CIMAC CONGRESS 25
ZURICH, MAY 19 – 23, 2025

2025 | 383

Study on the performance and optimization of pilot diesel-ignited HPDI methanol combusition

Dual Fuel / Gas / Diesel

minghao xiahou, Tianjin university

Tianlong Lu, Tianjin university
Zhen Zeng, Tianjin university
Tianyou Wang, Tianjin university
Haoye Liu, Tianjin university

ABSTRACT

To address the challenges of greenhouse gas emissions and environmental pollution caused by fossil fuel combustion, researchers have turned to methanol, a clean, efficient, and carbon-neutral fuel, as an alternative energy source. In recent years, the pilot diesel-ignited high-pressure direct-injection (HPDI) methanol combustion mode has attracted considerable attention due to its potential to achieve high thermal efficiency and ultra-low emissions with a high methanol substitution rate. However, further studies have revealed that this combustion mode suffers from combustion instability and incomplete combustion under low load condition, limiting its application in low load and constraining further improvement in the overall methanol substitution rate of engines. Therefore, optimization of low load condition is critical. This study investigated the combustion and emission characteristics of the pilot diesel-ignited HPDI methanol combustion. The impact of methanol substitution rate, intake condition, and injection parameter on engine combustion and emissions under low load was also explored, followed by an optimization of the low load operating condition. The results indicated that under low-load conditions, the low in-cylinder temperature combined leads to incomplete and unstable combustion. Reducing intake pressure and methanol injection pressure can reduce CO and NOx emissions, with minimal impact on combustion stability. Increasing intake temperature and reducing diesel injection pressure can reduce CO emissions and engine COV, but may lead to higher NOx emissions. Additionally, an optimal diesel injection timing can reduce CO emissions and improve combustion stability. Finally, through the optimization path of "delayed diesel injection timing - increased intake temperature - reduced intake pressure - reduced methanol injection pressure - reduced diesel injection pressure," the optimization of the pilot diesel-ignited HPDI methanol engine was achieved under low load condition, resulting in an efficient and stable combustion with a methanol substitution rate of 95.8% and an ITE of 51.34%.

1 INTRODUCTION

Compression ignition (CI) engines, as a high thermal efficiency and power density energy conversion device, are widely used in automobiles, ships, and construction machinery [1]. However, the majority of CI engines currently use conventional diesel fuel, leading to substantial emissions of CO_2, gaseous pollutants, and other significant environmental impacts [2]. Methanol is a clean and renewable fuel. Its liquid state at room temperature allows for easy transport and refueling, with an energy density comparable to that of diesel [3]. Replacing diesel with methanol in CI engines can improve emissions performance in the short term while offering substantial potential for carbon reduction and emissions mitigation in the medium to long term.

However, methanol has low reactivity, with a cetane number (~4) far lower than that of diesel (>50), a higher autoignition temperature (~738 K), and a high latent heat of vaporization (~1109 kJ/kg), which lead to ignition challenges and potential misfires in CI engines [4]. Therefore, high-reactivity fuels like diesel are typically used as ignition improvers or pilot fuels to facilitate methanol ignition and combustion in CI engines. Methanol-diesel blended fuel compression combustion is the simplest strategy, in which a high proportion of diesel fuel is mixed with methanol to form a blended fuel for compression combustion. However, due to the immiscibility of methanol and diesel, emulsifiers such as higher alcohols and biodiesel must be added to ensure the stability of the blended fuel, which increases the overall fuel cost. Additionally, the methanol content in the blended fuel is typically low (< 30%) [5, 6], resulting in a limited improvement in engine combustion performance. Piloted diesel-premixed methanol combustion is a widely researched strategy for methanol CI combustion [7, 8]. However, issues such as misfire and incomplete combustion at low load, as well as pre-ignition and knocking at medium to high loads, limit the methanol substitution rate [9]. To enable CI combustion with a high methanol substitution rate, the pilot diesel-ignited high-pressure direct-injection (HPDI) methanol combustion mode has been developed. In this mode, diesel is injected near top dead center (TDC), creating a high-temperature flame that ignites the subsequently injected methanol, resulting in highly efficient combustion [10]. This combustion mode significantly enhances control over methanol mixing and combustion processes, thereby improving combustion controllability and stability. It offers the potential for an ultra-high methanol substitution rate, maximizing the low-carbon emission benefits of methanol.

The first experimental study of pilot diesel-ignited HPDI methanol combustion was conducted by Saccullo et al. [11]. They modified the cylinder head of a heavy-duty engine with a 131 mm bore and 2.1 L displacement by installing a three-hole side diesel injector next to the central main methanol injector, successfully achieving stable pilot diesel-ignited HPDI methanol combustion. Under similar operating conditions, this combustion mode delivered thermal efficiency comparable to conventional diesel combustion, with slightly lower NO_x emissions and significantly reduced soot emissions. Further studies demonstrated that under low, medium, and high loads, the performance of pilot diesel-ignited HPDI methanol combustion was superior to that of conventional diesel combustion (CDC), with thermal efficiency improved by 3.5%, reduced emission levels, and methanol replacing over 90% of the diesel fuel at low load [12]. However, this mode also produced higher peak in-cylinder pressures and peak pressure rise rates.

