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Review article

Methanol for heavy-duty internal combustion engines: Review of experimental studies and combustion strategies

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ABSTRACT

Renewably produced methanol is a promising fuel for internal combustion engines in long-range transportation thanks to its scalability, liquid storage, and favorable combustion properties. However, the distinction between different injection and ignition strategies for methanol engines and the resulting combustion mechanisms has not been consistently defined. Moreover, diffusion combustion strategies are favored over premixed strategies in large engines because of higher methanol energy fractions, disregarding the advantages of premixed approaches, such as reduced nitrogen oxide emissions and retrofitting opportunities. To address ambiguity in terminology, this paper proposes a classification framework for injection and ignition strategies and applies it to methanol-fueled internal combustion engines. Subsequently, this review focuses on experimental studies of methanol-fueled heavy-duty engines, which are crucial for transitioning to renewable and sustainable energy in long-range transportation. This research summarizes the impact of the reviewed injection and ignition strategies on combustion characteristics, engine performance and emissions to identify key trends. Furthermore, this review highlights how specific design and operating parameters influence premixed dual-fuel combustion, offering insights into optimizing performance and emissions. While mono-fuel and premixed dual-fuel strategies with methanol can significantly promote methanol use in heavy-duty engines and reduce harmful emissions like nitrogen oxides, a rise in unburned hydrocarbon emissions may also be expected, necessitating further research in this area. Additionally, methanol injection location in premixed dual-fuel schemes affects its cooling effect, influencing volumetric and thermal efficiency. Overall, this study deepens our understanding of methanol's impact on heavy-duty engine performance, highlighting critical challenges to be addressed for advancing sustainable transportation.

Contents

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1. Introduction

Research into internal combustion engine (ICE) technologies using sustainable fuels is necessary to ensure a successful energy transition in transportation [1]. When a combination of power density, robustness, cost, and efficiency is considered, ICEs remain a future-proof, reliable power source, especially for remote operations over long distances or time, such as ships at sea [2]. As most greenhouse gas emissions are linked to the choice of fuel rather than the employed ICE technology, most research efforts now focus on decoupling ICEs from fossil fuels and adopting new synthetic net-zero carbon fuels [3]. Although green hydrogen and hydrogen-based fuels, such as ammonia, are promising synthetic fuels, the required technology and resources for such fuels are not sufficiently mature yet for near-term, large-scale adoption [4].

In light of these challenges, renewable methanol stands out as a promising fuel due to its favorable combustion properties [5], scalability [6], and liquid state at standard temperature and pressure, making it ideal for long-haul applications. These characteristics position methanol as a practical and cost-effective alternative fuel [7,8], especially for heavy-duty (HD) applications, for which full electrification faces greater barriers [9,10]. Thus, shipowners such as Maersk foresee renewable methanol as one of the most promising sustainable fuels for large marine engines in the coming decades [11]. However, methanol's low reactivity presents challenges for diesel compression ignition (CI) engines, which are dominant in the transportation sector due to their higher power density and fuel efficiency over spark-ignition (SI) engines [12,13]. To address these challenges, the two most widely explored approaches for methanol in CI engines are low-temperature combustion (LTC) strategies, such as homogeneous charge compression ignition (HCCI), and dual-fuel technology [14,15].

The majority of research and development efforts for methanol-fueled CI engines have centered on the more established dual-fuel (DF) technology [5], especially in the marine industry that is looking for fuel-flexible solutions in which full diesel operation remains possible [16]. In these DF strategies, the engine leverages the high cetane number (CN) of a small amount of a high reactivity fuel (HRF) like diesel to ignite a low reactivity fuel (LRF), like methanol or natural gas (NG). This trend may be attributed to the perceived advantages of DF technology in terms of combustion control, operational reliability, and fuel flexibility. While DF technology typically operates on the principle of simultaneous combustion of two different fuels, the combustion mode of such engines is highly dependent on the injection strategy for the LRF. Additionally, the injection timing of the HRF, combined with the direct injection of the LRF under high-pressure (HP), can be employed to introduce additional degrees of freedom (DoF) that can significantly influence the combustion process, engine efficiency, and emissions.

The growing research into renewable fuels and alternative engine technologies have led to inconsistency in terminology and definitions used for various combustion strategies, which has made the field less accessible and comprehensible, particularly for beginning researchers. This ambiguity is evident for multiple alternative fuels, including natural gas (NG) [15], and also applies to methanol. The introduction of LTC strategies exacerbates this issue, as overlapping terms often describe similar combustion modes, making their objectives difficult to discern. While several reviews have summarized ICE strategies suitable for methanol use, a more focused review that emphasizes these concepts through a clear combustion mode framework solves the ambiguity and provides additional valuable insights. In Section 2, this review therefore introduces a unified framework that classifies the various methanol combustion strategies. Rather than focusing solely on the numerous terminologies used in the literature, this study aims to define these strategies based on their dominant and intended combustion mechanism. This approach offers a more systematic way to understand different methanol ICE combustion strategies, simplifying the process for new researchers to start navigating this complex field. This constitutes the first contribution of this review article.

The second contribution of this study is its unique focus on HD engines, particularly for marine applications, in which complete electrification is a less feasible pathway. Other review studies focus more on experimental studies of light-duty (LD) methanol-fueled ICEs, leaving the HD applications under-explored, despite their unique design, thermal conditions, operational characteristics, and their significance for global energy transition [34,35]. Verhelst et al. [5] conducted a holistic review on methanol as an engine fuel, emphasizing challenges and potential future research directions. Moreover, numerous reviews have been conducted on specific aspects of methanol-fueled engines, including production pathways [24], SI technology [17,19,20], methanol blending [18,25,29,33], DF fumigation [22,32], DF direct injection [22,26] and LTC concepts [26,28]. Table 1 provides an overview of previous review articles that explored the potential of methanol as an engine fuel and the specific aspects they investigated. Furthermore, while some studies have examined methanol for marine applications [31,36,37], few have effectively distinguished between combustion modes while assessing their impact on performance characteristics of methanol-fueled HD engines. This review aims to address this gap in Section 3, summarizing findings from previous experimental studies on methanol-fueled HD engines and providing tables highlighting key trends in the performance of methanol DF engines.

Finally, this review identifies the premixed dual-fuel (PRDF) strategy as one of the most promising short-term solutions for using methanol in HD engines, especially for engines with a bore size of approximately 130–200 mm and ICE retrofits. To the best of the authors' knowledge, no prior study has thoroughly reviewed the design and operating parameters that can enhance the performance of methanol PRDF engines. To this end, Section 4 reviews experimental studies to examine how key parameters influence ICE performance. This can offer key insights for larger ICEs, especially marine engines, for which renewable methanol emerges as a promising alternative fuel. As efforts intensify to decarbonize the transport sector, this study deepens our understanding of how methanol impacts HD engine performance and highlights critical challenges to be addressed for accelerating the energy transition in the transport sector.

Table 1
Existing review papers on methanol-fueled ICEs.

Ref	Year	Production	Environmental safety	Economic	SI mono-fuel	CI DF methanol blend	CI DF methanol fumigation	CI DF direct injection	Low-temperature combustion strategies	Heavy-duty applications
[17]	2025				✓					
[18]	2024					✓	✓	✓		
[19]	2024				✓	✓			✓	✓
[20]	2024	✓			✓		✓			
[21]	2024						✓	✓	✓	
[22]	2023						✓	✓	✓	
[23]	2022									✓
[24]	2022	✓	✓	✓	✓	✓	✓	✓		
[25]	2022					✓	✓			
[26]	2022					✓	✓		✓	
[27]	2021					✓	✓	✓		✓
[28]	2021	✓							✓	
[29]	2021	✓				✓	✓			
[30]	2021		✓		✓	✓	✓		✓	✓
[31]	2020	✓	✓	✓			✓	✓		✓
[5]	2019	✓	✓		✓		✓	✓	✓	✓
[6]	2018	✓	✓							✓
[32]	2017						✓			
[33]	2015	✓	✓	✓	✓	✓				

It should be noted that the extent of elaboration on these topics varies across the papers reviewed.

2. Combustion pathways for methanol in ICEs

This section explores the various pathways for methanol combustion in ICEs. Methanol, as an alternative fuel, can be used in both SI and CI engines through different combustion strategies. The section provides an overview of the primary combustion mechanisms and describes how these mechanisms apply to methanol. Figures are included to illustrate these distinct combustion modes and the strategies used for methanol utilization in different engine types. Combustion in an ICE can fundamentally occur in three ways: Otto-type premixed flame propagation, HCCI-type premixed autoignition, and Diesel-type non-premixed (diffusion) combustion. Fig. 1 illustrates how combustion occurs in each distinct mode.

2.1. SI engines

High octane number (ON) alcohol fuels, such as methanol and ethanol, are suitable for use in gasoline engines [39,40]. In SI engines, the fuel is typically injected at low-pressure (LP) in the intake air, resulting in a homogeneous air–fuel mixture in the cylinder. Air path injection (API) can be implemented through a single-point injection (SPI) by carburating or spraying along the intake path, or through multipoint injection (MPI) using port-fuel injection (PFI) [41,42]. The former is often used for gaseous fuels such as NG [43], while for liquid fuels like methanol, the PFI strategy is typically employed [44]. Fig. 2 depicts the injection strategies found in SI engines.

Injection strategies in SI engines rely on premixed flame propagation, while combustion duration is highly sensitive to flame-turbulence interaction [14]. Enhancing turbulence intensity increases the flame velocity [45]. This is the foundation of the turbulent jet ignition (TJI) concept, which uses a pre-chamber to ignite a lean air–fuel mixture [19,46]. Apart from homogeneous premixed strategies, direct injection (DI) into the cylinder or combining API with a pre-chamber can enhance the efficiency of SI engines by stratifying the charge and allowing leaner mixtures [47,48]. These lean mixtures can simultaneously improve engine efficiency and lower emissions [49]. The TJI concept appears to be the most common strategy when applying the SI engine technology for HD applications like marine [50,51]. Despite the various injection strategies in SI engines, combustion is intended to occur via premixed flame propagation [52], while any premixed autoignition must be avoided. For instance, while gasoline direct injection is typically employed to create stratified charge within the cylinder to enhance performance, the fundamental and intended combustion mechanism remains flame propagation [53].

2.2. CI engines

In contrast to SI engines, CI engines can employ two distinct combustion concepts—LTC and conventional diesel combustion (CDC)—which complicates the definition of combustion strategies. Furthermore, the introduction of DF concepts has further expanded research on various combined approaches aimed at improving engine performance and incorporating alternative fuels. However, this growing body of research has also led to confusion, as inconsistent and overlapping terminologies are frequently used to describe different combustion strategies. The confusion is particularly evident when discussing alternative fuels, which also applies to methanol. For example, direct dual fuel stratification (DDFS), originally proposed as a new combustion concept based on a distinct injection strategy [54], has been used differently in some studies exploring methanol [55,56]. Such inconsistencies in terminology are not unique to methanol, as similar issues have been observed in the literature on other low reactivity fuels, such as NG [15].

Thus, the primary objective of this review is to establish common ground and propose a practical classification framework to help researchers better categorize and identify different strategies. To this end, this study aims to clarify methanol CI engine strategies by focusing on four degrees of freedom (DoF): fuel strategy (mono-fuel (MF) or DF), injection location of methanol, ignition strategy, and methanol to HRF ratio in premixed DF engines. These parameters influence the leading combustion mechanism. Fig. 3 illustrates the strategies for methanol utilization in CI engines, showing that regardless of the chosen strategy, combustion typically follows one of the three combustion mechanisms. While some strategies may involve a combination of combustion modes, this figure focuses on capturing the intended and dominant mechanism in each case [57]. The ignition strategy depends on the fuels' injection timing, further illustrated in Fig. 4, complementing the information in Fig. 3.

