

Experimental study on ultra-low raw emissions in diesel/methanol dual fuel engine based on dual-loop EGR

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Abstract. In this paper, an experimental investigation on achieving ultra-low raw emissions in a diesel/methanol dual fuel engine based on dual-loop EGR was carried out. The effect of dual-loop EGR (High pressure EGR and low pressure EGR) on the combustion, performance and emissions of methanol engine has been studied comprehensively. The results show that ultra-low NO_x (<0.4g/kWh) and PM (<10 mg/kWh) emissions can be achieved simultaneously in diesel methanol dual fuel engine with the help of EGR. The combustion phase is delayed with the increase of EGR rate in both EGR modes. However, the methanol equivalence ratio and in cylinder combustion temperature in high pressure EGR mode are significantly higher than those in low pressure EGR mode. Therefore, the CO and THC emissions are obviously lower in high pressure EGR mode than that in low pressure EGR mode. The combustion efficiency and brake thermal efficiency of the engine are 1.9% and 9.6% higher in high pressure EGR mode than those in low pressure EGR mode, respectively.

1. Background

In order to solve the oil shortage and environmental problems, the development of clean alternative fuels of petroleum is a practical and feasible technical approach^[1-2]. Methanol is one of the most promising clean alternative fuels to petroleum. Vigorously developing methanol clean utilization technology is of great significance for taking into account sustainable economic growth and global carbon emission reduction^[3].

In recent years, dual-fuel low-temperature combustion technology with port injection of low-reactivity fuel and direct injection of high-reactivity fuel in the cylinder has become a research hotspot^[4-6]. Compared with single-fuel low-temperature combustion, the dual-fuel low-temperature combustion technology of direct injection of low-reactivity fuel and direct

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injection of high-reactivity fuel in the cylinder has two significant advantages^[7-9]. On the one hand, the activity of the mixture can be flexibly adjusted according to the range of operating conditions. Greatly broaden the operating range of the engine for efficient and clean combustion. On the other hand, the in-cylinder direct injection fuel injection strategy can control the local mixture activity and concentration stratification to achieve effective control of the combustion phase and combustion rate^[10-12].

Diesel Methanol Dual Fuel (DMDF) has great potential in simultaneously reducing oil consumption and harmful emissions^[13-15]. Studies have shown that the DMDF engine can meet the China V heavy-duty diesel vehicle emission regulations without urea aftertreatment^[16]. Meeting the stringent China VI emission requirements is an important challenge for DMDF engines.

Exhaust Gas Recirculation (EGR) technology is the most effective measure to achieve low-temperature combustion mode and reduce NO_x emissions^[17]. EGR has two important effects on the combustion process in the engine cylinder. On the one hand, EGR has a dilution effect, that is, exhaust gas enters the cylinder and causes the oxygen concentration in the cylinder to decrease^[18-19]. On the other hand, EGR also has a thermal effect: the components such as CO₂ and H₂O in the exhaust gas have a higher specific heat capacity, which reduces the average temperature in cylinder^[20].

For DMDF engines, EGR plays an important role in regulating the activity and thermal state of the mixture and improving the controllability of combustion. High-proportion EGR is a necessary measure for DMDF engines to achieve extremely low NO_x original emissions (<0.4 g/kWh).

In this paper, the effect of EGR strategy (high pressure/low pressure EGR) on the combustion and emission performances of DMDF were studied through the engine experiments. This study is aim to enable DMDM engine achieve the the China VI emission regulations without urea aftertreatment, which will provide a reference for the research of ultra-low emission engines.

2 Experimental system and methods

2.1 Experimental equipments

The tests were carried out on a high pressure common rail in-line 4-cylinder compression ignition engine. The engine is equipped with an electronically controlled methanol injection device in the intake port, which can run the DMDF combustion mode. The specific technical parameters of the engine are shown in Table 1.

Table 1. The main technical parameters of the test engine.

Parameters/units	Parameters
Air intake form	Turbo charging with inter-cooling
Cylinder arrangement	Inline
Number of cylinders	4
Fuel system	High pressure common rail
EGR form	Dual loop (high pressure/low pressure) EGR
Compression ratio	16.8
Baseline emission	National V
Bore × stroke/mm×mm	94 ×102
Total displacement of piston/L	2.8
Rated power/speed (kW/rpm)	96/3000
Maximum torque/speed (Nm/rpm)	400/1200~2290

Figure 1 is a schematic diagram of the test engine bench. The dynamometer used in the tests is a hydraulic dynamometer (Hangzhou Yike, SG400). The diesel ECU is controlled by calibration software (ETAS, INCA 7.1), and the methanol injection parameters are controlled by the methanol ECU and calibration software developed by Tianjin University. As shown in Figure 1, the test engine is equipped with a high and low pressure compound EGR system. Among them, the high-pressure EGR valve is controlled by ETAS INCA 7.1. The low-pressure EGR system is self-developed and controlled by the methanol calibration system.