However, with the further study, it is found that the addition of more than 90% methanol fuel under low load will make the combustion stability deteriorate, limiting the possibility of achieving ultra-high methanol substitution rate under low load. Dong et al. [10] conducted experiments on a diesel engine with a bore of 111 mm and a displacement of 1.4 L, and achieved pilot diesel-ignited HPDI methanol combustion over a broad load range, from 4.2 to 13.8 bar IMEP. However, significant declines in combustion stability were observed at lower loads. At 4.2 bar IMEP, the methanol substitution rate was below 50%, with high CO and THC emissions. Wang et al. [13] conducted experiments on a light-duty two-valve diesel engine with a bore of 86 mm and a displacement of 0.42 L, to examine the impact of the methanol substitution rate on the performance and emissions of pilot diesel-ignited HPDI methanol combustion at low and medium engine loads. The results showed maximum methanol substitution rate (MSR) of up to 87% under medium load 5.5 bar IMEP, but only up to 69% MSR at low load 1.4 bar IMEP, and as the MSR increasing, CO and THC emissions increase significantly, resulting in a decrease in thermal efficiency. In terms of simulation, Li et al. [14, 15] conducted a series of simulation studies on a coaxial pilot diesel-ignited HPDI methanol combustion engine with a bore of 108 mm and a displacement of 1.05 L. The results demonstrated that this combustion mode effectively controls the heat release rate and suppresses knocking combustion. However, under low-load conditions, the high latent heat of vaporization of methanol interferes with the ignition and combustion of diesel, adversely affects the ignition of methanol sprays, prolongs the ignition delay of methanol, and increases emissions of unburned CO and THC. Li et al. [16] also built a coaxial pilot diesel-ignited HPDI methanol combustion engine model based on a diesel engine with an 82 mm bore and a displacement of 0.47 L. Through numerical simulations, they compared the combustion process and emission characteristics of this mode with the reactivity-controlled compression ignition (RCCI) mode at 3.7 bar IMEP. The results showed that compared to RCCI, the coaxial pilot diesel-ignited HPDI methanol combustion achieved higher thermal efficiency. However, it required a higher exhaust gas recirculation (EGR) rate to reduce ringing intensity and NO_x emissions. The addition of EGR further reduced the in-cylinder combustion temperature, leading to increased CO and THC emissions and negatively impacting combustion stability.

In summary, pilot diesel-ignited HPDI methanol combustion enabled efficient combustion across the wide load range. Compared to the CDC and RCCI modes, this combustion strategy achieved higher thermal efficiency and nearly eliminates soot emissions due to the high proportion of methanol involved in combustion. However, at low load, the high latent heat of vaporization and low combustion temperature of methanol could lead to issues such as combustion instability and incomplete combustion, which limited further increases in MSR under low load. To address this, optimization of the pilot diesel-ignited HPDI methanol engine at low load is necessary to enhance MSR and achieve efficient and clean combustion across the wide operating range. In this study, a single-cylinder compression ignition engine was modified with a centrally located HPDI methanol injector and a side HPDI diesel injector. Experimental investigation was conducted to examine the combustion and emission characteristics of pilot diesel-ignited HPDI methanol combustion. Specifically, for low load condition, the effects of MSR, intake condition, and injection parameter on engine combustion and emissions were studied. Optimization strategy for low load was proposed, including delaying diesel injection timing, increasing intake temperature, reducing intake pressure, and decreasing the injection pressures of both methanol and diesel.

2 EXPERIMENTAL SETUP AND METHOD

2.1 Engine and experimental facilities

The single-cylinder engine used in this study was adapted from the YC K12 six-cylinder commercial engine, retaining the same combustion chamber structure. The engine specifications of the single-cylinder engine were listed in Table 1. To enable pilot diesel-ignited HPDI methanol combustion, the cylinder head of the single-cylinder engine was modified to accommodate a high-pressure methanol injector and a high-pressure diesel injector, while maintaining the original four-valve configuration of the cylinder head. The methanol injector was positioned centrally in the original cylinder head, while the diesel injector was offset from the cylinder center and slightly tilted, as illustrated in Figure 1. The injection pressures of the two HPDI injectors were supplied by two independent high-pressure common rail systems. An open ECU was used to flexibly control the injection timing and injection frequency of both injectors.

Table 1. Engine specifications.

Parameters	Value
Bore (mm)	129
Stroke (mm)	155
Displacement (L)	2.02
Compression ratio	16.5
Inlet valve closing (CAD ATDC)	-159
Exhaust valves opening (CAD ATDC)	128
Main methanol injector	10×0.2 mm×149°
Upper limit of methanol injection pressure (MPa)	140
Pilot diesel injector	6×0.1 mm×140°
Upper limit of diesel injection pressure (MPa)	180

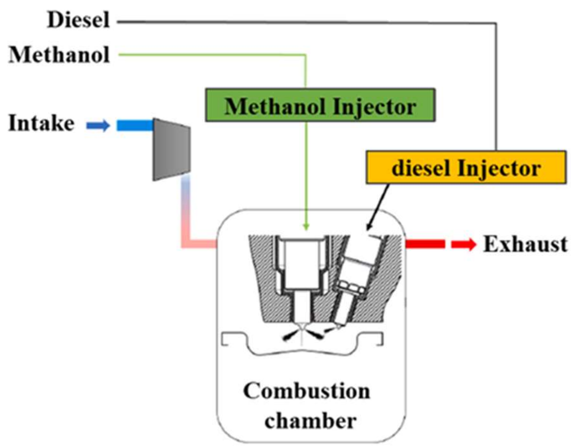

Figure 1. Schematic of the combustion chamber set-up.

