Investigation of Low Load Performance and Emissions of a Methanol Compression Ignition Engine Using Glow Plugs

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Abstract

This study evaluates a methanol compression ignition engine's stability, performance, and emissions utilising glow plugs at low loads. A Scania D13 engine modified to run on methanol was tested to assess the impact of glow plugs on combustion stability, engine efficiency, and emissions characteristics, particularly in combination with various injection strategies. The research objectives focused on investigating the influence of glow plugs on combustion stability and phasing, determining their impact on efficiency and energy balance, analysing emissions characteristics, and assessing the effects of the different injection strategies with glow plug usage. Results indicate that glow plug activation had minimal effect in single injection and pilot injection strategies. However, glow plug usage in PPC showed promise in advancing the ignition timing and providing better combustion and lower emissions but resulted in high cyclic variability due to improper glow plug placement. In summary, the study shows how the glow plug impacts the performance of engines under different injection strategies at low loads.

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Nomenclature

Greek Symbols	**Description**
φ	Equivalence Ratio
η	Efficiency
Latin Symbols	**Description**
A	Ampere
Abbreviations	**Description**
aTDC	After Top Dead Centre
CA50	Crank Angle at 50% Fuel Burnt
CAD	Crank Angle Degree
CI	Compression Ignition
CO	Carbon Monoxide
CO2	Carbon Dioxide
CoV	Coefficient of Variation of IMEPg
CR	Compression Ratio
DDA	Detroit Diesel Allison
Eff	Efficiencies
EV	Electric Vehicles
GHG	Greenhouse Gas
H/C	Hydrogen to Carbon Ratio
HC	Hydrocarbons
HCCI	Homogeneous Charge Compression Ignition
HCHO	Formaldehyde
ICE	Internal Combustion Engines
IMEPg	Gross Indicated Mean Effective Pressure
LTC	Low Temperature Combustion
M100	Neat Methanol
MEP	Mean Effective Pressure
NOx	Oxides of Nitrogen
O2	Oxygen
PM	Particulate Matter
PPC	Partially Premixed Combustion
RoHR	Rate of Heat Release
SI	Spark Ignition

SOI	Start of Injection
UHC	Unburnt Hydrocarbons
WTE	Waste-To-Energy

Subscripts	**Description**
GIE	Gross Indicated Efficiency
C	Combustion
T	Thermodynamic
IMEP	Gross Indicated Mean Effective Pressure

1 Introduction

1.1 Background

The severe increase in global energy demand, fuelled by population growth and economic development, has exerted immense pressure on transportation systems worldwide. The transportation sector accounts for 28% of the consumed energy (1). Thus, the surge in demand has increased concerns over transportation emissions, as they account for 20% of carbon dioxide (CO2) emissions and 17% of greenhouse gas (GHG) emissions as of 2020 (2).

Despite GHG emissions, fossil-fuelled piston engines benefit society with simplicity and low cost. The transport sector relies heavily on internal combustion engines (ICE) based on spark ignition (SI) and compression ignition (CI) designs. Modern engines operate more efficiently and emit fewer pollutants like oxides of nitrogen (NOx) and particulate matter (PM) due to advancements and effective after-treatment technology (3). However, the after-treatment systems are expensive, sophisticated, and do not effectively address CO2 emissions, which calls for other methods to reduce these emissions.

1.2 Alternatives to Fossil Fuels

Electric vehicles (EV) offer advantages over ICE vehicles such as zero tailpipe emissions, reduced maintenance needs and improved powertrain efficiency (4). However, considering the entire lifecycle of EVs is crucial to understanding their environmental impact. GHG emissions depend on factors like electricity sources, raw material procurement, and production processes where the supply chain can be problematic due to social and environmental issues (5). The supporting infrastructure such as chargers and electricity supply, also need to be scaled up at a quick pace to meet the demands of a transport fleet run entirely on EVs (6). Electrification remains underdeveloped for aircraft and maritime applications. A solution lies in a blend of electrification and renewable fuels, with biofuels assuming a significant role.

Biofuels, derived from renewable organic materials like crops and waste, are gaining traction globally as an alternative to fossil fuels, driven by concerns about climate change and energy security (7). Governments are implementing policies like mandates, tax incentives and subsidies to encourage their production and blending with conventional fuels alongside promoting research and development initiatives to further biofuel adoption (8). Biofuels offer a key advantage as virtually carbon-neutral energy sources, as the carbon emitted during combustion is offset by plant absorption during growth, creating a closed carbon cycle and making them attractive for lowering GHG emissions and mitigating climate change (9).

Biofuels are categorised based on their source and generation technique: first generation (from food crops), second generation (from non-food crops), and third generation (from aquatic cultivated feedstock). First generation biofuels face sustainability challenges due to changes in land use, competition with food production, high water requirements, and fertiliser usage. However, advancements in technology have made second generation and sustainable production of bioalcohols such as bioethanol and biomethanol possible (10).

Bioalcohols like methanol and ethanol, alongside their blends with conventional fossil fuels, are promising candidates as ICE fuels. This is due to their underlying combustion characteristics and emission attributes, significantly impacting engine functionality and emissions. These biofuels exhibit combustion properties at high temperatures similar to conventional fuels, although variations can affect performance in CI diesel engines. Generally, these fuels tend to yield lower intrinsic NOx and soot emissions compared to conventional fuels, primarily attributable to the reduction of fuel carbon, which helps to mitigate prompt NOx and soot formation due to the initial presence of carbon-oxygen bonds (11). However, drawbacks include lower calorific values and cold starting issues due to the high latent heat of vaporisation (7). There are also concerns about neat alcohol usage, including higher fuel consumption and engine compatibility issues (12).

Methanol production has evolved towards sustainability by embracing innovative approaches that significantly reduce GHG emissions. Two prominent methods involve utilising biomasses in waste-to-energy (WTE) technologies and CO2 as starting feeds. The latter involves directly capturing CO2 from various sources, including natural or industrial emissions and human activities, and chemically transforming it into methanol (13). This makes methanol an appealing choice for ICE fuel, warranting further investigation into its merits and limitations.

1.3 Overview of Methanol

Methanol, an alcohol with the chemical formula CH_3OH, is a promising contender for fuelling ICE. Its unique properties offer both opportunities and challenges in the search for more sustainable transportation solutions.

1.3.1 Properties

Table 1 Properties of Methanol (14)

Property	**Value**
Chemical formula	CH_3OH
Research Octane Number	107–109
Motor Octane Number	92
Hydrogen to Carbon ratio	4
Oxygen to Carbon ratio	1
Lower Heating Value (MJ/kg)	19.9
Air/Fuel Stoichiometric Ratio	6.45
Density (kg/m3)	790
Vapour density (kg/m3)	1.42
Boiling point at 1 bar (°C)	65
Heat of vaporization (kJ/kg)	1100
Dynamic viscosity (20°C) (mPas)	0.57
Molecular weight (kg/kmol)	32.04
Oxygen content by mass (%)	49.93
Hydrogen content by mass (%)	12.58
Carbon content by mass (%)	37.48
Auto-ignition temperature (°C)	465
Flashpoint (°C)	12
Adiabatic flame temperature (°C)	1870

It has a high Hydrogen to Carbon ratio and does not produce PM due to the lack of long-chain hydrocarbons (14). With half of its molecular mass composed of oxygen, methanol forms efficient fuel-air mixtures leading to lower stoichiometric air/fuel ratios lowering CO_2, soot and PM emissions (14). Methanol reduces combustion temperature leading to lesser NO_x formation down to IMO Tier III Limit of 2-4 g/kWh (15). Using methanol in diesel engines is a promising way to reduce both soot and NO_x emissions together (16). The sulphur-free structure of methanol results in no sulphur oxide emissions from the methanol combustion.

Methanol, in particular, has nearly four times higher heat of vaporization compared to diesel fuel (17). This inherent property results in a charge-cooling effect within the cylinder, leading to a reduction in in-cylinder temperature. Consequently, methanol combustion experiences lower heat transfer losses, decreased compression work, and ultimately, higher engine efficiency. Moreover, this charge cooling effect enhances the volumetric efficiency and intake air density of the engine. Additionally, the charge cooling effect of methanol contributes to a reduction in NOx emissions, as the combustion temperature remains lower compared to diesel fuel combustion (18).

Methanol exhibits significant molar expansion during combustion, which increases in-cylinder pressure without additional heat, enhancing the combustion process (16). It has a higher laminar flame velocity compared to conventional fuels, resulting in faster combustion, reduced heat loss to cylinder walls, and higher engine efficiency (19).

1.3.2 Use of Methanol in ICE

1.3.2.1 Material Compatibility

Ensuring material compatibility is crucial for vehicle components. Methanol's polar structure makes it highly corrosive to certain materials. It can cause dry corrosion on metals such as zinc, copper, lead, aluminium, and magnesium, as well as elastomers, plastics, and rubber (14). This presents a significant challenge in this regard, necessitating modifications to engine fuel systems. Metals and elastomers used in seals and fuel lines can be corroded by methanol, exacerbated by ionic impurities like chloride ions. However, studies show that with proper design, there are no technical barriers to creating compatible vehicles (20).

1.3.2.2 Fuel Delivery System Requirements

The lower volumetric energy content of methanol, especially in blends with a significant methanol fraction, necessitates fuel pumps and injectors with increased flow capacity to maintain peak power. Material compatibility issues extend to pump and injector internals. Due to its low lubricity due to its lower kinematic viscosity compared to diesel. Lubrication additives are necessary to prevent corrosion in injection pumps, injectors, and other fuel system components (14).

1.3.2.3 Peak Pressure Control

Methanol's strong knock resistance often eliminates the need for ignition retardation at maximum power. However, it might be necessary to control peak pressures. Engine modifications, including adjustments to the structure and cylinder head, are crucial to fully exploit methanol's benefits and manage increased peak pressures and thermal stresses (20).

1.3.2.4 Challenges at Low Loads

Methanol is a high-octane fuel that causes high auto-ignition resistance. The high latent heat of vaporization presents a challenge for combustion start in CI engines, with potential cooling effects inside the combustion chamber that can quench ignition sites, further mitigating auto-ignition. Strategies such as glow plugs (21), intake heaters (22), and increasing compression ratio (CR) have been explored to enhance available energy for autoignition, with temperature being a key factor (23). Studies indicate autoignition typically occurs above 900–1000 K, with increasing CR improving combustion stability without the need for intake heating (24). However, challenges persist at low loads, speeds, and during engine startup due to the high ignition energy required and long ignition delay, despite attempts to address them with intake heaters and glow plugs (25).

Low intake temperatures at low loads decreased combustion stability, increased ignition delay, and reduced peak cylinder pressure. Emissions varied, with unburnt hydrocarbons (UHC) increasing, NOX decreasing or remaining constant, and Carbon Monoxide (CO) remaining steady with decreasing intake temperature.

Svensson and Verhelst (26) demonstrated that elevating the compression ratio can facilitate methanol's ignition by elevating the combustion chamber temperature before fuel injection. However, this approach presents a trade-off, potentially resulting in higher peak pressures. To ensure engine safety, suboptimal, delayed injection timing might be required at higher loads to manage these increased pressures within acceptable limits.

Glow plugs can serve as a crucial component in heating the fuel-air mixture within the combustion chamber, facilitating the local combustion of methanol in CI engines. Experimental studies demonstrated that a glow plug surface temperature of 810°C is necessary for stable combustion, with increased injection nozzle holes enhancing performance (27). Implementing glow plug shields can extend their service life while reducing emissions, with NOx levels nearly 40% lower and minimal smoke, CO, and UHC emissions in methanol-fuelled engines (27). Ceramic glow plugs and conventional glow plugs for diesel engines were tested, and both were suitable across all loads but required advanced injection timing at low loads (28). A direct luminosity image analysis revealed flame propagation from one pair of sprays surrounding the glow plug to another, emphasizing the importance of proper spray glow plug orientation for optimal combustion (29)However, limited research exists on the use of glow plugs to stabilize combustion in CI engines, and further studies are warranted, which motivates the need for this study.

1.4 Research Objectives and Scope

The primary objective of this study is to evaluate the stability, performance, and emissions of a methanol compression ignition engine utilising glow plugs at low loads. This involves conducting broad engine testing to determine the impact of glow plugs on combustion stability, overall engine efficiency, and emissions characteristics. Additionally, the study will examine how various injection strategies interact with glow plug usage to influence these parameters.

The specific objectives are:

1. To investigate the influence of glow plugs on combustion stability and phasing.
    - Conduct a detailed study to determine how glow plugs affect the initiation and progression of combustion in methanol engines.
    - Study the variation in combustion stability and phasing under different multiple injection strategies to understand their combined effects with glow plugs.
2. To determine the impact of the glow plugs on the efficiency and energy balance of the engine.
    - Evaluate how the glow plug activation influences the gross indicated efficiency, combustion efficiency and thermodynamic efficiency of methanol engines.
    - Analyse how heat transfer losses, combustion losses and exhaust losses are affected by glow plug usage.
3. To analyse the emissions characteristics of methanol engines with glow plugs.
    - Examine the effect of glow plugs on the emission profiles of methanol engines, including pollutants such as NOx, CO, HC, Soot and Formaldehyde (HCHO).
    - Compare emission data from engines with and without glow plug assistance to identify if they meet the Euro VI emission limits.

4. Investigate how different injection strategies affect the engine characteristics with and without the glow plug.
    - Study the variation in combustion stability, engine efficiency, and emissions under different multiple injection strategies to understand their combined effects with glow plugs.
    - Conduct a comparative analysis of the engine under different injection strategies.

1.5 Limitations

It is important to acknowledge the inherent limitations that may affect the scope, methodology, and interpretation of findings. In the context of this thesis on the impact of glow plugs on methanol compression ignition engine performance, several limitations were encountered throughout the study. These limitations contextualise the research outcomes effectively.

Undetermined Temperature of Glow Plug: The temperature of the glow plug was not directly measured during the experiments. This limitation restricts the ability to correlate glow plug temperature with combustion characteristics and find a critical glow plug temperature for autoignition.

Lack of Time: With more time, additional experiments and analyses could have been conducted to explore the effects of glow plug activation on engine performance further.

Suboptimal Positioning of Glow Plug: The glow plug's positioning within the engine setup is not optimal. This influences the interaction between the glow plug and the fuel-air mixture, affecting combustion stability and efficiency.

Inconsistencies in Data Collection: There were a few inconsistencies noted in the data collection process, which could introduce variability in the results. Variations in experimental conditions contributed to these inconsistencies.

Scope of Investigation: The thesis focused primarily on the impact of glow plugs on methanol compression ignition engine performance, with an emphasis on specific injection strategies.