2.2.1. Mono-fuel strategies

Using neat methanol in CDC necessitates much higher compression ratios (CRs) compared to diesel fuel [58], along with higher intake air temperatures [59] or hot recirculated exhaust gases [60], potentially increasing nitrogen oxide (NO_x) emissions and risking engine durability. To facilitate combustion under such conditions, ignition aids like glow plugs are also employed [61], particularly during low-load and cold-start conditions [62]. For LRFs, a strategy that resembles CDC, wherein diffusion combustion is the intended mode, is often referred to as mixing-controlled compression ignition (MCCI) [63]. MCCI is

Abbreviations

BTE	Brake Thermal Efficiency
CA	Crank Angle
CA50	Combustion Phasing
CD	Combustion Duration
CDC	Conventional Diesel Combustion
CDF	Conventional Dual-Fuel
CI	Compression Ignition
CN	Cetane Number
CO_2	Carbon Dioxide
COV	Coefficient of Variance
CR	Compression Ratio
DDFS	Direct Dual Fuel Stratification
DF	Dual-Fuel
DFDC	Dual-Fuel Diffusion Combustion
DI	Direct-Injection
DMDF	Diesel-Methanol Dual-Fuel
DOC	Diesel Oxidation Catalyst
DoF	Degree of Freedom
EGR	Exhaust Gas Recirculation
HCCI	Homogeneous Charge Compression Ignition
HD	Heavy-Duty
HP	High-Pressure
HRF	High Reactivity Fuel
HRR	Heat Release Rate
ICE	Internal Combustion Engine
ID	Ignition Delay
IMEP	Indicated Mean Effective Pressure
IMO	International Maritime Organization
JCCI	Jet Controlled Compression Ignition
LD	Light-Duty
LP	Low-Pressure
LRF	Low Reactivity Fuel
LTC	Low-Temperature Combustion
MCCI	Mixing-Controlled Compression Ignition
MD97	Methanol with Ignition Improver
MEF	Methanol Energy Fraction
MeOH	Methanol
MF	Mono-Fuel
MPDF	Micro-Pilot Dual-Fuel
MSP	Methanol Substitution Percentage
NG	Natural Gas
NO_x	Nitrogen Oxide
ON	Octane Number
PCCI	Premixed Charge Compression Ignition
PFI	Port Fuel Injection
PM	Particulate Matter
Pmax	Peak Pressure
PPC	Partially Premixed Combustion
PPCI	Partially Premixed Compression Ignition
PRDF	Premixed Dual-Fuel
PREMIER	Premixed Mixture Ignition in the End-gas Region
PRR	Pressure Release Rate
RCCI	Reactivity-Controlled Compression Ignition
SACI	Spark Assisted Compression Ignition
SI	Spark Ignition
SO_x	Sulfur Oxide
SOF	Soluble Organic Fraction
SPI	Single-Point Injection
TDC	Top Dead Center
TJI	Turbulent Jet Ignition
UHC	Unburned Hydrocarbon

commonly facilitated by two-stage HP-DI of the LRF, such as methanol, near TDC [64].

The challenging requirements, such as high CRs, needed to operate MCCI with neat methanol, has led most research studies to focus on the methanol use with ignition improvers for HD applications, including marine-size engines. The effects of various ignition and lubricity improvers, along with their different ratios, on methanol diffusion combustion have been explored [65,66], reporting that stable combustion was not feasible with ignition improver ratios below 5%. However, a subsequent study demonstrated stable combustion with a reduced ignition improver ratio of 3% [37]. This strategy, termed as MD97 [37], is classified as an MF strategy [67].

An alternative approach to address the low reactivity of methanol in CI engines, without the need of ignition improver or an additional HRF, involves utilizing pre-chamber technology, commonly employed in SI engines [19]. This pre-chamber-based concept, often referred to as the TJI-HPDI mode [68], operates as an MCCI-type combustion mechanism and aims to mitigate the risk of knocking, which is a primary limitation of premixed injection strategies in HD engines. In this concept, a small quantity of methanol is injected into the pre-chamber and ignited by a spark plug. The resulting hot jets are expelled through small orifices into the main combustion chamber, where the remaining methanol fuel is sprayed using HP-DI directly into these induced jets. Due to the complexity of this technology and its relatively recent introduction in engine research, most studies to date have been limited to numerical simulations [69].

Alternative MF approaches, such as the LTC concepts, are notable for their potential to reduce NO_x and PM emissions while maintaining or even increasing efficiency [14]. LTC strategies aim to decouple injection and combustion phases in CI engines, thereby avoiding the diffusion combustion phase [70]. HCCI is often regarded as the foundational LTC concept, employing a combustion mechanism distinct from traditional gasoline SI and diesel CI processes. Historically, this concept appeared under different names, such as active thermo-atmosphere combustion (ATAC) in 1979 [71] and compression-ignited homogeneous charge (CIHC) in 1983 [72]. In both cases, the goal was to initiate combustion via spontaneous autoignition driven by chemical kinetics. This study adopts the widely accepted term HCCI, which introduces fuel into the cylinder via an API strategy to ensure a well-mixed charge [73]. The HCCI strategy has been studied for both diesel-like [74] and gasoline-like fuels, such as methanol [75].

Similar to HCCI, the premixed charge compression ignition (PCCI) concept aims for fully lean premixed combustion initiated by autoignition [76]. PCCI can be considered a DI version of HCCI [77]. To address the challenges of controlling combustion phasing in fully premixed strategies, a subsequent concept emerged involving a two-stage injection: an early main injection to form the premixed mixture, followed by a second injection at the desired start of combustion. This strategy was characterized as an HCCI concept, as it still relies on bulk autoignition, and has been termed as uniform bulky combustion system (UNIBUS) [78] and two-stage PCCI [79]. Multi-pulse ultra-HP injection strategy has also been explored in such PCCI combustion strategies [80,81].

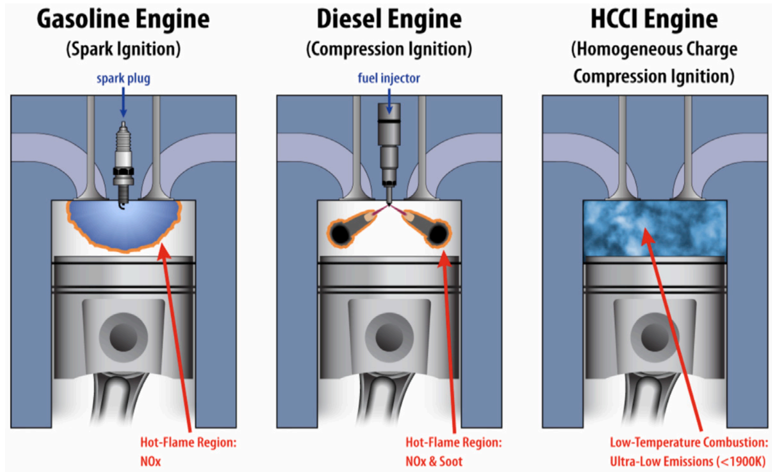

Fig. 1. Combustion concepts in ICEs [38].

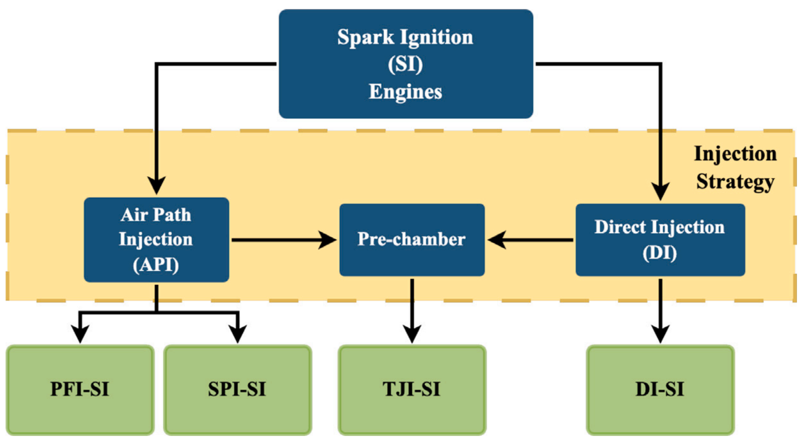

Fig. 2. Engine strategies in SI engines.

The two- or multi-stage version of this injection strategy is typically referred to as partially premixed combustion (PPC) [82,83], which also aims to separate the first injection stage from the start of combustion [84]. Similar approaches in diesel engines are also referred to by terms like split-premixed compression ignition (split-PCI) [85] and partially premixed compression ignition (PPCI) [86]. Furthermore, this study differentiates PPC from MCCI strategy to avoid confusion, as these terms have often been used in research to characterize the same strategy, where a first injection takes places before TDC to partially premix the mixture followed by a second that aims to control the combustion phasing with a diffusion-like combustion of the second injection spray [82]. In this study, PPC will refer to when most of the fuel is injected away from the TDC [87], compared to MCCI that the first injection phase is very close to TDC [88]. While this study aims to distinguish PPC from PCCI, it should be noted that these terms may have sometimes been used interchangeably in other sources. Furthermore, due to variations in conventions, this may hold true for other combustion strategies discussed in this study as well. Finally, spark assisted compression ignition (SACI) is another prominent strategy that relies on premixed autoignition as the dominant combustion mechanism [89]. In SACI, a spark discharge initiates reaction kinetics near the spark plug, which cascades into premixed autoignition throughout the charge [90].

2.2.2. Dual-fuel strategies

Although the term *DF strategy* is commonly linked with natural gas DF engines, it can accommodate any LRF, including liquid fuels such as alcohols [15]. It should be noted that Fig. 3 does not include the diesel-methanol blending strategy due to methanol's emulsion issues which limit its applicability in these engine strategies [29], typically restricting methanol ratios up to 20%. DF engines rely on HRFs like diesel to ignite low CN fuels like methanol. CN here is a measure of fuel reactivity. In DF engines, only methanol's injection location varies, with the three typical injection strategies: API, LP-DI, and HP-DI. Currently, the most commonly applied technology is the HP-DI injection strategy for the HRF. Similar to mono-fuel SI engines, the LP-API strategy is the most straightforward method for injecting methanol in DF engines, either using SPI or multipoint PFI strategy.

This injection technique has been termed "fumigation" in the context of alcohol DF engines [91]. Alperstein et al. [92] introduced the term "fumigation" in 1958 to describe LP-PFI of diesel in the intake to address, among others, mixing hurdles and smoke formation in diesel engines. Fumigation was defined as introducing a liquid fuel, such as diesel, as a fine mist or "fumes" in the intake manifold. However, fumigation has evolved to describe the introduction of alternative fuels in the air upstream of the manifold by a carburetor or LP injector [93,94]. Today, "fumigation" typically refers to methanol injection along the air path [95]. This study suggests that "fumigation" may not be an adequate descriptor for this injection strategy, as it deviates too much from the initial meaning and led to questions about injection location and evaporation. This work suggests to abandon the term "fumigation" and use the more fitting term *air path injection (API)*, as a synonym and general term for any air path injection technique.