Schematic of the experimental system was shown in Figure 2. An electric dynamometer (XYDC CAC200) was used to maintain the engine at a constant speed during testing. Simulated boosting was employed to control the intake pressure and temperature using an HP air system. In-cylinder pressure was measured with a Kistler 6125C piezoelectric pressure transducer, and combustion process characteristics such as apparent heat release rate (AHRR) and coefficient of variation (COV) were analyzed using a Kistler KiBox combustion analyzer. During the test, 300 consecutive cycles of cylinder pressure data were recorded and averaged, and the average data was a representative cylinder pressure trace. Gaseous emissions, including carbon monoxide (CO), unburned hydrocarbons (HC), and nitrogen oxides (NO_x), were measured using a CUBIC Gasboard-9801 exhaust gas analyzer. Exhaust smoke opacity was measured with an AVL 439 opacity meter.

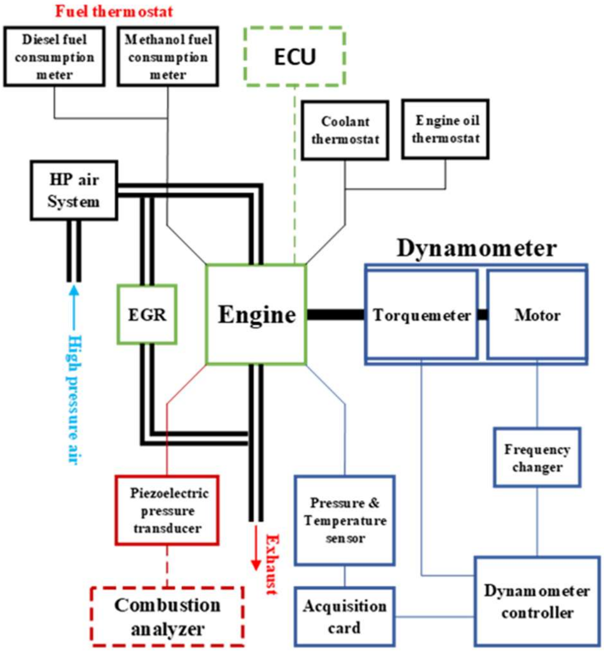

Figure 2. Schematic of the experimental system.

2.2 Test conditions and methodology

The test conditions were listed in Table 2. Experiments were conducted at 1200 r/min, with a basal injection pressure of 60 MPa for methanol and 80 MPa for diesel. Pilot diesel-ignited HPDI methanol combustion was tested over a wide load range corresponding to an indicated mean effective pressure (IMEP) of 4–14 bar. During the tests, injection timing was adjusted to maintain the combustion phasing CA50 as close as possible to 9 CAD ATDC, and the MSR was controlled within the range of 90–97%. The intake air temperature was controlled at 32±3℃, the cooling water temperature was maintained at 80±5℃, and the engine oil temperature was kept at 80±5℃. Low load tests were based on a reference condition of 4 bar IMEP and focused on examining the effects of MSR, intake condition, and injection parameter.

The apparent heat release rate (AHRR) was calculated using the following equation:

$$AHRR = \frac{\gamma}{\gamma-1} p \frac{dV}{d\theta} + \frac{1}{\gamma-1} V \frac{dp}{d\theta} \qquad (1)$$

where γ is the ratio of specific heat, V is the cylinder volume, θ is the crank angle, and p is the average in-cylinder pressure. The crank angles corresponding to 10%, 50%, and 90% of the accumulated apparent heat release are defined as CA10, CA50, and CA90, respectively.

The indicated thermal efficiency (ITE) and methanol substitution ratio (MSR) were calculated from:

$$ITE = W_i/(m_D \times Hu_D + m_M \times Hu_M) \qquad (2)$$

$$MSR = m_M \times Hu_M/(m_D \times Hu_D + m_M \times Hu_M) \qquad (3)$$

where W_i is the indicated work, m_D and m_M are diesel and methanol injection mass per cycle, respectively, Hu_D and Hu_M are the low heat values of diesel and methanol fuel.

Table 2. Engine test conditions.

Section	3.1	3.2 (Base)
Speed (r/min)	1200	1200
IMEP (bar)	4/6/8/10/12/14	4
Intake pressure (bar)	1.2/1.3/1.4/1.6/1.8/2	1.2
Diesel injection timing (CAD ATDC)	-18/-18/-20/-22/-24/-24	-18
Methanol injection timing (CAD ATDC)	-8/-8/-10/-12/-14/-14	-8
Diesel injection pressure (MPa)	80	80
Methanol injection pressure (MPa)	60	60
MSR (%)	90-97	90
overall equivalence ratio (-)	0.21/0.29/0.36/0.40/0.40/0.42	0.42

3 RESULTS AND DISCUSSION

3.1 Combustion and emission characteristics under different loads

This subsection investigated the combustion and emission characteristics of pilot diesel-ignited HPDI methanol combustion under wide load conditions. Preliminary tests revealed that advancing the diesel injection timing by 10 CAD results in a stable methanol ignition and combustion process. Consequently, in this subsection, the diesel pilot injection timing was maintained 10 CAD earlier than methanol injection. Since the ignition process is critical in pilot diesel-ignited HPDI methanol combustion, the diesel injection pressure and pulse width were kept constant at 80 MPa and 350 μs, respectively, across all load conditions. Load variations were achieved solely by adjusting the methanol injection pulse width with a constant 60 MPa pressure.

Figure 3 presented the in-cylinder pressure and AHRR results from 4 to 14 bar IMEP. The AHRR curves revealed that pilot diesel-ignited HPDI methanol combustion exhibits a distinct two-stage heat release process: the pilot diesel ignition and the main methanol combustion. Due to the small quantity of pilot diesel fuel, the initial heat release peak is relatively low. For the main methanol heat release stage, the characteristics vary with load. At low loads (4–6 bar IMEP), the methanol heat release displayed a single-peak dominated by partially premixed combustion. As the load increases (>8 bar IMEP), the methanol heat release gradually exhibited a dual-peak, with significant diffusion combustion characteristic appearing in the later stage. Overall, the peak AHRR of the methanol combustion stage does not significantly increase with load, effectively avoiding knocking issue at high load.