1.6 Outline

Chapter 1 consists of the background and introduction to methanol engines, as well as the research objective, scope, and limitations. Chapter 2 consists of a review of existing literature on the feasibility and optimization of methanol CI engines, covering engine performance, emissions, combustion behaviour, and fuel properties. In Chapter 3, the methodology, including experimental setup and test conditions, is outlined for investigating the operation of methanol CI combustion using glow plugs. In Chapter 4, results from experiments with varying parameters and experimental findings are discussed. Chapter 5 concludes the study, offering insights for future research, suggesting areas for improvement, and summarizing key findings.

2 Literature Review

2.1 Theoretical Background on Injection Strategies

2.1.1 Single Injection Strategy

The Single Injection Strategy in methanol ICE refers to a method where methanol is injected into the combustion chamber in a single injection event.

2.2.2 Pilot Injection Strategy

This strategy involves injecting a small quantity of fuel into the combustion chamber before the main injection event. The primary purpose of pilot injection is to initiate a controlled combustion process, improving overall combustion efficiency, reducing noise, and lowering emissions.

A small amount of fuel is injected into the combustion chamber early in the compression stroke. This initial injection helps to raise the temperature and pressure within the cylinder. The fuel from the pilot injection begins to combust, reducing the ignition delay for the main injection. This leads to a more controlled and gradual rise in cylinder pressure. Following the pilot injection, the main fuel injection occurs. The main fuel charge ignites more smoothly and rapidly because the combustion environment is already heated and pressurised. Multiple pilot injections and injection timings can be varied to get the desired combustion phasing (30).

2.2.3 Partially Premixed Combustion (PPC) Strategy

The Partially Premixed Combustion (PPC) strategy aims to achieve an ignition dwell, the period between the fuel injection event and the onset of combustion. This separation allows for a more homogeneous mixture of fuel and air. Earlier injection of fuel during the compression stroke allows more time for the fuel to mix with the incoming air, creating a more homogeneous mixture before ignition. The combustion process in PPC is more controlled due to the more uniform air-fuel mixture, which results in higher efficiency and lower emissions. The higher efficiency is a result of lower in-cylinder temperatures reducing the heat transfer losses, and the lower NOx is due to the more homogenous mixture, which reduces the localised hotspots which aid the formation of NOx (31).

2.2.4 Homogenous Charge Compression Ignition (HCCI) Strategy

The key principle of HCCI combustion is creating a homogeneous mixture of fuel and air. In methanol engines, achieving this homogeneity can be accomplished through methods such as very early injection in the intake stroke, which ensures thorough mixing before combustion. HCCI operates with a lean air-fuel mixture, meaning more air than fuel. This, along with the lack of localised hot spots due to the homogenous nature of the fuel mixture, reduces the formation of NOx. However, HC and CO emissions are very high due to the low in-cylinder temperature, which results in incomplete combustion. At high loads, HCCI experiences uncontrolled, rapid combustion. The rates of heat release and pressure rise increase, leading to knocking, which can potentially damage the engine (32). This restricts the maximum load in this study.

2.2 Feasibility of Methanol Engines

The feasibility of utilising methanol as a replacement for diesel fuel in heavy-duty applications was studied by Richards, particularly focusing on the Caterpillar 3406 engine (33). Engine modifications, including an ignition-assist combustion system consisting of a glow plug and impingement pin, were made to adapt the 3406 engines for methanol use. Laboratory tests verified the modifications' effectiveness, showing expected reductions in emissions. Two 3406 methanol engines were operated in line-haul service, accumulating significant mileage. Despite being in an early stage of development, the methanol engines closely matched the performance of their diesel counterparts. Post-test inspection indicated comparable or better component life, though some components required further development for commercial viability. The successful demonstration underscored the feasibility of heavy-duty methanol engines, with additional development potentially leading to commercial viability.

PPC emerged as the most promising approach for methanol combustion in CI engines. It offers the potential for higher engine efficiency compared to conventional CI without a loss in power. Additionally, it can reduce NOx and soot emissions while maintaining similar levels of UHC and CO emissions. Zincir et al. demonstrated that even at low engine loads of 10%, 15%, and 25%, methanol PPC has shown improved engine stability of 3.3%, 2.4%, and 1.4%, respectively, along with higher engine efficiency compared to conventional CI (34).

Svensson and Verhelst (23) compared methanol and gasoline performance in low-temperature combustion (LTC) for CI engines. Methanol, an alternative fuel, showed superior performance, with a 5.5% higher brake efficiency due to reduced in-cylinder exhaust losses as a result of its higher specific heats and combustion phasing. However, incomplete combustion due to fuel stuck in crevice volumes was not considered. Methanol's advantages include lower NOx emissions attributed to optimised injection timings and narrower equivalence ratio distribution, which ensured the fuel mix was more even, reducing the probability of hotspots due to the fuel being richer at some points. Its higher octane number allows for pre-combustion injection, resembling partially premixed combustion. Gasoline, on the other hand, requires a conventional diesel engine injection strategy. The study emphasises methanol's potential for improving efficiency and reducing emissions in heavy-duty engines.

2.3 Optimization Techniques

2.3.1 Injection Timing

Pucilowski (35) explored the utilization of methanol in PPC engines, focusing on the benefits of employing late injection timings. Investigation of various start of injection (SOI) timings reveals a trade-off between CO/UHC and NOx emissions, with the optimal balance observed at SOI -11 Crank Angle Degree (CAD) after Top Dead Centre (aTDC). This timing also yields the highest gross indicated efficiency due to moderate combustion temperatures within the range of $0.25 < \varphi < 0.9$. Leaner combustion at SOI -16 CAD aTDC and SOI -26 CAD aTDC results in poorer UHC and CO conversion compared to SOI -11 CAD aTDC. Conversely, SOI -3 CAD aTDC leads to higher combustion temperatures, causing increased wall heat losses and NOx emissions. The paper also sheds light on the unique ignition characteristics of methanol, with ignition kernels typically initiating in fuel-lean mixtures and subsequently propagating towards fuel-rich mixtures.

2.3.2 Mixture stratification

Xu et al. (36) examined methanol's suitability for low-temperature combustion, addressing challenges like high UHC and CO emissions at low loads. They propose controlling mixture stratification to improve emissions and highlight the impact of intake temperature on PPC. A higher intake temperature is recommended when SOI is retarded. Low UHC emissions in PPC are attributed to incomplete combustion in the piston bowl, while NOx emissions increase with retarded SOI due to smaller ignition delay. Mixture stratification affects combustion: low stratification enhances performance and reduces emissions, while high stratification increases NOx emissions and lowers engine thermal efficiency. This emphasizes the need to control mixture stratification and optimize combustion parameters for better engine performance and reduced emissions in methanol fuelled low temperature combustion (LTC) engines.

2.3.3 Injection Strategies

Aziz et al. (37) investigated the impact of multiple injection strategies on mitigating high UHC and CO emissions in methanol-fuelled PPC engines at low loads while enhancing gross indicated efficiency. Conducted on a single-cylinder heavy-duty Scania D13 engine at a gross indicated mean effective pressure (IMEPg) of 4 bar and 1200 rpm, the study implemented double and triple injections with varied dwells, injection timings, and fuel mass proportions. Results show that multiple injection strategies, with appropriate adjustments, enhance efficiency and reduce emissions compared to single injections. The double injection strategy, with a pilot injection at -40 CAD aTDC and a main injection at -30 CAD aTDC with an even mass proportion, emerges as the most effective option. However, CO and UHC emissions remain above Euro VI limits, indicating the need for further optimization.

2.3.4 Intake Temperature Heating

Research on low-load conditions with methanol is limited, particularly concerning intake temperature effects. However, Zincir et al. (22) investigated the impact of intake temperature on low-load methanol partially premixed combustion. Experimental tests were conducted at 800 rpm under varying loads. The study showed that higher intake temperature results in more stable engine operation with reduced CoV_{IMEP} (Coefficient of Variation) of IMEPg. The intake temperature was held constant at 150 °C to provide good engine stability. Lower intake temperatures decrease combustion stability, increase ignition delay, and reduce peak cylinder pressure, while higher intake temperatures improve combustion efficiency, reduce CoV_{IMEP} and lower emissions. The study highlighted the importance of optimizing intake temperature for methanol partially premixed combustion to enhance engine efficiency and reduce emissions.

2.4 Optimization Using Glow Plugs

Many studies were done to demonstrate the potential and effectiveness of glow plug-assisted ignition systems in optimizing the performance, efficiency, and emissions of methanol-powered CI engines. Through various approaches, such as the development of low-energy hot surface ignition systems, investigation of catalytic glow plugs, and optimization of engine configurations, significant conclusions were made that could contribute to the improvement of the engine.

2.4.1 Feasibility

Kroeger (21) developed a Caterpillar 3306 engine to utilize methanol as a fuel, which included a direct injection combustion system with glow plug ignition. The hot surface ignition assistance provided by the glow plug ensured consistent ignition across all engine operating conditions, demonstrating the feasibility of glow plug-assisted ignition of neat methanol in a diesel engine. The incorporation of a centre orifice fuel nozzle and impingement pin in the piston improved flame transfer between fuel sprays, enhancing low-load performance and emissions. Additionally, the cold start capability of the engine using glow plug-assisted ignition was also established.

2.4.2 Enhancing Mixture Formation

Havenith et al. (38) explored a low-energy hot surface ignition system to reduce fuel consumption and increase the life of glow plugs. This system involved a ceramic plug positioned downstream of the injection nozzle encircled by a perforated protective shield, enhancing mixture formation, decreasing cooling needs, and reducing the thermal loading on the glow plug. This concept was further validated by Hiilger et al. (39). Key considerations included glow plug positioning affecting ignition reliability, power consumption, and hydrocarbon emissions. Reduced protrusion of the glow plug lowered power consumption but led to incomplete combustion and increased emissions. The perforation size and number also impacted combustion efficiency and glow plug surface temperature; larger perforations accelerated combustion but required more electric power for maintaining proper ignition temperature.

Goetz et al. (40) explored using neat methanol and glow plug ignition in direct injection diesel engines to find effective engine setups for emissions reduction. They found swirl, injector parameters (number of holes and cone angle), and injection timing crucial for lowering emissions. Swirl notably reduced hydrocarbon emissions but increased NOx emissions due to reduced ignition delay leading to higher peak temperatures. Optimizing injection parameters suppressed NOx emissions, especially when fuel deposition occurred on the piston surface. However, advancing injection timing decreased NOx emissions at low to medium loads and high speeds but increased it at medium speeds and high loads.

Mueller and Musculus (29) delved into the utilization of neat methanol and glow plug ignition within direct injection diesel engines, aiming to pinpoint effective engine configurations for mitigating emissions. Their investigation revealed crucial insights: The efficacy of glow plug assisted ignition for M100 (neat methanol) hinged significantly on glow plug temperature and proximity to the fuel jet. The study discovered that the ignition of the injection jets from the six-hole injector occurred in three steps starting from the two jets nearest to the glow plug. The heat release also occurred in three steps. This was confirmed later by Krishnan et al. (41), who found that there was a sequential ignition of sprays, starting from the injector closest to the glow plug, leading to prolonged combustion, which results in lower peak heat release rates, which are beneficial for quieter engine operation.

2.4.3 Catalytically Coated Glow Plugs

Agama et al. (42) investigated the feasibility of catalytically igniting methanol using platinum and platinum/rhodium-coated glow plugs in a Detroit Diesel Allison (DDA) 3-53 Series engine. The study assessed the impact of these catalysts through measurements of glow-plug surface temperatures, analysis of cylinder pressure, and high-speed photography of the combustion chamber. The results demonstrated that catalytic glow plugs consistently reduced the temperature required for stable combustion by approximately 300°C compared to standard stainless steel glow plugs. However, no discernible difference in combustion performance was observed between catalytic and baseline glow plugs at temperatures around 860°C. It is noted that this conclusion did not extend to exhaust emissions or the rate of heat release due to the scope limitations of the investigation.

Similarly, Mitchell et al. (43) examined how platinum and palladium catalysts on glow plugs affect methanol combustion in a direct-injected Diesel engine compared to a non-catalytic baseline. Experiments at 6 and 10 KW and 2500 rpm assessed combustion, performance, and emissions. Results showed reduced glow plug temperatures by 100 K with platinum and 150 K with palladium. Palladium exhibited reduced ignition delay and distinct combustion behaviour with higher premixed burn but lower peak pressures compared to platinum or baseline cases. Platinum led to higher NOx emissions, while palladium lowered them due to a reduced rate of pressure rise. Both catalysts decreased aldehyde emissions, with minimal change in total unburnt hydrocarbons.

2.4.4 Critical Glow Plug Temperature

A glow-assisted methanol engine tested by Nakashima et al. (27) delivered high torque at low speeds with low pollution. A critical glow plug temperature threshold of 810°C was found, beyond which engine performance remains stable, but lower temperatures decrease brake thermal efficiency. Air motion during motoring, along with fuel evaporation, cools the glow plug, affecting combustion characteristics and overall engine performance. Importantly, this engine emits less NOx than spark-assisted ones, thanks to reduced flame temperature due to enhanced cooling from fuel evaporation and improved diffusion combustion.

3 Methodology

3.1 Experimental Setup

3.1.1 Scania D13

An in-line six-cylinder heavy-duty Scania D13 engine was customised to run on only one cylinder in the test cell. Since the combustion occurred in one cylinder, a heavier flywheel was included to compensate for the loading. The additional pistons were removed and replaced with hollow weights to remove the compression work and balance the crankshaft. The cylinder undergoes displacement of ~2124 cm3 while in operation. For the intake air supply, an 8-bar capacity air compressor was used to regulate the airflow and pressure to the engine using a variable valve. Downstream of the valve, a heater and airflow meter are positioned to change the intake air temperature and measure the air supply flow.

Pressure sensors were placed inside the cylinder head, intake, and exhaust to measure the crank angle resolved pressure.

Table 2 Engine Configuration

Parameter	**Value**
Displaced volume	2124 cc
Stroke	160 mm
Bore	130 mm
Connecting Rod	255 mm
Number of Valves	4

The fuelling system on the engine is a common rail type controlled by a solenoid valve and a pulse width modulation signal. The common rail system was adjusted to be run on only one cylinder. The Fuel supply involves a low-pressure fuel pump transferring fuel from an external tank to a high-pressure fuel pump. The high-pressure pump was factory-modified in terms of fuel flow rate and changing different gaskets and materials in contact with the fuel. This is required to keep the pump operation reliable when utilizing low lubricity, low viscosity, and corrosive fuels such as methanol. The injectors were also modified to withstand methanol corrosivity and fuel supply at a higher flow rate to accommodate the lower air-to-fuel ratio and heating value of light alcohols. Since methanol is harder to ignite than regular diesel fuel, an intake heater had to be utilized to achieve a stable combustion. Fuel flow from the external tank is measured using a precision gravity scale by Sartorius.

