



# Effects of diesel/PODE (polyoxymethylene dimethyl ethers) blends on combustion and emission characteristics in a heavy duty diesel engine



Jialin Liu<sup>a</sup>, Hu Wang<sup>a,\*</sup>, Ying Li<sup>b</sup>, Zunqing Zheng<sup>a</sup>, Zhenzhen Xue<sup>c</sup>, Hongyan Shang<sup>c</sup>, Mingfa Yao<sup>a</sup>

<sup>a</sup> State Key Laboratory of Engines, Tianjin University, Tianjin 300072, China

<sup>b</sup> Mechanical Engineering College, Guangxi University, Nanning 530004, China

<sup>c</sup> College of Science, China University of Petroleum, Qingdao 266580, China

## HIGHLIGHTS

- Clean combustion is achieved via fuel properties optimization and EGR control.
- Combustion rate in late combustion phase can be accelerated by adding PODE.
- Soot, HC and CO emissions can be reduced by fueling diesel/PODE blends.
- Diesel/PODE blends has the potential to improve BTE under low NOx conditions.
- The aftertreatment device can be simplified by fueling diesel/PODE blends.

## ARTICLE INFO

### Article history:

Received 20 October 2015

Received in revised form 25 January 2016

Accepted 7 March 2016

Available online 12 March 2016

### Keywords:

Polyoxymethylene dimethyl ethers (PODE)

Fuel property

Soot emission

Clean combustion

Cetane number

## ABSTRACT

Polyoxymethylene dimethyl ethers (PODE) is an emerging biofuel with properties of high cetane number (CN), high oxygen content and no C–C bond, which shows a significant potential to achieve high efficient and clean combustion and to be one of the competitive alternative fuels for diesel engine. In the current study, the effects of diesel/PODE blends on the combustion and emission characteristics with the PODE volume blending ratio of 15% and 25% have been experimentally investigated in a heavy duty diesel engine. Fuel properties optimization coupled with exhaust gas recirculation (EGR) is utilized to achieve high efficient and clean combustion. The combustion and emission characteristics of diesel, PODE15 and PODE25 are compared at low, medium and high loads. The experimental results show that blending PODE can accelerate the combustion rate in the late combustion phase and it is also beneficial for soot emission reduction, especially at low excess air ratio conditions. The HC and CO emissions can be improved by fueling diesel/PODE blends. The NOx emission of diesel/PODE blends can be slightly improved, while the brake thermal efficiency (BTE) is penalized at low and medium loads. As the NOx is further decreased to relatively low values by increasing EGR at high load, the BTE of diesel/PODE blends gradually gets close to that of diesel and shows the capability to improve BTE. The NOx–soot trade off relationship can be dramatically improved by fueling diesel/PODE blends. The weighted results over the World Harmonized Stationary Cycle (WHSC) indicate that the raw soot emission of PODE25 can meet the Euro VI soot emission standard when the weighted NOx is controlled at 2.7 g/kW h. In this case, a selective catalytic reduction (SCR) device with an average conversion efficiency of 85% is adequate to meet the Euro VI NOx emission standards for PODE25, which means that the requirement on aftertreatment device for achieving low emissions can be reduced by fueling diesel/PODE blends.

© 2016 Elsevier Ltd. All rights reserved.

**Abbreviations:** B7, diesel blended with 7% of FAME-type biodiesel; BMEP, brake mean effective pressure; BSFC, brake specific fuel consumption; BTE, brake thermal efficiency; CA50, crank angle at 50% of total heat release; CA90, crank angle at 90% of total heat release; CFR, cooperative fuel research; CN, cetane number; DPF, diesel particle filter; EGR, exhaust gas recirculation; FAME, fatty acid methyl esters; HRR, heat release rate; IBP, initial boiling point; LVH, low heat value; PAH, polycyclic aromatic hydrocarbons; PODE, polyoxymethylene dimethyl ethers; SCR, selective catalytic reduction; SOI, start of injection; T95, 95% distillation temperature; WHSC, World Harmonized Stationary Cycle.

\* Corresponding author.

E-mail address: [wang\\_hu@tju.edu.cn](mailto:wang_hu@tju.edu.cn) (H. Wang).

## 1. Introduction

Conventional compression ignition (CI) engine is well known for its good reliability, high efficiency and excellent power performance, which has been widely employed for more than one hundred years [1]. However, nitrogen oxides (NOx) and particulate matter (PM) emissions emitted from CI engine lead to serious environmental pollution. More stringent emission regulations have been legislated to protect the environment [2].

On the other hand, about 70% of the crude oil are consumed by internal combustion engines every day, which aggravates the energy crisis [1,3]. Therefore, more combustion and emission control strategies should be developed to satisfy the stringent emission regulations and to relieve the energy crisis simultaneously.

Alternative fuels and fuel properties optimizations are thought to be effective methods to alleviate energy crisis and achieve high efficient and clean combustion [4,5]. Experimental studies have shown that fuel properties, including the oxygen content, CN, distillation and others, have important effects on combustion and emissions [6–8]. Generally, fuel properties optimization can be achieved by blending oxygenated components, such as alcohol, ether and ester, which are widely studied alternative fuels to diesel [3,9,10]. The physical and chemical properties, the source of raw materials, the miscibility with diesel, the effects on combustion and emission and others should all be taken into consideration when evaluating if an alternative fuel can be used in practical engines. Until now, the main issue about the research on alternative fuels is how to achieve high efficient and clean combustion at all operation conditions with minor or without changing the structure of original engine.

Previous studies found that the alcohol, which are typically represented by methanol, ethanol and butanol, have significant effects on reducing the toxic emissions [5,11–14]. However, the shortcomings of methanol and ethanol, such as poor solubility in diesel and unlimited solubility in water, are prone to cause phase separation and water pollution, which limit their practical applications in diesel engine to some extent [15]. Butanol is thought to be a promising alternative to diesel because the properties of butanol are more similar to diesel compared to methanol and ethanol. Nevertheless, the low CN of butanol, which may weaken the auto-ignitability of the blend, is the main restriction to the utilization of butanol in diesel engines [5]. Consequently, there are still some obstacles to overcome when using alcohol in diesel engine.