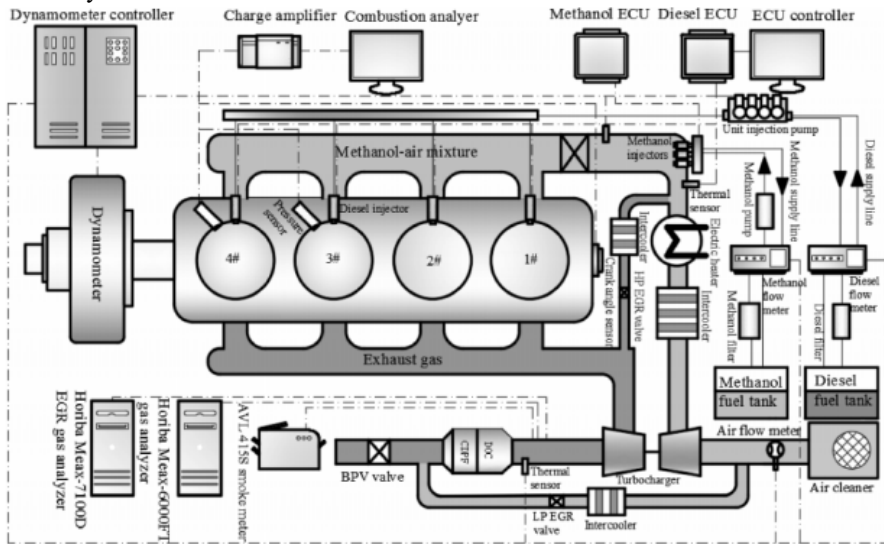


Fig. 1. Schematic diagram of the engine test bench.

2.2 Test fuels

The methanol used in the test is industrial methanol with a purity of 99.9%, and the diesel fuel is -10# China VI ultra-low sulfur diesel. The physical and chemical parameters of the test fuel are shown in Table 2.

Table 2. The physical and chemical parameters of the test fuels.

Parameters	Diesel	Methanol
Density@20°C (kg/m ³)	840	790
Cetane number	51	<5
Lower heating value (MJ/kg)	42.5	19.7
Latent heat of vaporization (kJ/kg)	260	1178
Theoretical air-fuel ratio	14.7	6.45
Sulfur content(mg/kg)	6	0
Spontaneous ignition point (°C)	316	464

2.3 Experimental procedure

In this study, 1690 r/min, 1.25 MPa BMEP was selected as the test conditions. The specific test boundary conditions are shown in Table 3. The other boundary conditions were kept unchanged during the experiment. Combustion and emission performance at different EGR

rates were measured in high-pressure EGR (HP-EGR) and low-pressure EGR (LP-EGR) modes, respectively.

In the tests, an AVL Indi-Smart 612 combustion analyzer was used to continuously measure 100 cycles of cylinder pressure data and averaged them to calculate the heat release rate and in-cylinder mean temperature. Gas emissions (including CO, THC, NO_x, CO₂) were measured with a exhaust gas analyzer (Horiba MEXA-7100DEGR). Data over 60 seconds (collection frequency is 1Hz) were continuously collected and averaged.

Table 3. The boundry conditions of the test.

Parameter	HP-EGR	LP-EGR
Speed/ r·min ⁻¹	1690	1690
BMEP/MPa	1.25	1.25
Methanol energy ratio/%	65	65
EGR rate/%	0~29	0~44
Intake air temperature /°C	35	35
Injection pressure/bar	1500	1500
Main injection timing/°CA BTDC	4	4
Pilot-injection amount/mg·cycle ⁻¹	5.0	5.0
Pilot-injection timing/°CA BTDC	44	44

The dry soot smoke was measured by a filter paper smoke meter (AVL 415S). PM emissions are calculated by dry soot smoke (FSN) according to the AVL empirical formula. The calculation method is shown in Equation 1.

$$PM = \frac{1}{0.405} \times 5.32 \times FSN \times e^{0.3062 \times FSN} \times 0.001 \times (m_{air} + m_{fuel}) / (1.2929 \times P_i) \quad (1)$$

In the formula, the unit of *PM* is g/kWh. In order to be consistent with the China VI emission standards, mg/kWh is used as the unit of *PM* in this article. *m_{air}* and *m_{fuel}* are the mass flow rates of air and fuel, respectively, in kg/h. *P_i* is the indicated power of the engine in kW.

