Investigation on Partially Premixed Combustion Fueled with Gasoline and PODE Blends in a Multi-Cylinder Heavy-Duty Diesel Engine

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ABSTRACT

Gasoline partially premixed combustion (PPC) has been reported as an advancing concept for high efficient and clean combustion, while there still remains some obstacles. In this study, polyoxymethylene dimethyl ethers (PODE), which has superior properties of high oxygen content, high cetane number and no C-C bond, is employed as an additive to optimize the properties of gasoline and solve the problems faced in gasoline PPC. The effects of gasoline/PODE blends with PODE volume blending ratio of 0, 10% and 20% on combustion and emission have been investigated from low to high loads in a multi-cylinder heavy-duty diesel engine. The experimental results show that the soot emission can be maximally reduced by 79% and 94% at high load when fueling PODE 10 and PODE20, respectively. The NO_x-soot trade off relationship can be dramatically improved without penalty of fuel economy by fueling gasoline/PODE blends. The raw NO_x and soot emissions can meet Euro V standards at high load and Euro VI standards at medium load by fueling both PODE10 and PODE20. Furthermore, the pressure rise rate can be maximally reduced by 24% and 47% when fueling PODE10 and PODE20. At medium load, the combustion controllability and sensitivity can be improved by gasoline/PODE blends. At low load, the COV_{IMEP} can be reduced to 2.7% by fueling PODE20 which means a stable combustion can be obtained. Furthermore, the combustion efficiency can be dramatically improved from 85.1% to 99.6% by fueling PODE20, which leads to lower HC and CO emissions. Overall, PODE shows great advantage in solving the obstacles faced in gasoline PPC.

Keywords

Partially premixed combustion (PPC); Polyoxymethylene dimethyl ethers (PODE); Gasoline; Combustion stability;

26 **Abbreviations**

ATDC: after top dead center	HP-EGR: high pressure EGR
BMEP: brake mean effective pressure	HRR: heat release rate
BSFC: brake specific fuel consumption	IBP: initial boiling point
BTE: brake thermal efficiency	ITE: indicate thermal efficiency
CA50: crank angle at 50% of total heat release	LP-EGR: low pressure EGR
CAI: control auto ignition	LVH: low heat value
CFR: cooperative fuel research	PODE: polyoxymethylene dimethyl ethers
CN: cetane number	PPC: partially premixed combustion
COV: coefficient of variation	PRR: pressure rise rate
EGR: exhaust gas recirculation	SOC: start of combustion
FSN: filter smoke number	SOI: start of injection
HCCI: homogeneous charge compression ignition	T95: 95% distillation temperature

27 **1. Introduction**

28 Partially premixed combustion (PPC) has been widely known as an advanced combustion concept which can achieve
29 low soot and NO_x emissions while still keeping high thermal efficiency [1, 2]. The end of main injection and the start of
30 combustion (SOC) are expected to be separated to produce low stratified air-fuel mixture in PPC [3]. The extension of
31 ignition delay is a key issue to achieve PPC, which is usually realized through excessive EGR rate, reduced compression
32 ratio and fuel reactivity [4]. PPC is therefore considered as a more promising combustion concept to be utilized in practical
33 engine than homogeneous charge compression ignition (HCCI) and control auto ignition (CAI) because of the relatively
34 better combustion controllability [1, 5].

35 Gasoline with high octane number is thought to be able to obtain the separation between injection and combustion
36 events because of its longer ignition delay. More homogeneous mixture is formed before auto-ignition by fueling gasoline in
37 PPC compared to conventional diesel combustion mode. Therefore, it is more prone to achieve clean combustion by fueling
38 gasoline compared to diesel [6, 7]. However, there still remains some obstacles in gasoline PPC mode which should be
39 solved before the practical utilization [4]. Firstly, it is hard to achieve cold start and stable combustion at low load due to the
40 low reactivity of gasoline fuel, which in turn results in low combustion efficiency at low loads [7-11]. Secondly, the
41 pressure rise rate is high at medium and high loads [9, 11, 12]; Therefore, the gasoline PPC load range has been shown to be
42 limited [3]. Thirdly, the combustion process is very sensitive to the boundary conditions, such as intake temperature, start of

injection (SOI), EGR and so on [13]. Lastly, higher injection pressure of gasoline cannot be obtained by the commercial common rail high pressure injection system at the moment due to the lower viscosity of gasoline; therefore, the injection and combustion can hardly be separated at high load, which results in higher soot emission [5, 14]. To solve these challenges in gasoline PPC, gasoline fuel property optimizations by blending some high cetane number fuel and oxygenated fuel are widely investigated as potential methods to achieve PPC operation in practical engine.

