditions. Addressing integration challenges, such as adapting existing engine hardware and control systems to new fuel types, is also crucial for the successful implementation of these advanced combustion technologies.

While the TJI concepts, particularly the TJCPC and TJCDC modes, present promising advancements for marine dual-fuel engines, their practical implementation in retrofitting existing engines can encounter several challenges:

(1) Injector Packaging: The integration of pre-chamber injectors within the confined space of an engine chamber poses a significant challenge that needs to be addressed in retrofit scenarios;
(2) Cooling: Pre-chamber systems may generate considerable heat, requiring effective cooling solutions to prevent overheating and maintain component integrity;
(3) Maintenance: The addition of pre-chamber systems could increase maintenance complexity and frequency, necessitating the development of robust maintenance procedures;
(4) Combustion Noise: The turbulent jets and combustion processes might increase engine noise levels, thus requiring strategies to manage acoustic emissions.

These practical challenges must be carefully considered and resolved to ensure the successful adoption and operation of TJI concepts in real-world marine engine applications. Future research should focus on developing strategies to overcome these retrofitting challenges, ensuring that TJI concepts can be effectively implemented in existing marine engines.

4. Comparative Summary of Combustion Modes

After describing the two combustion modes mentioned above, the following is an experimentally based comparison of the two, including performance, emissions, and energy distribution. Figure 17 is a comparison of EISFC and NOx emission, showing the comparison of Indicated Specific Fuel Consumption (EISFC) and Nitrogen Oxide (NOx) emission for TJCPC and TJCDC modes, and it can be seen that the TJCDC mode displays a higher ISFC value and NOx emission. This indicates that the TJCDC mode increases NOx emissions while improving combustion efficiency. Figure 18 shows the combustion efficiency comparison, comparing the combustion efficiencies in the TJCPC and TJCDC modes—including thermal efficiency (TE), indicated thermal efficiency (ITE), and mechanical efficiency (CE)—and it can be seen that the TJCPC mode outperforms the TJCDC in all the efficiency indexes, showing a higher energy conversion efficiency; Figure 19 shows the comparison of CO_2 emission and the amount of unburned CH_4, which shows that the CO_2 emission in the TJCDC mode is significantly higher than that of TJCPC, indicating that TJCDC performs poorly in reducing GHG emissions; Figure 20 is a comparison of the crankshaft angle, which compares the crankshaft angle changes in different combustion stages between the TJCPC and TJCDC modes, and it can be seen that the combustion process in the TJCDC mode is more concentrated near the upper stop, while the TJCPC mode shows a more uniform combustion process; Figure 21 is a comparison of energy and exhaust distribution, which shows that the TJCPC mode is more reasonable in energy utilization and exhaust distribution, reducing the loss of unburned energy. Comparison of combustion, performance, and emission index parameters for the two combustion modes of TJCPC and TJCDC is shown in Table 5. From Table 5, it can be seen that the TJCPC mode is more advantageous in terms of the equivalent fuel consumption rate, NOx, and CO_2 emissions, while the TJCDC mode performs better in terms of combustion efficiency and CH_4 emissions.

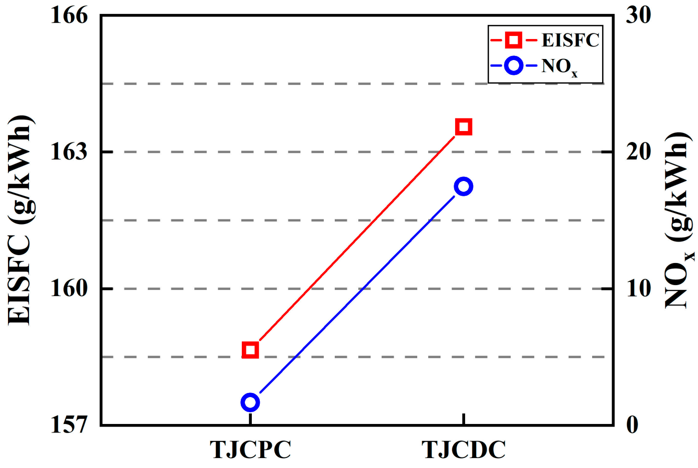

Figure 17. Comparison of EISFC and NOx emissions.