Methanol Energy Ratio (MER) refers to the ratio of the calorific value of the methanol fuel premixed with intake air to the total calorific value of the fuel, and the unit is %. The calculation method is shown in formula 2:

$$MER = \frac{m_M \times LHV_M}{m_M \times LHV_M + m_D \times LHV_D} \times 100 \quad (2)$$

In the formula, *m_M* and *m_D* are the mass consumption rates of methanol and diesel in kg/h. *LHV_M* and *LHV_D* are the low calorific values of methanol and diesel, respectively, taking 19.7MJ/kg and 42.5MJ/kg according to literature for the definition of other working indicators of DMDF engine^[21].

3 Results and discussion

3.1 Intake and exhaust parameters

Figure 2 shows the effect of high/low pressure EGR on intake and exhaust parameters. It can be seen from the Fig.2(a) Under this test condition, the maximum EGR rate reached by the high-pressure EGR and the low-pressure EGR when fully opened is 23% and 21%, respectively, without the aid of the throttle valve. The further increase of the EGR rate needs to be achieved by increasing the closing degree of the back pressure valve (BPV).

It can be seen from the Fig.2(b) that low-pressure EGR has little effect on intake pressure. Only when the BPV is gradually closed, the pressure in front of the turbin will

rise. The difference is that low-pressure EGR has little effect on the performance of the supercharger, so the decrease in intake air flow is relatively light.

In addition, under low pressure EGR, the addition of components such as CO_2 and H_2O with high heat capacity can significantly increase the heat capacity of the cylinder charge. Therefore, the excess air coefficient of LP-EGR is much higher than that of HP-EGR under the same EGR rate.

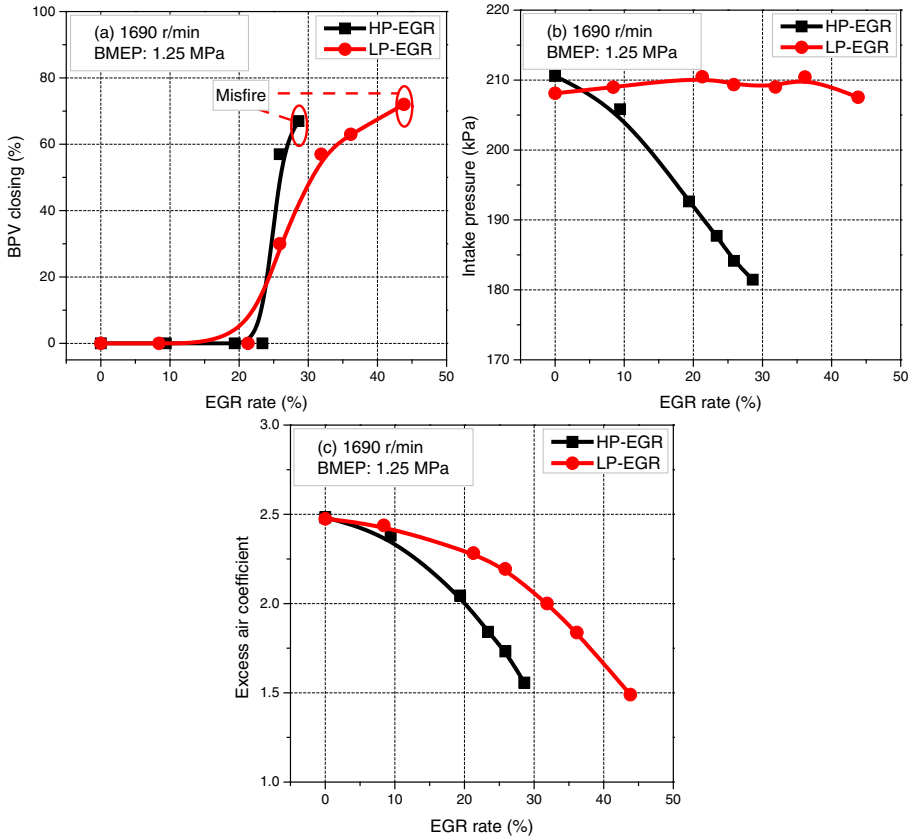


Fig. 2. The influence of EGR on intake and exhaust parameters.