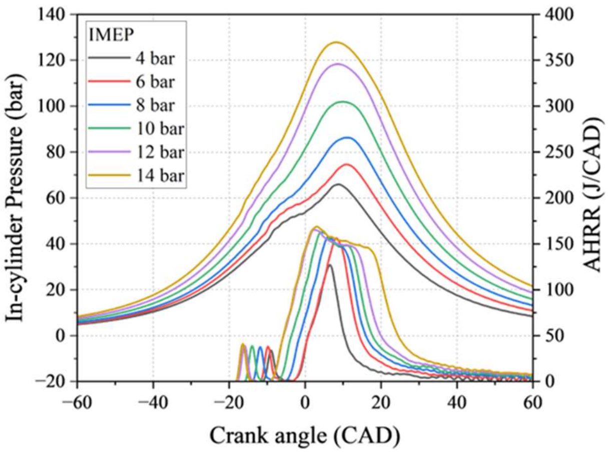

Figure 3. In-cylinder pressure and apparent heat release rate under different IMEPs.

Figure 4 illustrated the variations in the MSR, ITE, and COV as the IMEP increases for pilot diesel-ignited HPDI methanol combustion. Since the diesel injection pressure and pulse width were kept constant during the test, the diesel injection mass per cycle remained approximately unchanged across all conditions. As engine load increased, the methanol injection mass per cycle also increased, leading to a higher MSR. At low load 4 bar IMEP, the MSR was only 90%, whereas at medium or high loads (>8 bar IMEP), the MSR exceeded 95%. However, the COV was significantly higher at low load compared to other loads, indicating unstable combustion at low load.

Figure 5 presented the emissions of NO_x, CO, and THC across the wide load range for pilot diesel-ignited HPDI methanol combustion. At low load, NO_x emissions were relatively low but increased significantly with load. This can be attributed to the rapid mixing of methanol and air. At low load, methanol combustion predominantly occurred as partially premixed combustion, resulting in lower local equivalence ratio and local combustion temperature, reducing NO_x formation. At higher loads, the diffusion combustion characteristic of methanol became more prominent, leading to substantial NO_x generation in the diffusion flame. For medium or high loads, CO and THC emissions were minimal. However, at low load, especially at 4 bar IMEP, CO and THC emissions were significantly higher. This was mainly due to the dominance of partially premixed combustion at low load and the high latent heat of vaporization of methanol, which caused low local temperature in the cylinder and increased the amount of unburned CO and THC.

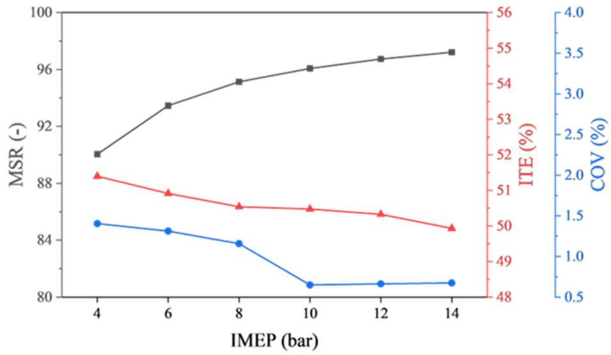

Figure 4. Combustion characteristics under different IMEPs.

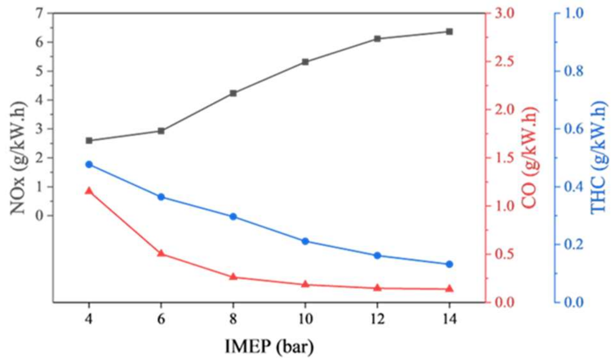

Figure 5. Emission characteristics under different IMEPs.

3.2 The influence factor of combustion and emission under low load

This subsection investigated the influencing factors on the combustion and emissions of pilot diesel-ignited HPDI methanol engine under low load, focusing primarily on the effects of various parameters on the COV and unburned CO emissions. Using the 4 bar IMEP operating condition described in Table 2 as the base case, only the parameters of the studied factors were varied during the tests, while other control parameters were kept constant to ensure comparability of results. The study specifically examined the effects of MSR, intake pressure and temperature, injection timing and pressure.

3.2.1 Methanol substitution rate

Figure 6 showed the in-cylinder pressure and AHRR under different MSR at low load of 4 bar IMEP. MSR were controlled by adjusting the injection pulse widths of diesel and methanol while maintaining constant injection pressures (diesel is 80 MPa, methanol is 60 MPa). The AHRR curves indicated that as the MSR increases, the peak of diesel heat release decreases while peak of the methanol heat release increases. Overall, the methanol heat release process under different MSR is predominantly characterized by single-peak partially premixed combustion.