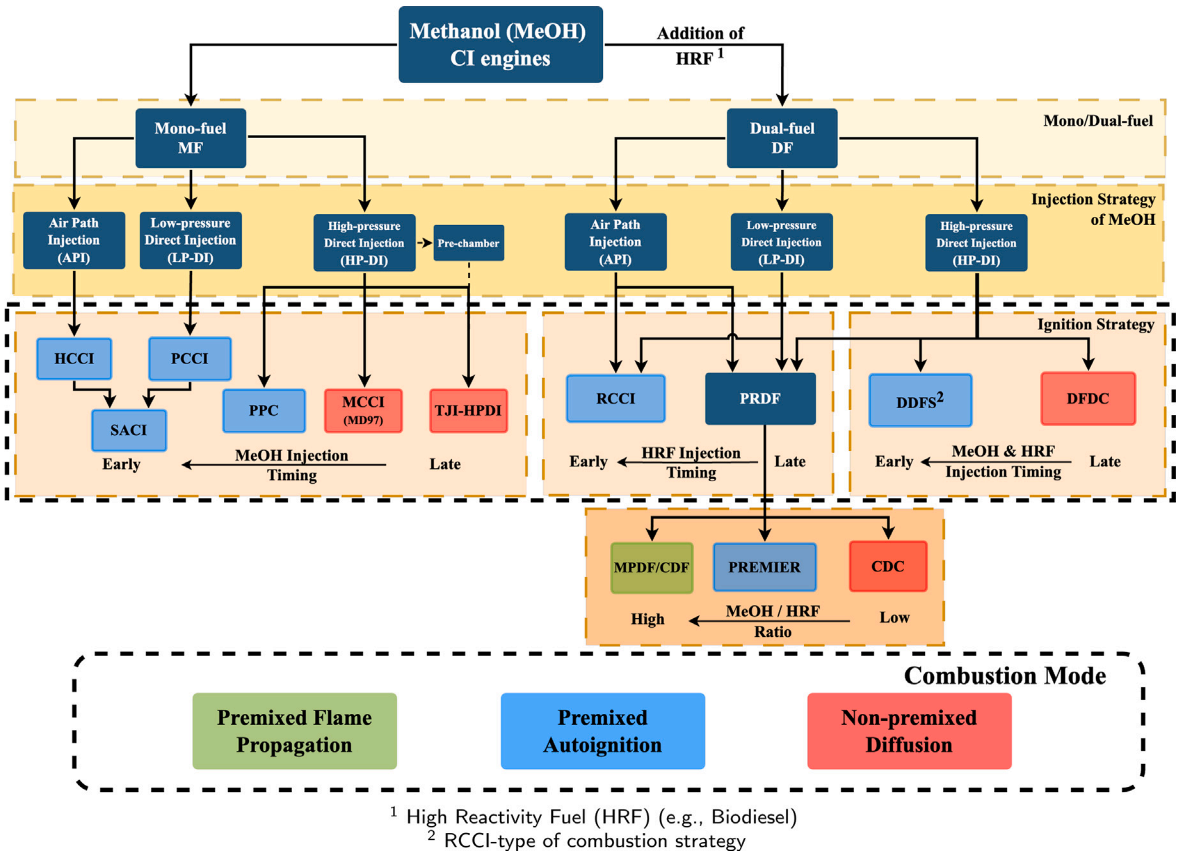

Fig. 3. Classification framework for methanol CI engine strategies.

An alternative LP injection strategy is to inject methanol directly in the cylinder, a technique that is typically applied in large two-stroke marine NG DF engines [16,96]. In these premixed strategies, combustion is primarily influenced by the DI of a HRF, such as diesel. Two combustion strategies can arise from this manner: the reactivity controlled compression ignition (RCCI) [97] and the premixed dual-fuel (PRDF). RCCI evolved from efforts to better control premixed autoignition strategies such as HCCI and PCCI, introducing the LRF via API to create a homogeneous charge. The HRF is then directly injected well before TDC to modulate reactivity, differing from PRDF in which diesel injection timing remains similar to CDC, i.e., a late pilot injection near TDC, to ignite the premixed methanol–air mixture. PRDF is commonly referred to as the conventional dual-fuel (CDF) strategy [15,98,99]. In methanol DF engines, this premixed strategy is often called diesel methanol dual-fuel (DMDF) [100–102], or diesel methanol compound combustion (DMCC) [103–105]. However, since these terms do not clearly describe the injection or combustion mechanisms, this study proposes the term methanol PRDF to better convey the combustion strategy employed.

In strategies that use HP-DI of both fuels, methanol injection timing can be adjusted to offer a range of combustion regimes [55]. The methanol non-premixed combustion strategy, which dominates current large marine DF engine developments [16], involves HP-DI of both fuels close to TDC, resembling CDC combustion but applied to both fuels [106]. This strategy typically follows the conventional late diesel injection near TDC, followed by the LRF's injection [50], as explored in several studies on methanol [107,108]. When methanol is injected prior to diesel [109,110], the increased ignition delay due to methanol's cooling effect often results in a more premixed burn, akin to the PRDF combustion strategy [111]. To assist experimental studies and explore the optimization parameters of the DFDC concept, numerical simulations have been conducted. Li et al. [112] investigated injection strategies involving the splitting of methanol injection before and after the diesel injection, referred to as methanol/diesel/methanol (M/D/M). Yang et al. [113] examined how the structure of the pilot fuel injection could enhance the combustion performance of methanol. This review proposes the term methanol dual-fuel diffusion combustion (DFDC) for these concepts, as it appropriately describes the intended combustion mechanism—primarily diffusion-driven combustion for both fuels.

Additionally, premixed autoignition combustion mechanisms, such as in RCCI, can be achieved with HP-DI injection of both fuels early in the compression stroke. DDFS combines elements of RCCI and PPC [54,114], allowing for flexible injection pulses between the fuels [56]. This flexibility enables better control over concentration and reactivity gradients compared to traditional RCCI. In similar studies that explore flexible stratification combustion concepts, this approach is referred to as intelligent charge compression ignition (ICCI) combustion mode [115] and premixed micro pilot combustion (PMPC) [116]. To unify terminologies and avoid confusion, this review proposes to use DDFS to describe strategies aiming to achieve LTC via stratification controlled by the direct injection of both fuels. Fig. 5 illustrates the cylinder layout for the four typical DF ignition strategies.

An interesting and distinct strategy is the jet controlled compression ignition (JCCI) concept [117], also developed to address the combustion control challenges faced by HCCI and PCCI. In JCCI, a small ignition chamber, similar to the (TJI) concept, is mounted on the cylinder and contains an HRF injector and a spark plug [118]. Combustion-rich gases, controlled by spark discharge, are then expelled through small orifices into the main combustion chamber to trigger the premixed autoignition of the charge. Therefore, it differs from the conventional TJI concept, which relies on flame propagation, as the intended combustion mechanism in JCCI is premixed autoignition, similar to HCCI, SACI, PCCI, PPC, RCCI, and DDFS. This strategy has also been explored with ammonia-methanol mixtures in the main chamber, where hydrogen-fueled jets, ignited in the pre-chamber, initiate

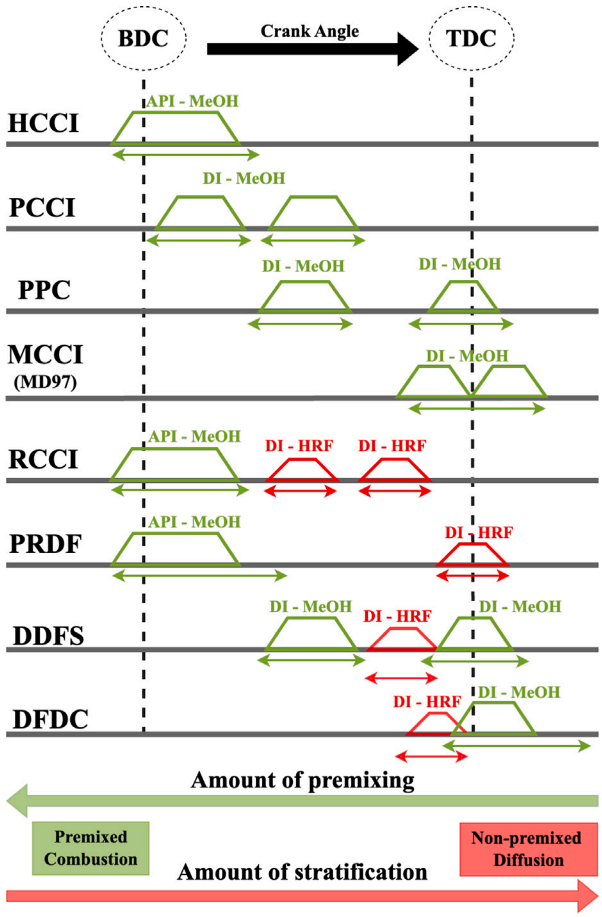

Fig. 4. Fuel injection timing in different ICE strategies.

combustion in the main charge [119]. While this concept introduces additional combustion pathways for both mono-fuel [19] and dual-fuel [119] in CI engines, incorporating it into the framework of Fig. 3 would add complexity, which contradicts the framework's goal of simplification.

Notably, the PRDF strategy's combustion mechanism is highly dependent on the methanol-to-HRF fuel ratio. In PRDF engines, the goal is to minimize diesel pilot fuel required to initiate combustion [120]. Nevertheless, challenges like misfiring and knocking necessitate reducing the methanol quantity to protect the engine [121]. Numerous studies have shown that combustion in methanol PRDF engines is highly sensitive to varying methanol-to-HRF ratios [57,121–124].

At very high methanol-to-HRF ratios, the combustion of a small amount of HRF behaves as a "liquid spark", leading to a premixed flame propagation type of combustion [57]. In the micro pilot dual fuel (MPDF) concept, also termed as the CDF [15], the multipoint ignition of the pilot fuel generates multiple flame fronts to propagate through the combustion chamber and consume the methanol–air mixture in a premixed fashion [125]. The MPDF strategy could be characterized as a deflagration-based combustion system [96] since it relies on premixed flame propagation, like in SI engines. However, these deflagration-based combustion systems are prone to knock, where the pressure waves generated by the reaction zone compress fuel–air mixture in front of the flame above its autoignition temperature [126]. Reducing the CR is commonly used to mitigate knock in diesel engines converted to PRDF operation, similar to SI technology.

At lower methanol-to-HRF ratios in a PRDF engine, the mixture ahead of the flame is lean, and the combustion profile mirrors that of the CDC, as illustrated in Fig. 6. When the ratio increases towards the MPDF strategy, the combustion dynamics become more complex, because richer mixtures enhance flame propagation and premixed autoignition reactions. Fig. 7 highlights the three distinct combustion phases observed in a PRDF strategy. Each phase's intensity influences the overall cumulative heat release rate (HRR) profile:

1. The initial phase derives from HRF combustion.
2. The subsequent phase, dependent on the initial stage, results from the energy release of the methanol premixed autoignition near or ahead of the flame front.
3. The final phase reflects the HRR from the turbulent flame propagation through the rest of the unburned methanol–air mixture.

As the ratio of methanol-to-HRF increases, the mixture ahead of the flame becomes richer, with pilot HRF primarily combusting in a premixed mode, thus intensifying the risk of knocking [124]. The resulting combustion involves complex interactions between the flame fronts initiated by HRF's combustion and the methanol–air mixture's premixed autoignition near the flame. Trying to mimic the SACI combustion mechanism, Azimov et al. [127] investigated a PRDF strategy. Here, combustion relied on a controlled NG–air mixture's premixed autoignition that avoids spontaneous knocking [57]. The study termed this combustion mode as the premixed mixture ignition in the end-gas region (PREMIER) mode, which relies on premixed autoignition as the dominant combustion mode. Although the PREMIER combustion mode has been further studied in the context of methane [128], methane–hydrogen mixtures [129] and syngas combustion [130,131], to the best of the authors' knowledge, no studies have applied this concept to methanol.

3. Experimental studies on methanol HD ICEs

Although methanol has been subject to substantial experimental research in recent decades, most investigations have explored its use in high-speed LD engines. Nonetheless, low-medium speed HD engines' operating regimes and thermal conditions are significantly different [34,35,96]. The classification of engines as low-, medium-, or high-speed follows the speed ranges provided in Table 2 [132]. This section reviews the results of previous experimental studies on low-medium speed HD engines using methanol. We evaluate the impact of methanol on combustion characteristics, engine performance, and emissions of these engines. The analysis targets previous experimental studies on engines designed for HD applications under steady-state conditions. These engines typically operate at lower speeds and have larger bore and stroke sizes.

3.1. Dual-fuel engines

Introducing methanol in DF engines aims to maximize the substitution of diesel fuel. The extent of this substitution is vital for the decarbonization of HD engines and depends on various factors such as combustion strategy and load. For a consistent analysis of DF engines, a standardized variable indicating diesel replacement by a LRF like methanol is vital. However, terminology in the literature varies and lacks consistency.