As a representative of ester fuel, FAME-type biodiesel with the characteristics of high CN, high oxygen content and sulfur-free, has been widely studied as an alternative in diesel engine. The most common viewpoint about the effects of FAME-type biodiesel in diesel engine is that the HC, CO and PM emissions can be reduced and the NOx emission can be slightly increased [16]. However, some disadvantages about FAME-type biodiesel should also be mentioned. For instance, FAME-type biodiesel is unstable when exposed to air at high temperature condition [17]. FAME-type biodiesel can corrode some metal materials and inflate some plastics or rubbers [18,19]. FAME-type biodiesel has poor volatility property, which diminishes the positive effect of oxygen content on PM reduction, especially at high load operation conditions [17]. Moreover, the fuel filter is prone to be plugged when fueled with FAME-type biodiesel, because of the poor low temperature properties such as cloud point and pour point [17,20]. In view of the above reasons, the properties of FAME-type biodiesel should be further optimized in order to be better used in diesel engine.

Furthermore, ether are found to be more effective in decreasing PM than alcohol and ester [21]. Dimethyl ether (DME) and dimethoxymethane (DMM) are the most extensively studied ester fuels in heavy duty diesel engines [22]. Both DME and DMM show excellent performance in reducing soot emission [21,23]. Nonetheless, the superior volatility of DME makes it easy to form high vapor pressure, which in turn leads to vapor lock phenomenon and low solubility in diesel [23]. Studies have shown that the moving components in diesel engine can be damaged by DMM or DME because of the poor lubricity [24]. Thus, the intrinsic properties of DME and DMM make it hard to be directly used in existing diesel engines without modifications.

As an emerging alternative fuel, polyoxymethylene dimethyl ethers (PODE) has been reported as an excellent component for

diesel fuel because it shows the capability to greatly reduce the soot emission [25–28]. It has better auto-ignition capability than alcohols, better chemical stability than FAME-type biodiesel and a volatility more suitable to diesel than DME and DMM. Previous studies showed that PODE as an alternative to diesel has great potential to achieve high efficient and clean combustion and to be utilized in practical engine without changing the structure or with only minor modifications of original engine [25,26,28–30]. The effects of neat and blended PODE on combustion and emissions in a light duty diesel engine were investigated by Pellegrini et al. [25,26]. The results show that using 10–12% PODE as a component in diesel can reduce 40% PM emission and 50% PODE can meet the Euro 6 NOx emission limit at the same PM emission level of pure diesel. Liu et al. [30] also found that soot emission can be significantly reduced by fueling PODE/diesel blends in a light duty diesel engine. By blending 20% PODE into B7 (diesel blended with 7% of FAME-type biodiesel), the soot emission, PM emission and particle number can be reduced by 60%, 40% and 25% respectively over European Stationary Cycle (ESC) [28]. The injection profile can be greatly changed when the PODE blending ratio is up to 50% [26]. Therefore, the injection system is required to be re-optimized. The detailed properties of PODE will be discussed in next section. Until now, there are a couple of articles dealing with PODE in heavy duty diesel engines and further investigation about PODE is necessary.

In this study, PODE is used as a component to optimize the properties of diesel. The combustion and emission characteristics of diesel/PODE blends with different volume blending ratios, including 0, 15%, 25%, have been investigated in a multi-cylinder heavy duty diesel engine. The effects of PODE on combustion and emissions are summarized and its mechanism for soot reduction is discussed in this paper. To meet the Euro VI emission target, different SCR efficiencies are assumed and taken into consideration, and their corresponding weighted NOx control targets can be obtained by varying the EGR ratio. The comparisons of performance, fuel economy and other emissions are conducted under these NOx emission targets conditions. Finally, the potential of PODE as a component to meet the Euro VI emission regulation are evaluated and discussed.

## 2. Experimental setup

### 2.1. Engine test bench

All experiments have been conducted in an inline, 6-cylinder, 24-valve, water-cooled, turbocharged heavy duty diesel engine equipped with a common rail injection system. The original production engine equipped with a SCR can meet the Euro IV emission regulations and its model year is 2009. The specifications of the engine are shown in Table 1 and the schematic of the experimental setup is presented in Fig. 1. In this experiment, the SCR is left out and all the emissions are the raw emissions. The fuel supply system and the turbocharger are original without modification. While the injection parameters in this investigation are differing from the

**Table 1**  
Specifications of the engine.

Displacement	8.42L
Connecting rod length	209 mm
Compression ratio	17.5:1
Swirl ratio	1.25
Combustion chamber	Reentrant type
Fuel injection system	Common rail
Max. injection pressure	160 MPa
Number of nozzle holes	8
Included spray angle	148°
Hole diameter	0.163 mm

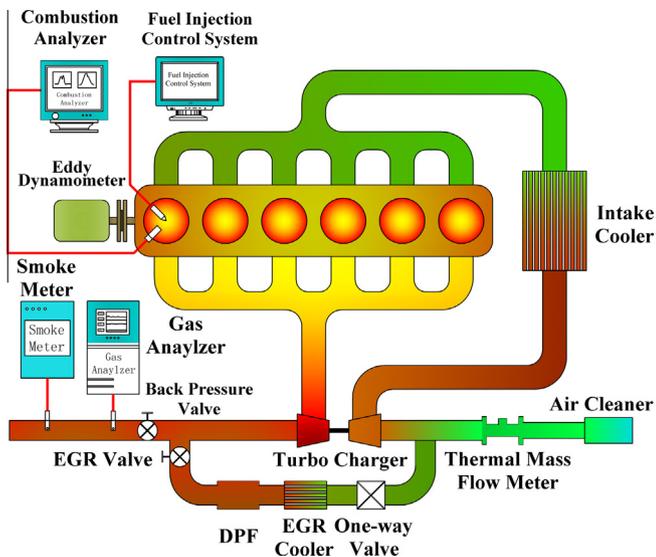


Fig. 1. The schematic of the experimental setup.

original injection map. To obtain different weighted NO<sub>x</sub> emissions, a low pressure EGR loop is set up on the original engine. However, it is not because of the changing of the fuel properties that the original engine is modified.