The engine speed is controlled by an electric-motoring dyno to maintain a constant value independent of engine load, with a crank angle encoder used to measure engine speed and position.

Emissions are measured using an AVL SESAM i60FT FTIR emission analyser, capable of accurately measuring concentrations of Oxygen (O2), CO, CO2, unburnt HC(Hydrocarbons), NOx, and Formaldehyde (HCHO). For this analysis, NOx, CO, Formaldehyde and Hydrocarbon emissions were measured. Pre-experiment procedures included sensor calibration and testing for accurate measurements. Figure 1 shows the schematic of the engine test set cell.

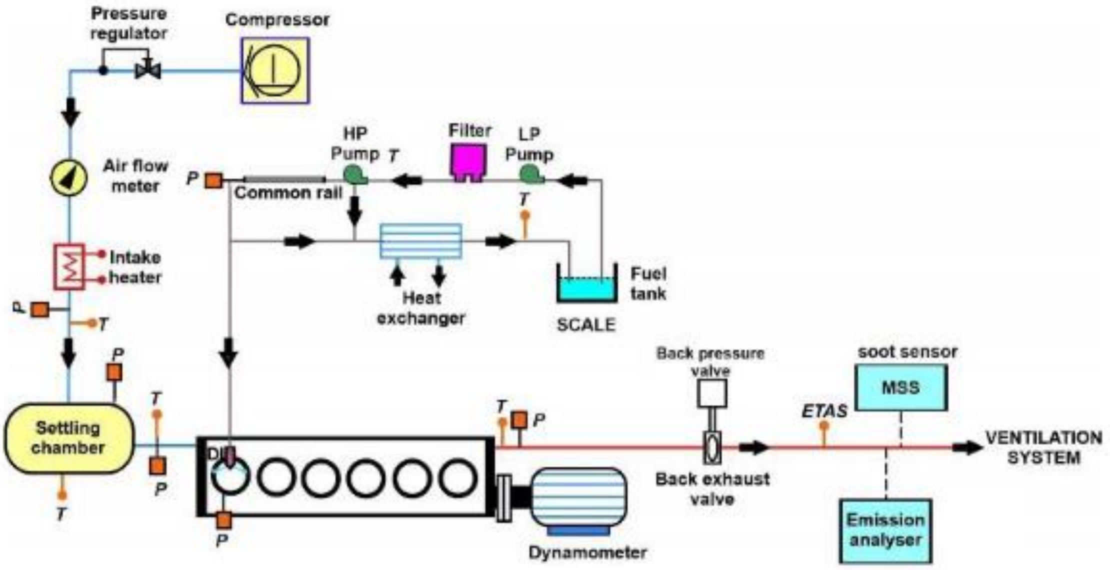

Figure 1 Engine Test Setup Schematic with measuring equipment (44).

Table 4 provides details of the measuring equipment used, along with their measuring range and accuracy.

Table 3 Measuring Equipment Details

Variable Measured	Instrument	Model	Measuring Range	Accuracy
In-cylinder pressure	Pressure Sensor	Kistler 7061B, Kistler 5011B10	0-250 bar	± 1.25 bar
Intake/exhaust pressure	Pressure Sensor	Kistler 4075A10	0-10 bar	± 0.2% FS
Crank angle degree, engine speed	Crank angle encoder	Kistler 2614CK	0-12000 rpm	± 0.03 CAD
Fuel injection pressure	Pressure Sensor	Kistler 4067C	0-3000 bar	± 0.1% FS
Air Flow	Mass flow meter	Bronkhorst F-106bi	Max 125 g/s	± 1% FS
Fuel Flow	Precision gravity scale	Vettek APP 25.R2	0-25000 g	± 0.1 gr
Emissions	Emissions analyser	AVL SESAM i60FT	0-max 10000 ppm	≤ 2% of the measured value

3.1.2 Glow Plug Setup

Two different setups were tested to determine the impact of glow plug configurations on the combustion characteristics of methanol. The glow plug was installed and tested initially. Following the initial testing, modifications were made to the glow plug to enhance its performance. The modified glow plug specifications and the initial specifications for comparison, are presented in Table 3. Its positioning relative to the injector and spray cone is shown in Figure 2. Both glow plugs were installed and held in place in the cylinder head using a machined sleeve.

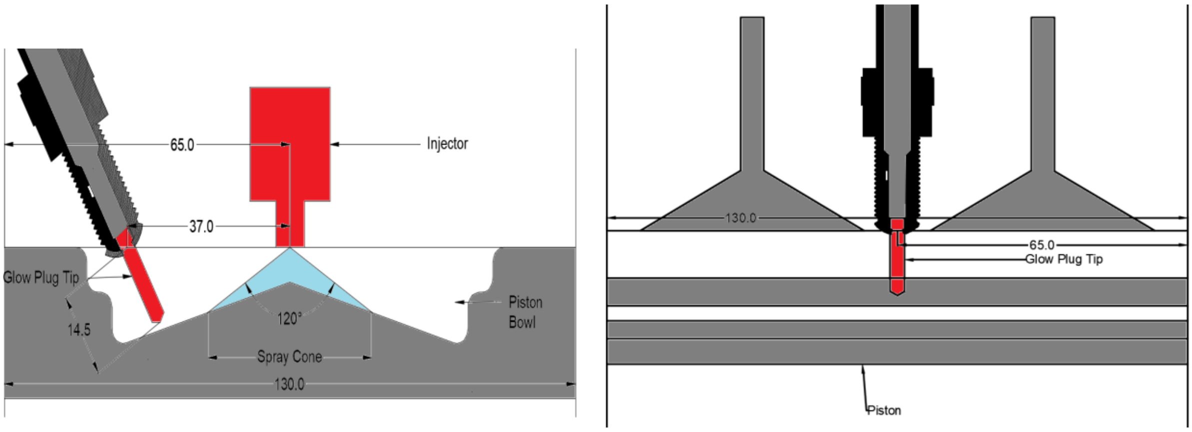

Figure 2 Schematic Of Modified Glow Plug Setup (i) From the Bottom (ii) From the Side

The goal of these modifications was to ensure that the glow plug tip reached closer to the fuel injection. After machining the modifications, the glow plug was reinstalled and tested under identical conditions to the initial configuration and a few other conditions. This allowed for a direct comparison of the performance outcomes of the two configurations, assessing the impact of the glow plug's length and protrusion on the combustion characteristics of methanol as well as other significant outcomes.

Table 4 Glow Plug Specifications

Glow Plug Configuration	**Original**	**Modified**
Terminal Type	Pin	Pin
Body Material	Ceramic	Ceramic
Glow Tube Length	28mm	30mm
Heating Characteristic	Sheathed Coil	Sheathed Coil
Voltage	7V	7V
Protrusion from the cylinder head	12.5 mm	14.5 mm

A controller managed the glow plug power, enabling adjustments to both current and voltage using a pulse width modulation signal. In this study, the current was varied to achieve the required power.

3.2 Test Conditions

The tests conducted in this study are based on the neat methanol marine engine and adhere to emission regulation testing using the ISO 8178 E3 cycle. The ISO 8178 E3 cycle is defined by a propeller curve based on an engine's maximum power output and the corresponding speed at which this peak power is achieved. While the standard has four modes at 100%, 75%, 50% and 25% load points, for this study, a lower load point was tested, representing 10% of the maximum power. The aim was to investigate the impact of glow plug utilization on methanol combustion under low-load conditions. Previous studies compared various fuel formulations, including neat methanol and methanol with ignition improver and diesel, while another explored altering pilot injection parameters like dwell times and injection duration (30) (45)This study tested the impact of multiple injection strategies with and without glow plugs and the importance of glow plug placement at low loads. To eliminate the errors caused by engine drift, a triangle test method was employed to measure the parameters before activation and after deactivation of the glow.

To evaluate engine performance under low-load conditions, an IMEPg of 5 bar, a speed of 950 rpm, no boost pressure over ambient, and a fuel injection pressure of 520 bar were selected.

3.2.1 Single Injection Strategy

The first case involved a thorough investigation termed as a "glow plug sweep" to evaluate the effects of varying glow plug current on engine performance when using a single injection strategy at an intake heating temperature of 73 °C. The injection timing was set at -6.9 degrees aTDC, and the injection length was kept at 1430 µs. The primary objective of the glow plug sweep was to adjust the glow plug current from 0 A to 8 A in steps of 2 A to observe its effects on combustion characteristics and engine performance. This can help identify the impact of glow plug positioning. The details of these conditions are given in Table 5.

Table 5 Single Injection Strategy Specifications

Injection Type	**Single Injection**	**Single Injection**
IMEPg [bar]	5	5
Intake Air Temperature [°C]	73	73
Glow Plug Configurations	Initial	Modified
Main Injection Length [µs]	1430	1430
Glow Plug Current [A]	1,2,3,4,8	0,2,4,6,8

3.2.2 Pilot Injection Strategy

Next, the impact of combining pilot injection with a glow plug was examined. Previous tests used an intake temperature of 61°C for pilot injections (30). The previous study identified that dwell times around 15 to 20 CAD and pilot injection lengths around 250 to 375 µs were interesting to explore to identify potential improved configurations. For this study, a pilot injection time of 20 CAD was used with a dwell time of 375 µs and the intake temperature was reduced until the stability, CoV_{IMEP}, reached>3%. The COV remained below 3% until an intake temperature of 35 °C was reached. This temperature point was then used to compare the impact of the activation of the glow plug at a full current capacity of 8A. The specifications of the operating condition are given in Table 6.

Table 6 Pilot Injection Strategy Specifications

Injection Type	**Pilot Injection**
IMEPg [bar]	5
Glow Plug Configuration	Modified
Intake Air Temperature [^{0}C]	35
Main Injection Timing [CAD aTDC]	-6.9
Main Injection length [µs]	1430
Pilot Injection Timing [CAD aTDC]	-28.7
Pilot Injection length [µs]	1430
Glow Plug Current [A]	0,8

3.2.3 HCCI Injection Strategy

The experiment transitioned to a different injection strategy, utilizing the Homogeneous Charge Compression Ignition (HCCI) approach with the modified glow plug configuration. This strategy aimed to enhance mixing and facilitate the propagation of the fuel closer to the glow plug. By adjusting the main injection timing and length, the experiment aimed to achieve improved fuel-air mixing and combustion initiation, leading to more uniform combustion throughout the combustion chamber. A lower load of 4 bar was used for this strategy to reduce the possibility of unstable combustion and knock due to the nature of HCCI operation. Glow plug current was varied between 0 and 8 A to evaluate its impact on the engine under the HCCI strategy. The details of this operating condition are given in Table 7

Table 7 HCCI Injection Strategy Specifications

Injection Type	**HCCI**
IMEPg [bar]	4
Glow Plug Configurations	Modified
Intake Temperature [^{0}C]	35
Main Injection Timing [CAD aTDC]	-325
Main Injection length [µs]	1250
Glow Plug Current [A]	0,8

3.2.4 HCCI and PPC Strategy

The study continued by employing a combination of HCCI and PPC injection strategies, along with a modified glow plug configuration. The specific injection timing and length parameters for both HCCI and PPC injections were carefully selected to ensure a stable operating condition. To determine the impact of the glow plug, the glow plug current was varied between 0 and 8 A.

Table 8 HCCI and PPC Strategy Specifications

Injection Type	**HCCI and PPC**
IMEPg [bar]	4
Glow Plug Configurations	Modified
Intake Temperature [ºC]	35
HCCI Injection Timing [aTDC]	-350
HCCI Injection length [µs]	1110
PPC Injection Timing [aTDC]	-60
PPC Injection length [µs]	680
Glow Plug Current	0,8

3.2.5 PPC Strategy

The final leg of the study was performed using a PPC injection strategy and a modified glow plug configuration. The experiment aimed to achieve a stable operating condition by adjusting the injection timing and length. The glow plug current varied between 0 and 8 A to evaluate the glow plug's impact.

Table 9 PPC Strategy Specifications

Injection Type	**PPC**
IMEPg [bar]	4
Glow Plug Configurations	Modified
Intake Temperature [ºC]	35
PPC Injection Timing [aTDC]	-40
PPC Injection length [µs]	1220
Glow Plug Current	0,8

Factors to be evaluated include the correlation between CoV_{IMEP} and glow plug activation under various injection strategies. Similarly, the analysis will extend to emissions of NOx, CO, UHC, HCHO, PM, and soot, examining their relationship with glow plug currents for different injection strategies and comparing them to the Euro VI limits for heavy-duty engines shown in Table (46). Additionally, the investigation will cover combustion efficiency and gross indicated efficiency to ascertain their dependence on these variables. By systematically examining these factors, a thorough understanding of the effects of glow plug activation and injection strategies on combustion stability, emissions, and engine performance can be achieved. An additional glow plug current sweep will be conducted for the single injection strategy to determine the impact of these factors.

Table 10 Euro VI Emission Limits for heavy duty engines (46)

Emission	Limit (g/kWh)
CO	1.5
HC	0.13
NOx	0.4

3.3 Post Processing

Post-processing of measurements was conducted using MATLAB. The parameters calculated and their method are defined below (45).