3.1.1. Methanol energy fraction

Common terms for an energy basis ratio of methanol relative to diesel include methanol energy fraction (MEF) [133] or methanol substitution ratio (MSR) [134], defined as:

$$\mathrm{MEF} = \frac{\dot{m}_m \cdot \mathrm{LHV}_m}{\dot{m}_m \cdot \mathrm{LHV}_m + \dot{m}_d \cdot \mathrm{LHV}_d} \cdot 100\%, \quad (1)$$

where $\dot{m}_m$ and $\dot{m}_d$ represent the mass flow rates of methanol and diesel, respectively. LHV_m and LHV_d denote their respective lower heating

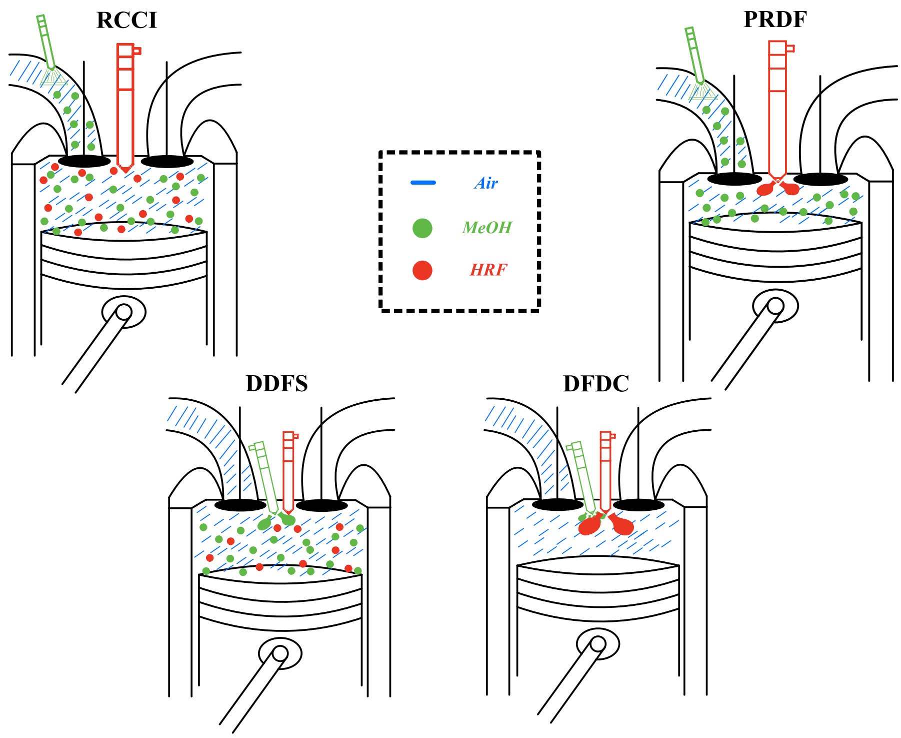

Fig. 5. Dual-fuel main ignition combustion strategies.

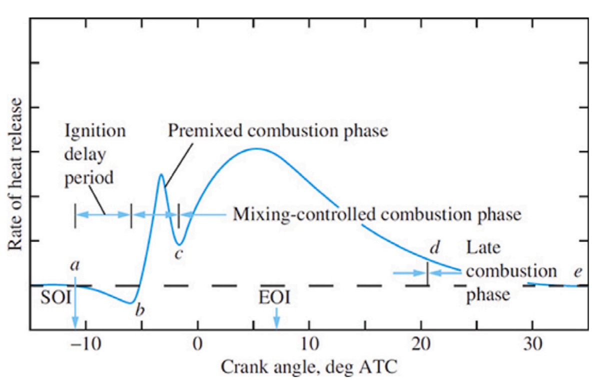

Fig. 6. Typical combustion phases in a CDC [14].

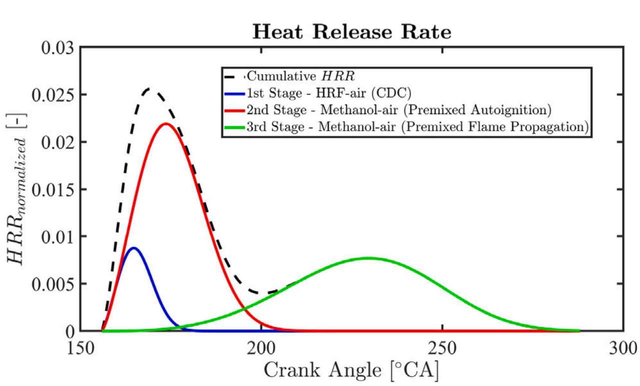

Fig. 7. Typical combustion phases in a PRDF strategy [15].

Table 2
Engine classification by speed [132].

	Engine Speed (rpm)
Low-speed	50–275
Medium-speed	275–1000
High-speed	1000–3600

values. Conversely, when quantified on a mass basis, the prevalent term is the methanol substitution percentage (MSP) [135], defined as:

$$MSP = \frac{\dot{m}_d - \dot{m}_m}{\dot{m}_d} \cdot 100\% \quad (2)$$

Given methanol's low-energy content, using an energy-based ratio seems reasonable. Yet, there is inconsistency in the literature regarding naming conventions. For instance, on the energy ratio basis, several terms have been used, such as energy ratio of methanol (Rme) [136], methanol diesel energy share (MDES) [137], and methanol co-combustion ratio (CCR) [55]. This ambiguity also exists for mass ratio terms [102,115,138,139]. In the subsequent analysis, this paper will adopt MEF and MSP for the respective ratio definitions to minimize confusion and ensure consistency.

3.1.2. Methanol substitution limitations in DF engines

Blending methanol with diesel offers a straightforward way to introduce methanol into diesel engines. Yet, emulsification issues with methanol often limit its fractions in the blend [29]. Tol [140] evaluated the effect of blending diesel with methanol on the performance of a MAN 4L20/27 four-stroke CI engine, using two different methanol/diesel blends (MEF of 10 and 20%) and compared them to conventional diesel-only mode. His study revealed that the engine could not maintain stable operation across its entire operating range when 20% of MEF was used. Previous studies have highlighted the importance of injecting methanol and diesel separately into the cylinder to achieve higher MEF [29].

As a result, the majority of research has focused on the more simplistic API [141], LP-DI [142], or HP-DI methods, employing either an additional [108] or single dual-channel [143] injector. Given the prevalent use of diesel engines in HD transport systems, the API strategy presents a promising pathway for transforming existing engines towards sustainable operation. Dierickx et al. [144] adapted a high-speed marine diesel engine for methanol operation through different API strategies, an SPI and a PFI strategy. Their objective was to evaluate the influence of methanol on the engine performance across multiple operating points and to determine the maximum MEF for each point. Misfiring at low loads and knocking at high loads limited MEF. The highest MEF reached was 84% using SPI at medium load and high speed, compared to a maximum MEF of 80% with PFI found at low load and speed. However, PFI proved more robust, achieving greater MEF across more operating points, with an average maximum MEF above 60%.

Wang et al. [105] further explored methanol's impact on a marine diesel engine using an API with SPI. Roar combustion restricted MSP to 60.6% at 75% load and 39.4% at 100% load. On the other hand, using PFI strategy, Guan et al. [141] investigated the influence of methanol on a single cylinder HD diesel engine. Increasing MEF, both the pressure rise rate (PRR) and peak pressure increased, reaching engine design limits of 30bar/CAD and 180 bar, respectively. This restricted MEF to 28%. Due to methanol's cooling effect, prolonged ignition delay and increased diesel premixed combustion occur in PRDF engines, which often result in elevated PRR and peak pressure.

The DFDC strategy shows great potential to overcome MEF restrictions deriving from combustion instability found in premixed modes such as PRDF and RCCI [145]. DFDC can mitigate issues like misfiring at low loads and roar combustion at high loads. Notably, MAN has reported attainable MEF of up to 95% in one of its commercially available methanol two-stroke marine engines by incorporating an additional injector [146]. These attainable MEF in DFDC mode align with the experimental studies of Saccullo et al. [108] and Dong et al. [106], who reported MEF of up to 96.6% and 95.3% using two separate methanol and diesel injectors, respectively. Similarly, Wärtsilä, using a single co-axial dual-channel injector [143], has achieved MEF up to 92% in its commercial medium-speed four-stroke engines [147].

3.1.3. Impact of methanol on combustion characteristics

In ICEs, several parameters are needed to characterize the combustion process [14,148]. For example, the ignition delay (ID) represents one of the crucial factors that influence the engine performance, defining the time duration between the start of injection and that of combustion. The combustion phasing (CA50) and duration (CD) should also be evaluated. Typically, HRR analysis is used to study these parameters. Peak pressure (Pmax) and PRR are also important parameters affecting the engine design.

Ignition delay, peak pressure, and pressure rise rate. Wang et al. [105] explored the effect of methanol on the combustion characteristics of a PRDF engine at different engine loads. They found that ID significantly increases with increasing MEF in the whole load range. This correlation aligns with the experimental studies in similar engines [138,144,149]. Two main factors contribute to the increase in ID in engines using the PRDF strategy. First, methanol's cooling effect draws heat from the charge, reducing both temperature and pressure in the cylinder. Second, methanol's presence within the cylinder influences the low temperature chemical oxidation of the injected diesel. Xu et al. [150] employed a skeletal model to investigate the effect of methanol in the oxidation mechanism of n-heptane in a diesel engine. Their simulation revealed that the addition of methanol to n-heptane leads to the conversion of active radicals $OH^{\cdot}$ to inactive H_2O_2 species at temperatures below 1000 K, decreasing the overall reactivity and increasing the ID. However, once the temperature surpassed 1000 K, the H_2O_2 species started decomposing back into $OH^{\cdot}$ radicals before completely disappearing at around 1200 K.

Prolonged ID due to methanol addition results in a larger fraction of diesel participating in premixed combustion with methanol, generally leading to increased PRR and Pmax [91]. High PRR induces roar combustion, limiting the maximum MEF achievable in PRDF engines, as discussed in 3.1.2. Wang et al. [105] found that maximum PRR was higher in the PRDF mode using methanol compared to CDC at all loads except for the low load points. In a similar study on a modified single-cylinder engine, Guan et al. confirmed similar patterns. However, this study optimized diesel injection timing as the MEF was increased. It becomes more challenging to distinguish the specific impact of MEF on combustion characteristics when other variables are altered simultaneously. On the contrary, using the DDFS strategy, Jia et al. [151] reported that while increasing MEF from 53% to 63% led to increased ID, they found lower PRR and Pmax.

In DFDC strategy, an additional HP-DI system injects methanol at high pressure near TDC, typically after the diesel injection. Notably, using the diffusion combustion strategy, Saccullo et al. [108] observed lower ID when introducing methanol in a diesel engine. While a slightly advanced diesel timing was used in the methanol-mode, ID decreased from 0.37 to 0.15 ms. Siebers and Edwards [156] reported that methanol requires temperatures above 950 K to reach a similar ID to diesel fuel. When the temperature is higher than 1100 K, ID of methanol is slightly shorter than isooctane and normal hexadecane. Therefore, the combination of higher reactivity of methanol at these temperatures and its oxygen content might explain this ID trend in the DFDC mode. Regarding PRR and Pmax, experimental studies have identified similar trends using the methanol DFDC [108,153,157], as seen in PRDF. A summary of the previous studies exploring the impact of methanol on the combustion characteristics of HD DF engines is shown in Table 3. The trends presented in Table 3 regarding the impact of methanol are compared to the diesel-only mode of the same engine, which serves as the baseline.

***Heat release and combustion phasing*.** Ma et al. [121] explored the possible combustion profiles in a methanol PRDF engine using experiments in a constant volume combustion chamber coupled with a computational model. Analyzing the HRR profiles, the study identified four combustion modes, termed DMDF modes:

- In DMDF mode 1, combustion is dominated by the premixed combustion of both fuels.
- The DMDF mode 2 displays a two-phase combustion profile: starting with a premixed combustion of diesel and surrounded methanol, followed by the diffusion combustion of diesel and the flame propagation through the remaining methanol–air mixture.
- In DMDF mode 3, autoignition of methanol occurs before diesel injection, leading to knocking and misaligned combustion phasing between the two fuels.
- In DMDF mode 4, misfire occurs, with the majority of methanol charge failing to combust following pilot diesel ignition.

These modes, illustrated in Fig. 8, are mostly sensitive to the MEF ratio. DMDF mode 1, typically found at relatively high MEF, is dominated by an HCCI-like premixed combustion of methanol–air mixture in the vicinity of diesel flame. Conversely, DMDF mode 2, observed at lower MEF, mirrors the CDC mode. These trends align with the analysis in 2.2.2 and the sensitivity of the combustion profile to LRF ratio in the PRDF combustion strategy. DMDF mode 1, similar to the PREMIER mode [57], might require exhaust gas recirculation (EGR) and delayed diesel injection timing to control the spontaneous autoignition of methanol–air mixture [121]. Both PREMIER and CDC combustion modes were observed during the experimental studies of Dierickx et al. [144], as shown in Fig. 9. Additionally, the spontaneous autoignition of methanol before diesel injection, as seen in DMDF mode 3, was identified in this study. Referring to DMDF modes 3 and 4 as 'combustion abnormalities' rather than combustion modes might be more appropriate. This type of autoignition found in these modes can also be characterized as preignition knock [14].