The fuel injection parameters were controlled by an electronic control unit (ECU) made by Bosch. The in-cylinder pressure was measured by Piezoelectric pressure sensor (Kistler 6125C) coupled with a charge amplifier (Kistler 5011B10). The optical crank angle encoder (Kistler 2614A4) was used to trigger the cylinder pressure data acquisition with an increment of 0.5 degree crank angle (°CA). The heat release rate (HRR) traces were obtained by utilizing the experimental pressure traces according to the thermodynamic modeling in [31]. The gaseous exhaust, including CO, CO<sub>2</sub>, HC and NO<sub>x</sub>, as well as EGR rate, were measured by an emission analyzer (HORIBA MEXA 7100DEGR). The measuring principle of CO and CO<sub>2</sub> was non-dispersive infra-red (NDIR), while HC was measured via the hydrogen flame ionization (FID) and the chemiluminescent analyzer (CLA) method was adopted to quantify NO<sub>x</sub> emission. The CO<sub>2</sub> concentrations in the intake and exhaust pipes were measured to calculate the EGR ratio via the following formula Eq. (1):

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

Furthermore, a filter paper smoke meter (AVL 415S) was employed to measure the filter smoke number (FSN) and the indicated specific dry soot emission (unit: g/kW h) can be calculated according to the following formula Eq. (2) according to the reference [32]:

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

where  $m_{\text{air}}$ ,  $m_{\text{fuel}}$  and  $P_i$  refer to the intake mass flow rate (kg/h), fuel mass flow rate (kg/h) and indicated power (kW).

## 2.2. Properties of PODE

PODE is a mixture that composed of many short oligomers. The general chemical formula is CH<sub>3</sub>O-(CH<sub>2</sub>O)<sub>*n*</sub>-CH<sub>3</sub> with *n* ranging from 1 to 6. It can be derived from natural gas, coal and waste biomasses and whether it is a second-generation biofuel depends on the feedstock [29,33]. The production cost of PODE can be reduced to an acceptable level because of the low cost raw materials and optimized production technologies [29,34]. The appearance comparison between PODE and diesel is exhibited in Fig. 2. PODE have

excellent miscibility with diesel [35]. PODE with *n* = 1 (abbreviated as PODE<sub>1</sub> and the same below) is DMM, which has been discussed previously. The flash point by closed cup of PODE<sub>2</sub> is below 40 °C leading to unsafe transportation. PODE<sub>6</sub> with the melting point of about 48 °C has poor flow property and small amounts of PODE<sub>6</sub> can dissolve into PODE with *n* ranging from 3 to 5. Generally, PODE with *n* = 3–5 or small amounts of *n* = 6 can be utilized as components in diesel without changing the structure of original engine [29]. The detailed properties and molecular structure of PODE with *n* ranging from 2 to 6 are presented in Table 2.

The CN of PODE reported in previous studies [34,36] are always the blending CN (shown in Table 2), in which the CN of PODE is calculated via the formula shown in [37]. Higher CN is beneficial for HC and CO oxidation, resulting in higher combustion efficiency, especially at low load conditions [38]. PODE with the characteristics of no C–C bond and high H/C ratio as well as high oxygen content (above 47 wt%) indicates its high capability to prohibit the formation of polycyclic aromatic hydrocarbons (PAH) and soot [29]. However, high oxygen content in PODE is also prone to produce higher NO<sub>x</sub> emission [8]. Nevertheless, the NO<sub>x</sub>–soot trade-off is demonstrated to be improved by fueling diesel/PODE blends [26].

The low heat value (LHV) of each component in PODE was reported as the calculation value in [28] and the LHV of PODE was calculated as the weighted heat of each component [27]. However, the LHV of PODE measured by the experiment is slightly different from the calculation value [25]. In this paper, the LHV of PODE was obtained by experimental measurements according to the standard test method of GB/T 384-1981 in China. The LHV of PODE is almost half to that of diesel. Therefore, to obtain the same power output, more cyclic fuel mass is usually needed, resulting in longer injection duration with the same injection pressure. However, the combustion phasing loss caused by longer injection duration can be partially compensated by the fast combustion rate in the late combustion phase with PODE component [26]. In addition, the volatility of diesel can be improved by blending PODE, which has the advantage to reduce the locally fuel-rich region and to suppress the soot formation. According to the properties of PODE mentioned above, it can be seen that PODE has the potential to be one of the ideal alternative fuels in diesel engine.

## 2.3. Test fuels

In this study, PODE is used as an oxygenated component to diesel with volume blending fraction of 0, 15% and 25% (abbreviated as Diesel, PODE15 and PODE25). The mass fraction of each compo-

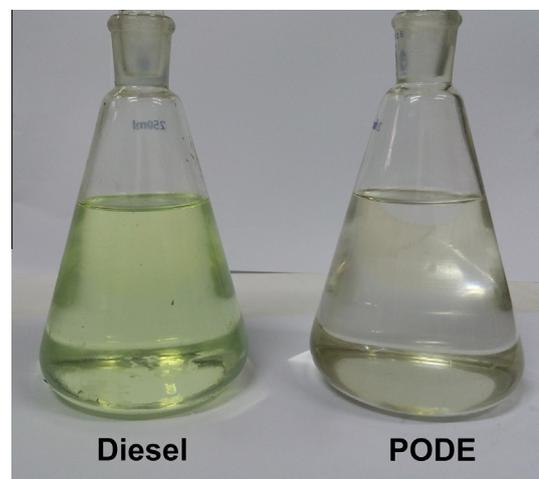


Fig. 2. Appearance comparison between diesel and PODE.