Fuel Mean Effective Power (FuelMEP)

The FuelMEP and the total heat in the fuel injected were calculated using the fuel flow rate (mf), the fuel's lower heating value (Q_{LHV}), and the displaced volume (V_d).

$$\boldsymbol{Fuel\ MEP} = \frac{m_f Q_{LHV}}{V_d} \tag{1}$$

Combustion Efficiency (η_c)

It measures how efficiently the fuel is converted into useful heat. It was calculated from the molar mass (M_i), wet concentration (x_i), the lower heating value of the emissions ($Q_{LHV,\,i}$), the molar mass of the products (M_p), the lower heating value of the fuel ($Q_{LHV,\,f}$) and the air-to-fuel ratio (A/ F)

$$\boldsymbol{\eta_c} = 1 - \frac{\sum \frac{M_i}{M_p} Q_{LHV,i}}{\frac{Q_{LHV,f}}{1+\frac{A}{F}}} \tag{2}$$

Heat Mean Effective Pressure (QMEP)

It represents the total usable heat after fuel combustion, calculated using the fuel mean effective pressure (FuelMEP) and combustion efficiency (Eff_{comb}). The following equation gives the relationship:

$$\boldsymbol{QMEP} = FuelMEP * Eff_{comb} \tag{3}$$

Gross Indicated Mean Effective Pressure ($IMEPg$)

It represents the average pressure exerted on the piston during the power and expansion stroke of the engine cycle. The following equation gives the relationship:

$$\boldsymbol{IMEPg} = \frac{1}{V_d} \int \int_{TDC-180}^{TDC+180} pdV \tag{4}$$

Gross Indicated Efficiency (η_{GIE})

It was calculated from the ratio of IMEPg and FuelMEP. The following equation gives the relationship:

$$\boldsymbol{\eta_{GIE}} = \frac{IMEP_g}{FuelMEP} * 100 \tag{5}$$

Thermodynamic Efficiency (η_T)

It was calculated from the ratio of IMEPg and QMEP. The following equation gives the relationship:

$$\boldsymbol{\eta_T} = \frac{IMEP_g}{QMEP} * 100 \tag{6}$$

Exhaust Mean Effective Pressure (ExhMEP)

It was calculated from the heat lost to the exhaust (Qex), exhaust mass flow (m), the specific heat capacity of the exhaust (C_p), exhaust temperature (T_{exh}), ambient temperature (T_{amp}) and displaced volume (V_d). The following equation gives the relationship:

$$\boldsymbol{Exh_{MEP}} = \frac{Qex}{Vd} = \frac{m_{Cp}(Texh-Tamp)}{V_d} \tag{7}$$

Heat Transfer Mean Effective Pressure (HTMEP)

It was calculated from QMEP, IMEPg and ExhMEP. The following equation gives the relationship:

$$\boldsymbol{HTMEP} = QMEP - IMEPg - ExhMEP \tag{8}$$

Heat Transfer Losses

Heat transfer losses were calculated from HTMEP and FuelMEP. The following equation gives the relationship:

$$\boldsymbol{Heat\ Transfer\ Losses} = \frac{HTMEP}{FuelMEP} * 100 \tag{9}$$

Exhaust Losses

They were calculated from ExhMEP and FuelMEP. The following equation gives the relationship:

$$\boldsymbol{Exhaust\ Losses} = \frac{ExhMEP}{FuelMEP} * 100 \tag{10}$$

Rate of Heat Release (RoHR)

The rate of heat release was calculated from the specific heat ratio (ɣ), pressure (P) and volume (V). The following equation gives the relationship:

$$\boldsymbol{RoHR} = \frac{\gamma}{\gamma-1}\ P\frac{dV}{d\theta} + \frac{1}{\gamma-1}V\frac{dp}{d\theta} \tag{11}$$

4 Results

4.1 Single Injection Strategy

Table 11 Combustion Parameters of Original Glow Plug under Single Injection Strategy

Glow Plug Current [A]	**1**	**2**	**3**	**4**	**8**
IMEP [bar]	5	5	5	5	5
CoV$_{IMEP}$ [%]	2.4	2.3	2.3	2.32	2.5
Lambda	2.7	2.7	2.8	2.8	2.8
CA50 [CAD aTDC]	6.2	6.3	6.3	6.3	6.2
Ignition Delay [CAD]	10.7	10.9	11	11	10.9
Combustion Duration [CAD]	9.7	9.2	8.8	9	9.2
Fuel Flow [g/s]	1.1	1.1	1.1	1.3	1.4
Fuel MEP [bar]	12.8	12.8	12.6	15.7	16
Net IMEP [bar]	5	5	4.9	4.9	4.9
Maximum Cylinder Temperature [ºC]	1618	1618	1615	1618	1619
Exhaust Temperature [ºC]	260	261	260	260	260

Table 12 Combustion Parameters of Modified Glow Plug under Single Injection Strategy

Glow Plug Current [A]	**0**	**2**	**4**	**6**	**8**	**0**
IMEP [bar]	5	5	5	5	5	5
CoV$_{IMEP}$ [%]	2.3	2.7	3	2.4	2.5	2.6
Lambda	2.9	2.9	2.9	3	2.9	2.9
CA50 [CAD aTDC]	6.82	6.27	6.25	6.52	6.26	6.26
Ignition Delay [CAD]	11.9	10.8	10.7	11.4	10.7	10.6
Combustion Duration [CAD]	6.6	9.5	9.9	7.6	9.8	9.8
Fuel Flow [g/s]	1.2	1.3	1.3	1.1	1.3	1.3
Fuel MEP [bar]	13.9	14.8	15.5	13.5	15.5	15.3
Net IMEP [bar]	5	5.1	5.1	4.9	5.1	5.1
Maximum Cylinder Temperature [ºC]	1614	1588	1579	1592	1582	1582
Exhaust Temperature [ºC]	246	253	253	245	252	252

4.1.1 Combustion Stability

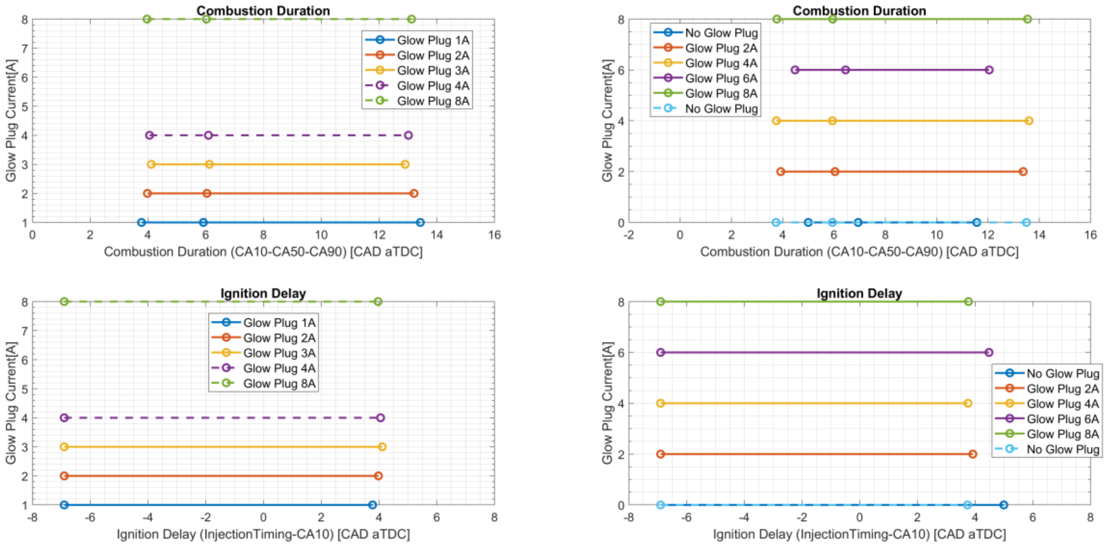

Figure 3 Combustion Phasing (i) Original Glow Plug (ii) Modified Glow Plug

Before proceeding, it must be pointed out that the data for the modified glow plug in the single injection case show two distinct differences. The first no-glow plug condition and the glow plug with 6A current are consistent, while the last no-glow plug condition and the rest of the active glow plug conditions are consistent. This discrepancy is due to a slightly elevated fuel flow rate during the latter set of tests, which was caused by some issues encountered during testing.

Tables 11 and 12 show that the CoV$_{\text{IMEP}}$ remains consistent across different glow plug configurations and currents. Similarly, the ignition delay is unaffected by these variations. The CA50 (crank angle at 50% fuel burnt) also shows minimal change, regardless of the glow plug settings. This suggests that the glow plug did not significantly impact the combustion in the Single Injection strategy. The change in positioning of the glow plug also had no impact.

4.1.2 Rate of Heat Release

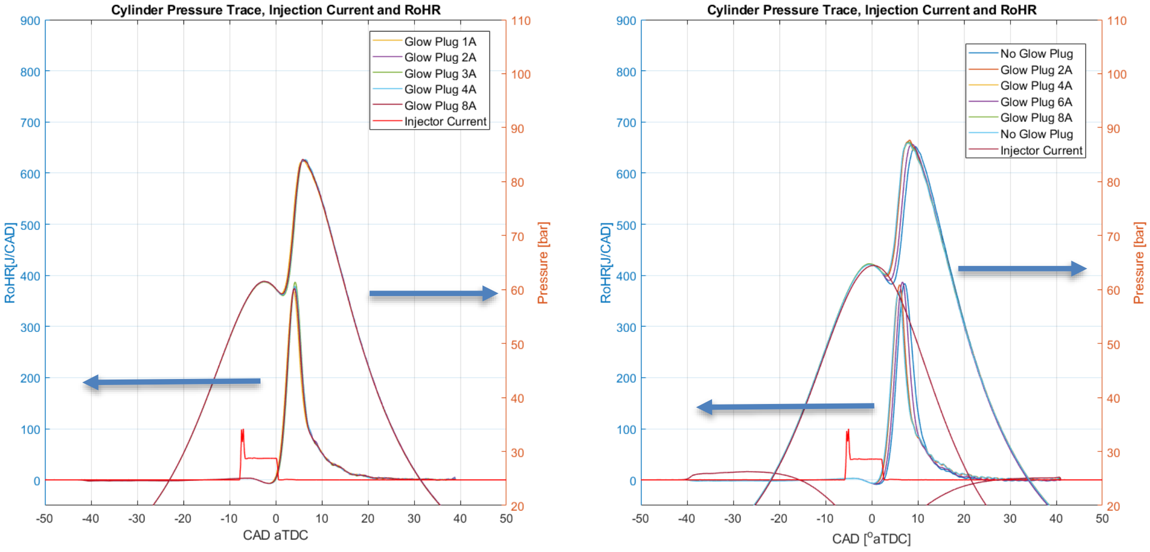

Figure 4 In-Cylinder Pressure Curve and RoHR Curve for (i) Original Glow Plug (ii) Modified Glow Plug

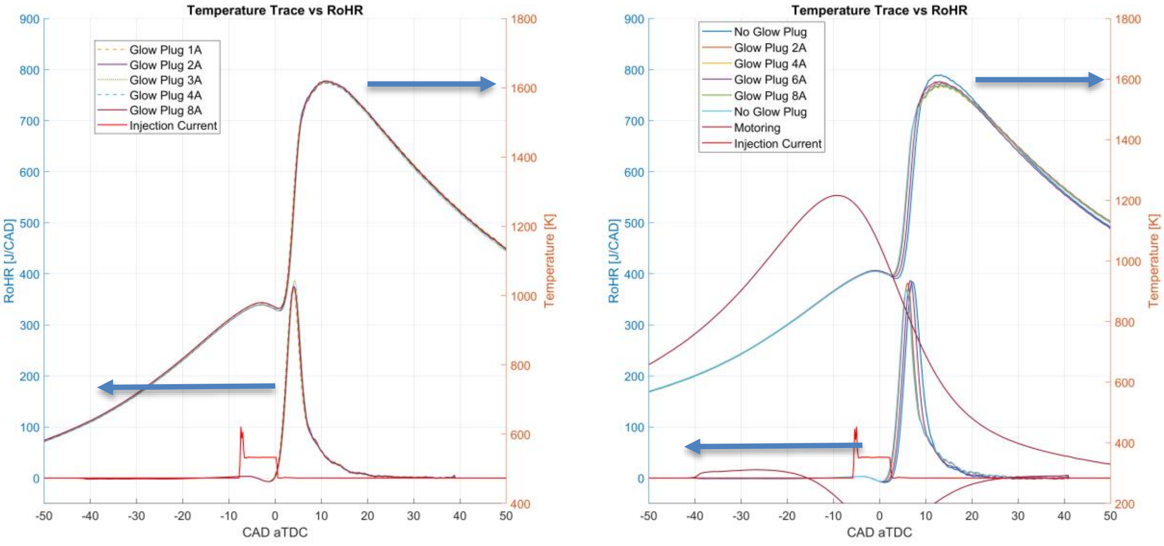

Figure 5 In-Cylinder Temperature Curve and RoHR Curve for (i) Original Glow Plug (ii) Modified Glow Plug

The same can be seen in the RoHR, Cylinder Pressure, and Temperature plots in Figures 4 and 5, where no significant difference was seen, which cannot be explained due to the inconsistency in data collection.

4.1.3 Efficiency

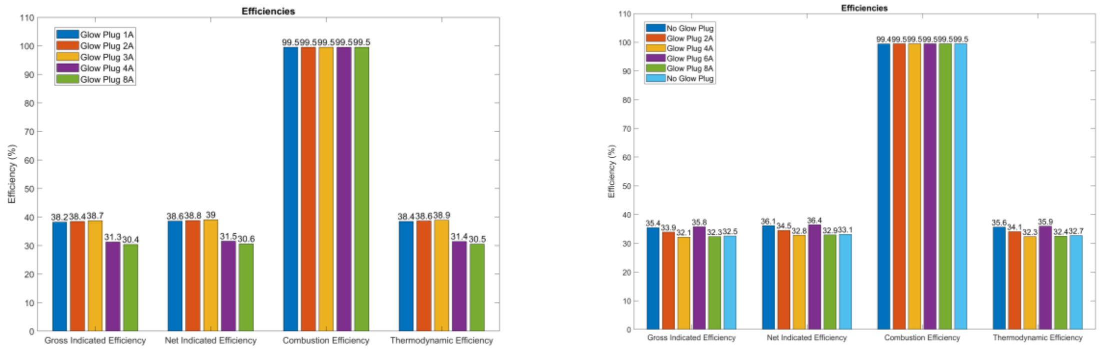

Figure 6 Efficiencies for (i) Original Glow Plug (ii) Modified Glow Plug

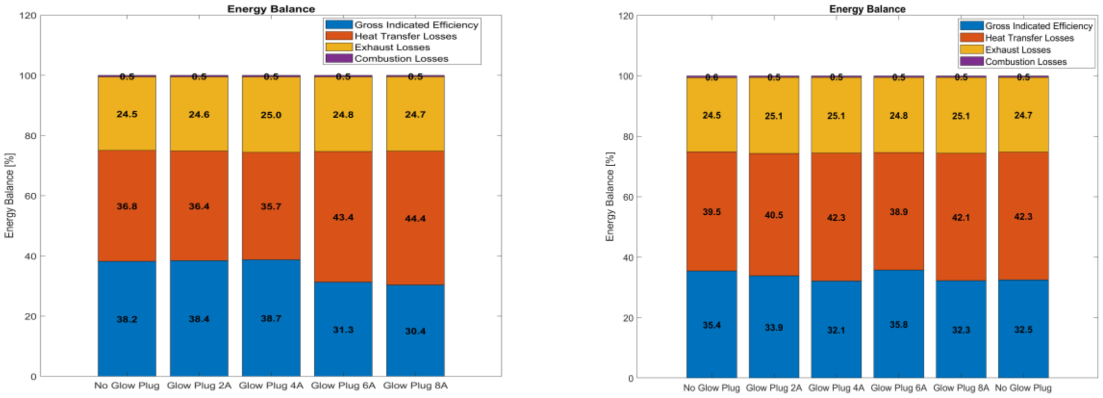

Figure 7 Energy Balance for (i) Original Glow Plug (ii) Modified Glow Plug

Figures 6 & 7 show the different Efficiencies and Energy Balance of the engine under the single injection strategy with the original and modified glow plug operating at different glow plug currents, respectively. The variation in glow plug current has no significant impact on the η_{GIE} or energy balance. The difference in η_{GIE} between the two glow plug configurations can be attributed to variations in fuel flow.