Introducing methanol using the PRDF strategy typically results in more advanced and faster combustion compared to diesel. Like

Table 3
Methanol impact on combustion characteristics of HD DF engines from experimental studies.

Ref.	Engine type	CR [–]	Bore × Stroke [mm]	Rated power [kW/c]	Injection (Ignition) Strategy	MEF test [%]	Speed [rpm]	Load	Combustion characteristics					
									ID	CD	CA50	PRR	Pmax	HRR max
[105]	Marine 4x 6c	16.8	–	43	API (PRDF)	51 39.4	1134 1800	Low High	↑ ↑	~ ~	~ A	↓ ↑	↓ ↓	↓ ↑
[133,144]	Marine 4x 6c	19	108 × 130	32.5	API (PRDF)	44 78	1500	Low High	↑ ↑	↓ ↓	D A	– ↑	– ↑	– ↑
[141]	Marine 4x 1c	16.8	129 × 155	49	API (PRDF)	28	1200	High	–	↓	D	↑	↓	↑
[138]	Truck/ Bus 4x 6c	17	126 × 130	42	API (PRDF)	40	1500	High	↑	↓	A	–	–	↑
[152]	Truck/ Bus 4x 6c	18.1	108 × 130	32	API (PRDF)	30	1400	Low	–	↓	A	–	–	↑
[149]	Truck/ Bus 4x 6c	17	126 × 130	42	API (PRDF)	60	1900	High	↑	~	A	~	~	↑
[108]	Truck/ Bus 4x 1c	16.7	131 × 158	73.5	HP-DI (DFDC)	96.6	1262	High	↓	↓	A	↑	↑	↑
[151]	Truck/ Bus 4x 1c	16.6	131 × 158	73.5	HP-DI (DDFS)	53 to 63	1500	High	↑	↑	D	↓	↓	↓
[145]	Marine 2x 4c	–	500 × 2250	1624	HP-DI (DFDC)	High*	105	Low–High	–	↓	A	–	–	↑
[153]	Marine 2x 6c	–	500 × 2500	1264	HP-DI (DFDC)	High	88.5	High	–	↓	A	–	↑	↓
[154]	Marine 4x 8c	–	320 × 400	500	HP-DI (DFDC)	High	720	High	–	↓	A	–	–	↓
[155]	Marine 4x 6c	–	210 × 320	220	HP-DI (DFDC)	95	1000	Low–High	–	↓	~	~	↑	↑

The baseline is the corresponding engine operating in diesel-only mode.
A: Advanced, D: Delayed, ↑: Increase, ↓: Decrease, ~ : Constant , – : Data not available.
c: cylinder, 2x: two-stroke, 4x: four-stroke.
*Ethanol used in engine experiments.

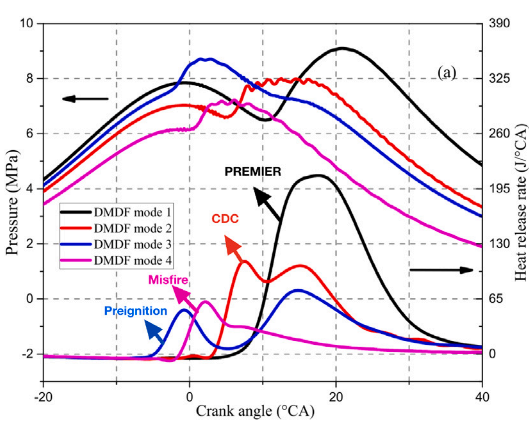

Fig. 8. Combustion modes in a methanol PRDF engine.
Source: Adapted from [121].

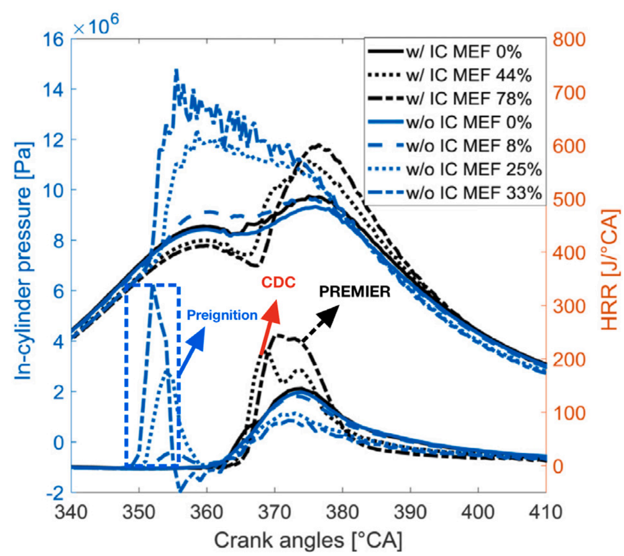

Fig. 9. Combustion mechanisms found in a methanol PRDF marine engine.
Source: Adapted from [144].

ID trends, reactivity-controlled combustion strategies, like RCCI and DDFS, exhibit different correlations using methanol. Jia and Ingemar [151] revealed that an increasing MSR delayed combustion in DDFS mode, likely due to methanol's cooling effect and lower reactivity, highlighting the strategy's sensitivity to fuel mixture reactivity.

In premixed strategies, methanol is typically evaporated before combustion. Nevertheless, in DFDC mode, evaporation and combustion phases occur consecutively and simultaneously. Typically, methanol's injection is directed towards the diesel flame, where it rapidly evaporates before its ignition [108]. The overall influence of methanol on the DF mode results in an advanced combustion phasing and greater peak in HRR due to a faster diffusion combustion of methanol compared to the diesel-only mode. Further, the typical premixed combustion phase of CDC was absent when methanol was used in the DFDC mode. The unimodal HRR shape reported by Saccullo et al. [108] with methanol aligns with similar experimental studies using the DFDC strategy [153, 155].

3.1.4. Impact of methanol on engine performance

Methanol can potentially improve the overall brake thermal efficiency (BTE) in ICEs. Higher combustion rates with methanol, together with its cooling effect, can further enhance the thermal efficiency of the engine. While methanol can increase engine efficiency and reduce emissions, its evaporation challenges may increase combustion variability in premixed strategies [141], particularly at low loads, potentially offsetting these benefits. Most studies report a positive impact of methanol on BTE using either the PRDF or DFDC strategy, as seen in Table 4. Despite methanol's lower calorific value and the API in the PRDF strategy, its use can improve both the volumetric efficiency and specific fuel consumption. Only Wei et al. [149] reported a decrease in these two efficiencies. Their study, which assessed the effect of methanol in a six-cylinder truck engine using the PRDF strategy, showed a 2% reduction in BTE compared to diesel-only mode, likely due to delayed combustion phasing away from TDC.

Although the PRDF may not achieve as high MEF as the DFDC strategy, most studies demonstrate that both can achieve higher BTE with methanol addition. In the PRDF strategy, the efficiency boost primarily derives from methanol's cooling effect as well as advanced and/or shorter combustion. This is supported by the study of Guan et al. [141], which reported faster combustion rates and a maximum increase in efficiency of approximately 2% in methanol operation compared to diesel-only, despite an increase in coefficient of variance (COV) of IMEP and decrease in combustion efficiency. Dierickx et al. [133] observed a maximum 12% increase in BTE in a high-speed marine diesel engine converted to methanol PRDF, with the greatest gains at higher load points but a slight decrease at low loads. Wang et al. [133] similarly reported BTE gains of up to 10% in methanol mode, while an efficiency gain was also found at low loads.

The increasing trend in BYE with methanol is also confirmed in DFDC strategies for large marine engines. Repo et al. [147] reported a 2% efficiency gain during methanol operation compared to diesel, with the highest gains at maximum load points. Aabo et al. [153] showed that large two-stroke MAN marine diesel engines exhibited an increase in indicated efficiency at all load points, with gains up to 4% in methanol mode. Similar BTE improvements have been observed in developing other large marine engines using the DFDC strategy [154,157].

3.1.5. Impact of methanol on emissions

Utilizing renewable methanol in next-generation HD engines offers significant potential to reduce greenhouse gas and other harmful emissions in transportation, especially for hard-to-abate transport sectors like maritime [6]. Methanol is free of sulfur and carbon-to-carbon bonds, which eliminates sulfur oxide (SO_x) emissions and significantly reduces particulate matter (PM) formation, such as soot, in marine engines [5].

Nitrogen oxide emissions. NO_x emissions remain a great challenge in diesel engines. Very high temperatures near the diffusion flame and high oxygen concentration due to lean combustion contribute to high levels of NO_x in diesel engines. The key factors influencing NO_x formation include maximum in-cylinder temperatures, air residence at high temperatures, and oxygen concentration within the cylinder [14].

Across various combustion strategies and engine sizes, studies consistently report a decrease in in-cylinder temperatures when methanol is used in diesel engines [153,158]. Methanol's cooling effect and the shortened combustion duration it induces, as discussed in , outweighs its oxygen content, which could otherwise increase NO_x formation, resulting in an overall reduction in NO_x emissions compared to diesel-only mode.

In methanol PRDF engines, higher MEFs are expected to result in lower NO_x emissions for three main reasons. First, the cooling effect of methanol increases as MEF rises. Second, higher MEF promotes a more dominant premixed lean combustion mode through flame propagation, reducing the amount of diesel undergoing diffusion combustion. This effect is also supported by experimental studies on PRDF strategies with NG, where increasing NG-to-diesel ratio decreased NO_x due to smaller hot-flame diffusion regions [125]. Third, the combustion duration is shortened as MEF increases, leading to less time being available for NO_x formation. This aligns with the studies of Wang et al. [105] and Dierickx et al. [133], who reported that methanol addition led to faster combustion rates and reduced NO_x emissions at all tested load conditions. Wang et al. [105] reported a reduction range of 15% to 40%, with the maximum reduction at 75% load where the highest MEF was achieved, while Dierickx et al. [133] reported a reduction between 40% up to 75%.

Despite the general decreasing trend with methanol addition in diesel engines, direct comparison between different combustion strategies remains challenging due to variations in parameters tested, such as engine size and load points. While all reviewed combustion strategies with methanol demonstrate NO_x reduction, directly comparing different combustion strategies is challenging due to parameter variations like engine size and load points. For instance, in methanol PRDF concepts, some studies report lower NO_x reduction [105,138,141], while others demonstrate stronger NO_x reduction capabilities [133,144]. Similar trends are observed for methanol DFDC engines compared to their diesel baseline. The study of Wang et al. [107] on a high-speed LD engine showed a 60% NO_x reduction with approximately 80% MEF across all load points compared to CDC, while Sacculio [108] reported a 20% reduction in a HD single-cylinder setup with a higher MEF of 96%.

Despite methanol's NO_x reduction potential, it remains unclear whether this reduction is sufficient to comply with stringent regulations such as International Maritime Organization (IMO) Tier III for shipping. Several studies suggest that exhaust gas after-treatment may still be required for marine engines to meet Tier III levels [144,157]. Fridell et al. [159] investigated the exhaust emissions from a large marine four-stroke medium-speed diesel engine converted to methanol DFDC. Although NO_x levels ranged from 6.5 to 12.3 g/kWh in methanol mode, which are lower than the typical values in diesel-only mode, after-treatment is still required to meet Tier III levels. MD97 remains the only methanol-based combustion strategy to meet the Tier III standards without exhaust after-treatment [37].

Introducing water into the cylinder is a viable direct strategy to further reduce NO_x emissions in methanol engines [28]. Dierickx et al. [160] tested various methanol–water (MeOH–W) blends to investigate the potential of water addition in a marine diesel engine. They concluded that a higher water ratio (MeOH-50 and MeOH-64 blends) could help the engine reach Tier III NO_x legislation but at the cost of reducing the maximum MEF that could be used. Although water addition generally leads to a small decrease in engine efficiency [161], this experimental study demonstrated an increase in BTE compared to pure methanol. The MeOH-50 blend resulted in a 3.3% and 4.9% increase in BTE compared to pure methanol and diesel-only modes, respectively. According to the study, this improvement can be attributed to the advancement of combustion phasing caused by the enhanced cooling effect and longer ID with water addition. The extended ID led to a greater portion of isochoric combustion closer to TDC, thereby increasing thermodynamic efficiency. Additionally, water addition mitigates the inhibition effect of methanol on OH· radical production, which improves mixture reactivity [134], further enhancing combustion efficiency.