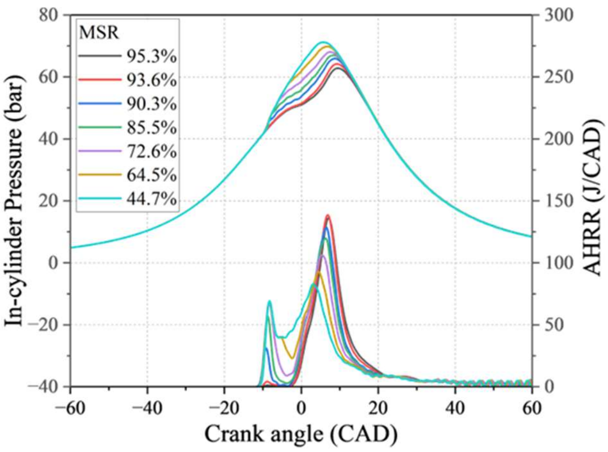

Figure 6. In-cylinder pressure and AHRR under different MSR at 4 bar IMEP.

Figure 7 and Figure 8 depicted the combustion and emission characteristics under different MSR at low load of 4 bar IMEP. The combustion results showed that increasing the MSR leads to higher COV, along with reductions in combustion efficiency and ITE. Especially, at high substitution rate (MSR>90%), the COV increased significantly, resulting in substantial deterioration in combustion stability, and the decline in combustion efficiency further reduced engine thermal efficiency. From the emission results, higher MSR leaded to increased CO emissions due to the methanol's high latent heat of vaporization, which reduced local in-cylinder temperature and contributed to incomplete combustion. This is the primary cause of the reduced combustion efficiency. However, the decrease in local combustion temperature also reduced NO_x emissions. In summary, increasing the MSR in the low load effectively reduced NO_x emissions. However, challenges related to combustion stability and incomplete combustion must be addressed to optimize performance.

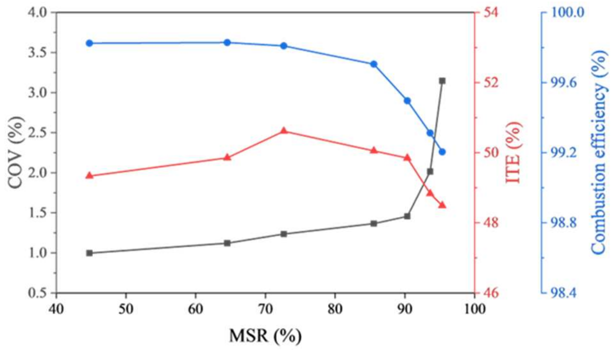

Figure 7. Combustion characteristics under different MSR at 4 bar IMEP.

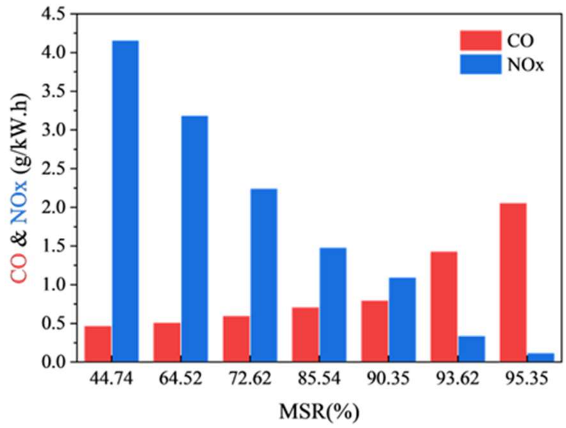

Figure 8 Emission characteristics under different MSR at 4 bar IMEP.

3.2.2 Intake condition

Normally, intake pressure and temperature have a significant impact on engine combustion and emissions. Figure 9 showed the effects of different intake pressures on the COV, CO and NO_x emissions at low load of 4 bar IMEP. It can be observed that as intake pressure increases, both CO and NO_x emissions rise. This is likely due to the increased intake pressure leading to a higher intake mass, which raised the average in-cylinder density. As a result, the spray penetration length of the diesel and methanol is shortened, resulting in a more concentrated fuel-air mixture and higher local combustion temperature, thereby increasing NO_x emissions. Simultaneously, the shorter diesel spray penetration length slightly reduced ignition efficiency, reducing combustion efficiency. And the increase in intake pressure leaded to a decrease in the average in-cylinder temperature during the combustion phase, which further contributed to the increase in CO emissions. Intake pressure has a minimal effect on COV at low load. Therefore, reducing intake pressure appropriately can help decrease both CO and NO_x emissions at low load.

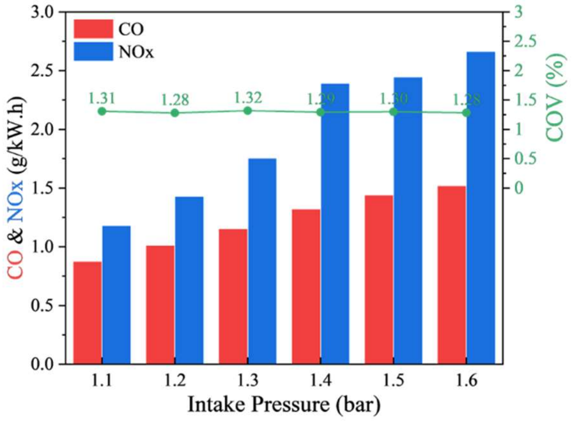

Figure 9. CO, NO_x emission and COV under different intake pressures at 4 bar IMEP.

Figure 10 showed the effects of different intake temperatures on the COV, CO and NO_x emissions at low load of 4 bar IMEP. It can be seen that increasing intake temperature effectively reduced CO emissions. This is because higher intake temperatures raised the average in-cylinder temperature, which enhanced combustion efficiency at low load and improved the incomplete combustion issue. Additionally, increasing intake temperature can reduce COV, leading to more stable combustion and allowing for a higher MSR under low load. However, increasing intake temperature also resulted in a significant rise in NO_x emissions. Therefore, it is advisable to avoid excessively high intake temperature, and a balance between CO and NO_x emissions should be considered.