3.2 Combustion characteristic

Figure 3 shows the effect of high pressure/low pressure EGR on cylinder pressure and heat release rate. It can be seen from Figure 3 that as the EGR rate increases, the compression pressure of the high-pressure EGR decreases significantly. This is mainly caused by the decrease in the charge density in the cylinder caused by the substantial decrease in the intake air volume. However, the compression pressure of low-pressure EGR does not change much with the EGR rate, which shows that low-pressure EGR has little effect on the in-cylinder charge density. It can also be seen from Figure 3 that the two EGR methods both cause the combustion phase to be delayed, and the maximum explosion pressure and peak heat release rate are reduced.

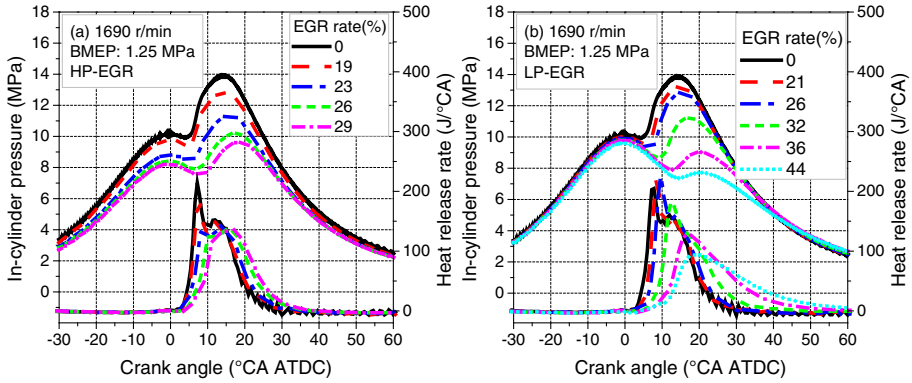


Fig. 3. The influence of EGR on in-cylinder pressure and heat release rate.

Figure 4 shows the effect of high pressure/low pressure EGR on the average temperature in the cylinder. It can be seen from the figure that the two EGR methods have different effects on the average temperature in the cylinder. It can be seen from Figure 4(a) that for high-pressure EGR, as the EGR rate increases, the average in-cylinder temperature of the compression stroke not only does not decrease, but rather increases. The average temperature rise rate in the cylinder after ignition under high pressure EGR is the same as that without EGR, and the highest average temperature in the cylinder rises, and the high temperature duration is prolonged.

This is mainly caused by the following three reasons. 1) As the EGR rate increases, the oxygen concentration of the high-pressure EGR method decreases, resulting in a downward trend in the combustion rate. However, the minimum excess air coefficient in this test condition is still greater than 1.5, and the methanol energy is relatively high (>60%), and the premixed combustion ratio is high, so the decrease in oxygen concentration did not cause a significant decrease in the combustion rate. 2) High-pressure EGR leads to a significant decrease in intake air volume and a decrease in the total heat capacity of the cylinder charge, which is the main reason for the increase in the average temperature in the cylinder. 3) The intake air flow rate under high-pressure EGR is greatly reduced, and the cylinder charge density is reduced. The methanol equivalent ratio increases from 0.26 without EGR to 0.44 at 29% EGR rate. The methanol combustion rate increases, which also helps in-cylinder. The average temperature rises.

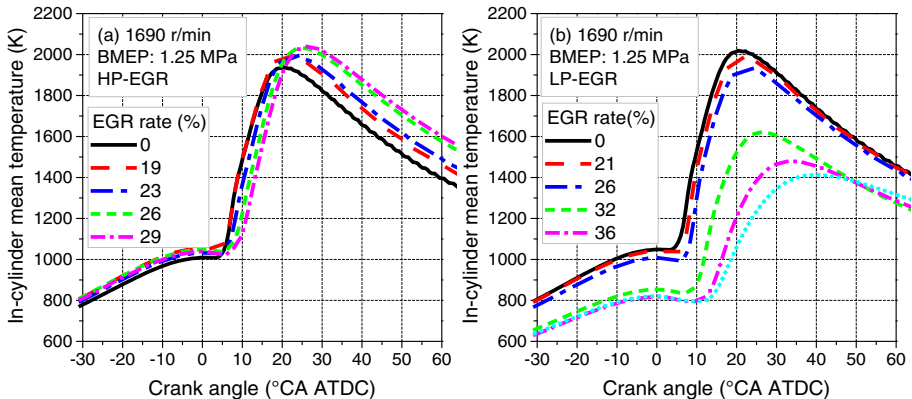


Fig. 4. The influence of EGR on in-cylinder mean temperature.

Figure 5 shows the effect of high pressure/low pressure EGR on combustion phase. It can be seen from the figure that there are significant differences in the influence of

high-pressure EGR and low-pressure EGR on the combustion phase. It can be seen from Fig. 5(a) that under high-pressure EGR, as the EGR rate increases, the stagnation period is significantly prolonged, the combustion center of CA50 is slightly delayed, and the combustion duration is slightly prolonged.