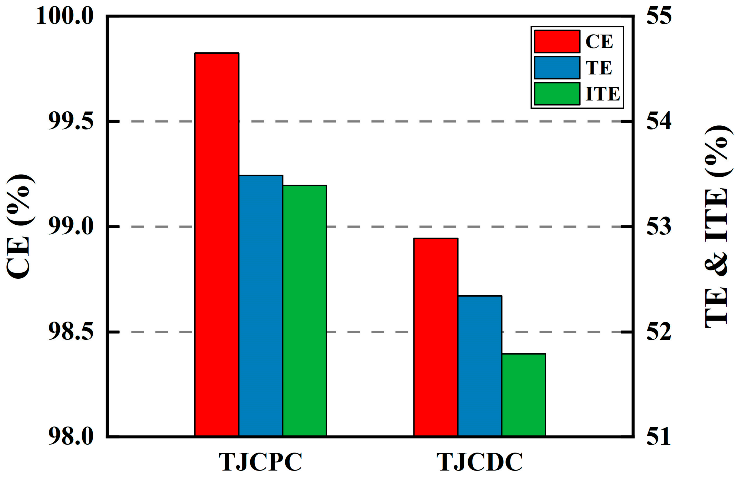

Figure 18. Comparison of combustion efficiency.

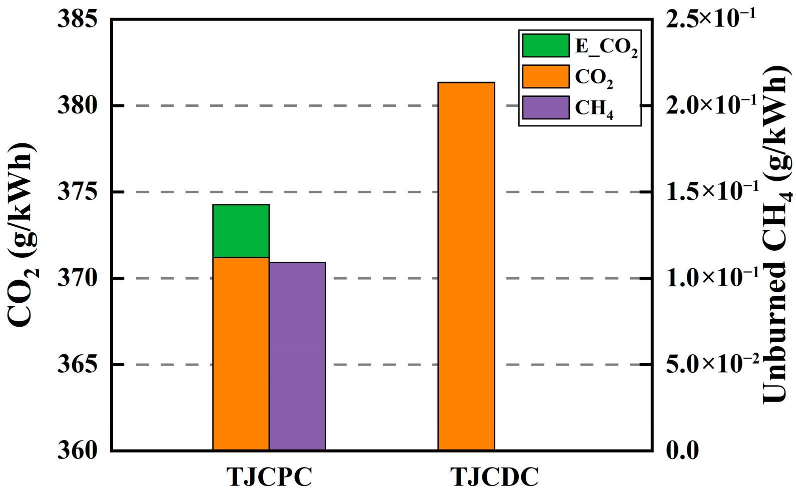

Figure 19. Comparison of CO_2 emissions and unburned CH_4 amounts.

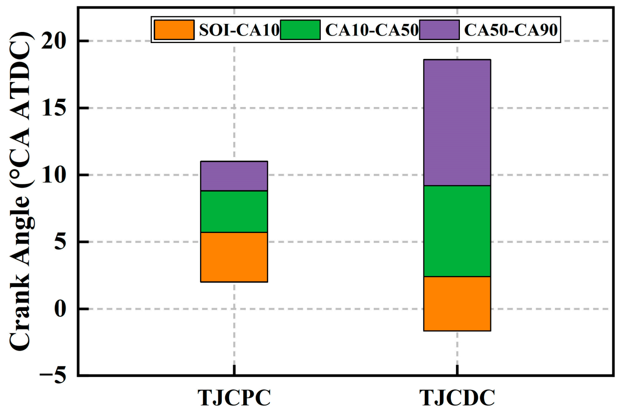

Figure 20. Comparison of crankshaft angles at different combustion stages.

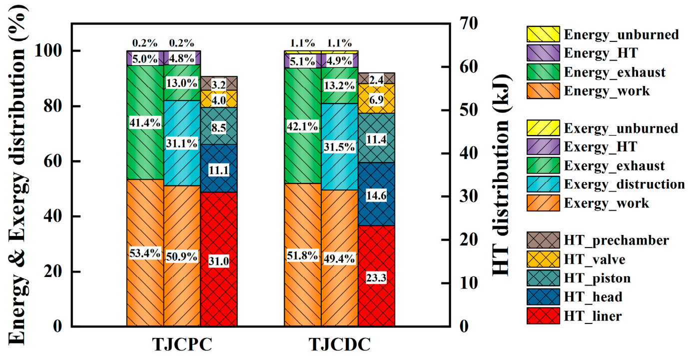

Figure 21. Comparison of the energy and exhaust gas distribution.

Table 5. Comparison of indicator parameters for different combustion modes.