Previous studies have shown that the combustion stability and controllability problems in gasoline PPC at low and medium loads can be improved by blending diesel into gasoline because the fuel reactivity can be increased [15, 16]. Meanwhile, the combustion efficiency can be significantly improved and the operation region can also be dramatically extended to low load by fueling gasoline/diesel blends [17]. However, the injection event and the combustion process are not easy to be separated at high load because of the shorter ignition delay. Thus, high soot emission can be observed at high load, since the premixed combustion ratio is greatly decreased [6, 18]. Therefore, diesel fuel is not suitable to be blended with gasoline fuel to achieve PPC combustion mode because it is difficult to solve both the combustion stability issue at low load and smoke emission problem at high load. Thus, it is of great significance to further extend the research on the alternatives for diesel and additive for gasoline.

Polyoxymethylene dimethyl ethers (PODE) is a promising emerging fuel, which has been investigated as an alternative fuel for diesel in recent years [19-25]. It has the properties of high cetane number (CN), high oxygen content, no C-C bond, sulfur-free, high volatility and so on [19, 26]. Smoke-less combustion can be obtained by fueling neat PODE because of its superior fuel properties [23, 24]. The NO_x-soot trade off relationship in conventional diesel engine can be dramatically improved by fueling diesel/PODE blends [19, 20]. Therefore, PODE shows great potential to replace diesel as a clean additive. Theoretically, PODE can also be utilized in gasoline PPC combustion mode as a clean additive to gasoline. From the perspective of PODE's physico-chemical properties, it has the potential to utilize gasoline/PODE blends to solve both the combustion stability at low load and soot emission at high load in gasoline PPC mode. However, rare research on the effects of PODE on gasoline PPC combustion mode can be found from the literatures. Therefore, it is necessary to conduct extensive study to explore the effects of PODE on the combustion and emission characteristics in gasoline PPC and the

67 potential of PODE to improve the critical challenges faced in the practical utilization of gasoline PPC.

68 In this study, PODE is employed as an additive to optimize the fuel properties of gasoline. The combustion and
69 emission characteristics of gasoline/PODE blends with different PODE volume blending ratio, including 0, 10% and 20%,
70 have been investigated at low, medium and high loads in a multi-cylinder heavy-duty diesel engine. The underlying reasons
71 for the improvement in combustion efficiency, combustion stability, combustion controllability, pressure rise rate and
72 exhaust emissions by fueling gasoline/PODE blends are presented and discussed in this paper.

73 **2. Experimental setup**

74 **2.1. Test bench**

75 The experiments in this study were conducted on a six-cylinder, turbocharged heavy-duty diesel engine equipped with
76 a Bosch commercial common rail injection system. The detailed specifications of the engine are given in Table 1 and the
77 schematic of the experimental setup is illustrated in Fig. 1.

78 Table 1. Specifications of the experimental engine.

Parameters	Value
Displacement	8.42L
Bore x Stroke	113mm x 140mm
Connecting rod length	209mm
Compression ratio	16.8
Number of valves	24
Swirl ratio	1.25
Combustion chamber	Reentrant type
Fuel injection system	Bosch Common rail
Number of nozzle holes	8
Included spray angle	148°
Hole diameter	0.163mm

79 A high pressure common rail injection system, with maximum injection pressure of 160 MPa, was used in this engine
80 for gasoline injection. A two-stage turbocharge system and a compound EGR system were used in the experiments, in which
81 an intercooler was installed between the HP-stage and LP-stage compressor to improve the turbocharger efficiency. The
82 intake temperature was controlled by the intake intercooler. The measurement of in-cylinder pressure was accomplished via
83 a piezoelectric pressure sensor (Kistler 6125C) coupled with a charge amplifier (Kistler 5011B10). The cylinder pressure
84 data acquisition system was triggered by the optical crank angle encoder (Kistler 2614A4) with an increment of 0.5 °CA.

The rate of heat release was calculated via the in-cylinder pressure data according to the first law of thermodynamics and the Woschni heat transfer model [27]. An exhaust emission analyzer (HORIBA MEXA 7100DEGR) was utilized to measure the exhaust gaseous emissions, including NO_x, THC, CO and CO₂. The CO₂ concentrations in the intake pipe and the exhaust pipe were measured by the exhaust emission analyzer to calculate the EGR ratio via formula Eq. (1) according to reference [28]. The filter smoke number (FSN) of the exhaust gas was measured by a filter smoke meter (AVL 415S) and the indicated specific dry soot emission (unit: g/kWh) can be calculated via formula Eq. (2) according to reference [29]. The specifications and accuracies of the experimental instruments are shown in Table 2.