While methanol generally reduces NO_x emissions, special attention should be paid to NO_2 emissions when methanol is employed in ICEs. Several experimental studies have confirmed an increase in NO_2 emissions despite the overall decrease in NO_x emissions [104,138,158,162]. This rise occurs when NO rapidly converts to NO_2 in certain areas of the charge, due to leaner mixtures and cooler temperatures [163]. The NO_2 emissions rising trend raises health concerns, to which research has given little attention.

Table 4
Methanol impact on engine performance and emission characteristics of HD DF engines.

Ref.	Engine type	CR [–]	Bore × Stroke [mm]	Rated Power [kW/c]	Injection (Ignition) strategy	MEF test [%]	Speed [rpm]	Performance		Emissions				
								VE	BTE	NO_x	PM	UHC	CO	CH_2O
[105]	Marine 4x 6c	16.8	–	43	API (PRDF)	51	1800	↑	↑	↓	↓	↓ **	↓ **	↓ **
[133,144]	Marine 4x 6c	19	108 × 130	32.5	API (PRDF)	60	1500	~	~	↓	↓	–	–	–
[141]	Marine 4x 1c	16.8	129 × 155	49	API (PRDF)	28	1200	↑	↑	↓	–	↑	↑	–
[138]	Truck/ Bus 4x 6c	17	126 × 130	42	API (PRDF)	40	1500	–	↑	↓	↓	↑	↑	↑
[152]	Truck/ Bus 4x 6c	18.1	108 × 130	32	API (PRDF)	30	1400	–	–	–	↑	–	–	–
[149]	Truck/ Bus 4x 6c	17	126 × 130	42	API (PRDF)	60	1900	↓	↓	↓	↓	↑	↑	–
[108]	Truck/ Bus 4x 1c	16.7	131 × 158	73.5	HP-DI (DFDC)	96.6	1262	–	↑	↓	↓	–	–	–
[145]	Marine 2x 4c	–	500 × 2250	1624	HP-DI (DFDC)	High	105	–	~	↓	↓	↑	~	–
[147,159]	Marine 4x 8c	–	400 × 560	660	HP-DI (DFDC)	High	530	–	–	↓	↓	↑	–	–
[147]	Marine 4x 16c	–	320 × 400	580	HP-DI (DFDC)	High	750	–	↑	↓	–	–	–	–
[153]	Marine 2x 6c	–	500 × 2500	1264	HP-DI (DFDC)	High	88.5	–	↑	↓	–	–	–	–
[154]	Marine 4x 8c	–	320 × 400	500	HP-DI (DFDC)	High	720	–	↑	↓	↓	–	–	–
[155,157]	Marine 4x 6c	–	210 × 320	220	HP-DI (DFDC)	93	1000	–	↑	↓	↓	–	–	–

The baseline is the corresponding engine operating in diesel-only mode.
A: Advanced, D: Delayed, ↑: Increase, ↓: Decrease, ~ : Constant , – : Data not available.
c: cylinder, 2x: two-stroke, 4x: four-stroke.
*Ethanol used in engine experiments.
**After diesel oxidation catalyst (DOC).

PM and soot emissions. PM emissions pose another challenge in diesel engines [164], with a typical trade-off existing between NO_x and soot emissions. Soot, which appears as black smoke, is the primary constituent of PM emissions in diesel engines, with methanol having the potential to mitigate soot formation due to its oxygen content and lack of carbon-to-carbon bonds. Geng et al. [152] conducted an experimental study on a 6-cylinder HD diesel engine using the methanol PRDF strategy to assess methanol's impact on PM emissions. Methanol operation resulted in a reduction of dry-soot emissions by up to 92% compared to CDC at low to medium loads, with PM distribution shifting towards smaller particles. This trend aligns with findings from similar studies on smaller engines [164,165]. However, at higher load points, an increase in soot particles was observed in methanol mode, which can be explained by the methanol combustion before diesel injection, which reduced oxygen availability during diesel combustion. Under normal operating conditions, methanol typically reduces soot emissions at all load points, as shown by Dierickx et al. [133,144], with the reduction reaching up to 86% at the highest MEF.

Methanol's great potential in diesel engines lies in its potential to eliminate their typical soot-NO_x trade-off [95]. Although previous studies have reported this elimination in methanol PRDF engines [138, 149], Dierickx et al. [133] found that this trade-off elimination was not evident at all operating points. Specifically, at higher loads, there was a threshold beyond which the trade-off was reintroduced, as NO_x began to rise again. According to the study, this probably originated from the elevated temperature of more premixed combustion taking place at higher MEF. Using methanol with DFDC strategy, all reviewed studies report a reduction of both PM and NO_x emissions, as summarized in Table 4. Fridell et al. [159] observed PM levels as low as 0.1 g/kWh, significantly below those in diesel-only mode, along with NO_x reduction. Similarly, Sacculio [108] reported decreasing soot emissions from 3.2 to 0.05 mg/kWh in methanol DFDC mode.

Despite the general reduction in PM emissions with methanol, an increase in the soluble organic fraction (SOF) of PM can be expected [152, 166]. Zhang et al. [104] confirmed that methanol operation results in higher SOF proportions in PM. While SOF poses additional health concerns, there is limited research on such unregulated emissions in methanol-fueled HD engines, highlighting the need for further investigation.

Unregulated emissions. Introducing methanol in CI engines, particularly through premixed strategies, often leads to higher levels of unburned hydrocarbons (UHCs), including methanol (CH_3OH) and formaldehyde (CH_2O), as well as increased carbon monoxide (CO) emissions [32]. The increase in these emissions in PRDF engines with methanol can be attributed to three main factors: (1) incomplete combustion due to lower in-cylinder temperature and leaner mixtures, (2) 'wall wetting effect', causing a portion of methanol to stick to the walls and crevices, and (3) absorption of methanol into oil layers [95,109]. CO is particularly sensitive to the first, whereas UHC is more sensitive to the last two. The mechanism of the UHC is similar to that in SI engines [167]. Ning et al. [109] compared the emissions of methanol, ethanol, and n-pentanol in a non-road PRDF engine and reported that all alcohols resulted in lower CO and soot but higher UHC levels compared to the diesel baseline. Among the three alcohols, methanol showed the best CO and soot reduction performance but had the highest UHC emissions, likely due to increased wall wetting and absorption into oil layers. At 40% MEF, UHC increased from around 0.14 to 0.57 g/kWh, while CO decreased from around 3.15 to 1.55 g/kWh.

Unoxidized methanol, after combustion, escapes in the exhaust, with some partial oxidation to formaldehyde taking place in the exhaust stream. While both molecules are intermediate products from the combustion of diesel fuel, they are relatively low in CDC [104]. Diesel combustion involves a range of species during its oxidation reactions, whereas the only methanol oxidation path is through formaldehyde [91]. Aniolek and Wilk [168] investigated the low-temperature oxidation of methanol in a constant volume stirred reactor, which could mimic the lower-temperature oxidation process occurring during the exhaust stroke. They observed that methanol is quickly oxidized at low temperatures, while formaldehyde, its principal intermediate product, accumulates rapidly before being oxidized to CO. They also concluded that formaldehyde oxidation results in a high increase in CO but few CO_2 at low temperatures.

While numerous studies have examined methanol's impact on UHC in diesel engines using the PRDF strategy, detailed data on methanol and formaldehyde emissions are still scarce, particularly for HD DF engines. Investigating the impact of methanol on the performance of six-cylinder HD methanol PRDF engine, Wang et al. [105] reported almost no methanol emission in all tested load conditions and only slightly higher formaldehyde levels after the diesel oxidation catalyst (DOC) compared to baseline CDC mode. These findings are consistent with the results of Zhang et al. [105] in a LD four-cylinder methanol PRDF engine, which also reported low methanol levels post-DOC (around 0.028 g/kWh) but found the DOC having less impact on formaldehyde emissions. However, without the DOC, this study demonstrated that unburned methanol emissions are expected to increase significantly in methanol PRDF engines. At 30% MEF, methanol PRDF engines emitted 0.86 g/kWh of methanol and approximately 0.92 g/kWh of formaldehyde, while in the CDC mode, both emissions were low at 0.03 g/kWh.

In methanol DFDC engines, information about unregulated emissions is even more limited. However, an increase might not be as significant as in PRDF strategy due to the nature of diffusion combustion. The absence of a premixed fuel–air mixture eliminates the risk of unburned methanol due to the aforementioned reasons. This might explain this lack of data on such emissions in methanol DFDC engines. In the study of Fridell et al. [159], UHC emissions were 1.6 g/kWh at 80% engine load, which are higher than the typical UHC emissions seen in these engines of around 0.2 g/kWh [169]. Aldehyde emissions were found at low levels not exceeding 0.0005 g/kWh, with CO emissions ranging from 3.7 g/kWh at high loads to 6.6 g/kWh at low loads. Schmid et al. [145] reported an increase in UHC with ethanol use, but the rise was much smaller compared to the increase observed in methanol PRDF engines. This trend is also mirrored in CO emissions.

To mitigate the expected rise in UHC, the DOC technology can be employed, which can effectively reduce not only CO and UHC but also PM emissions, including SOF [170,171]. The DOC performance is also highly sensitive to exhaust temperature [172], supported by the study of Geng et al. [152] where the reduction of PM concentration increased at higher loads. This study also demonstrated that DOC could significantly lower SOF and UHC in the exhaust from a PRDF engine with methanol, with a total particulate number concentration reduction of up to 60%. Wang et al. [105] reported similar findings, showing DOC's capability to eliminate methanol from the exhaust and substantially decrease CO and UHC. Methanol operation with DOC exhibited unburned methanol emissions that were even lower than the diesel baseline. However, formaldehyde emissions were found higher than the diesel baseline, even with DOC use. The maximum increase occurred at 75% load, where emissions rose from approximately 0.015 g/kWh in diesel-only mode to 0.045 g/kWh, which load points corresponds to the highest MEF used of 60.6%.

3.2. Dedicated MF methanol engines

Because diesel engines dominate HD transport, research has mainly focused on methanol use in DF schemes. However, exploring other strategies like mono-fuel SI and low-temperature combustion could offer improved trade-offs between emissions and efficiency and enable operation fully on renewable fuels like methanol, thus reducing the reliance on diesel. Despite limited research on these alternative concepts, this subsection seeks to gather and review experimental research on HD engines that have utilized MF approaches with methanol.

3.2.1. HD SI engines

The gasoline engine's affordability and low emissions have made it prevalent in the LD automotive sector. In contrast, the diesel engine is favored in HD applications due to its superiority in power density, robustness, and efficiency [12]. As engine bore size increases for heavier applications, so does the flame distance within the combustion chamber. This, along with higher pressure and lower flame velocities associated with typically slower speed regimes, exacerbates knocking in SI engines, thus limiting their capability to meet higher load torque demands and consequently their efficiency due to restricted CR [13].

Despite DF concepts currently leading in HD applications, growing experience with methanol can pave the way for dedicated methanol HD SI engines [173,174]. Methanol allows for higher CR in SI engines than traditional gasoline-type fuels due to its higher ON. Wouters et al. [175] explored the CR limits in a methanol DI SI engine, testing CR from 10.8 to 20.6. The authors reported that the engine could operate at high loads, including the highest of 18 bar indicated mean effective pressure (IMEP), resulting in higher efficiencies. The greatest gain in efficiency was observed at the highest CR, with an IMEP of 16 bar and lean mixture. The study of Güdden et al. on a large-bore 5-l PFI SI engine showed that despite knock limitations, an efficiency of 44% at 17 bar IMEP can be achieved while meeting the IMO Tier III regulations without the need for additional exhaust after-treatment technologies. [176]. Nevertheless, a rise in formaldehyde might necessitate the use of an oxidation catalyst in the exhaust system.