**Table 2**Properties and molecular structure of the components in PODE with  $n$  ranging from 2 to 6.

Formula	$\text{CH}_3\text{O}-(\text{CH}_2\text{O})_n-\text{CH}_3$					Molecular structure
$n$	2	3	4	5	6	
Abbreviation	PODE <sub>2</sub>	PODE <sub>3</sub>	PODE <sub>4</sub>	PODE <sub>5</sub>	PODE <sub>6</sub>	
Melting point (°C)	-69.7	-42.5	-9.8	18.3	48	
Boiling point (°C)	105	156	202	242	280	
Density (g/mL@25 °C)	0.96	1.02	1.07	1.10	1.13	
Blending CN	63	78	90	100	104	
Oxygen content (wt%)	45.2	47	48.1	48.9	49.5	
Kinetic viscosity (mPa s)	0.64	1.05	1.75	2.24	-	

ment in PODE used in this experiment are shown in Table 3 and the properties of diesel and PODE blends are shown in Table 4. The comparison of distillation properties between diesel and PODE is shown in Fig. 3. The initial boiling point (IBP) and 95% distillation temperature (T95) of PODE are significant lower than those of diesel, which means that PODE has better volatility than diesel. It should be noted that the cetane numbers of PODE, PODE15 and PODE25 in Table 4 are measured in a standard cooperative fuel research (CFR) engine according to the standard test method of GB/T 386-2010 in China and they are not the blending CN. Based on the CN of PODE25, the blending CN of PODE is calculated as 75.5 according to the formula in [37,39].

It is seen that the LHV of PODE is almost half to that of diesel. To fairly compare the fuel economy between diesel and diesel/PODE blends, all the brake specific fuel consumption (BSFC: g/kW h) of diesel/PODE blends have been converted to equivalent BSFC of diesel according to the following formula Eq. (3):

Equivalent BSFC of diesel/PODE blends : BSFC

$$= \frac{1000}{P_b} \times \left\{ \frac{\rho_{\text{PODE}} \times \eta \times \text{LHV}_{\text{PODE}} + \rho_{\text{Diesel}} \times (1 - \eta) \times \text{LHV}_{\text{Diesel}}}{[\rho_{\text{PODE}} \times \eta + \rho_{\text{Diesel}} \times (1 - \eta)] \times \text{LHV}_{\text{Diesel}}} \right\} \quad (3)$$

where  $\rho_{\text{PODE}}$  and  $\rho_{\text{Diesel}}$  ( $\text{kg}/\text{m}^3$ ) denote the density of PODE and diesel respectively;  $\text{LHV}_{\text{PODE}}$  and  $\text{LHV}_{\text{Diesel}}$  ( $\text{MJ}/\text{kg}$ ) represent the LHV of PODE and diesel.  $\eta$  (%) refer to the volume blending fraction of PODE and  $P_b$  (kW) represents the brake power of the engine.

#### 2.4. Test methods

The comparison of diesel, PODE15, PODE25 were all carried out over the WHSC test cycle, which is a regulatory emission test procedure for heavy duty truck and bus engines in the Euro VI regulation. The speed and torque of each test point in the WHSC test cycle are shown in Fig. 4. The number in the circle represents the test sequence in the WHSC test cycle. The same injection strategy as the original engine was employed under both cold and warm idle conditions to obtain better combustion stability and cold-start performance. The other eleven test conditions were all using single injection strategy with injection pressure of 160 MPa. The earliest injection timing was restricted by the maximum pressure rise rate ( $dp/d\phi < 12 \text{ bar}/^\circ\text{CA}$ ) or the maximum cylinder pressure ( $P_{\text{max}} \leq 165 \text{ bar}$ ). The combustion and emission characteristics of

**Table 3**

The mass fraction of each component in PODE.

Components	Mass fraction (wt%)
PODE <sub>3</sub>	44.80
PODE <sub>4</sub>	28.24
PODE <sub>5</sub>	17.09
PODE <sub>6</sub>	9.87

**Table 4**

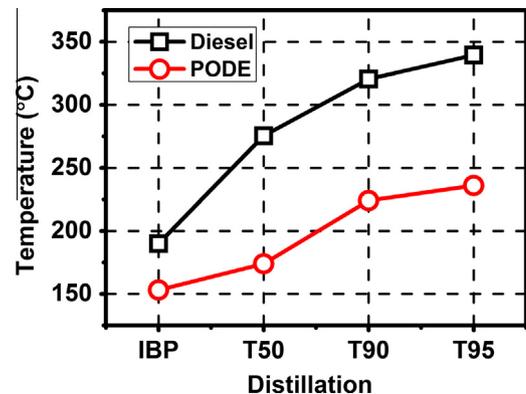
The properties of diesel, PODE and diesel/PODE blends.

Properties	Diesel	PODE	PODE15	PODE25
Density@20 °C ( $\text{kg}/\text{m}^3$ )	834.2 <sup>b</sup>	1047.1 <sup>b</sup>	866.1 <sup>c</sup>	887.4 <sup>c</sup>
Cetane number <sup>a</sup>	51	60.7	54	57.8
LHV( $\text{MJ}/\text{kg}$ )	42.83 <sup>b</sup>	21.77 <sup>b</sup>	36.62 <sup>c</sup>	33.79 <sup>c</sup>
C (wt%)	86.55 <sup>b</sup>	43.53 <sup>c</sup>	78.75 <sup>c</sup>	73.86 <sup>c</sup>
H (wt%)	13.45 <sup>b</sup>	8.52 <sup>c</sup>	12.56 <sup>c</sup>	12.00 <sup>c</sup>
O (wt%)	0	47.95 <sup>c</sup>	8.69 <sup>c</sup>	14.14 <sup>c</sup>
Aromatics (wt%)	17.48 <sup>b</sup>	0	15.84 <sup>c</sup>	12.32 <sup>c</sup>
PAH (wt%)	9.37 <sup>b</sup>	0	7.67 <sup>c</sup>	6.61 <sup>c</sup>
Sulfur (ppm)	4.7 <sup>b</sup>	0	3.85 <sup>c</sup>	3.31 <sup>c</sup>
Closed flash point (°C)	81.5 <sup>b</sup>	59 <sup>b</sup>	-	-

<sup>a</sup> Measured in a standard CFR engine.