Table 2. Specification and measuring accuracy of experimental apparatus

Apparatus	Measuring principle	Accuracy
Exhaust analyzer (HORIBA MEXA 7100DEGR)	Chemiluminescent analyzer (CLA)	±0.5% FS
	Hydrogen flame ionization (FID)	
	Non-dispersive infra-red (NDIR)	
Smoke meter (AVL 415S)	Filter-type (photoelectric measuring)	0.005 FSN+3% RS
Fuel flow meter (AVL COMPACT)	Coriolis principle	±0.1%
Cylinder pressure (Kistler 6125C)	Piezoelectric effect	±1%
Air flow meter (Toceil)	Thermal diffusion theory	±1%

$$\text{EGR Ratio} = (\text{CO}_2\%)_{\text{intake}} / (\text{CO}_2\%)_{\text{exhaust}} \times 100\% \quad (1)$$

$$\text{Soot} = 0.0102 \times \text{FSN} \times e^{0.3062 \times \text{FSN}} \times (m_{\text{air}} + m_{\text{fuel}}) / P_b \quad (2)$$

Where m_{air} , m_{fuel} and P_b refer to the intake mass flow rate (kg/h), fuel mass flow rate (kg/h) and brake power (kW).

2.2. Test fuels

In this experiment, pure gasoline fuel is used as the baseline fuel and PODE is blended into gasoline with the volume blending ratio of 10% and 20% (abbreviated as PODE10, PODE20). PODE is a mixture composed of many short oligomers [19]. The mass distributions and the molecular structure of PODE used in this experiment are shown in Table 3. It can be seen that each carbon atom is connected to an oxygen atom and there is no C-C bond in the PODE, which is a superior molecular structure to suppress soot formation [30]. The properties of gasoline, PODE and gasoline/PODE blends are presented in Table 4. The properties of high CN and high oxygen content of PODE indicate it has the potential to greatly improve the performance of gasoline PPC. The viscosity of PODE is higher than that of gasoline, which should be helpful to reduce the wear problem of the injection system. The comparison of distillation curve between gasoline and PODE is exhibited in Fig. 2. The initial boiling point (IBP) and the 95% distillation temperature (T95) of PODE are higher than those

of gasoline, which means that PODE has inferior volatility compared to gasoline. More information about the physic-chemical properties of PODE and its components can be found in reference [19].

Table 3. Mass distributions and molecular structure of PODE.

Components	Mass fraction (% wt)	Molecular structure
PODE ₃	44.80	$\begin{array}{c} \text{H} \\ \\ \text{H}-\text{C}-\text{O}-\left[\begin{array}{c} \text{H} \\ \\ \text{C}-\text{O} \end{array} \right]_n-\begin{array}{c} \text{H} \\ \\ \text{C}-\text{H} \end{array} \\ \\ \text{H} \end{array}$
PODE ₄	28.24	
PODE ₅	17.09	
PODE ₆	9.87	

Table 4. The properties of gasoline, PODE and gasoline/PODE blends.

Properties	Gasoline	PODE	PODE10	PODE20
Density (kg/m ³ @20 °C)	762	1047	791	820
Cetane Number	—	60.7*	—	—
Research Octane Number	95	—	—	—
C (% wt)	86.35	43.53	79.99	74.82
H (% wt)	13.65	8.52	12.25	11.72
O (% wt)	0	47.95	7.76	13.46
LHV (MJ/kg)	43.5	21.77	40.62	37.95
Kinematic viscosity (mm ² /s@40 °C)	0.62	1.11	—	—

*: It is measured in a CFR engine and not the blending cetane number [19].

It should be noted that the low heat value (LHV) of gasoline/PODE blends is lower than that of gasoline. To make a fair comparison of the fuel economy performance between gasoline and gasoline/PODE blends, all the brake specific fuel consumption (BSFC) of gasoline/PODE blends have been converted to the equivalent BSFC of gasoline according to the following formula Eq. (3):

$$\text{BSFC}_{\text{eq}} = \frac{1000 \times \dot{m}_{pb_ac}}{P_b} \times \frac{\rho_p \times \eta \times \text{LHV}_p + \rho_g \times (1-\eta) \times \text{LHV}_g}{[\rho_p \times \eta + \rho_g \times (1-\eta)] \times \text{LHV}_g} \quad (3)$$

Where BSFC_{eq} is the equivalent BSFC of gasoline/PODE blends to gasoline (g/kWh); $\dot{m}_{pb_ac}$ is the actual fuel mass flow of gasoline/PODE blends (kg/h); ρ_p and ρ_g represent the density of PODE and gasoline respectively (kg/m³); LHV_p and LHV_g refer to the low heat value of PODE and gasoline respectively (MJ/kg); η indicates the blending ratio of PODE into gasoline and P_b is the brake power (kW).