This is mainly because the ignition of DMDF is mainly controlled by the diesel combustion process. The decrease in oxygen concentration caused by high-pressure EGR suppresses the ignition of pre-mixed diesel and prolongs the flame retardation period. The CA50 and combustion duration are not only related to the moment of ignition, but also related to the combustion rate. On the one hand, the decrease in excess air ratio under high pressure EGR will cause the diesel combustion rate to decrease. On the other hand, the higher average temperature in the cylinder under high pressure EGR greatly increases the flame propagation rate of methanol. These two factors compete with each other, and ultimately lead to a slight backward delay of CA50 as the high-pressure EGR rate increases, and the average combustion rate does not change much.

However, after the EGR rate exceeded 23%, the back pressure valve began to close, the oxygen concentration in the cylinder decreased sharply, and CA50 showed a significant delay.

It can be seen from Fig.5(b) that for low-pressure EGR, before BPV intervention (EGR%<21%), the stagnation period and combustion duration are basically unchanged, and the CA50 is slightly delayed. This is mainly due to the high excess air coefficient under low-proportion low-pressure EGR, and the combustion process is not sensitive to changes in the oxygen concentration in the cylinder. Therefore, low-proportion low-pressure EGR (EGR%<21%) has little effect on the combustion phase. However, after the intervention of the back pressure valve, the excess air coefficient quickly dropped below 1.5, and the dilution effect of the reduced oxygen concentration was significantly enhanced. In addition, a large amount of exhaust gas enters the cylinder, which increases the heat capacity of the mixture, reduces the compression end temperature, greatly prolongs the flame retardation period, and reduces the combustion rate, and the CA50 is significantly delayed.

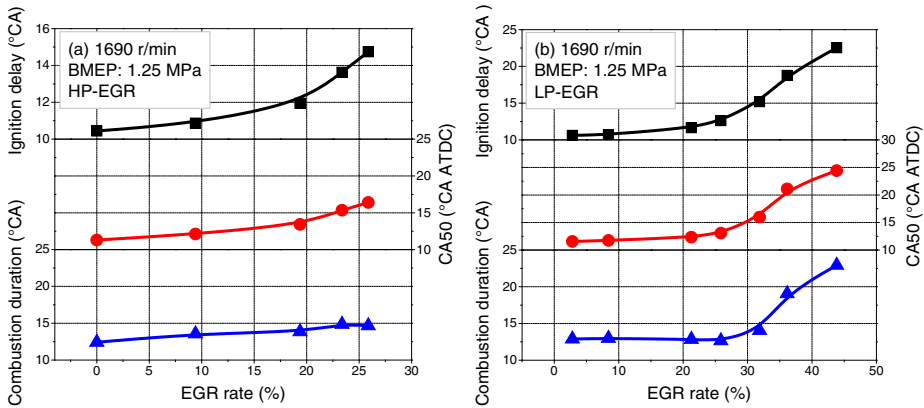


Fig. 5. The influence of EGR on combustion phase.

3.3 Thermal efficiency

Figure 6 shows the effect of high pressure/low pressure EGR on effective thermal efficiency (BTE) and combustion efficiency. As shown in Fig.6(a), it can be seen that under high pressure EGR, the combustion efficiency increases significantly with the increase of EGR rate. When the EGR rate is increased from 0 to 29%, the combustion efficiency increases by 2.6 percentage points. The increase in the high-pressure EGR rate not only

reduces the excess air ratio and increases the methanol equivalent ratio, but also increases the average temperature in the cylinder. These two factors make methanol burn more fully and improve combustion efficiency. To further increase the high-pressure EGR rate, exhaust gas throttling is required. The exhaust back pressure increases to form a higher internal EGR, and the oxygen concentration decreases rapidly, leading to a significant delay in diesel ignition. After CA50 is pushed, BTE is significantly reduced.

It can be seen from Fig. 6(b) that for the low-pressure EGR mode, as the EGR rate increases, the combustion efficiency first increases and then decreases, and the BTE first decreases slightly and then rapidly decreases. When the EGR rate increases from 0 to 21% (low-pressure EGR valve is fully opened), the increase in combustion efficiency is mainly caused by the decrease in excess air ratio, which increases the methanol equivalent ratio. In the small interval after BPV intervention, the combustion efficiency still increases slightly, which is mainly caused by the continued decrease of the excess air coefficient. If the low-pressure EGR rate continues to increase, the total heat capacity of the mixture increases, and the temperature in the cylinder decreases significantly, resulting in a decrease in both combustion efficiency and BTE.