<sup>b</sup> Experimental test results.

<sup>c</sup> Calculation value.

**Fig. 3.** The distillation curve of diesel and PODE.

the tested fuels were compared at five different weighted NO<sub>x</sub> targets, which were achieved by varying the EGR ratio.

### 3. Results and discussion

#### 3.1. Effects of PODE on combustion characteristics at different loads and EGR rates

##### 3.1.1. In-cylinder pressure and heat release rate

The in-cylinder pressure and HRR characteristics of diesel, PODE15 and PODE25 at low, medium and high load operation conditions are shown in Fig. 5. The operation conditions of  $n = 1348 \text{ r}/\text{min}$  with  $\text{BMEP} = 4.8 \text{ bar}$ ,  $n = 1348 \text{ r}/\text{min}$  with  $\text{BMEP} = 13.4 \text{ bar}$  and  $n = 1503 \text{ r}/\text{min}$  with  $\text{BMEP} = 19.1 \text{ bar}$ , are chosen to represent the low, medium and high load conditions, respectively. The comparisons are made at fixed CA50 and EGR rate conditions. The difference in HRR among diesel, PODE15 and PODE25 depend on the engine load. At low load, the peak HRR is lowered by blending PODE. Since the peak HRR is mainly dominated by the mixture formed during the ignition delay period, although the superior

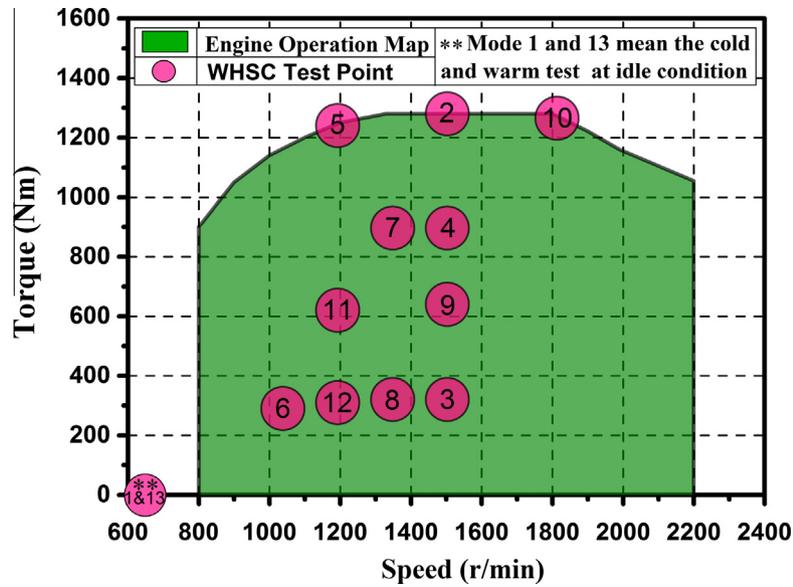


Fig. 4. Operation conditions for WHSC cycle.

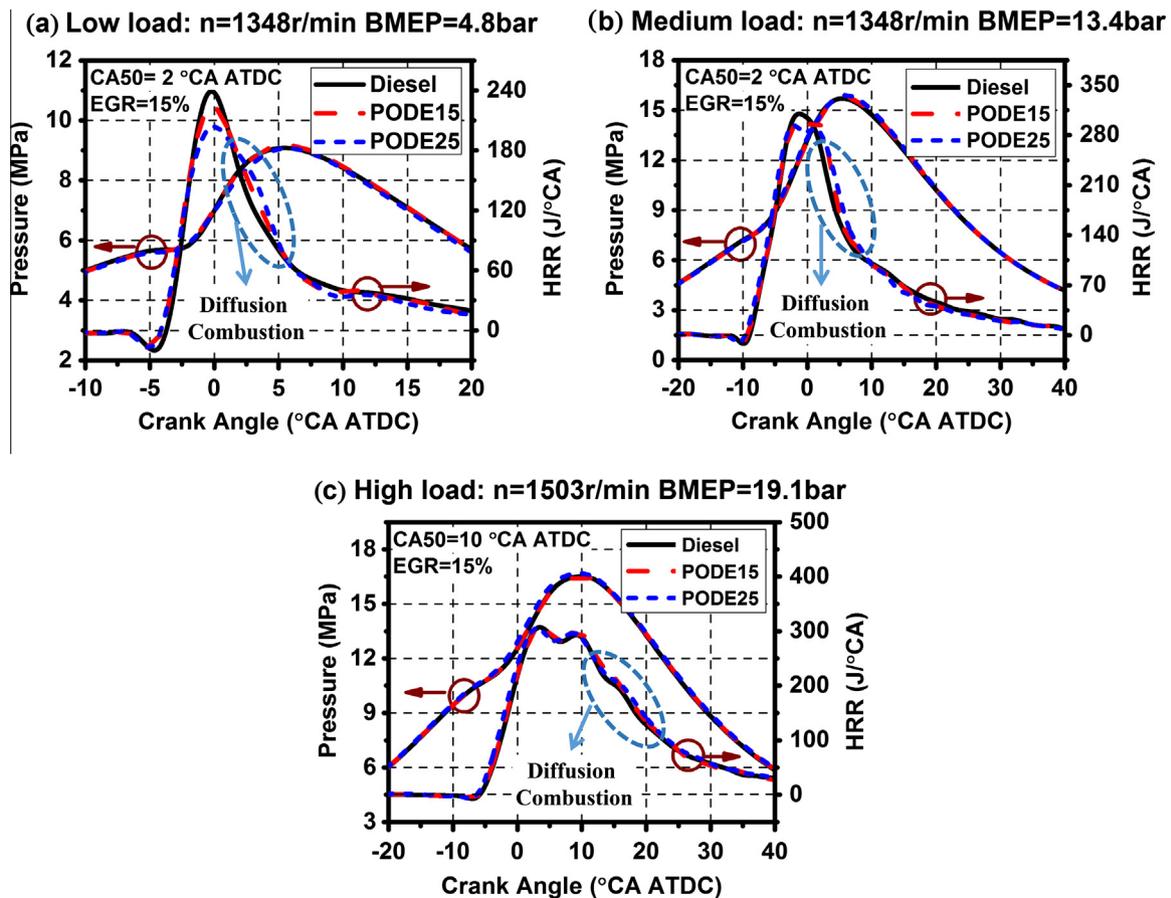


Fig. 5. In-cylinder pressure and heat release rate at low, medium and high load conditions.