4.1.4 Emissions

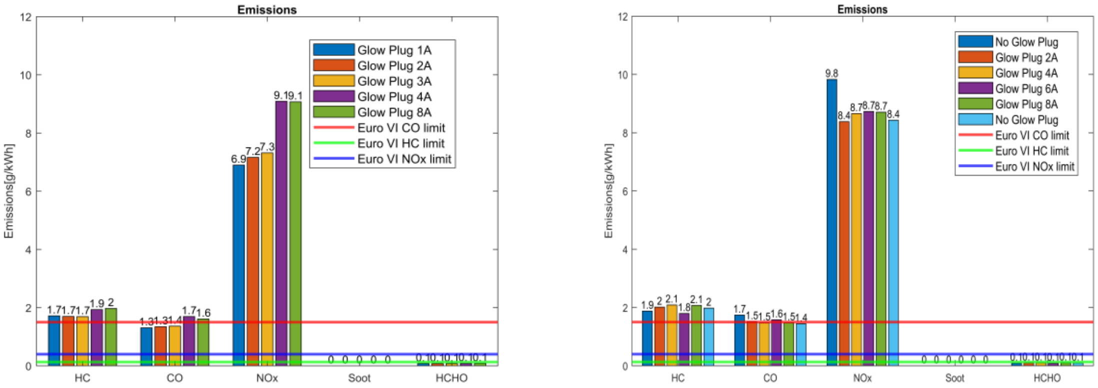

Figure 8 Emissions for (i) Original Glow Plug (ii) Modified Glow Plug

Figure 8 shows the emissions produced by the engine. There is no significant difference in the emissions due to the change in the glow plug current in either glow plug configuration. The changes seen across the two configurations are largely a result of the inconsistency in the fuel flow rate. The HC and NOx emissions are much higher than the Euro VI limits for both configurations. The CO emissions are close to the limit in all cases.

4.2 Pilot Injection Strategy

Table 13 Combustion Parameters for Modified Glow Plug under Pilot Injection Strategy

Glow Plug Current [A]	**0**	**8**	**0**
IMEP [bar]	5	4.9	4.9
COV [%]	2.4	2.2	2.4
Lambda	3.2	3.2	3.2
CA50 [CAD aTDC]	6.3	6.3	6.3
Ignition Delay [CAD]	29	29	29.1
Combustion Duration [CAD]	11.7	11.7	11.6
Fuel MEP [bar]	13.5	13.5	13.6
Net IMEP [bar]	5	5	5

4.2.1 Combustion Phasing & Stability

The pilot injection strategy demonstrates stable combustion at a low intake temperature of 35°C. The CoV_{IMEP} and Efficiency resemble those achieved by the engine operating with a single injection strategy at a higher temperature of 75°C. This is significant as intake heating consumes energy, which can be prevented by using a pilot injection strategy.

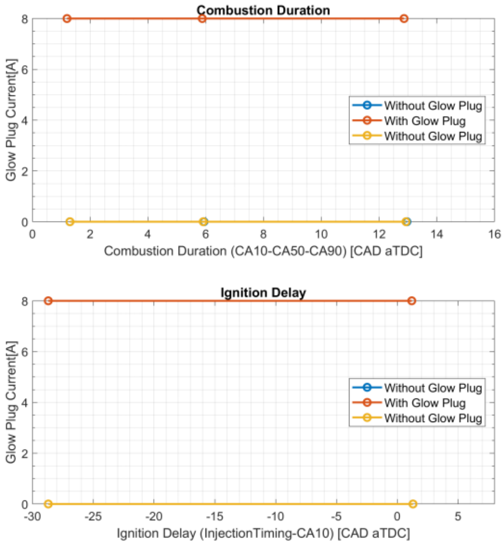

Figure 9 Combustion Phasing under Pilot Injection Strategy

Table 13 shows a few key combustion parameters for the modified glow plug under the pilot injection strategy. The activation of the glow plug in a pilot injection strategy does not have an impact on the combustion characteristics of the engine. The ignition delay, combustion duration and CA50 remain similar with or without the glow plug. This suggests that the glow plug does not substantially affect the timing or duration of combustion events within the engine cycle, as seen in Figure 9. However, a slight decrease in CoV_{IMEP} is seen with an activated glow plug from 2.4% to 2.12%, which increases again to 2.4% when the glow plug is deactivated. This indicates that the glow plug may contribute to a more consistent and stable combustion process. However, it does not translate into an increase in efficiency.

4.2.2 Rate of Heat Release

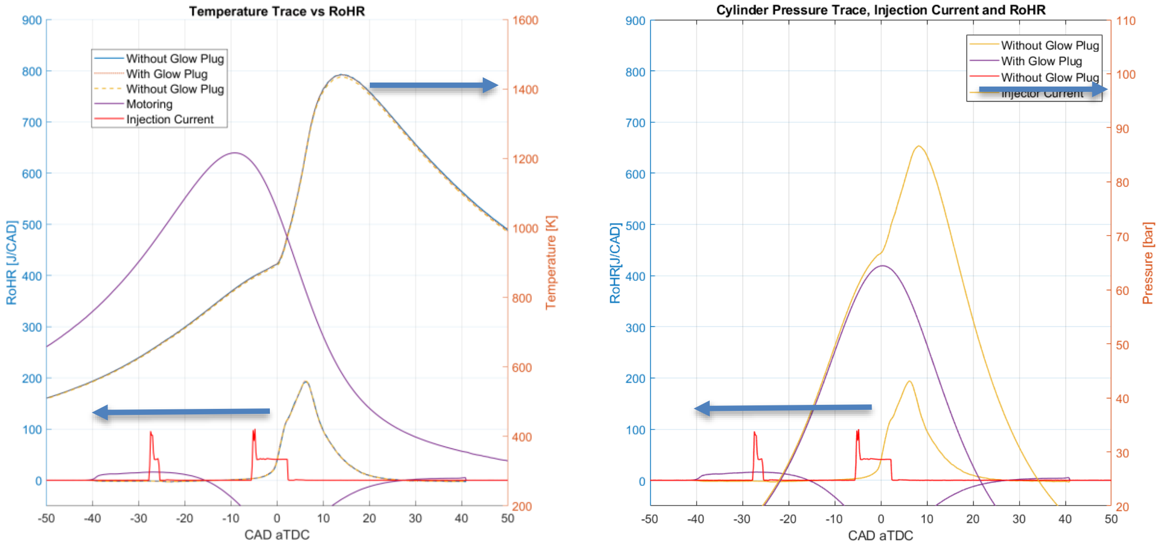

Figure 10 RoHR for Pilot Injection Strategy and In-Cylinder (i)Temperature Curve and (ii) Pressure Curve.

There is no observable difference in the RoHR, cylinder pressure, and cylinder temperature with or without the glow plug, as shown in Figure 10. This suggests that the glow plug does not impact the heat release rate or the pressures and temperatures within the cylinder. Compared to the single injection strategy, it can be seen that the RoHR is more gradual due to the pilot ignition before the main injection, resulting in a lower peak RoHR and temperature.

4.2.3 Efficiencies

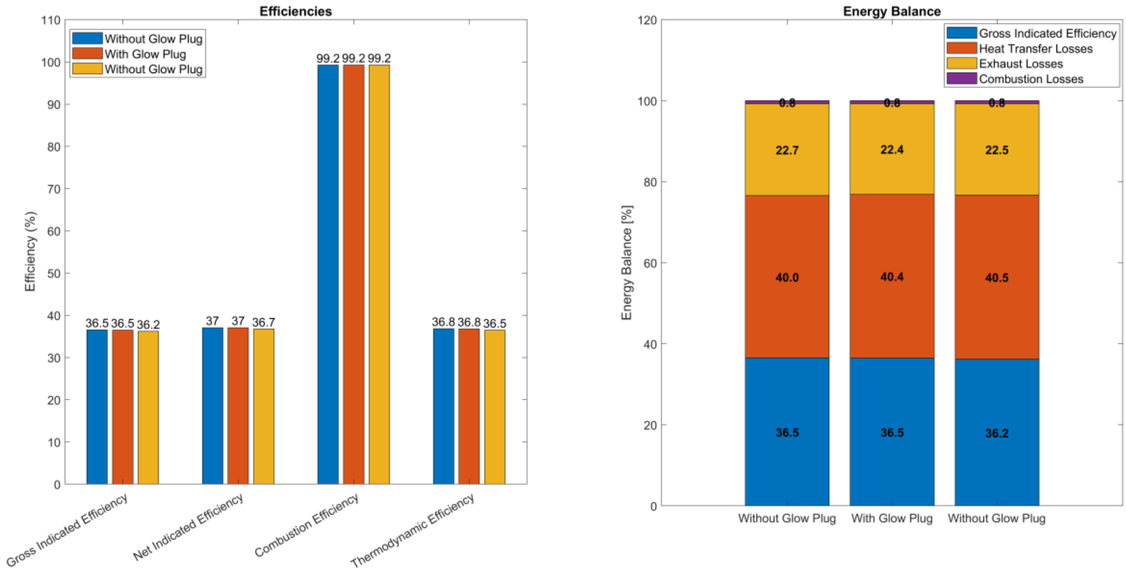

Figure 11 (i) Efficiencies and (ii) Energy Balance under Pilot Injection Strategy

There is no difference between the Gross Indicated Efficiency, Net Indicated Efficiency, Combustion Efficiency, or the Thermodynamic Efficiency, with or without the glow plug. This suggests that the glow plug has no impact on the efficiency when using the pilot injection strategy. However, it is important to note that the pilot injection strategy achieved similar efficiencies as the single injection strategy at a much lower temperature.

4.2.4 Emissions

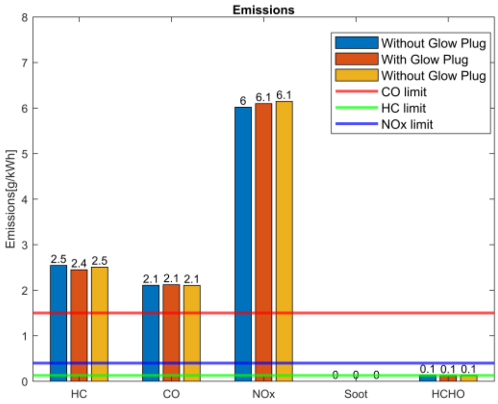

Figure 12 Emissions under Pilot Injection Strategy

There is no difference in the emission characteristics with and without the glow plug. However, it can be seen in Figure 12 that the emissions are much higher than the Euro VI limits for CO, HC, and NOx. The higher HC and CO emissions are due to the fuel accumulating in the crevices at low temperatures before ignition, causing incomplete combustion. The HC and CO emissions of 2.4 g/kWh and 2.1 g/kWh, respectively, with an activated glow plug are 12.5% and 28.5% higher compared to the HC and CO emissions under the single injection strategy with an activated glow plug at 2.1 g/kWh and 1.5 kWh. Elevated in-cylinder temperatures cause NOx emissions. Since the pilot injection strategy displays lower RoHR and cylinder temperatures than the single injection strategy, it can be seen that the NOx emissions are lower for the pilot injection strategy with an activated glow plug at 6.1 g/kWh compared to 8.7 g/kWh which is a decrease of almost 30%.

4.3 HCCI Injection Strategy

Table 14 Key Combustion Parameters for HCCI Injection Strategy

Glow Plug Current [A]	**0**	**8**	**0**
IMEP [bar]	4	4.1	4
COV [%]	3.2	3.3	3
Lambda	3.7	3.7	3.7
CA50 [CAD aTDC]	6.5	4	7.7
Ignition Delay [CAD]	328.2	326.4	328.9
Combustion Duration [CAD]	5.9	4.8	6.7
Fuel MEP [bar]	11.2	11.1	11.4
Net IMEP [bar]	4	4.1	4

4.3.1 Combustion Phasing & Stability

Table 14 shows some combustion parameters of the engine with the HCCI strategy; it can be seen that the CoV_{IMEP} is slightly high, indicating some issues with combustion stability. With the addition of a glow plug, the CA50 decreases from 6.5 CAD aTDC to 4 CAD aTDC, going back up to 7.7 CAD aTDC once the glow plug is removed. The ignition delay is also decreased when using the glow plug going from 328.3 CAD to 326.3 CAD and then back to 328.9 CAD when the glow plug is removed. The Combustion duration also falls from 5.9 CAD to 4.8 CAD, increasing to 6.7 when the glow plug is removed. These observations suggest that the glow plug is slightly effective in igniting the fuel-air mixture faster, resulting in earlier and faster combustion.

4.3.2 Rate of Heat Release

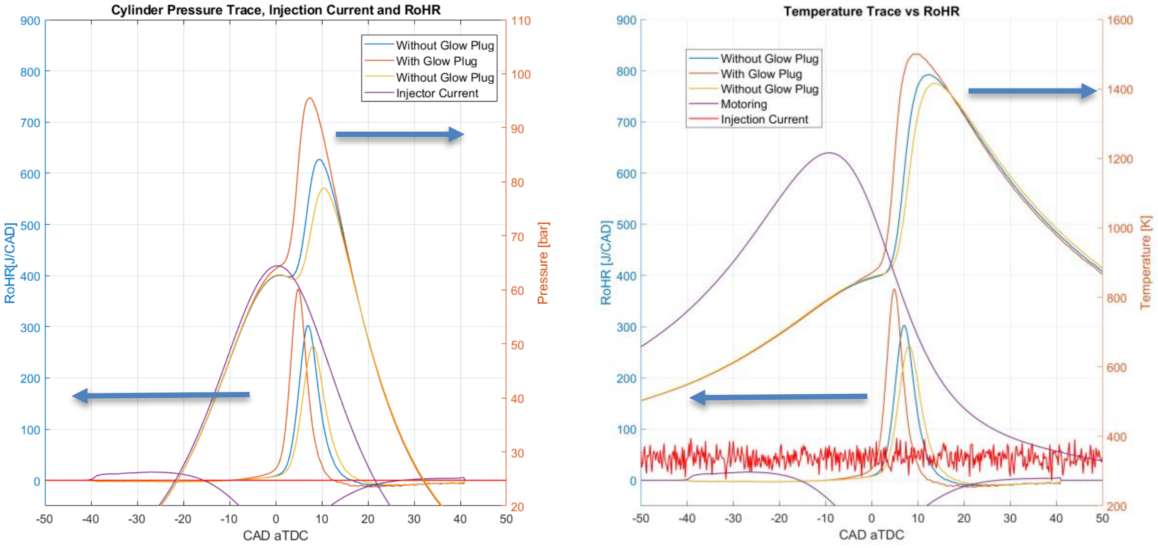

Figure 13 RoHR and In-Cylinder (i) Pressure and (ii)Temperature Curves for HCCI Injection Strategy

The RoHR curve with the glow plug in Figure 13 shows a slow initial rise shortly after ignition, followed by a steep increase to a higher peak than without the glow plug. This is due to the temperature rising earlier due to the heating effect of the glow plug. This earlier temperature rise ensures that the fuel-air mixture is closer to the ignition point leading to a more intense and faster combustion once ignition occurs. This is supported by the pressure curve which has a higher peak with the glow plug compared to without the glow plug. The more intense combustion facilitated by the glow plug often translates to improved combustion efficiency.