When NO_x emissions are controlled at the China VI level, the BTE of high-pressure EGR and low-pressure EGR strategies are 42.2% and 38.5%, respectively, and the BTE of high-pressure EGR is 9.6% higher than that of low-pressure EGR.

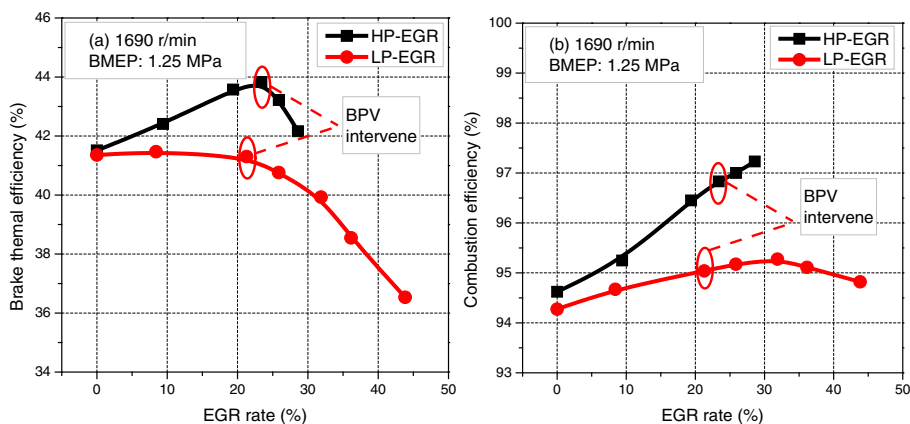


Fig. 6. The influence of EGR on BTE and combustion efficiency.

3.4 Emission characteristic

Figure 7 shows the effect of high pressure/low pressure EGR on emission characteristics. It can be seen from Fig.7(a) that with the increase of EGR rate, NO_x is significantly reduced in the low-pressure EGR mode of high-pressure EGR, and the rate of NO_x reduction of high-pressure EGR is greater than that of low-pressure EGR. The maximum NO_x reductions of high-pressure EGR and low-pressure EGR are 87.7% and 97.5%, respectively. This is mainly because the two EGR methods both reduce the oxygen concentration in the cylinder, and the high-pressure EGR reduces more. However, due to the limitation of unstable combustion of the engine, it is difficult for the high-pressure EGR method to control NO_x below the national VI limit. Low-pressure EGR can achieve a higher EGR rate, and can reduce NO_x to below 0.4 g/kWh. The above results show that in the DMDF combustion mode, EGR technology is still an effective means to control NO_x emissions.

It can be seen from Fig.7(b) that under all test conditions, PM emissions are lower than the national VI limit of PM (10 mg/kWh). Among them, under the condition of no exhaust

throttling, both high-pressure EGR and low-pressure EGR modes of DMDF combustion can maintain extremely low PM emissions close to zero.

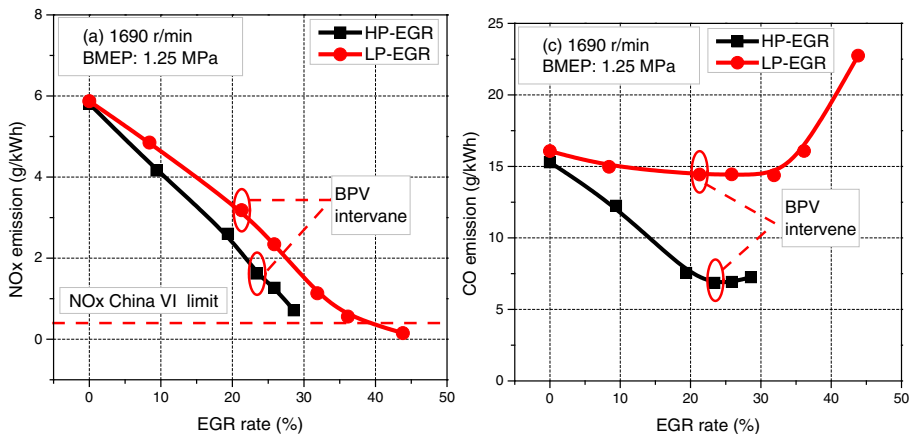
This is mainly because in the dual-fuel premixed stratified combustion mode, the proportion of premixed fuel is quite high, and the flame retardation period is long, and a relatively sufficient oil and gas mixing process has been completed before the fire, and there is basically no local over-concentration that can generate PM. Area. However, when the EGR rate is too high, BPV assistance is required, the exhaust back pressure is large, there is a high internal EGR, and the oxygen concentration in the cylinder is too low, resulting in increased PM emissions, but it is still less than 10 g/kWh.