2.3. Test methods

The effects of PODE on combustion and emission characteristics in gasoline PPC were comprehensively evaluated at low load (BMEP=3 bar), medium load (BMEP=9.5 bar) and high load (BMEP=16 bar) with a fixed engine speed of 1660

r/min. In these experiments, the injection pressure of gasoline cannot reach the pressure with diesel due to the significantly lower viscosity of gasoline, thus, the maximum injection pressure has been restricted to 120 MPa to protect the injection pump in this study. Double injection strategy (pilot fuel quantity=4 mg/cycle, the interval between pilot and main injection=10 °CA) is adopted at low load for stable combustion and single injection is adopted at medium and high loads. The intake temperature is kept at 65±5 °C. The maximum in-cylinder pressure and the pressure rise rate are restricted to be lower than 17 MPa and 15 bar/°CA, respectively. The engine operating conditions are illustrated in Table 5.

Table 5. Engine operating conditions

Operation condition	Low load	Medium load	High load
Engine speed (r/min)	1660	1660	1660
BMEP (bar)	3	9.5	16
SOI (°CA ATDC)	−12	−9.5	−14
Injection strategy	Double injection	Single injection	Single injection
Injection pressure (bar)	1200	1200	1200
Intake temperature (°C)	65±5	65±5	65±5
Coolant temperature(°C)	85	85	85
EGR rate	0	15%-40%	5%-30%

The mixing process before auto-ignition is affected by both the injection duration and ignition delay. Therefore, the injection duration and ignition delay are compared to investigate the mixture quality discrepancy between gasoline and gasoline/PODE blends. The injection duration ($\Delta\theta$) is calculated via formula Eq. (4) according to reference [27]. The ignition delay is defined as the interval between CA5 and injection timing. The ignition delay also greatly affects the premixed combustion ratio, which has great impact on both the pressure rise rate and soot emission. Consequently, the premixed combustion ratio is calculated based on the fitting of Gaussian profile, which was adopted in [31-33].

$$m_f = C_D A_n \sqrt{2\rho_f \Delta p} \times \Delta\theta / 6n \times 10^6 \quad (4)$$

Where m_f is the mass flow rate (mg/cyc); A_n is the nozzle minimum area (m^2); C_D is the discharge coefficient; ρ_f is the fuel density (kg/m^3); Δp is the injection pressure (Pa); $\Delta\theta$ is the injection duration (°CA) and n is the engine speed (r/min).

One of the challenges in gasoline PPC is the combustion controllability, which indicates that the combustion phasing sensitivity to injection timing. It was proposed to use the sensitivity of combustion phasing (CA50) to injection timing (SOI) as indicator to quantify the combustion controllability. The definition of combustion controllability (S_{ID}) is given in Eq. (5)

[31], which is the derivative of CA50 ($\partial CA50$) with respect to a change in injection timing (∂SOI) and it can be used as an indicator to evaluate whether a low reactivity fuel can be practically implemented [13, 31].

$$S_{ID} = \partial CA50 / \partial SOI \quad (5)$$

The cycle-to-cycle variations of IMEP is employed to evaluate the combustion stability at low load and it is defined as the standard deviation in IMEP (σ_{IMEP}) divided by the mean IMEP ($\overline{IMEP}$), which is given in formula (6) according to the reference [27].

$$COV_{IMEP} = \sigma_{IMEP} / \overline{IMEP} \times 100\% \quad (6)$$

The combustion efficiency of gasoline PPC at low load is usually low and the effect of PODE on combustion efficiency will be discussed in this paper. The combustion efficiency can be calculated with Eq. (7).

$$\eta_c = 1 - (\dot{m}_{CO} \times LHV_{CO} + \dot{m}_{HC} \times LHV_{fuel} + \dot{m}_{H_2} \times LHV_{H_2}) / (\dot{m}_{fuel} \times LHV_{fuel}) \quad (7)$$

Where $\dot{m}_{fuel}$, $\dot{m}_{CO}$, $\dot{m}_{HC}$ and $\dot{m}_{H_2}$ mean the mass flow rate of fuel, CO, HC and H₂, respectively; The LHV_{CO} , LHV_{fuel} and LHV_{H_2} mean the low heat value of CO, fuel and H₂. The concentration of H₂ can be calculated via the formula shown in [34].