Bosklopper et al. [177] studied an eight-cylinder NG engine converted to methanol, achieving stable operation across all test loads (25%, 50% and 75%) with improved efficiency over NG. Zhu et al. [178] also converted an NG HD SI engine to methanol, observing a BTE over 40% across 12.7 to 21.7 bar BMEP and 1000 to 1700 rpm, together with a reduction in NO_x and CO emissions compared to NG. However, an increase in UHC was observed. Björnestrand [179] investigated an HD DI SI engine with methanol, noting knock limiting high load operation. Retarding spark discharge and employing EGR mitigated knock and resulted in gross indicated efficiency of 54%. Similarly, Mahendar et al. [180] explored methanol's diluted combustion characteristics in an HD SI engine, comparing it with gasoline and ethanol. Methanol could operate at the highest load, over 25 bar IMEP and even at stoichiometric conditions, increasing indicated efficiency at 48%.

3.2.2. Partially premixed combustion

The PPC concept, an emerging low-temperature combustion (LTC) strategy, involves adjusting injection timing during the compression stroke to create a partially premixed charge and separate the injection and combustion events [84,181]. To explore methanol's potential in PPC, a series of experimental studies were conducted in a converted marine six-cylinder Scania D13 engine into a single-cylinder configuration [36,182–185]. Shamun et al. [182] explored the PM characteristics in the exhaust gas from the PPC engine fueled with naphtha gasoline, ethanol, and methanol and compared them with CDC. Intake concentration of O_2, intake temperature and injection pressure were varied during the experiments. The study demonstrated extremely low PM emissions and elimination of the NO_x-soot trade-off when both alcohol fuels were employed. Although neither methanol nor ethanol produced any particle with diameters greater than 30 nm, methanol resulted in more particles than ethanol. According to the study, this might derive from the corrosive nature of methanol, which may affect the surrounding metallic components that methanol gets in contact with.

Subsequently, the same authors attempted to quantify the cooling effect of methanol and compare it to that of iso-octane fuel [183]. Analyzing the in-cylinder pressure measurements, methanol's cooling effect resulted in lower compression work, leading to a slightly higher BTE. Lower achieved temperatures with methanol reduced both the heat losses and NO_x emissions. Zincir et al. [36] later conducted a study to investigate the potential of a methanol PPC engine in the context of slow-speed and low loads, a strategy increasingly adapted by ships to lower emissions [186]. Compared to marine gas oil, the methanol-fueled PPC engine resulted in higher BTE, increased from 31% to 43% in the low-load range. Methanol use reduced CO_2 and led to NO_x levels below the IMO Tier III while eliminating both SO_x and PM emissions. In a follow-up study, Zincir et al. [83] investigated the impact of intake air temperature on these low load operating conditions. The results showcased that decreasing the intake air temperature led to lower combustion stability and longer ID, similar to the PRDF engine concept.

Svensson et al. [185] investigated the timing and duration of dual methanol injections in low load operation with neat methanol. Their strategy included an early pilot injection coupled with a diffusion-controlled main injection in the context of PPC combustion (Fig. 4). The study's findings demonstrated that low levels of CO, UHC, and NO_x emissions can be obtained by optimizing the dwell time and injection duration. This highlights the potential reductions in hazardous emissions through injection optimization in methanol PPC engines.

3.2.3. Additized methanol in CI engines

In addition to SI and PPCI, using methanol with an ignition improver demonstrated promising conventional diffusion combustion performance. Aakko-Saksa et al. [67] explored the potential of renewable methanol blended with ignition improvers and lubricity additives in a Scania ethanol engine. Operating the engine on MD95 (95% of methanol and 5% of ignition improvers), the engine exhibited lower emissions compared to the ethanol mode. This study concluded that this engine strategy could be suitable for HD applications such as smaller marine vessels with engines ranging from 800 to 1200 kW of power. In a subsequent study, a higher methanol ratio of 97% (MD97) was achieved, leading to the certification of a commercial engine capable of meeting IMO Tier III NO_x levels without additional treatment system [37].

4. Impact of design and operating parameters on diesel-methanol dual fuel engines

DF technology is often regarded as the most effective strategy to utilize methanol in HD engines due to its potential to lower emissions and enhance efficiency in the diesel engine [5,147,153] while offering the flexibility of switching between methanol and diesel operation. The flexibility provided by the DFDC strategy is crucial to meet the growing demand for global trade power [187]. While the DFDC strategy can reach high MEF and offer this adaptability for HD diesel engines, it is restricted to a certain range of engine sizes due to space constraints in the cylinder head when an additional injection system needs to be mounted. A highly complex injection system is required to realize DFDC strategy in smaller engine sizes [147]. Further, DFDC still faces challenges with the relatively high levels of NO_x deriving from the diffusive nature of combustion.

In contrast, the simpler-to-adopt PRDF strategy applies to a broader spectrum of engine sizes while having the potential of significantly reducing NO_x emissions. This approach can contribute to the sustainable conversion of existing engines. Yet, PRDF combustion faces challenges like misfires at low loads and knocking at high loads [121]. Optimizing design and operational parameters could extend MEF limits and enhance the performance of these methanol PRDF engines. This section reviews experimental studies on PRDF engines using methanol to evaluate the impact of several design and operating parameters on engine performance of these DF engines. Table 5 compiles these findings, offering insights into optimizing PRDF engine performance.

4.1. Engine speed

The lower speed operating regime is a distinct feature of HD engines compared to LD applications, highlighting the importance of better understanding how engine speed influences the behavior of methanol DF engines. Chen et al. [188] examined a methanol-fueled engine using the PRDF strategy across various speeds. At 25% MEF, increasing engine speed resulted in higher peak pressure, reduced cylinder-to-cylinder variation, and slightly delayed combustion phasing. The reduced variation and higher Pmax were likely due to improved mixing from increased turbulence [196], while delayed combustion phasing is expected as timing narrows with increasing speed. This effect in combustion phasing might be confirmed by Cheung et al. [189], who reported rising exhaust temperatures with increasing speed from 1280 to 2560 rpm, exhibiting a drop in BTE from 30.8% to 24.8%. These findings might also be confirmed by studies suggesting that lower engine speeds extend the maximum achievable MEF [91,133,190], possibly due to more favorable combustion phasing and more time available for methanol to evaporate and properly mix. Dierickx et al. [133] found the maximum MEF to be 70% at 1000 rpm, decreasing to 37% at 2000 rpm. Further, the most efficient operating region for methanol shifted to lower speeds compared to diesel-only mode, with maximum BTE of 38% at 1400 rpm under methanol DF operation, compared to 36% in diesel-only. Wang et al. [190] also reported higher brake specific fuel consumption at 2090 rpm compared to 1660 rpm at all tested MSP.

Despite these findings, drawing definitive conclusions about the effect of engine speed on methanol PRDF engine performance remains challenging, as multiple factors that are not kept constant might influence engine behavior across different studies. However, a general hypothesis is that lower engine speeds typically lead to delayed combustion phasing, which can decrease thermodynamic efficiency. The overall impact may reflect a trade-off between higher thermodynamic efficiency at lower speeds and the corresponding increase in heat losses due to prolonged exposure to high temperatures within the cylinder. This is supported by Dierickx et al. [133] and Cheung et al. [189], who reported that lower speeds resulted in reduced soot but increased NO_x emissions. Extended combustion gas residence time at high temperatures at lower speeds could explain the increase in NO_x and an expected rise in heat losses.

These research findings underscore the impact of engine speed on the overall performance of these PRDF engines fueled by methanol. Methanol's better performance at lower speeds could benefit larger engines operating at lower speed regimes. However, the scarcity of experimental results calls for further investigation into how engine speed affects MEF limitations in engines using the PRDF strategy.

4.2. Methanol injection location

Injecting methanol at LP with the API strategy is the simplest and most cost-effective way to retrofit diesel engines compared to more complex and expensive HP-DI systems [144]. Depending on the intake geometry of each engine design, there are several API locations for methanol when SPI strategy is employed. Therefore, the PRDF ignition concept can be facilitated via the different SPI, PFI and LP-DI strategies, as discussed in 2.2.2. The injection location is expected to affect the overall performance of the engine. This subsection reviews experimental studies that compare different injection locations for the PRDF concept and their impact on engine performance.

Xu et al. [41] experimentally evaluated the effects of methanol API locations on a four-cylinder common rail diesel engine at varying loads, exploring three alternative locations: (1) pre-intercooler (I/C) SPI, post-I/C SPI, and PFI. Four injectors were employed for each case of the SPI strategies. The authors observed that the optimal API location was highly sensitive to the operating load. The pre-I/C SPI strategy was the most effective in promoting combustion at low loads, post-I/C SPI at medium loads, and PFI at high loads. The improved combustion was

Table 5
Impact of operating/design parameters on the performance of methanol dual-fuel engines.

Ref.	Parameter varying	Combustion characteristics					Performance (BTE)	Emissions				MEF maximum
		ID	CD	CA50	COV	Pmax		NO_x	PM	UHC	CO	
[188]	Speed ↑	↑	↑	D	–	↑	↓	–	–	–	–	–
[189]	Speed ↑	–	–	–	–	–	↓	↓	↓	↓	↑	–
[91]	Speed ↑	–	–	–	–	–	↓	↑	–	↑	↑	↓
[190]	Speed ↑	↑	↑	D	–	↓	↓	↑	↑	↑	↓	↓
[133]	Speed ↑	–	–	–	–	–	↑	↓	↑	–	–	↓
[41]	Injection location (SPI to PFI)	↓	↓	A	↓	↑	↑	↑	–	↓	↓	–
[144]	Injection location (SPI to PFI)	–	–	–	↓	–	↓	↓	–	–	–	↑
[42]	Injection location (SPI to PFI)	–	–	–	↑	~	–	↓	↑	↓	↓	–
[142,191]	Injection location (PFI to LP-DI)	↑	↑	–	↑	↑	↑	↑	↑	↓	↓	–
[192]	Intake air temperature (low load) ↑	↓	↓	A	–	↑	↑	↑	↓	–	–	–
[162]	Intake air temperature (low load) ↑	↓	↓	A	–	↑	↑	↑	↓	↓	↓	–
[138]	Intake air temperature (high load) ↑	↓	↓	A	–	↑	↑	↑	↑	↓	↓	–
[164]	Intake air temperature (high load) ↑	↓	↓	A	–	↑	↓	–	–	–	–	–
[141]	Intake air temperature (high load) ↓	↑	↓	–	↑	↑	↑	↓	↑	↑	↑	–
[193]	Intake air temperature (low load) ↑	↓	↓	A	–	↑	↑	↑	–	–	↓	↑
[193]	Intake air pressure ↓	↑	↑	D	–	↓	↓	↑	↓	–	↑	↓
[193]	EGR ↑	–	–	–	–	–	↓	↓	–	–	↑	↑
[190]	EGR ↑	↑	~	–	–	↓	–	↓	↑	–	–	~
[194]	Injection timing (A)	↓	↓	–	↑	↑	–	↑	↓	↓	↓	–
[192]	Injection timing (A)	↑	↓	A	↑	↑	↑	↑	↓	↓	↓	–
[195]	Injection pressure ↑	↓	↓	A	~	↑	↑	↑	↓	↓	↓	–
[194]	Injection pressure ↑	↓	↓	–	↓	↑	–	↑	↓	↓	↓	–

The baseline is the corresponding engine operating in methanol–diesel mode prior to the corresponding adjustment of the operating/design parameter.
A: Advanced, D: Delayed, ↑: Increase, ↓: Decrease, ~ : Constant , – : Data not available.

characterized by lower ignition delay and greater combustion efficiency resulting in lower UHC and CO but higher NO_x emissions. At all load points, regardless of the injection strategy, methanol operation resulted in higher efficiency compared to diesel-only mode. At high load and 40% MSP, PFI strategy resulted in 42.5% BTE compared to 41% for diesel baseline, 41.5% for post-I/C SPI, and 42% for pre-I/C SPI.

As previously discussed in 3.1.2, the study of Dierickx et al. on the pre-I/C SPI strategy chose to bypass the I/C to prevent methanol condensation [144]. In this study, the PFI strategy was found to be the most effective API strategy for maximizing MEF. However, comparing SPI and PFI directly from this study is challenging due to variations in air conditions induced by the I/C. The authors highlight the importance of controlling the I/C's cooling effect in pre-I/C SPI setups for methanol. Investigating the impact of this cooling effect on the performance of these engines is interesting for further studies.