volatility performance of PODE can promote the air–fuel mixing rate of diesel/PODE blends, however, the available mixing time still reduces because of the high CN of diesel/PODE blends. In addition, more air–fuel mixture is needed for diesel/PODE blends to obtain the same heat as that of diesel because of the lower LHV of diesel/PODE blends. Therefore, as the blending ratio increases, the

peak HRR is lowered because of lower LHV and shorter mixing time. As the load increases, the temperature in the cylinder increases while the ignition delays of these fuels are mostly affected by the high temperature. Thus, the ignition delays of these fuels are almost the same at medium and high loads. As the temperatures are getting higher, the combustion process shifts from

a predominantly kinetic control to a predominantly thermodynamic control, the effects of fuel properties on combustion are getting smaller. Therefore, the difference in HRR is getting smaller among these fuels as the load increases. During the diffusion combustion period at each load, the HRR of PODE15 and PODE25 are slightly higher than diesel. This illustrates that blending PODE can promote the air–fuel mixing rate and accelerate the combustion rate of diesel/PODE blends. This conclusion was also found by Pellegrini et al. [26] in a single cylinder optical engine. Nevertheless, at different operation conditions, the in-cylinder pressure characteristics have no significant difference among diesel, PODE15 and PODE25.

3.1.2. Combustion phasing

Due to the lower HRR of diesel/PODE blends caused by lower LHV and shorter mixing time, advanced SOI is required for diesel/PODE blends to keep the same CA50, which is shown in Fig. 6. The combustion rate in the late combustion phase is described as the interval between CA50 and CA90 (i.e., CA90–CA50) [40,41]. Lower value of CA90–CA50 indicates fast combustion rate in the late combustion phase and vice versa. The comparison of the combustion rate in the late combustion phase between diesel, PODE15 and PODE25 is shown in Fig. 6. It shows that blending PODE have the tendency to accelerate the combustion rate in the late combustion phase, which can compensate the longer injection duration caused by the lower LHV of PODE. With the increase of EGR, the ambient oxygen concentration decreases, leading to the reduction of combustion rate for all fuels.

Moreover, the superior volatility and high oxygen content in PODE can also be beneficial to promote the combustion rate. Therefore, with the increase of blending ratio, the CA90–CA50 decrease, which means faster combustion rate in the late combustion phase.

3.1.3. Fuel economy

Fig. 7 shows the comparison of diesel, PODE15 and PODE25 on BTE and BSFC at different loads. At low load, with the increase of EGR, the prolonged ignition delay results in higher premix combustion ratio and the combustion efficiencies can be maintained at high levels because of the sufficient fresh air supply. Therefore, the BTE of all fuels depict slightly increase with the increase of EGR. At medium load, the BTEs of all fuels decrease with the increase of EGR because of the deteriorated combustion efficiency. At both low and medium loads, BTE decreases with the increase of blending ratio because of the lower premix combustion fraction, which is shown in Fig. 5. Moreover, with the increase of blending ratio, more cyclic fuel mass is needed to maintain the same total energy, combined with the higher fuel density, resulting in higher spray momentum, which is prone to increase the spray liquid and vapor penetrations, thus more fraction of air–fuel mixture may diffuse and burn closer to cylinder liner than diesel, which in turn may increase the heat transfer loss. At high load, the difference in BTE between diesel, PODE15 and PODE25 is getting smaller than that at low and medium loads. When the EGR is above 10%, the BTEs of diesel/PODE blends are higher than diesel because of the higher combustion efficiency and higher combustion rate in the late combustion phase. When the EGR is further increased up