3. Results and discussion

3.1. Effects of gasoline/PODE blends on combustion and emission characteristics at high load

The effects of PODE on the combustion characteristics of gasoline PPC are firstly investigated at high load with a fixed injection timing of -14 °CA ATDC and EGR from 5%-30%. The results with 5% (a) and 30% (b) EGR are presented in Fig. 3. At each EGR ratio, the maximum premixed heat release rate can be reduced by fueling gasoline/PODE blends and the reduction extent increases with the increase of PODE blending ratio. Accordingly, the premixed combustion ratio and pressure rise rate (PRR) can be significantly reduced by fueling gasoline/PODE blends. This phenomenon can be attributed to the fact that the octane number of gasoline is decreased by blending PODE, which leads to shorter ignition delay and mixing timing, as can be seen in Fig. 3 (c). In addition, the LHV of gasoline/PODE blends are lower than that of gasoline, which means that in order to maintain the same power output, more fuel is required, results in longer injection duration. Therefore, the energy contained in the gasoline/PODE-air mixture formed before auto-ignition is lower than that of gasoline-air mixture. As shown in Fig. 3 (c), the injection duration is longer than ignition delay for all fuels, which implies that the fuel injection event and the combustion event cannot be separated at this load. As a result, diffusion combustion can

be obviously observed in Fig. 3 (a) and Fig. 3 (b). Moreover, the heat release process, especially the premixed combustion process, shows different sensitivity to EGR among these fuels. As shown in Fig. 3 (a) and Fig. 3 (b), the maximum premixed heat release rate of gasoline can be significantly increased compared to gasoline/PODE blends when EGR is increased from 5% to 30%. This phenomenon indicates that the ignition delay of gasoline is more sensitive to EGR, while blending PODE is helpful to reduce the sensitivity to EGR; as consequence, the premixed combustion ratio and PRR show lower sensitivity to EGR by fueling gasoline/PODE blends, especially with PODE20, as shown in Fig. 3 (c).

The effects of gasoline/PODE blends on the mechanical efficiency and fuel economy at high load are illustrated in Fig. 4. The mechanical efficiency is defined as the BMEP divided by the $IMEP_{net}$. At fixed operation condition and injection pressure, the mechanical efficiency remains almost the same when EGR or SOI varies [35]. Therefore, the effect of PODE on the mechanical efficiency in gasoline PPC at 30% EGR is chosen as a representative, which is shown in Fig. 4 (a). The mechanical loss in fuel pump and injector due to internal leakage caused by lower viscosity of gasoline can be reduced by fueling gasoline/PODE blends because of the higher viscosity, which in turn affects the mechanical efficiency [35]. It can be seen that the mechanical efficiency can be improved from 90.8% to 92.7% when the PODE blending ratio is increased from 0% to 20%. The improvement in mechanical efficiency by fueling gasoline/PODE blends is also beneficial to improve the brake thermal efficiency (BTE). However, the net indicate thermal efficiency (ITE_{net}) of gasoline/PODE blends is decreased from 43.9% to 43.3% with higher PODE blending ratio due to the longer combustion duration caused by shorter ignition delay and lower LHV of PODE. Consequently, the BTE is eventually determined by both the ITE_{net} and mechanical efficiency. As shown in Fig. 4 (b), the BTE and brake specific fuel consumption (BSFC) among these fuels are almost the same over the whole EGR range. However, it can also be observed that the difference in BTE and BSFC among these fuels becomes larger as EGR increases. The BTE of gasoline/PODE blends are slightly higher than that of gasoline when EGR exceeds 15%, because the combustion efficiency with PODE is slightly higher, which can be inferred from the lower CO emissions of gasoline/PODE blends, as shown in Fig. 5. According to this phenomenon, it is seen that the advantage of PODE on fuel economy improvement will be stronger under higher EGR circumstance.

The effects of gasoline/PODE blends on exhaust emissions at high load are presented in Fig. 5. NO_x emission is

193 mostly dominated by EGR rather than fuel properties. The NO_x emission slightly increases with gasoline/PODE blends due
194 to the higher oxygen content. In the meanwhile, high oxygen content in PODE can be also beneficial to enhance the CO
195 oxidation process, especially under high EGR condition, and the improvement extent of CO emission becomes increasingly
196 evident with the increase of EGR. Furthermore, the HC emission for all fuels are almost the same and close to zero at this
197 load.