This shows that the trade-off relationship between NO_x and PM is completely broken in the DMDF pre-mixed stratified combustion mode. After the optimization of fuel injection parameters and methanol energy ratio, PM can always be maintained at an extremely low emission level close to zero. This laid the foundation for the use of EGR technology to control NO_x emissions at an extremely low level.

From Fig.7(c) and Fig.7(d), it can be seen that with the increase of the high-pressure EGR rate, both CO and THC decrease rapidly, and the maximum decreases are 52.6% and 47.7%, respectively. This is due to the increase in methanol equivalent ratio caused by the decrease in excess air coefficient and the increase in cylinder temperature caused by the decrease in the total heat capacity in the cylinder.

For low-pressure EGR, as the EGR rate increases, THC first decreases, but remains basically unchanged after BPV intervention. This is caused by the competition between the beneficial effect of the reduction in excess air ratio and the adverse effect of the decrease in the temperature in the cylinder. In addition, CO emissions remain unchanged at first and then increase rapidly as the low-pressure EGR rate increases. When the EGR rate reaches below 32%, as the low-pressure EGR rate increases, although the methanol equivalent ratio increases, which is conducive to the reduction of CO, the decrease in the in-cylinder temperature leads to a decrease in the oxidation rate of CO, so the two cancel each other out, making CO Has not changed much.

Further increase the BPV degree, the oxygen concentration in the cylinder drops rapidly, and the temperature in the cylinder decreases, and the local high equivalence ratio area is incompletely burned, so that CO emissions increase drastically. From the point of view of CO and THC emission control, high-pressure EGR can effectively reduce the CO and THC of DMDF premixed fractional combustion combustion. However, low pressure EGR has little effect on the reduction of CO and THC, and even worsens CO emissions at high EGR rates.



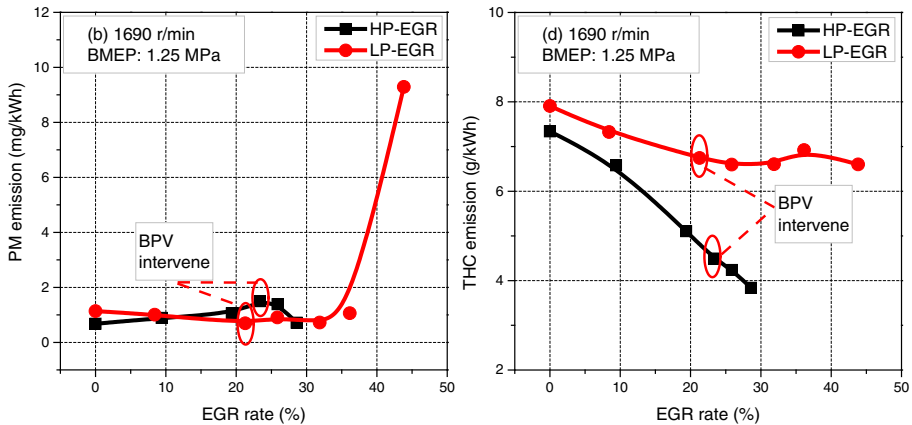


Fig. 7. The influence of EGR on emission characteristics.

4 Conclusion

In this paper, a systematic investigation to achieve ultra-low raw emissions in diesel/methanol dual fuel engine was carried out. The effect of dual-loop EGR (High pressure EGR and low pressure EGR) on the combustion, performances and emissions of methanol engine has been studied in detail. The main conclusions are as follows:

Under the diesel methanol dual fuel combustion mode, with the help of high proportion EGR, ultra-low raw NO_x ($<0.4\text{g/kWh}$) and PM ($<10\text{mg/kWh}$) emissions can be achieved simultaneously.

In both EGR modes, the combustion phase is delayed with the increase of EGR rate. However, the methanol equivalence ratio and in cylinder combustion temperature in high pressure EGR mode are significantly higher than those in low pressure EGR mode.

The maximum brake thermal efficiency of diesel/methanol dual fuel engine in high-pressure EGR is 9.6% higher than that of low-pressure EGR.

Under the near zero raw PM emission target, the NO_x raw emission can be controlled at an ultra-low level below 0.4g/kWh in both EGR mode. However, the CO and THC emissions are obviously lower in high pressure EGR mode than that in low pressure EGR mode.