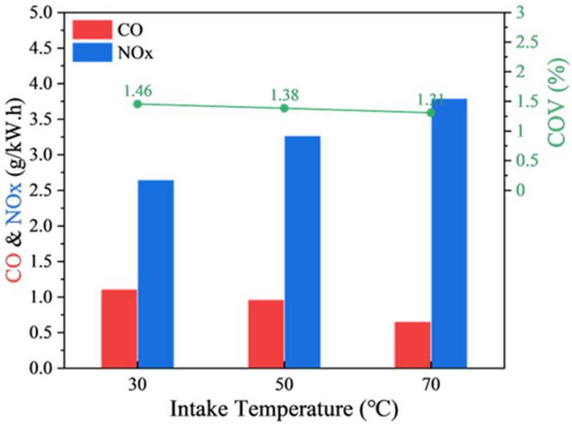

Figure 10. CO, NO_x emission and COV under different intake temperatures at 4 bar IMEP.

3.2.3 Injection parameter

Injection parameters are one of the most commonly used methods for controlling engine combustion and emissions. Figure 11 illustrated the effects of different diesel and methanol injection pressures on the COV, CO and NO_x emissions at low load of 4 bar IMEP. When adjusting the methanol injection pressure, the overall injection timing of both fuels would be further optimized to ensure that CA50 remained near 9 CAD ATDC. From Figure 11(a), it can be observed that decreasing the diesel injection pressure slightly reduced CO emissions and engine COV. This is primarily due to the fact that when the diesel injection pressure is reduced, the injection pulse width of diesel will increase to maintain a consistent fuel mass per cycle. This resulted in a prolonged diesel combustion phase, which enhanced the ignition efficiency of pilot diesel and improved combustion efficiency. As a result, CO emissions decreased and combustion stability was improved. However, reducing the diesel injection pressure slightly increased NO_x emissions. Figure 11(b) showed that decreasing the methanol injection pressure slightly reduced both CO and NO_x emissions. This occurred because decreasing the methanol injection pressure can reduce the mass of methanol injected per unit of time, which alleviated the issue of local temperature reduction caused by methanol's high latent heat of vaporization. Thereby, CO emissions are reduced. Additionally, the longer methanol injection duration increased the proportion of premixed combustion, thereby reducing NO_x formation. Although decreasing the methanol injection pressure resulted in a slight increase in the COV, the effect is relatively small.

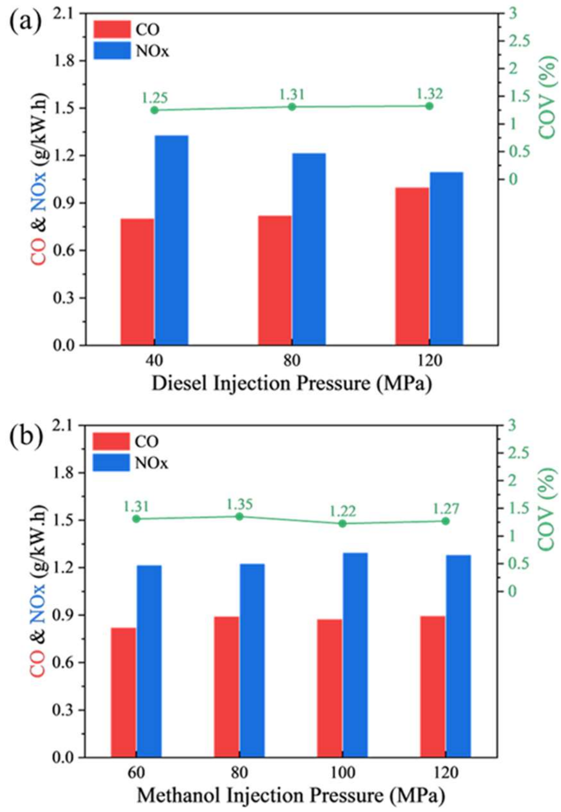

Figure 11. CO, NO_x emission and COV under different injection pressures at 4 bar IMEP.

Since altering methanol injection timing directly affects the combustion phase CA50, leading to decreased combustion work and reduced thermal efficiency, adjusting methanol injection timing is not suitable for optimizing pilot diesel-ignited HPDI methanol combustion. This subsection only presented the effects of different diesel injection timings on the COV, CO and NO_x emissions at low load of 4 bar IMEP, as shown in Figure 12. It can be seen that premature diesel injection timing deteriorated ignition efficiency, resulting in reduced combustion stability and increased CO emissions. However, it allowed for more methanol to be partially premixed combustion, thereby reducing NO_x emissions. Delaying the diesel injection timing effectively improved CO emissions and combustion stability. However, excessively delayed injection timing leaded to a short time dwell between the diesel and methanol injections. The latent heat of vaporization of methanol then restrained diesel ignition, leading to higher CO emissions and reduced thermal efficiency. Therefore, selecting an appropriate diesel injection timing is crucial.