198 The improvement in soot emission by fueling gasoline/PODE blends is a one of the most important aspects to evaluate
199 the performance of PODE at high load. The properties of high oxygen content, no C-C bond, sulfur-free and no aromatics in
200 PODE and the dilution effect to gasoline by PODE, are all potentially beneficial for soot reduction. The soot emissions of
201 gasoline and gasoline/PODE blends are depicted in Fig. 5 (d). It can be seen that the soot emission can be significantly
202 improved by fueling gasoline/PODE blends, though the premixed combustion ratios are obviously decreased. Taking the
203 soot emission of pure gasoline as a benchmark, the relative soot reduction ratios of PODE10 and PODE20 over a wide EGR
204 range are presented in Fig. 5 (e). The soot reduction performance can be increased with the increase of PODE blending ratio.
205 In average, the soot reduction ratio can be increased by about 13.6% when the PODE blending ratio is increased from 10%
206 to 20%. Moreover, it can be clearly seen that the soot reduction ratio increases as the EGR increases. The soot reduction
207 ratio can be increased from 38% to 79% by fueling PODE10 and it can be increased from 50% to 94% by fueling PODE20
208 when EGR is increased from 5% to 30%.

209 Previous studies [31] have demonstrated that increasing the premixed combustion ratio is an effective approach to
210 reduce soot emission while it also brings in the problems of high pressure rise rate and high combustion noise, which
211 directly restrict the practical utilization of gasoline PPC in present commercial heavy duty truck and bus engines. The
212 properties of high oxygen content and high CN of PODE should favor the suppression in pressure rise rate and soot
213 emission in gasoline PPC at high load, and the experimental results are illustrated in Fig. 6. It can be seen that the NO_x-soot
214 relationship can be significantly improved by fueling gasoline/PODE blends. The NO_x and PM emission limits of Euro IV
215 and Euro V standards within steady state test can be met without aftertreatment system at this load by fueling both PODE10
216 and PODE20. The aftertreatment can also be simplified with gasoline/PODE blends to meet the Euro VI NO_x and PM

emission limits. Moreover, the pressure rise rate (PRR) can be decreased to an acceptable level with gasoline/PODE blends, especially PODE20. Meanwhile, the fuel economy can also be slightly improved with gasoline/PODE blends.

3.2. Effects of gasoline/PODE blends on combustion and emission characteristics at medium load

The effects of gasoline/PODE blends on combustion characteristics at medium load are investigated with SOI of -12 °CA ATDC and injection pressure of 120 MPa, and the results are illustrated in Fig. 7. It is well known that the combustion characteristics are predominantly dominated by the mixing process and fuel properties, which are actually controlled by the injection duration and ignition delay, and thus the effects of PODE on injection duration and ignition delay are discussed firstly. As can be seen from Fig. 7 (e), since the power output is fixed, more cyclic fuel quantity is needed for gasoline/PODE blends to maintain the same power output as the combustion efficiency reduces. As a result, the injection duration of gasoline is firstly shorter than gasoline/PODE blends because of higher LHV and comparative combustion efficiency compared to gasoline/PODE blends, but gradually becomes longer than that of gasoline/PODE blends because the combustion efficiency of gasoline is obviously deteriorated with the increasing of EGR, which is depicted in Fig. 8 (a). Furthermore, the ignition delay is apparently decreased by fueling gasoline/PODE blends and it is essentially increased for all fuels with the increase of EGR, except the EGR ratio above 35% for gasoline. It should be noted that the combustion efficiency for gasoline is greatly deteriorated when the EGR ratio exceeds 35%, thus more cyclic fuel quantity is needed to maintain the same power output. Therefore, higher equivalent ratio leads to a shorter ignition delay and advanced CA50. Moreover, a small proportion of diffusion combustion can be observed for gasoline with EGR ratio of 39% as shown in Fig. 7 (c), this phenomenon can be mainly attributed to that the injection event is not ended before the ignition under this EGR ratio.

The combustion process for all fuels at 39% EGR are quite different from the combustion process at 16% and 30% EGR. It can be seen from Fig. 7 (a) and Fig. 7 (b) that the ignition timing can be apparently advanced by fueling gasoline/PODE blends, leading to a shorter ignition delay for mixture formation, as a result, the peak heat release rate of gasoline/PODE blends is lower than that of gasoline. The peak heat release rates and the premixed combustion ratios of gasoline/PODE blends increase with the increasing of EGR due to longer ignition delays. The trend of PRR against EGR

are dominated by both the peak premixed heat release rate and CA50 at medium load; as a result, the PRR can be greatly reduced by fueling gasoline/PODE blends, which is beneficial to reduce the combustion noise and favors the practical utilization of gasoline PPC.