References

1. Ghadikolaei M A. Effect of alcohol blend and fumigation on regulated and unregulated emissions of IC engines - a review [J]. *Renewable and Sustainable Energy Reviews*, 2016, 57: 1440-1495.
2. Yang C J, Jackson R B. China's growing methanol economy and its implications for energy and the environment [J]. *Energy Policy*, 2012, 41: 878-884.
3. Shih C F, Zhang T, Li J, et al. Powering the future with liquid sunshine [J]. *Joule*, 2018, 2(10): 1925-1949.
4. Li J, Yang W M, An H, et al. Effects of fuel ratio and injection timing on gasoline/biodiesel fueled RCCI engine: A modeling study [J]. *Applied Energy*, 2015, 155: 59-67.
5. Nieman D E, Dempsey A B, Reitz R D. Heavy-duty RCCI operation using natural gas and diesel [J]. *SAE International Journal of Engines*, 2012, 5(2):270-285.

6. Curran S, Hanson R, Wagner R. Effect of E85 on RCCI performance and emissions on a multi-cylinder light-duty diesel engine [C]. SAE Technical Paper, 2012, 2012-01-0376.
7. Abedin M J, Imran A, Masjuki H H, et al. An overview on comparative engine performance and emission characteristics of different techniques involved in diesel engine as dual-fuel engine operation [J]. *Renewable and Sustainable Energy Reviews*, 2016, 60: 306-316.
8. Lu X, Han D, Zhen H. Fuel design and management for the control of advanced compression-ignition combustion modes [J]. *Fuel and Energy Abstracts*, 2011, 37(6): 741-783.
9. Kokjohn S L, Reitz R D. Reactivity controlled compression ignition and conventional diesel combustion: A comparison of methods to meet light-duty NO_x and fuel economy targets [J]. *International Journal of Engine Research*, 2013, 14(5): 452-468.
10. Reitz R D, Duraisamy G. Review of high efficiency and clean reactivity controlled compression ignition (RCCI) combustion in internal combustion engines [J]. *Progress in Energy and Combustion Science*, 2015, 46: 12-71.
11. [160] Mohan B, Yang W, Chou S K. Fuel injection strategies for performance improvement and emissions reduction in compression ignition engines—A review [J]. *Renewable and Sustainable Energy Reviews*, 2013, 28: 664-676.
12. Abedin M J, Imran A, Masjuki H H, et al. An overview on comparative engine performance and emission characteristics of different techniques involved in diesel engine as dual-fuel engine operation [J]. *Renewable and Sustainable Energy Reviews*, 2016, 60: 306-316.
13. Yao C, Cheung C S, Cheng C, et al. Effect of diesel/methanol compound combustion on diesel engine combustion and emissions [J]. *Energy Conversion and Management*, 2008, 49(6): 1696-1704.
14. Zhang Z H, Cheung C S, Chan T L, et al. Experimental investigation on regulated and unregulated emissions of a diesel/methanol compound combustion engine with and without diesel oxidation catalyst [J]. *Science of the Total Environment*, 2010, 408(4): 865-872.
15. Zhang Z H, Cheung C S, Chan T L, et al. Experimental investigation of regulated and unregulated emissions from a diesel engine fueled with Euro V diesel fuel and fumigation methanol [J]. *Atmospheric Environment*, 2010, 44(8): 1054-1061.
16. Wei H, Yao C, Pan W, et al. To meet demand of Euro V emission legislation urea free for HD diesel engine with DMCC [J]. *Fuel*, 2017, 207: 33-46.
17. Tomita E, Kawahara N, Piao Z, et al. Effects of EGR and early injection of diesel fuel on combustion characteristics and exhaust emissions in a methane dual fuel engine [C]. SAE Technical Paper, 2002, 2002-01-2723.
18. Mohan B, Yang W, Chou S K. Fuel injection strategies for performance improvement and emissions reduction in compression ignition engines—A review [J]. *Renewable and Sustainable Energy Reviews*, 2013, 28: 664-676.
19. O'connor J, Musculus M P B, Pickett L M. Effect of post injections on mixture preparation and unburned hydrocarbon emissions in a heavy-duty diesel engine [J]. *Combustion and Flame*, 2016, 170: 111-123.
20. Benajes J, Martín J, García A, et al. Swirl ratio and post injection strategies to improve late cycle diffusion combustion in a light-duty diesel engine [J]. *Applied Thermal Engineering*, 2017, 123: 365-376.

21. Wei L, Yao C, Han G, et al. Effects of methanol to diesel ratio and diesel injection timing on combustion, performance and emissions of a methanol port premixed diesel engine [J]. *Energy*, 2016, 95: 223-232.