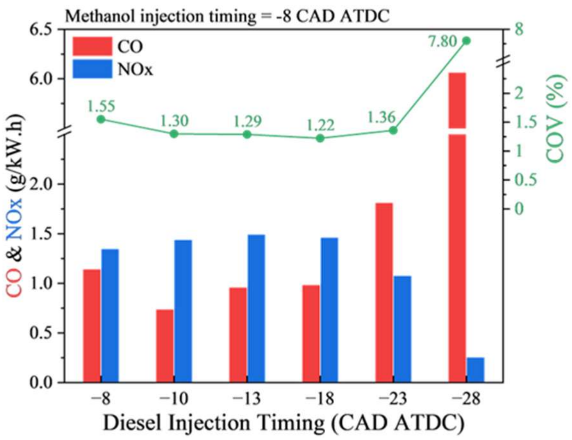

Figure 12. CO, NO_x emission and COV under different diesel injection timings at 4 bar IMEP.

3.3 Optimization at low load

Figure 13 showed the base case of low load condition for pilot diesel-ignited HPDI methanol engine, with specific combustion and emission parameters provided in Table 3. As shown, CO and THC emissions were relatively high under low load condition, and when the MSR reached 93.5%, the engine COV exceeded 3%, appearing combustion instability. This is primarily due to the low in-cylinder temperature at low load, while methanol has a high ignition temperature, leading to incomplete and unstable combustion. Furthermore, to ensure reliable ignition, a certain mass of diesel fuel was required, making it difficult to further increase the MSR at low load. Therefore, this section focused on optimizing the engine's combustion and emissions at low load to achieve efficient and stable combustion with 95% MSR.

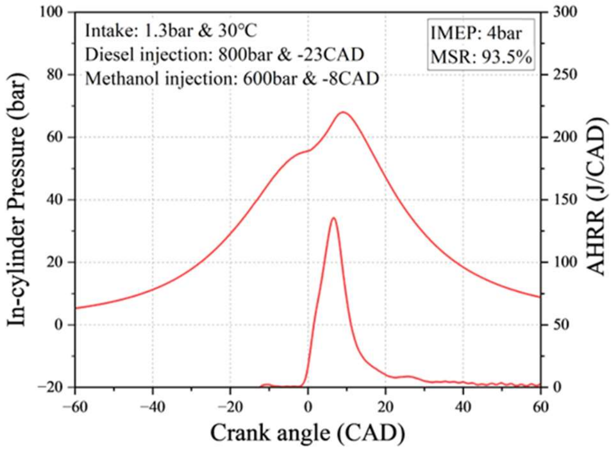

Figure 13. In-cylinder pressure and heat release rate under base case of low load.

Table 3. Combustion and emission characteristics under base case of low load.

Parameters	Unit	Value
CO	g/kW.h	3.74
THC	g/kW.h	1.07
NO_x	g/kW.h	1.98
MSR	-	93.5%
ITE	-	50.92%
Combustion Efficiency	-	98.79%
R_{max}	bar/deg	4.00
COV	%	3.02

Based on the findings in Section 3.2, it is evident that increasing intake temperature, decreasing intake pressure, reducing the injection pressures of both diesel and methanol, and adjusting the appropriate diesel injection timing can effectively reduce CO emissions and engine COV, thereby improving combustion stability and increasing MSR. Hence, this section optimized the base case of low load condition by adjusting injection parameters and intake conditions. The specific operating parameters were provided in Table 4, and the optimization processes were illustrated in Figure 14. It can be seen that, through the optimization path of “delayed diesel injection timing - increased intake temperature - reduced intake pressure - reduced methanol injection pressure - reduced diesel injection pressure,” ultimately resulted in an efficient and stable combustion under low load condition with a MSR of 95.8% and an ITE of 51.34%. Additionally, unburned CO and THC emissions were reduced to half of the base case, while NO_x emissions slightly increased. This optimization achieves ultra-high methanol substitution and efficient, clean, stable combustion in the pilot diesel-ignited HPDI methanol engine under low load condition.

Table 4. Engine operating conditions under optimization path at low load condition.

	Diesel injection timing (CAD ATDC)	MSR	Intake temperature (℃)	Intake pressure (bar)	Methanol injection pressure (MPa)	Diesel injection pressure (MPa)
Base	**-23**	**93.5%**	**30**	**1.3**	**60**	**80**
1	**-18**	93.5%	30	1.3	60	80
2	-18	**95.8%**	30	1.3	60	80
3	-18	95.8%	**40**	1.3	60	80
4	-18	95.8%	40	**1.1**	60	80
5	-19	95.8%	40	1.1	**50**	80
6	-19	95.8%	40	1.1	50	**60**

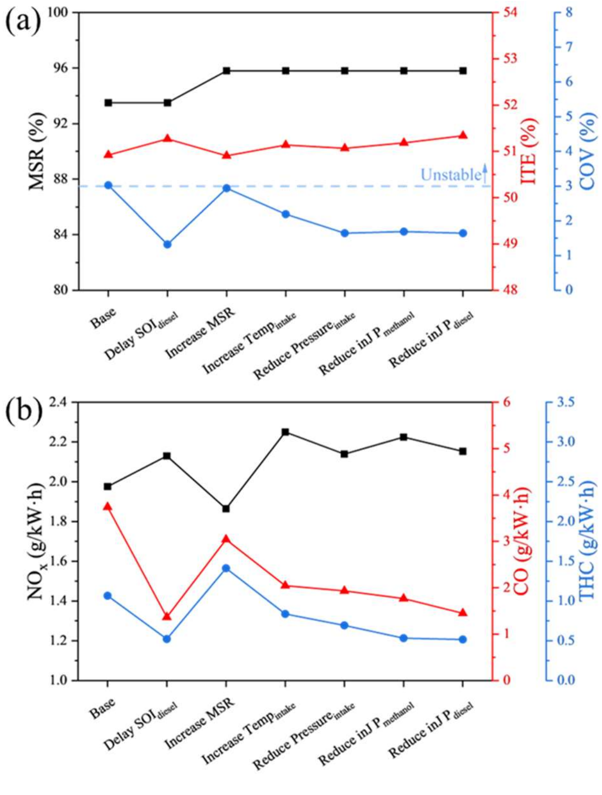

Figure 14. Combustion and emission characteristics under optimization path at low load.