The effects of PODE on combustion efficiency and fuel economy at medium load are presented in Fig. 8. It can be seen that the combustion efficiency can be significantly improved by fueling gasoline/PODE blends, especially at high EGR rate conditions, which is shown in Fig. 8 (a). Relatively higher combustion efficiency can be obtained with gasoline/PODE blends over wide EGR ratio conditions, while the combustion efficiency of gasoline is very sensitivity to EGR and deteriorates rapidly with the increase of EGR. The improvement mechanism of combustion efficiency with gasoline/PODE blends can be attributed to the following factors: firstly, the combustion stability enhances due to the higher stratification of fuel concentration caused by shorter ignition delay; secondly, high oxygen content in PODE is beneficial to promote the oxidation of CO and HC; lastly, the volatility of PODE is lower than that of gasoline, thus, the over-lean regions can be reduced. Moreover, at high equivalent ratio or EGR regions, it is obviously that high oxygen content in PODE molecular plays a significant role in improving combustion efficiency. The low combustion efficiency for gasoline can mainly be attributed to the insufficient CO and HC oxidation due to the over-lean mixture caused by longer ignition delay. Moreover, higher misfire probability exists in the over-lean region, resulting in higher HC emission, which is another reason for the low combustion efficiency with gasoline. At high equivalent ratio or EGR regions, the lack of oxidizer and the properties of non-oxygen content in gasoline molecular exacerbate the combustion efficiency, as shown in Fig. 8 (a).

The effects of gasoline/PODE blends on BTE and BSFC are illustrated in Fig. 8 (b). The gasoline/PODE blends show significant advantage for fuel economy improvement compared to gasoline. This advantage is becoming increasingly evident with the increase of EGR. In addition, the fuel economy can be improved with the increase of PODE blending ratio. The improvement in combustion efficiency with gasoline/PODE blends is the critical factor to improve BTE and reduce BSFC. The improvement in mechanical efficiency by fueling gasoline/PODE blends, which have already been demonstrated in Fig. 4, is also beneficial for fuel economy improvement. Therefore, it can be concluded that PODE has great potential to improve fuel economy at medium loads in gasoline PPC mode.

Fig. 9 illustrates the comparison of exhaust emissions between gasoline and gasoline/PODE blends at medium load condition. As shown in Fig. 9 (a), large amount of EGR is introduced to reduce the NO_x emission to meet the Euro VI NO_x emission limit (0.4 g/kWh), and obvious advantage in soot reduction by fueling gasoline/PODE blends can be observed in Fig. 9 (b) when EGR exceeds 35%. When NO_x is kept at 0.4 g/kWh, the soot emission of gasoline/PODE blends are almost below 0.01 g/kWh. When EGR exceeds 35%, the soot emission of gasoline increases rapidly because there is not enough oxygen for soot oxidation. Moreover, it can be observed that the soot emission of PODE20 is slightly higher than that of gasoline when EGR rate is below 35%, because there still exists diffusion combustion with PODE20 and the gasoline in PODE20 produces soot emission during diffusion combustion process. The CO and HC emissions are shown in Fig. 9 (c) and Fig. 9 (d), and it is seen that the CO and HC emissions can be dramatically reduced by fueling gasoline/PODE blends, which can be mainly attributed to that the higher local combustion temperature caused by stronger fuel concentration stratification, which is beneficial for CO and HC oxidation. Furthermore, high oxygen content in the PODE molecular is also favorable for CO and HC oxidation. However, the CO and HC emissions are increased with the increase of EGR ratio because more mixture is diffused into the edge of the cylinder where the temperature is too low for CO and HC oxidation, and the lack of oxidizer is also a critical factor, leading the increase of both CO and HC.

The previous study shows that the combustion phasing is very sensitivity to injection timing in gasoline PPC, which is one of the major challenges in this combustion mode for combustion control [31]. Consequently, the effects of gasoline/PODE on combustion controllability and sensitivity in gasoline PPC are investigated and the experimental results are shown in Fig. 10. The NO_x emission is controlled by regulating both the injection timing and EGR rate. Fig. 10 (a) shows the combustion sensitivity for gasoline, PODE10 and PODE20 at a fixed NO_x emission of 8.0 g/kWh. The S_{ID} of gasoline is about 1.86, which means that the combustion phasing is very sensitivity to injection timing. The S_{ID} can be reduced to 1.19 by fueling PODE10, and then 0.97 with PODE 20, indicating that PODE20 can obtain similar combustion controllability compared to diesel. The improvement in combustion controllability and sensitivity with gasoline/PODE blends can be mainly attributed to that the fuel concentration stratification is increased due to the shorter ignition delay. Moreover, the combustion sensitivity for these fuels are compared at different NO_x emission conditions, which are shown

in Fig. 10 (b). The S_{ID} of gasoline decreases quickly with the reduction of NO_x , because injection duration apparently increases leading to stronger fuel concentration stratification. The S_{ID} of PODE is gradually increased with the reduction of NO_x , because the fuel concentration stratification becomes weaker due to the longer ignition delay. Even though, the S_{ID} of PODE remains almost unchanged over the whole NO_x emission conditions because the fuel concentration stratification always exists. A slightly increase in S_{ID} for PODE20 at NO_x emission of 0.4 g/kWh is observed because the fuel concentration stratification reduces. In conclusion, gasoline/PODE blend, especially PODE20, show great advantage in improving combustion controllability and sensitivity in gasoline PPC at medium load.