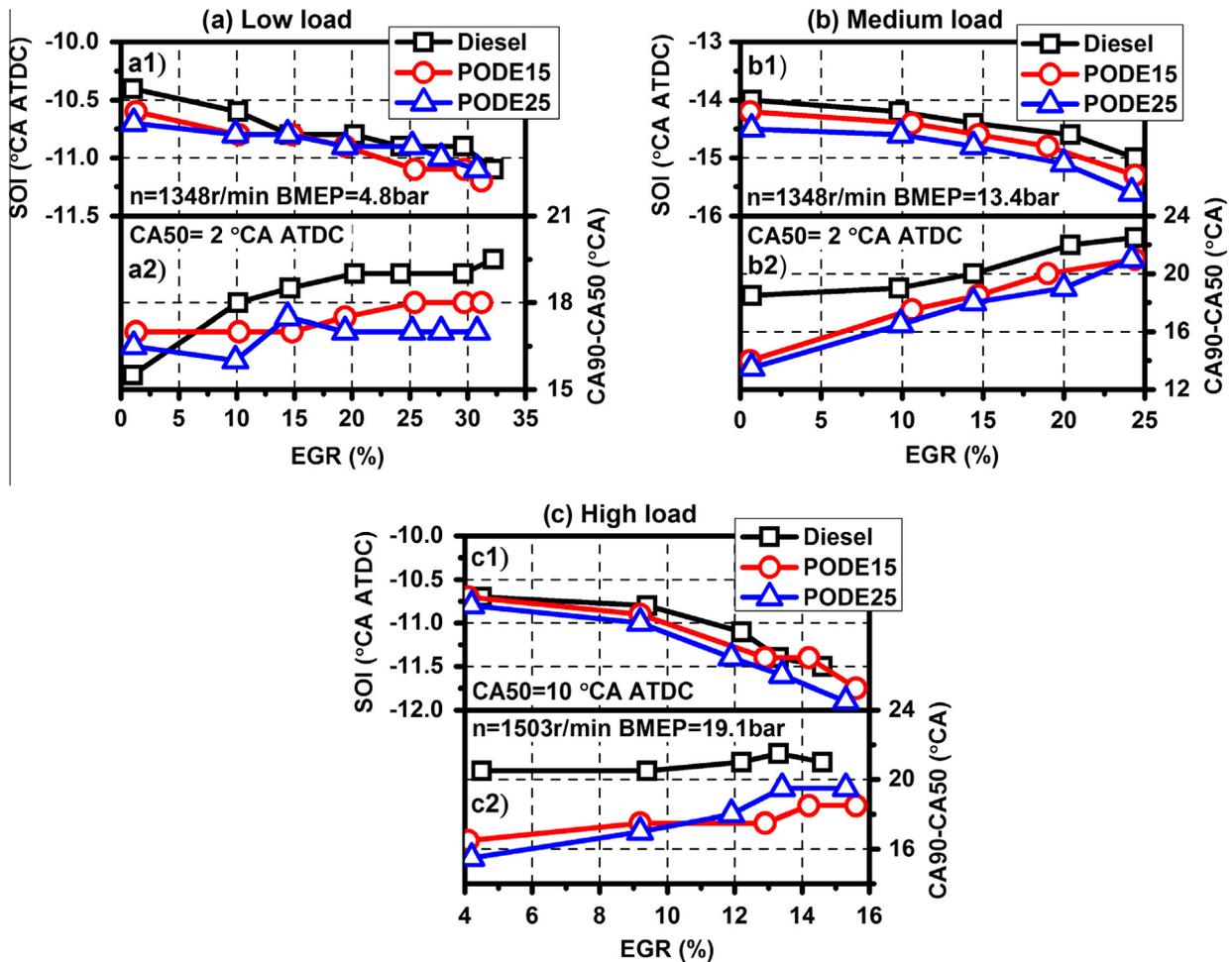


Fig. 6. SOI timing and CA90–CA50 of diesel, PODE15 and PODE25 at different loads.

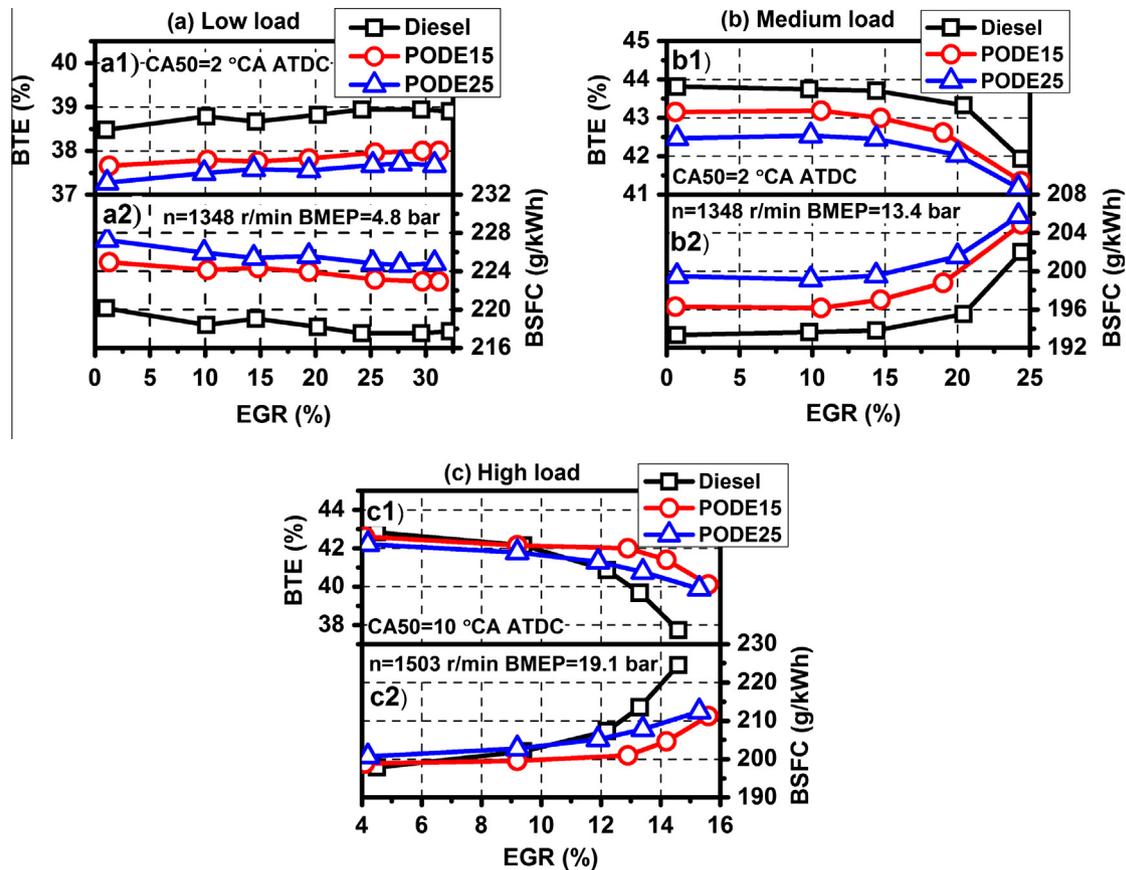


Fig. 7. BTE and BSFC of diesel, PODE15 and PODE25 at different loads.

to 15%, the BTE decrease rate of diesel is obviously higher than those of diesel/PODE blends. This indicates that the advantage of high oxygen content and high volatility of PODE can fully exhibited it's capability in improving combustion efficiency and show greater BTE improvement at high load conditions with heavy EGR. Combined the synergistic effects of heat transfer loss, combustion rate and combustion efficiency, PODE15 shows the highest BTE at high EGR ratio conditions. However, it should be noted that, when the EGR is further increased, PODE25 has higher potential to improve the BTE than PODE15 because the oxygen content in the fuel may play more important role in improving combustion efficiency at such low excess air ratio conditions.