4.3.3 Efficiency

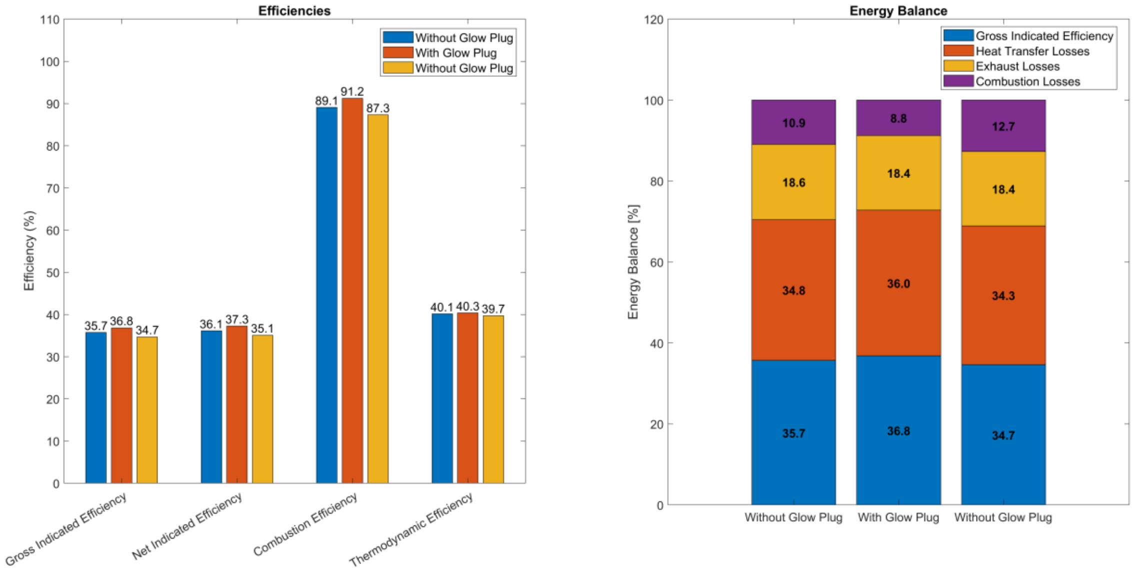

Figure 14 (i) Efficiencies and (ii) Energy Balance under HCCI Injection Strategy

The data indicates that adding a glow plug improves combustion efficiency, increasing it from 89.1% to 91.2%. When the glow plug is removed, combustion efficiency drops to 87.3%. This improvement with the glow plug is attributed to lower combustion losses, as illustrated in Figure 14. The more intense combustion observed in the RoHR with the glow plug confirms this increase in combustion efficiency. Consequently, the gross indicated efficiency also improves, rising from 35.7% to 36.8% with the glow plug, but falls back to 34.7% when the glow plug is removed. This results from the lower combustion losses compensating for the higher heat transfer losses.

4.3.4 Emissions

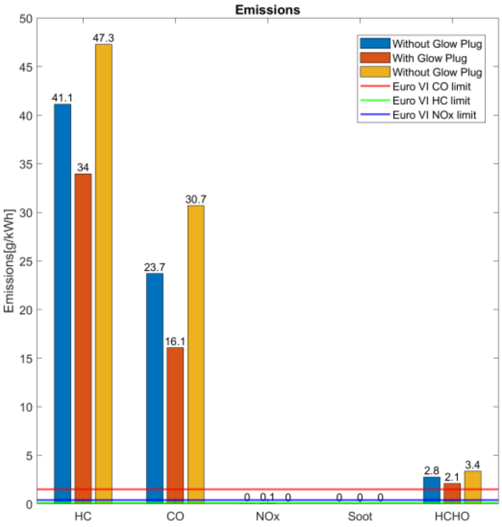

Figure 15 Emissions under HCCI Strategy

Figure 15 illustrates the impact of the glow plug on various emissions. With the addition of the glow plug, HC emissions decrease from 41.1 g/kWh to 34 g/kWh, while they increase to 47.3 g/kWh when the glow plug is removed. Similarly, CO emissions decrease from 23.7 g/kWh to 16.1 g/kWh with the glow plug but rise to 30.7 g/kWh without it. HCHO emissions, which are relatively high, improve with the glow plug, decreasing from 2.8 g/kWh to 2.1 g/kWh, and rising to 3.4 g/kWh when the glow plug is removed. The high HC, CO, and HCHO emissions are primarily due to the extremely early injection timing of –325 CAD aTDC in the HCCI strategy. This early timing causes fuel to get trapped in crevices within the combustion chamber, leading to incomplete combustion and higher emissions. The glow plug facilitates earlier ignition, which helps burn off some of the fuel before it gets trapped in these crevices, thereby improving emissions.

The increased emissions observed when the glow plug is removed can be attributed to the higher fuel flow rate compared to the case before the glow plug was activated. Consequently, more fuel is injected into the combustion chamber, leading to a greater amount of fuel becoming trapped in the crevices. This accumulation of unburnt fuel contributes to the heightened emissions observed in this scenario compared to the initial case without the glow plug.

The NOx emissions are almost negligible in this case. This is because HCCI combustion has a more uniform distribution of the air-fuel mixture within the combustion chamber due to the time allowed for it to mix due to the early injection. This homogeneous mixture allows for more complete combustion and reduces the formation of localised high-temperature zones where NOx formation is favoured.

The HC, CO, and HCHO emissions are much higher than the limits defined in Euro VI making HCCI an unsuitable injection strategy. The data also shows a slight improvement in combustion stability, efficiency, and emissions. While this indicates that the glow plug has some effect, it does not seem large enough to warrant the addition of the glow plug.

4.4 HCCI plus PPC Injection Strategy

Table 15 Key Combustion Parameters for HCCI plus PPC Injection Strategy

Glow Plug Current [A]	**0**	**8**	**0**
IMEP [bar]	3.9	4	3.9
COV [%]	2.1	1.7	2
Lambda	3.7	3.8	3.8
CA50 [CAD aTDC]	7.2	5.0	6.2
Ignition Delay [CAD]	353.4	352.1	352.8
Combustion Duration [CAD]	6.6	5.3	6
Fuel MEP [bar]	11.1	11.1	10.9
Net IMEP [bar]	3.9	4	3.9

4.4.1 Combustion Phasing & Stability

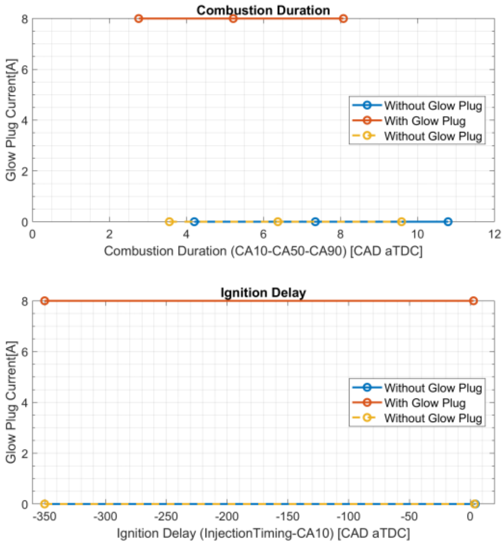

Figure 16 Combustion Phasing under HCCI plus PPC Strategy

The addition of the glow plug resulted in a lower CoV_{IMEP} of 1.69% compared to 2.14% before the activation of the glow plug and 1.98% after it was deactivated. The CA50 occurred earlier with the activated glow plug at 5 CAD aTDC compared to 7.2 CAD aTDC before activation and 6.2 CAD aTDC after deactivation, indicating an advancement in the combustion timing. The ignition delay slightly decreased for the activated glow plug case. This resulted in a combustion duration of 5.3 CAD when the glow plug was activated, which was notably shorter than when the glow plug was deactivated, with a duration of 7.2 CAD and 6.2 CAD before activation and after deactivation, respectively. This suggests that the presence of the glow plug improved combustion stability, advanced combustion timing, and shortened the combustion duration. This can be visualised in the RoHR plots.

4.4.2 Rate of Heat Release

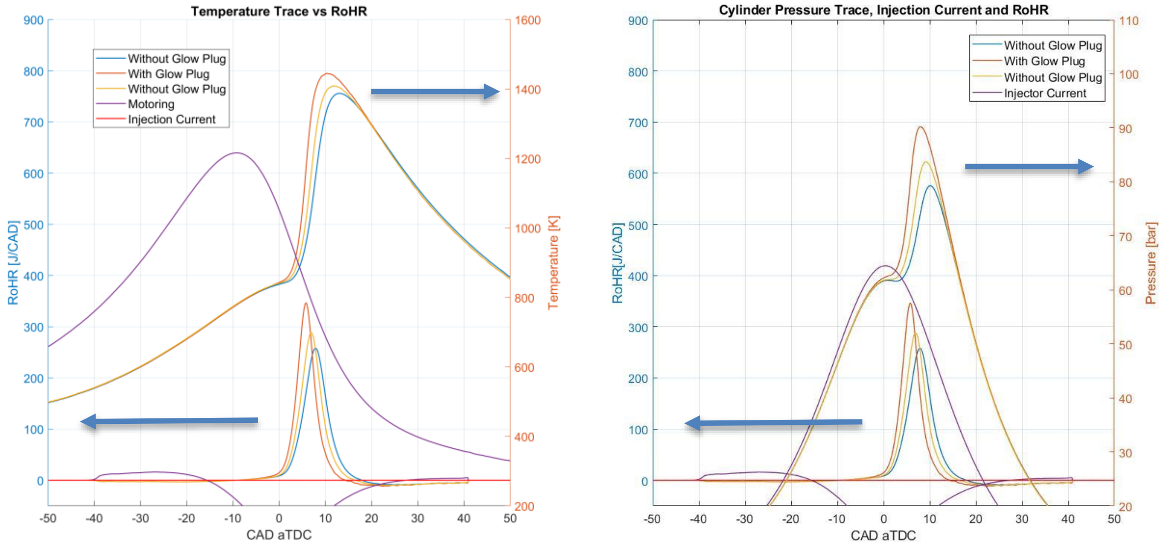

Figure 17 RoHR curve for HCCI plus PPC Injection Strategy along with (i)Temperature curve (ii) Pressure curve.

With the glow plug activated, few changes are observed in the RoHR curve and cylinder temperature profile as seen in Figure 17. Firstly, the RoHR curve begins to increase slightly earlier than when the glow plug is deactivated. Additionally, the peak of the RoHR curve is higher with the glow plug activated. Furthermore, the RoHR curve appears to be slightly narrower in comparison. Meanwhile, the cylinder temperature profile starts increasing slightly earlier and is marginally higher than the case with the deactivated glow plug before rising to higher levels than observed with the deactivated glow plug after the start of combustion. The pressure curve starts with the glow plug also starts increasing earlier and has a higher peak. These observations indicate that the presence of the glow plug facilitates earlier and more intense combustion due to a slight temperature increase, which leads to higher heat release rates, cylinder temperatures and pressures.

4.4.3 Efficiency

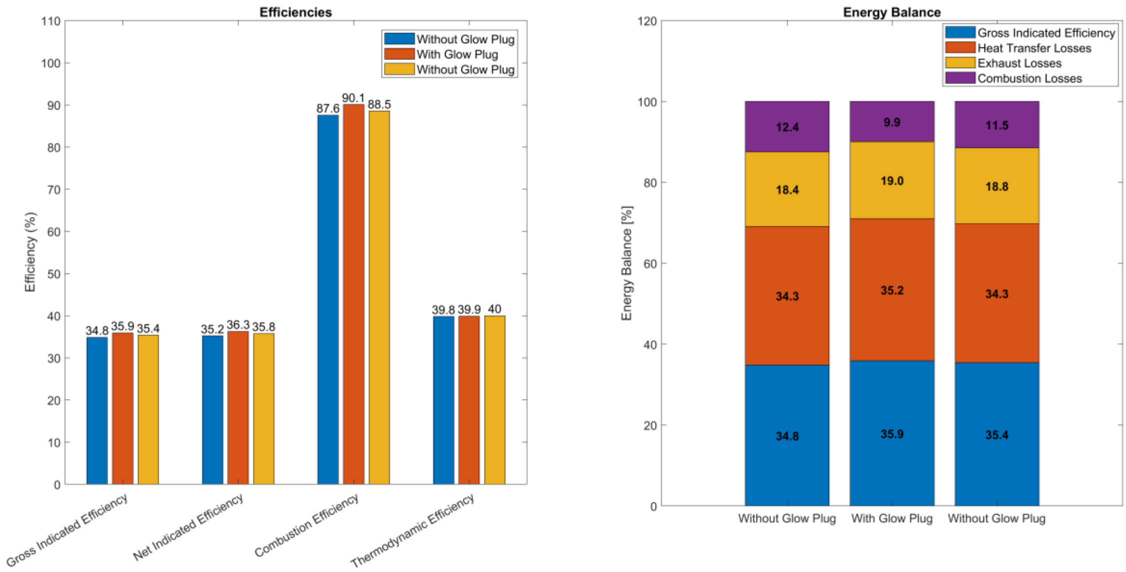

Figure 18 (i) Efficiency and (ii) Energy Balance under HCCI plus PPC Injection Strategy

Figure 18 shows that the combustion efficiency with the activated glow plug is higher at 90.1% compared to 87.6% before and 86.5% after the deactivation of the glow plug. The higher peak in the RoHR curve and pressure curve indicates a more intense combustion process, which translates to higher combustion efficiency. This can also be seen in Figure 18, the combustion loss for the activated glow plug is lower at 9.9% compared to 12.4% before activation and 11.5% after deactivation of the glow plug. The lower combustion loss indicates less unburnt fuel and more efficient fuel utilisation. This results in a slight gross indicated efficiency increase of 1.1% from 34.8% to 35.9% after activation of the glow plug and a reduction in gross indicated efficiency to 35.4% after deactivation.