4 CONCLUSION

This study investigated the combustion and emission characteristics of the pilot diesel-ignited HPDI methanol combustion. The impact of MSR, intake condition, and injection parameter on engine combustion and emissions under low load was also explored, followed by an optimization of the low load operating condition. The main conclusions are as follows:

- The pilot diesel-ignited HPDI methanol combustion achieves efficient combustion with a MSR of 90-97% across a wide load range of 4-14 bar IMEP. However, combustion instability and incomplete combustion issues were observed under low load condition.
- Increasing the MSR at low load can effectively reduce NO_x emissions and achieve clean combustion. However, at high MSR (>90%), further increase in the MSR resulted in a significant increase in COV, along with a considerable rise in unburned CO emissions, leading to a deterioration in thermal efficiency.
- Under low load condition, reducing intake pressure and methanol injection pressure can reduce CO and NO_x emissions, with minimal impact on combustion stability. Increasing intake temperature and reducing diesel injection pressure can reduce CO emissions and engine COV, but may lead to higher NO_x emissions. Both too early and too late diesel injection timing significantly increase CO emissions and COV, and deteriorated thermal efficiency. Therefore, selecting an appropriate diesel injection timing is crucial, and a diesel-to-methanol injection timing dwell of 5-15 CAD is recommended to effectively reduce CO emissions and improve combustion stability.
- Through the optimization path of "delayed diesel injection timing - increased intake temperature - reduced intake pressure - reduced methanol injection pressure - reduced diesel injection pressure," the optimization of the pilot diesel-ignited HPDI methanol engine was achieved under low load condition, resulting in an efficient and stable combustion with a MSR of 95.8% and an ITE of 51.34%. Additionally, unburned CO and THC emissions were reduced to half of the base case, while NO_x emissions slightly increased.

5 REFERENCES

[1] Reitz RD, Ogawa H, Payri R, Fansler T, Kokjohn S, Moriyoshi Y, et al. IJER editorial: The future of the internal combustion engine, *International Journal of Engine Research*, 2019;21(1):3-10.

[2] Conway G, Joshi A, Leach F, García A, Senecal PK. A review of current and future powertrain technologies and trends in 2020, *Transportation Engineering*, 2021;5.

[3] Verhelst S, Turner JWG, Sileghem L, Vancoillie J. Methanol as a fuel for internal combustion engines, *Progress in Energy and Combustion Science*, 2019;70:43-88.

[4] Zhen X, Wang Y. An overview of methanol as an internal combustion engine fuel, *Renewable and Sustainable Energy Reviews*, 2015;52:477-93.

[5] Hasan AO, Osman AI, Al-Muhtaseb AaH, Al-Rawashdeh H, Abu-jrai A, Ahmad R, et al. An experimental study of engine characteristics and tailpipe emissions from modern DI diesel engine fuelled with methanol/diesel blends, *Fuel Processing Technology*, 2021;220.

[6] Sayin C, Ozsezen AN, Canakci M. The influence of operating parameters on the performance and emissions of a DI diesel engine using methanol-blended-diesel fuel, *Fuel*, 2010;89(7):1407-14.

[7] Yao C, Pan W, Yao A. Methanol fumigation in compression-ignition engines: A critical review of recent academic and technological developments, *Fuel*, 2017;209:713-32.

[8] Wang B, Yao A, Yao C, Chen C, Lu H, Feng J. Experimental investigation on methanol auto-ignition in a compression ignition engine under DMDF mode, *Fuel*, 2019;237:133-41.

[9] Wang Q, Wei L, Pan W, Yao C. Investigation of operating range in a methanol fumigated diesel engine, *Fuel*, 2015;140:164-70.

[10] Dong Y, Kaario O, Hassan G, Ranta O, Larmi M, Johansson B. High-pressure direct injection of methanol and pilot diesel: A non-premixed dual-fuel engine concept, *Fuel*, 2020;277.

[11] Saccullo M, Benham T, Denbratt I. Dual Fuel Methanol and Diesel Direct Injection HD Single Cylinder Engine Tests, *SAE Technical Paper Series*, 2018.

[12] Saccullo M, Nygren A, Benham T, Denbratt I. Alcohol flexible HD single cylinder diesel engine tests with separate dual high pressure direct fuel injection, *Fuel*, 2021;294.

[13] Wang Y, Xiao G, Li B, Tian H, Leng X, Wang Y, et al. Study on the performance of diesel-methanol diffusion combustion with dual-direct injection system on a high-speed light-duty engine, *Fuel*, 2022;317.

[14] Li Z, Wang Y, Geng H, Zhen X, Liu M, Xu S, et al. Effects of diesel and methanol injection timing on combustion, performance, and emissions of a diesel engine fueled with directly injected methanol and pilot diesel, *Applied Thermal Engineering*, 2019;163.

[15] Li Zhiyong. Study of combustion process and emissions on a diesel engine with directly injected methanol and pilot diesel, *Univ. of Tianjin*, 2019.

[16] Li Y, Jia M, Xu L, Bai X-S. Multiple-objective optimization of methanol/diesel dual-fuel engine at low loads: A comparison of reactivity controlled compression ignition (RCCI) and direct dual fuel stratification (DDFS) strategies, *Fuel*, 2020;262.