Chen et al. [42] explored different methanol injection locations and their effect on COV and emissions of a four-cylinder diesel engine, investigating three strategies: SPI at two points and PFI. PFI exhibited the greatest cooling effect on the intake charge, increasing volumetric efficiency and allowing more methanol to enter the engine in gaseous form At 50% MSP, the temperature of the intake manifold dropped around 40 K relative to diesel-only, while both SPI strategies led to a decrease of around 20 K. The increased cooling effect was confirmed by the lower NO_x emissions across the entire operating range and tested MSPs. This can be attributed to a more effective cooling of the intake air compared to early SPI, where cooling losses occur in the intake pipes.

Ning et al. [142] compared PFI and LP-DI strategies of methanol injection in a single-cylinder diesel engine using the PRDF concept. A high-pressure common rail system was used for LP-DI, while a LP system was used for PFI. LP-DI resulted in higher BTE, lower UHC and CO emissions, despite exhibiting higher COV. The lower COV in PFI might be attributed to better mixing, which could also explain the reduced NO_x emissions. The earliest LP-DI tested showed better overall performance than PFI, but it is difficult to directly compare the injection location impact between the LP-DI and PFI due to the different injection systems used in the two strategies. Additionally, comparing trends across different studies poses challenges, as the specific fuel injection equipment employed for the pilot fuel may influence the results. For instance, one study used a common rail system [109], while another [144] used a pump-line-nozzle system.

4.3. Intake conditions

Despite methanol's cooling effect and its potential to enhance the engine's efficiency, great attention should be given to the intake air conditions in methanol-fueled engines, especially when API schemes are considered. Methanol's high heat of evaporation makes its mixture formation highly sensitive to intake conditions, eventually affecting engine operation. Strategies like EGR can modify the intake air conditions, such as the reactivity gradients in the mixture, and subsequently affect overall engine performance. This subsection will examine the effect of variations in intake conditions, such as temperature, pressure, and EGR, on the methanol PRDF engine operation.

To explore the potential of higher intake air temperatures and overcome the part load challenges in a methanol PRDF engine, Wang et al. [192] conducted experiments on a diesel engine at low loads. At nominal conditions and MEF of 60%, methanol PFI decreased the intake temperature by 27.45 K, showcasing its dominant cooling effect during the evaporation phase. This slowed flame propagation due to low-temperature and lean mixtures after diesel injection. Pre-heating of intake air could help overcome these combustion challenges at low loads. By increasing the intake air temperature to 348.15 K and 388.15 K with an electric heater, the combustion phasing and BTE improved significantly. Thus, MEF ratios at low loads can be increased by assisting heating strategies, as also reported by Kumar et al. [162]. Improved combustion efficiency is observed with higher temperatures, leading to lower CO and UHC, but higher NO_x emissions.

On the contrary, increasing intake air temperature at high loads has a reverse effect on the efficiency of methanol PRDF engines while leading to further rise in NO_x emissions [162]. Exploring the impact of various intake air temperatures at high loads in an HD methanol PRDF engine, Pan et al. [138] reported an increase in both NO_x and soot emissions with higher intake air temperatures. Specifically, increasing the intake air temperature initially led to rising BTE until its maximum value at 333.15 K of intake air temperature. However, further increasing intake air temperature deteriorated BTE. This trend aligns with the experimental results reported by Chen et al. [164], who concluded that higher intake temperatures at high loads can lead to auto-ignition of methanol, affecting combustion stability and emissions. At high loads, methanol PRDF engines encounter the opposite challenges with uncontrolled combustion compared to low loads when partial combustion occurs. To address high PRR and Pmax resulting from roar combustion at high loads, Guan et al. [141] reduced the intake air temperature using an air-to-water cooler in a single cylinder HD methanol PRDF engine. By decreasing the intake temperature from 323 K to 305 K, they lowered average in-cylinder temperatures during compression and allowed for more advanced diesel injection timing. This intake condition resulted in lower PRR, improved volumetric and thermal efficiency, and less NO_x emissions. However, COV and combustion efficiency slightly decreased, leading to higher soot, CO, and UHC emissions.

Besides the impact on performance, it is crucial to explore the effects of these variations in intake conditions on MEF limitations in methanol DF engines. To this end, Dierickx et al. [193] investigated the impact of intake air temperature, pressure, and EGR on the MEF limits, as well as the engine performance. At low loads, misfiring was the main limiting factor for higher MEF ratios. Increasing intake air temperature resulted in greater MEF until the maximum level of 74% at 333.15 K. Instead of misfiring, knocking and pre-ignition were the limiting factors for further increasing MEF beyond 333.15 K. Further, the impact of higher temperature aligns with the experimental studies discussed earlier, leading to better combustion phasing, BTE, and higher NO_x. By varying the waste-gate valve in the exhaust, the effects of intake air pressure were studied at a constant air temperature of 303.15 K. Lower intake air pressures resulted in decreased attainable MEF ratios while knocking transitioned to misfiring as the main limiting factor. Additionally, lower intake pressure deteriorated combustion phasing, BTE, and higher NO_x emissions. This NO_x trend at lower intake pressure might result from poorer volumetric efficiency that led to higher maximum temperature during combustion. Finally, employing EGR at medium load and two set intake temperatures, the authors reported that EGR can improve diesel displacement ratios and lower NO emissions, albeit at the expense of combustion and thermal efficiency. EGR is promising at extending MEF limits, particularly at high loads, where knocking is the main constraint [193]. However, Wang et al.'s similar studies indicated that using EGR did not contribute to any extension of MEF limits [190]. The scarce information on the effect of EGR in methanol PRDF engines necessitates further exploration to understand the capabilities of this technology better.

4.4. Injection parameters of pilot diesel

Combustion control in PRDF engines depends on the injection characteristics of the HRF, like diesel. Injection timing dominates the combustion dynamics, similar to pilot diesel used in PRDF strategies. Knocking at high loads could be overcome by optimizing diesel injection parameters. This subsection reviews experimental studies to identify the effect of pilot fuel injection parameters on combustion characteristics, performance, and emissions of methanol PRDF engines.

Li et al. [194] studied the effects of pilot fuel injection pressure and timing in a methanol PRDF engine. Similar to CDC, they observed that advancing diesel injection resulted in earlier combustion phasing, with higher Pmax and HRR. Advancing injection timing from 4 to 12° CA before TDC at 35.7% MEF increased IMEP from 7.4 to 8.3 bar and advanced Pmax by 5° CA. This advancement in combustion reduced soot, CO, and UHC emissions due to higher in-cylinder temperatures, albeit with an increase in NO_x emissions. Wang et al. [192] reported similar trends, including improved BTE, with advanced diesel injection timing across all tested operating points [192]. The sweep in injection timing ranged from 4.6° CA after TDC to 17.4° CA before TDC. The BTE improvement came at the expense of higher NO_x emissions, with a 70% increase at 60% MSP and an intake temperature of 348.15 K, compared to the most retarded timing.

Liu et al. [195] explored the influence of diesel injection pressure on methanol PRDF engine performance in a 6-cylinder HD diesel engine. Similar to injection timing, diesel injection pressure effects in PRDF strategy resembles those in CDC mode. Increasing injection pressure from 700 to 1300 bar shortened CD from 66.9 to 23.5° CA, advanced combustion phasing from 28.6 to 13.6° CA, lowered specific fuel consumption from 202.3 to 187.3 g/kWh, and reduced UHC emissions from 1850 to 950 ppm. However, NO_x emissions rose from 450 to 800 ppm, while both soot and CO exhibited a decreasing trend. Li et al. [194] similarly observed that increasing injection pressure from 721 to 1082 bar led to faster combustion, higher Pmax, and IMEP, along with reduced CO and UHC emissions and increased NO_x emissions. These trends align with the general understanding from CDC, where higher injection pressures improve atomization and mixing, leading to faster combustion and higher in-cylinder pressures and temperatures [197].

5. Conclusions

This study reviewed and clarified the state-of-the-art of combustion strategies for using methanol in heavy duty (HD) engines, highlighting the need for clearer definitions and naming conventions. This study critically examined various terms, such as the commonly used term "fumigation" found in the literature, proposing to replace it with a more precise term, *air path injection (API)*, to encompass any form of injection along the air path. It proposes a unified classification framework to aid researchers in understanding the different injection and ignition strategies used in methanol-fueled engines, resulting in Figs. 2, 3 and 4.

Furthermore, this review summarizes findings from previous experimental studies on methanol-fueled HD engines and provides tables that highlight key trends in the performance of methanol dual-fuel (DF) engines. This investigation indicates that DF technology appears to be the most effective method to use methanol in these engines in the near future, offering the flexibility of retaining diesel engine technology while enabling sustainable operation using renewably produced methanol. However, dedicated monofuel (MF) strategies like spark ignition (SI), mixing controlled compression ignition (MCCI) using methanol with ignition improvers as in MD97, and Partially Premixed Compression Ignition (PPCI) could provide an improved trade-off between emissions and efficiency for specific applications and eliminate the reliance on diesel. While existing studies on these MF strategies show promising results, the available information remains limited. This lack of comprehensive data, especially in the context of HD engines, represents a knowledge gap that requires further research. Regarding DF concepts, achieving a high methanol energy fraction (MEF) remains a key factor in choosing the engine strategy for HD applications. Based on the reviewed studies, this paper outlines the effects of methanol on combustion characteristics, engine performance, and emissions of HD DF engines, as summarized in Tables 3 and 4. This review reveals a notable scarcity of experimental data on advanced DF concepts, such as reactivity-controlled compression ignition (RCCI) and direct dual-fuel stratification (DDFS), using methanol in HD engines. The diffusion concept, i.e., dual-fuel diffusion combustion (DFDC), using HP-DI of both methanol and diesel, prevails in large low-speed two-stroke and medium-speed four-stroke marine engines due to its ability to achieve very high MEFs and fuel flexibility. Notably, the highest MEF reported in the diffusion combustion concept is 96.6%, significantly surpassing the 78% in premixed dual-fuel (PRDF) strategies.

Nevertheless, for medium- to high-speed marine engines with smaller bore sizes, the PRDF strategy may be the only option in the short term, especially for retrofits. The same applies to the broad spectrum of HD engines other than marine, such as truck and locomotive engines, since the simpler-to-adopt PRDF strategy is applicable to a broader spectrum of engine sizes. Cylinder head space requirements and cost to employ DFDC strategy make its application in smaller-size HD engines difficult. Additionally, the PRDF strategy can potentially mitigate the inherent soot-NO_x trade-off observed in diffusion concepts. These advantages of PRDF, however, are offset by abnormal combustion events like misfiring at low loads and knocking at high loads, limiting MEF. These MEF challenges, together with unburned and unregulated hydrocarbon emissions like methanol and formaldehyde, which may increase for PRDF engines, highlight the need for intensified research in this area, especially in the HD context.

The analysis of relevant studies to discern trends shows that engine design and operating parameters, such as intake air temperature and methanol injection location, affect MEF limits and engine efficiency in PRDF strategies. The analysis is summarized in Table 5, offering insights into optimizing PRDF engine performance. The injection location, for instance, determines the extent of methanol's cooling effect, resulting from its relatively high latent heat of vaporization. An API location further along the intake path, e.g. port fuel injection (PFI), enhances the cooling effect, improving both volumetric and thermal efficiency. However, detailed experimental information remains scarce on the impact of various design and operating strategies on methanol PRDF HD engine performance, as well as their potential to expand MEF limits.

The findings of this study suggest that renewably-produced methanol can enhance the efficiency of HD engines and reduce their environmental footprint. Despite the trend in the industry to focus on the DFDC concept, intensifying research in MF and PRDF strategies is needed to reach a deeper understanding of these concepts in the context of methanol use and further promote its use in HD engines. Such research will play a significant role in the transport sector's defossilization efforts and transition towards sustainable and renewable energy.

CRediT authorship contribution statement

Konstantinos I. Kiouranakis: Conceptualization, Investigation, Methodology, Visualization, Roles/writing – original draft. **Peter de Vos:** Conceptualization, Supervision, Visualization, Writing – review & editing. **Konstantinos Zoumpourlos:** Investigation, Visualization, Writing – review & editing. **Andrea Coraddu:** Writing – review & editing. **Rinze Geertsma:** Funding acquisition, Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

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Data availability

No data was used for the research described in the article.

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