4.4.4 Emissions

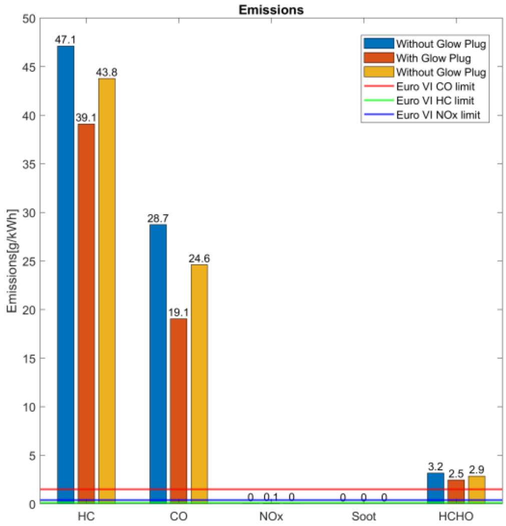

Figure 19 Emissions under HCCI plus PPC injection strategy.

Figure 19 shows that the HC, CO, and HCHO emissions are very high. However, with the activation of the glow plug they can be decreased. The HC emissions reduced from 47.1 g/kWh to 39.1 g/kWh after activation and went back up to 43.8 g/kWh after deactivation of the glow plug. This reduction suggests that the glow plug facilitates more complete combustion of the fuel-air mixture, resulting in fewer unburnt hydrocarbons in the exhaust gases. The CO emissions decrease from 28.7 g/kWh to 19.1 g/kWh after activation and increase to 24.6 g/kWh after deactivation. The HCHO emissions fall from 3.2 g/kWh to 2.5 g/kWh and rise to 2.9 g/kWh after the deactivation of the glow plug. These reductions suggest that the glow plug facilitates more complete combustion of the fuel-air mixture, resulting in fewer unburnt hydrocarbons, CO and HCHO in the exhaust gases. Conversely, emissions tend to increase when the glow plug is deactivated, with HC, CO, and HCHO levels rising again. This highlights the importance of the glow plug in facilitating more complete combustion and reducing emissions. The NOx and Soot emissions are negligible in this strategy.

Despite the improvements observed with the activation of the glow plug, it is evident that the emissions levels remain unacceptably high and fail to meet Euro VI limits. This limitation makes the strategy impractical.

4.5 PPC Injection Strategy

Table 16 Key Combustion Parameters under PPC Injection Strategy

Glow Plug Current [A]	**0**	**8**	**0**
IMEP [bar]	4	4	4
Lambda	3.9	3.9	3.9
COV [%]	3	32.1	2.7
CA50 [CAD aTDC]	6	0.5	7
Ignition Delay [CAD]	43	37.7	43.5
Combustion Duration [CAD]	4.9	4	5.6
Fuel MEP [bar]	8.5	8.8	8.8
Net IMEP [bar]	4.1	4	4.1
Maximum Cylinder Temperature [^{0}C]	1528	1566	1508
Exhaust Temperature [^{0}C]	181	179	181

4.5.1 Combustion Stability

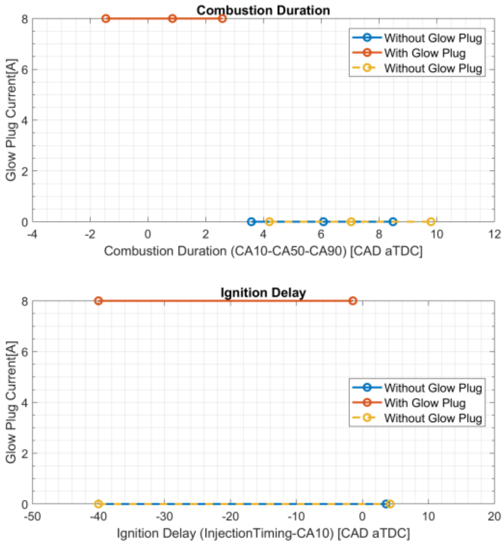

Figure 20 Combustion Phasing for PPC Strategy

Table 16 shows some important parameters for assessing the influence of the glow plug. The activation of a glow plug led to a significantly advanced CA50 going from 6 CAD aTDC to 0.5 CAD aTDC retarding to 7 CAD aTDC, suggesting an earlier start of combustion when the glow plug is activated. This is supported by Figure 20 which shows the contrast in combustion phasing with and without the glow plug. It can also be seen that the ignition delay is shorter. This indicates that the glow plug accelerates the ignition process, initiating combustion sooner than when the glow plug is not activated.

However, high cyclic variability was observed when using the glow plug. While it is usually undesirable to have high cyclic variability, it can be explained in this context. The efficacy of the glow plug is dependent on its proximity to the injected fuel. However, due to the suboptimal placement of the glow plug, the fuel does not come in contact with the glow plug consistently. As a result, the glow plug influences combustion only during some cycles when the fuel mixes under the right conditions and reaches the glow plug, leading to the observed cyclic variability.

4.5.2 Rate of Heat Release

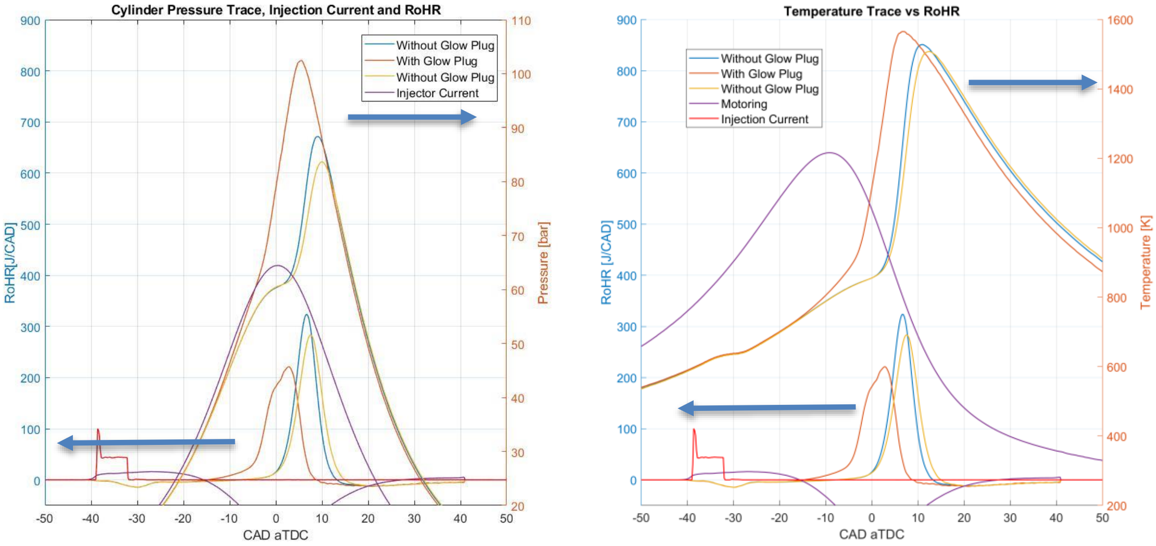

Figure 21 RoHR Curve for PPC Injection Strategy with In -Cylinder (i) Pressure Curve and (ii) Temperature Curve.

In Figure 21, the RoHR plot with the glow plug activated is wider and has a lower peak, this is a result of the high variability of the engine when the glow plug is activated. Some cycles when the glow plug is effective have a high rate of heat release and other cycles when the glow plug is not effective have a much lower rate of heat release as shown in Figure 22. This uneven rate of heat release averages out through the cycles and appears as a longer and more sustained heat release with a lower peak. In contrast, we can see that the cylinder pressure and the temperature plots start rising much earlier and have higher peaks with the glow plug than the scenario with the deactivated glow plug. This higher peak temperature and pressure is due to the earlier, more intense, and efficient combustion facilitated by the glow plug, leading to more complete fuel combustion.

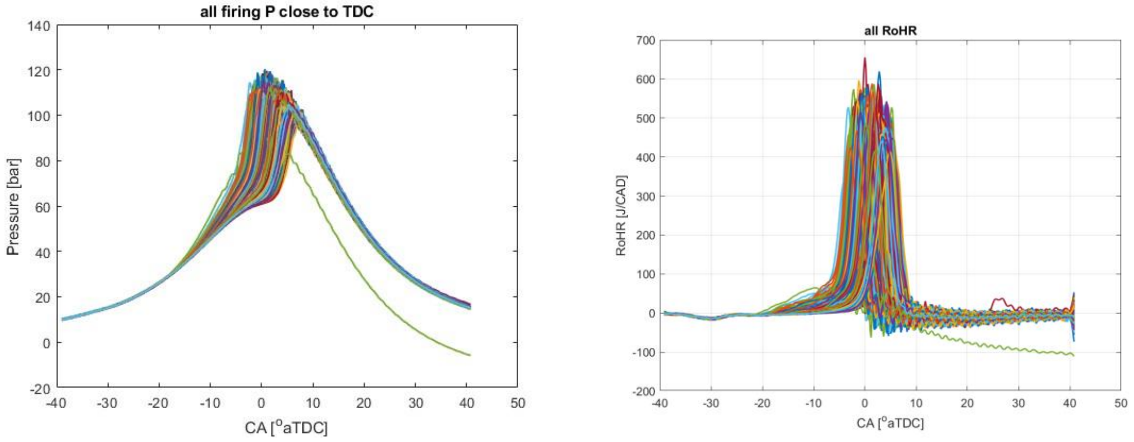

Figure 22 Plot of (i) Pressure (ii) Rate of Heat Release for each individual cycle

4.5.3 Efficiency

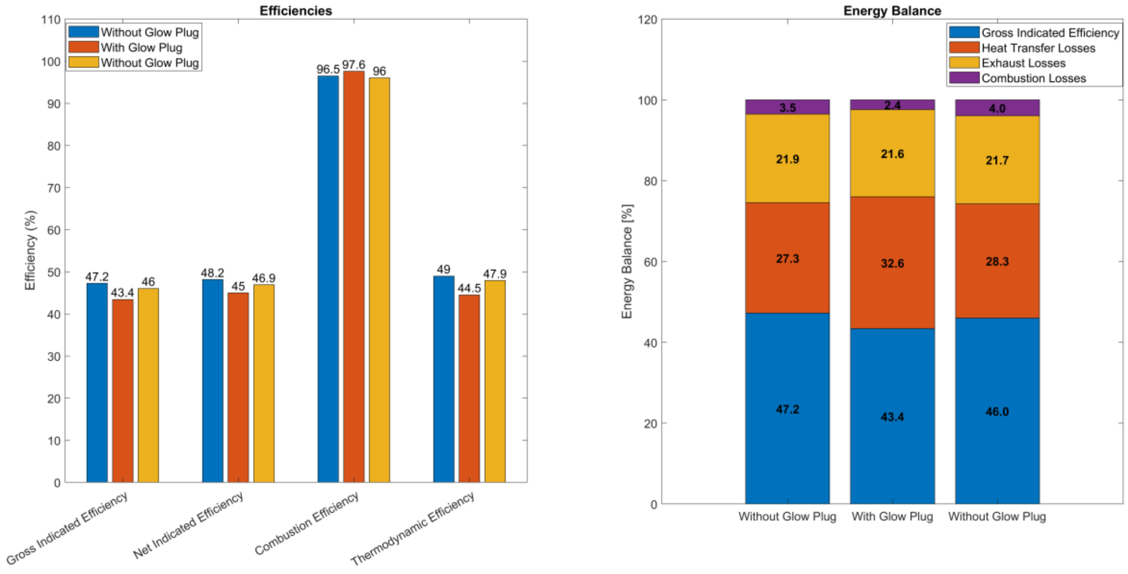

Figure 23 (i) Efficiency and (ii) Energy Balance under PPC Injection Strategy

An increase in Combustion efficiency was seen with the use of a glow plug. This can be due to the earlier ignition and more controlled combustion, which results in lesser incomplete combustion. However, there was a decline in thermodynamic efficiency which can be explained by the higher heat transfer loss. The heat transfer losses are due to earlier onset of combustion, as a result, some of the combustion happens before TDC which results in the heat not being used in the power stroke and being lost to the cylinder walls. This significantly impacts the gross indicated efficiency, resulting in a lower efficiency than the non-glow plug case.

4.5.4 Emissions

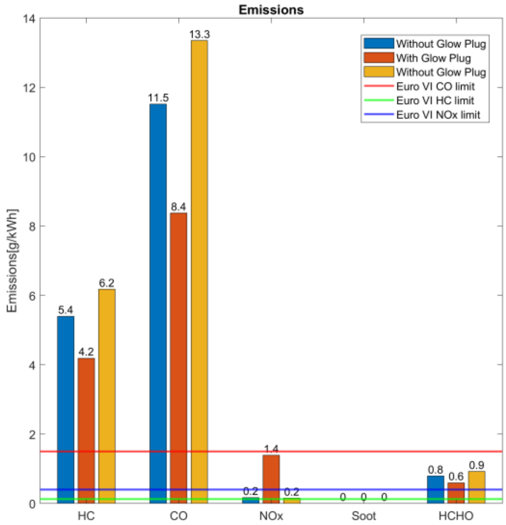

Figure 24 Emissions under PPC Injection Strategy

Figure 24 shows the emissions produced under the PPC injection strategy. When the glow plug is activated the emissions of HC, CO, and HCHO are lowered from 5.4 g/kWh, 11.5 g/kWh and 0.8 g/kWh to 4.2 g/kWh, 8.4 g/kWh and 0.6 g/kWh respectively as shown in the figure. This can be attributed to more complete combustion. The glow plug initiates combustion earlier in the cycle, ensuring a more controlled and complete burn as indicated by the combustion efficiency. This reduces HC, CO, and HCHO by minimizing incomplete combustion. Early ignition also extends the duration of high-temperature combustion, increasing the likelihood of complete oxidation of the fuel. However, this results in a trade-off as the use of a glow plug increases peak combustion temperatures, increasing NOx formation. Regardless, the emissions are still over the limits specified in EURO VI.

Overall, the PPC strategy seems to be the most promising for this engine, with the high efficiency, comparatively lower emissions and effectiveness of the glow plug, which can help with cold starts and engine stability if the glow plug is placed such that it comes in contact with the fuel when it is injected.

5 Conclusion

This research addressed its primary objectives regarding the impact of glow plugs on the stability, performance, and emissions of a methanol compression ignition engine, focusing on various injection strategies. Table 17 summarises the results.