Parameters	TJCPC Mode	TJCDC Mode
CA10 (°CA ATDC)	5.7	2.4
CA50 (°CA ATDC)	8.8	9.2
CA10-CA90 (°CA)	5.3	16.2
CE (%)	99.82	98.95
ITE (%)	53.39	51.79
EISFC (g/kWh)	158.65	163.55
NOx (g/kWh)	1.66	17.48
CO_2 (g/kWh)	371.2	381.3
Unburned CH_4 (g/kWh)	0.11	0.0

5. Conclusions and Outlook

Driven by the sustained growth of the global economy, industry, and transportation sectors, marine internal combustion engines remain a critical power source in the shipping industry. Dual-fuel engines employing natural gas as an alternative fuel demonstrate significant potential for mitigating pollutant emissions. To achieve further reductions in emissions and comply with increasingly stringent regulatory mandates, the development of advanced combustion technologies for marine low-speed dual-fuel engines has become a principal area of research. This review paper focused on two novel combustion modes for marine two-stroke natural gas dual-fuel engines, leveraging pre-chamber jet ignition technology. Based on this analysis, the following main conclusions are drawn:

The TJCDC mode exhibits a higher swirl ratio and turbulence kinetic energy during initial combustion, leading to shorter ignition delay and reduced combustion duration. However, it incurs slightly higher indicated specific NOx emissions compared to the traditional DJCDC mode.

Adjusting the start and duration of the LPNG injection significantly affects in-cylinder mixture quality and emissions. Delaying injection or extending its duration can increase methane slip, indicating the need for precise injection control to optimize combustion and reduce emissions. Increasing λ (excess air ratio) delays combustion phasing but improves thermal efficiency, suggesting a trade-off between combustion timing and efficiency.

While the current review provides a comprehensive overview of the advanced combustion technologies for marine dual-fuel engines, several areas warrant further investigation. Future research should focus on empirical validation of the simulation results through extensive experimental testing. This includes conducting full-scale engine tests to assess the real-world performance and emission characteristics of the TJCPC and TJCDC modes under various operating conditions. Additionally, research efforts should be directed towards optimizing the combustion strategies to balance efficiency improvements with combustion stability, particularly in ultra-lean mixtures where misfire risks are higher.

Integration challenges also need to be addressed, such as the compatibility of these advanced combustion modes with existing engine hardware and control systems. Further work is required to develop robust control algorithms that can dynamically adjust the combustion parameters, such as injection timing and excess air ratio, to ensure optimal performance across different load conditions. Moreover, the potential for integrating these combustion technologies with other emission reduction strategies—such as exhaust gas recirculation (EGR) and selective catalytic reduction (SCR)—should be explored to achieve even lower emissions.

In conclusion, the development and implementation of advanced combustion technologies for marine dual-fuel engines hold significant promise for reducing emissions and enhancing efficiency. However, realizing their full potential will require continued research, empirical validation, and addressing integration challenges to ensure their successful deployment in the maritime industry.

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Nomenclature

The following abbreviations are used in this manuscript:

3D	Three-dimensional
ATDC	After Top Dead Center
CA	Crank angle
CA10	Crankshaft angle for 10% combustion
CA50	Crankshaft angle for 50% combustion
CA90	Crankshaft angle for 90% combustion
CE	Combustion Efficiency
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
DJCDC	Diesel Jet-Controlled Diffusion Combustion
ECA	Emission Control Areas
EGR	Exhaust gas recirculation
EISFC	Equivalent Indicated Specific Fuel Consumption
GHG	Greenhouse gases
HPDI	High-pressure direct injection

IMO	International Maritime Organization
ITE	Indicated thermal efficiency
LHV	Lower heating value
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
LPDI	Low-pressure direct injection
LPNG	Low-pressure natural gas
MMT	Maximum mean temperature
NOx	Nitrogen oxides
PC	Pre-combustion chamber
PC-MCC	Pre-chamber-Enabled Mixing-Controlled Combustion
PI-HPDI	Pre-chamber-Ignited High-Pressure Direct Injection
PM	Particulate matter
SCR	Selective catalytic reduction
SOI	Start of injection
SOx	Sulfur Oxides
TDC	Top Dead Center
TE	Thermodynamic efficiency
TJCDC	Turbulent Jet-Controlled Diffusion Combustion
TJCPC	Turbulent Jet-Controlled Premixed Combustion
TJC-PDMC	Turbulent Jet-Controlled Premixed-Diffusion Multi-Mode Combustion

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