3.3. Effects of gasoline/PODE blends on combustion and emission characteristics at low load

The effects of gasoline/PODE blends on combustion stability in gasoline PPC are also investigated at 3 bar BMEP without EGR. The injection pressure and the injection timing are kept at 120 MPa and -12 °CA ATDC, respectively. The comparison of combustion stability among these fuels are shown in Fig. 11. The COV_{IMEP} of gasoline is 6.5%, which exceeds the crucial value (5%). When PODE10 is used, the COV_{IMEP} can be reduced to 5.6%, which indicates that the combustion is still not very stable. However, the COV_{IMEP} of PODE20 can be further reduced to 2.7%, which indicates a stable combustion can be obtained with PODE20. The improvement in combustion stability at low load with gasoline/PODE blends can be mainly attributed to its properties of high CN leading to shorter ignition delay, which in turn results in stronger fuel concentration stratification. Moreover, higher average IMEP is necessary for gasoline to maintain the same engine load (BMEP=3 bar) compared to gasoline/PODE blends, which implies that the mechanical efficiency of gasoline is lower than that of gasoline/PODE blends. As a result, the combustion stability and mechanical efficiency can be simultaneously improved with gasoline/PODE blends at low load.

One of the challenges in gasoline PPC at low load are the high CO and HC emissions, and low combustion efficiency. The improvements in combustion efficiency and CO/HC emissions with gasoline/PODE blends are illustrated in Fig. 12. It can be seen that the HC and CO emissions with gasoline are higher than those of gasoline/PODE blends, which indicates a low combustion efficiency with gasoline. The misfire probability of gasoline at over-lean region increases because of the high volatility, and consequently leads to higher HC emission. As a result, the combustion efficiency for gasoline at this low

load is about 85.1%, which is too low to be acceptable in practical utilization. However, with the increase of PODE blending ratio, the CO/HC emissions and combustion efficiency can all be greatly improved. The in-cylinder over-lean region can be reduced with gasoline/PODE blends because of the relatively poor volatility and shorter ignition delay compared to gasoline. Therefore, the CO oxidation process can be enhanced by higher local combustion temperature and HC emission can be decreased due to the lower misfire probability with gasoline/PODE blends. On the other hand, high oxygen content in the gasoline/PODE blends is also helpful to reduce CO and HC emissions. Eventually, the combustion efficiency can be dramatically improved from 85.1% to 99.3% by blending 10% PODE into gasoline, and this value can be further improved to 99.6% with PODE20 at this low load.

4. Conclusions

In this study, PODE is used as an additive to optimize the fuel properties of gasoline. The effects of gasoline/PODE blends with PODE volume blending ratio of 0, 10% and 20% on PPC combustion and emission characteristics are investigated in a multi-cylinder heavy-duty diesel engine under various loads. The main conclusions can be summarized as follows:

1. At high load, the pressure rise rate can be maximally reduced by 24% and 47% when fueling PODE10 and PODE20. 79% and 94% soot reduction can be obtained by PODE 10 and PODE20 respectively due to the dilution effect and the smoke-less combustion characteristics of PODE.
2. The NO_x-soot relationship can be significantly improved without penalty in fuel economy by fueling gasoline/PODE blends. The NO_x and soot emissions limits in Euro V and Euro VI can be met without aftertreatment system at high load and medium load respectively by fueling both PODE10 and PODE20.
3. The mechanical efficiency can be improved from 90.8% to 92.7% at high load when the PODE blending ratio increased from 0% to 20% because of the lower internal leakage caused by higher viscosity, which can compensate the thermal efficiency loss caused by longer combustion duration of gasoline/PODE blends.
4. At medium load, the combustion sensitivity to injection timing and EGR can be greatly improved by fueling gasoline/PODE blends due to the stronger fuel concentration stratification caused by lower octane number.

5. At low load, the COV_{IMEP} can be reduced from 6.5% to 2.7% by fueling PODE20 which indicates that a stable combustion can be obtained. Moreover, the combustion efficiency can be dramatically improved from 85.1% to 99.3% and 99.6% by fueling PODE10 and PODE20, respectively. As consequences, both HC/CO emissions can be greatly reduced.

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