Table 17 Summary of Key Results

Injection Strategy	Load	Intake Temperature	Combustion Phasing	Stability (%)	Efficiency (%)			Emissions (g/kWh)		
	IMEPg	^{0}C	CA50 (CAD aTDC)	CoV_{IMEP}	η_{GIE}	η_{c}	η_{T}	HC	CO	NOx
Comparison between pilot and single injection strategy										
Single with 8A Glow Plug	5	73	6.3	2.5	32.3	99.5	32.4	2.1	1.5	8.7
Pilot with Glow Plug	5	35	6.3	2.2	36.5	99.2	36.8	2.4	2.1	6.1
Comparing the effectiveness of glow plug										
HCCI										
HCCI – No Glow Plug	4	35	6.5	3.2	35.7	89.1	35.7	41.1	23.7	0
HCCI – Glow Plug	4	35	4	3.3	36.8	91.2	36.8	34	16.1	0.1
PPC										
PPC – No Glow Plug	4	35	6	3	47.2	96.5	49	5.4	11.5	0.2
PPC – Glow Plug	4	35	0.5	32	43.4	97.6	44.5	4.2	8.4	1.4

The study found that glow plug activation did not significantly affect combustion stability, efficiency, or emissions when using single injection and pilot injection strategies. There was no visible difference in the case with the modified glow plug either. However, pilot injection strategies matched the efficiency and emissions of a single injection at much lower intake temperatures, which is beneficial due to reduced energy consumption as lesser energy is required to heat the air. The pilot injection strategy resulted in higher HC and CO emissions but lower NOx emissions than a single injection strategy.

In the case of the HCCI strategy, glow plugs led to earlier CA50, faster combustion duration, and shorter ignition delay, as evidenced by the rate of heat release curves. This resulted in higher combustion efficiency, an increase in gross indicated efficiency, and lower combustion losses, indicating more controlled and efficient combustion. However, the strategy produced high HC, CO, and HCHO emissions. The use of glow plugs reduced these emissions slightly by facilitating earlier combustion. Despite negligible NOx emissions due to the homogenous mixture preventing hotspots, the high levels of HC, CO, and HCHO emissions make HCCI impractical for practical applications.

For the PPC strategy, using glow plugs resulted in a significant advancement in CA50, a much shorter ignition delay, and high cyclic variability. This variability was likely due to the inconsistent impingement of fuel on the glow plug because of poor placement. Despite lower combustion losses, high heat transfer losses negated these gains, resulting in a loss of gross indicated efficiency. Glow plug usage in the PPC strategy lowered HC, CO, and HCHO emissions while NOx emissions increased. However, these results are promising, and further investigations can be conducted into improving emissions by adjusting the injection timing with the effective placement of the glow plug to ensure impingement of the fuel mixture.

The broad investigation into the impact of glow plugs on methanol compression ignition engine performance has yielded valuable insights across various injection strategies. This research underscores the nuanced effects of glow plug activation across different combustion strategies and highlights the trade-offs between efficiency, emissions, and combustion stability in methanol compression ignition engines.

5.1 Future Study

Exploring additional PPC strategies with glow plugs holds significant promise for future research. Further investigations could explore optimising injection parameters, such as timing and duration, to enhance combustion efficiency and reduce emissions. Later injection timings could help reduce HC and CO emissions by limiting the amount of unburnt fuel while reducing the efficiency lost due to some of the fuel burning before TDC, but it may cause a rise in NOx emissions(47). However, these trade-offs must be studied. PPC strategies with multiple injections can also be experimented upon (37).

Additionally, studying the effects of glow plug placement, particularly by positioning it closer to the injection, could offer valuable insights into its interaction with the fuel-air mixture and combustion process. This can be done by changing the location of the glow plug or in the current setup, an injector with a wider spray angle could be used. This adjustment may mitigate issues related to cyclic variability observed in the current study, leading to more consistent and stable combustion.

Monitoring the temperature of the glow plug to understand the minimum temperature of the glow plug required for autoignition, and its impact on the power required for autoignition is an interesting proposition.

6 References

1. Annual Energy Outlook 2023 - U.S. Energy Information Administration (EIA) [Internet]. [cited 2024 Mar 6]. Available from: https://www.eia.gov/outlooks/aeo/index.php

2. Ritchie H, Rosado P, Roser M. Emissions by sector: where do greenhouse gases come from? Our World in Data [Internet]. 2024 Jan 5 [cited 2024 Mar 6]; Available from: https://ourworldindata.org/emissions-by-sector

3. Leach F, Kalghatgi G, Stone R, Miles P. The scope for improving the efficiency and environmental impact of internal combustion engines. Transportation Engineering. 2020 Jun 1;1:100005.

4. Hawkins TR, Singh B, Majeau-Bettez G, Strømman AH. Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. Journal of Industrial Ecology. 2013;17(1):53–64.

5. Manzetti S, Mariasiu F. Electric vehicle battery technologies: From present state to future systems. Renewable and Sustainable Energy Reviews. 2015 Nov 1;51:1004–12.

6. Al-Hanahi B, Ahmad I, Habibi D, Masoum MAS. Charging Infrastructure for Commercial Electric Vehicles: Challenges and Future Works. IEEE Access. 2021;9:121476–92.

7. Awogbemi O, Kallon DVV, Onuh EI, Aigbodion VS. An Overview of the Classification, Production and Utilization of Biofuels for Internal Combustion Engine Applications. Energies. 2021 Jan;14(18):5687.

8. Ebadian M, van Dyk S, McMillan JD, Saddler J. Biofuels policies that have encouraged their production and use: An international perspective. Energy Policy. 2020 Dec 1;147:111906.

9. Searchinger TD. Biofuels and the need for additional carbon. Environ Res Lett. 2010 Apr;5(2):024007.

10. Magda R, Szlovák S, Tóth J. Chapter 7 - The role of using bioalcohol fuels in sustainable development. In: Bochtis D, Achillas C, Banias G, Lampridi M, editors. Bio-Economy and Agri-production [Internet]. Academic Press; 2021 [cited 2024 Mar 21]. p. 133–46. Available from: https://www.sciencedirect.com/science/article/pii/B9780128197745000072

11. Bergthorson JM, Thomson MJ. A review of the combustion and emissions properties of advanced transportation biofuels and their impact on existing and future engines. Renewable and Sustainable Energy Reviews. 2015 Feb 1;42:1393–417.

12. Characterization of the Combustion of Light Alcohols in CI Engines: Performance, Combustion Characteristics and Emissions. Lund: Department of Energy Sciences, Lund University; 2019.

13. Dalena F, Senatore A, Marino A, Gordano A, Basile M, Basile A. Chapter 1 - Methanol Production and Applications: An Overview. In: Basile A, Dalena F, editors. Methanol

[Internet]. Elsevier; 2018 [cited 2024 Mar 12]. p. 3–28. Available from: https://www.sciencedirect.com/science/article/pii/B9780444639035000017

14. Verhelst S, Turner JW, Sileghem L, Vancoillie J. Methanol as a fuel for internal combustion engines. Progress in Energy and Combustion Science. 2019 Jan 1;70:43–88.

15. Andersson K, Salazar CM. Methanol as a Marine fuel report. FCBI Energy; 2015.

16. Tunér M. Combustion of Alternative Vehicle Fuels in Internal Combustion Engines.

17. Mikulski M, MKC, TUDelft. Public final report-Methanol as an alternative fuel for vessels. 2018.

18. Shamun S, Zincir B, Shukla P, Garcia P, Verhelst S, Tunér M. Quantification and Analysis of the Charge Cooling Effect of Methanol in a Compression Ignition Engine Utilizing PPC Strategy. 2018.

19. Zincir B, Deniz C. Methanol as a Fuel for Marine Diesel Engines. In: Shukla PC, Belgiorno G, Di Blasio G, Agarwal AK, editors. Alcohol as an Alternative Fuel for Internal Combustion Engines [Internet]. Singapore: Springer; 2021 [cited 2024 Apr 22]. p. 45–85. Available from: https://doi.org/10.1007/978-981-16-0931-2_4

20. Bromberg L, Cheng WK. Methanol as an alternative transportation fuel in the US: Options for sustainable and/or energy-secure transportation. Cambridge, MA: Sloan Automotive Laboratory, Massachusetts Institute of Technology. 2010;

21. Kroeger CA. A Neat Methanol Direct Injection Combustion System for Heavy-Duty Applications [Internet]. Warrendale, PA: SAE International; 1986 Sep [cited 2024 Mar 13]. Report No.: 861169. Available from: https://www.sae.org/publications/technical-papers/content/861169/

22. Zincir B, Shukla P, Shamun S, Tuner M, Deniz C, Johansson B. Investigation of effects of intake temperature on low load limitations of methanol partially premixed combustion. Energy and Fuels. 2019;33(6):5695–709.

23. Svensson E, Verhelst S. Simulation Based Investigation of Achieving Low Temperature Combustion with Methanol in a Direct Injected Compression Ignition Engine. In 2019 [cited 2024 Feb 18]. p. 2019-01–1152. Available from: https://www.sae.org/content/2019-01-1152/

24. Seko T, Kuroda E, Hamano Y. Methanol Lean Burn in an Auto-Ignition DI Engine. In 1998 [cited 2024 Mar 13]. p. 980531. Available from: https://www.sae.org/content/980531/

25. García A, Monsalve-Serrano J, Micó C, Guzmán-Mendoza M. Parametric evaluation of neat methanol combustion in a light-duty compression ignition engine. Fuel Processing Technology. 2023 Oct 1;249:107850.

26. Svensson E, Verhelst S. Numerical Optimization of Compression Ratio for a PPC Engine running on Methanol. In: SAE Technical Papers [Internet]. Society of Automotive Engineers; 2019 [cited 2024 Feb 20]. Available from: http://lup.lub.lu.se/record/050fc786-ee30-431e-afb7-7a987c7f952c

27. Nakashima N, Shiino S, Shimada T, Oikawa H. Development of the Heavy-Duty Methanol Engine [Internet]. Warrendale, PA: SAE International; 1989 Nov [cited 2024 Mar 13]. Report No.: 891188. Available from: https://www.sae.org/publications/technical-papers/content/891188/

28. Ramesh A, Nagalingam B, K. V. G. Investigations on the Design and Performance of Two Types of Hot Surface Ignition Engines. In 1992 [cited 2024 Mar 13]. p. 921632. Available from: https://www.sae.org/content/921632/

29. Mueller CJ, Musculus MP. Glow Plug Assisted Ignition and Combustion of Methanol in an Optical DI Diesel Engine. In 2001 [cited 2024 Feb 15]. p. 2001-01–2004. Available from: https://www.sae.org/content/2001-01-2004/

30. Svensson M, Tuner M, Verhelst S. Experimental Investigation of Pilot Injection Strategies to Aid Low Load Compression Ignition of Neat Methanol. In Detroit, Michigan, United States; 2024 [cited 2024 Apr 25]. p. 2024-01–2119. Available from: https://www.sae.org/content/2024-01-2119

31. Svensson E, Tuner M, Verhelst S. Influence of Injection Strategies on Engine Efficiency for a Methanol PPC Engine. SAE Int J Adv & Curr Prac in Mobility. 2019 Sep 9;2(2):653–71.

32. Sharma TK, Rao GAP, Murthy KM. Homogeneous Charge Compression Ignition (HCCI) Engines: A Review. Arch Computat Methods Eng. 2016 Dec 1;23(4):623–57.

33. Richards BG. Methanol-Fueled Caterpillar 3406 Engine Experience in On-Highway Trucks. In 1990 [cited 2024 Feb 15]. p. 902160. Available from: https://www.sae.org/content/902160/

34. Zincir B, Deniz C, Tunér M. Investigation of environmental, operational and economic performance of methanol partially premixed combustion at slow speed operation of a marine engine. Journal of Cleaner Production. 2019 Oct 20;235:1006–19.

35. Pucilowski M, Fatehi H, Jangi M, Lonn S, Matamis A, Andersson O, et al. Numerical Investigation of Methanol Ignition Sequence in an Optical PPC Engine with Multiple Injection Strategies. In 2019 [cited 2024 Feb 20]. p. 2019-24–0007. Available from: https://www.sae.org/content/2019-24-0007/

36. Xu L, Treacy M, Zhang Y, Aziz A, Tuner M, Bai XS. Comparison of efficiency and emission characteristics in a direct-injection compression ignition engine fuelled with iso-octane and methanol under low temperature combustion conditions. Applied Energy [Internet]. 2022 [cited 2024 Feb 20];312. Available from: http://lup.lub.lu.se/record/e8bdf3e5-c7bf-4fc3-ba6b-1a7fdc123224

37. Aziz A, Garcia A, Pinto Dos Santos C, Tuner M. Impact of Multiple Injection Strategies on Performance and Emissions of Methanol PPC under Low Load Operation. In 2020 [cited 2024 Feb 18]. p. 2020-01–0556. Available from: https://www.sae.org/content/2020-01-0556/

38. Havenith C, Kuepper H, Hilger U. Performance and Emission Characteristics of the Deutz Glow Plug Assisted Heavy-Duty Methanol Engine. In 1987 [cited 2024 Feb 15]. p. 872245. Available from: https://www.sae.org/content/872245/

39. Hilger U, Jain G, Scheid E, Pischinger F, Bruetsch R, Bernhardt W, et al. Development of a Direct Injected Neat Methanol Engine For Passenger Car Applications. In 1990 [cited 2024 Feb 15]. p. 901521. Available from: https://www.sae.org/content/901521/

40. Goetz WA, Barringer CG, Bozzelli MA. Utilizing Neat Methanol and Glow Plug Ignition in DI Diesels: Laboratory Testing of a Single and Multi-Cylinder Engine. SAE Transactions. 1994;103:711–26.

41. Krishnan RA, Panda K, Ramesh A. Simulation Studies on Glow Plug Assisted Neat Methanol Combustion in a Diesel Engine. In 2022.

42. Agama JR, Abata DL, Mullins ME. Catalytic Ignition of Methanol in a Diesel Engine with a Platinum-Coated Glow Plug. In 1991 [cited 2024 Feb 15]. p. 911737. Available from: https://www.sae.org/content/911737/

43. Mitchell WL, Litzinger TA, Santavicca DA. Neat Methanol Combustion in a D.I. Diesel Engine Using Catalytically Coated Glow Plugs. In 1991 [cited 2024 Feb 15]. p. 912418. Available from: https://www.sae.org/content/912418/

44. Aziz A. High octane number fuels in advanced combustion modes for sustainable transportation. Lund: Faculty of Engineering, Department of Energy Sciences, Lund University; 2020. 95 p.

45. Svensson M, Tuner M, Verhelst S. Investigation of Combustion Characteristics of a Fuel Blend Consisting of Methanol and Ignition Improver, Compared to Diesel Fuel and Pure Methanol. In Detroit, Michigan, United States; 2024 [cited 2024 Apr 25]. p. 2024-01–2122. Available from: https://www.sae.org/content/2024-01-2122

46. Emission Standards: Europe: Heavy-Duty Truck and Bus Engines [Internet]. [cited 2024 May 30]. Available from: https://dieselnet.com/standards/eu/hd.php

47. Pucilowski M. Numerical Studies of Methanol PPC Engines and Diesel Sprays. Energy Sciences. 2019;