### 3.2. Effects of PODE on emission characteristics at different loads and EGR rates

#### 3.2.1. CO and HC emissions

Fig. 8 presents the effects of PODE on CO and HC emissions at different loads and EGR rates. At low and medium loads, PODE15 and PODE25 have no significant effect on the reduction of CO emission compare to neat diesel because the oxygen concentration in cylinder is sufficient at these conditions, which is the key factor to oxidize the CO to CO<sub>2</sub>. Therefore, the function of the high oxygen content in the PODE blends is not completely exploited. However, when the operation condition shifts to high load, the available oxygen in cylinder is reduced, which affects the CO oxidization. In this case, the advantage of the high oxygen content in PODE can be effectively exhibited. Furthermore, superior volatility of PODE is also beneficial to improve the oxygen utilization in the fresh air. It clearly shows that blending PODE can dramatically reduce the CO emission, especially at high load conditions with high EGR.

The HC emission is higher for all fuels at low load than at high loads because of the over-lean mixture and low in-cylinder temperature. At medium or high load, HC emission is extremely low due to the high combustion temperature and high cylinder wall temperature, thus the incomplete combustion and wall quenching phenomenon can be reduced. Therefore, the high oxygen content of PODE blends can hardly present its capability to reduce HC emission at this condition.

#### 3.2.2. NO<sub>x</sub> and soot emissions

The NO<sub>x</sub> and soot emissions of diesel, PODE 15 and PODE 25 at different loads are shown in Fig. 9. Theoretically, the presence of oxygen in diesel/PODE blends has the tendency to increase the NO<sub>x</sub> emission. However, the experimental results show that blending PODE can actually reduce the NO<sub>x</sub> emission under low and medium loads because of lower CN and lower LHV of diesel/PODE blends resulting in lower peak HRR and lower premixed combustion ratio. Previous studies also made conclusions that higher peak HRR generally produces more NO<sub>x</sub> emission and fuel with high CN is beneficial to NO<sub>x</sub> reduction because of shorter ignition delay resulting in lower premixed combustion fraction [38,40,42]. With the increase of load, the differences of peak HRR and ignition delay between these fuels are getting smaller, resulting in quite close NO<sub>x</sub> emission between diesel, PODE15 and PODE25. Moreover, when the EGR is increased to a relative higher level at low or medium load, the difference of NO<sub>x</sub> emission between these fuels are getting smaller. While at high load, the difference of fuel properties has almost no effects on NO<sub>x</sub> emission. It is said that EGR is the primary factor while the difference of fuel properties is the secondary factor that effects the NO<sub>x</sub> emission at low excess air ratio conditions. The conclusion was also made by Ruggero et al. [43].

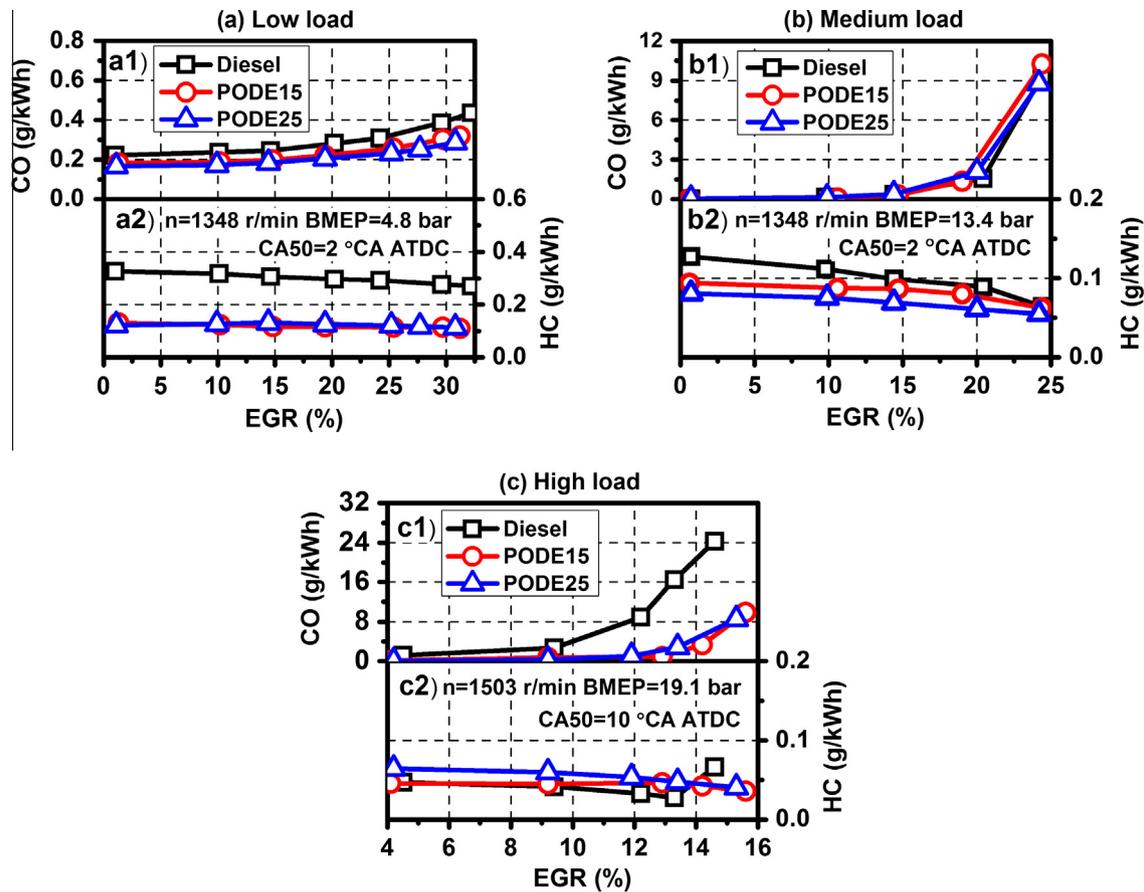


Fig. 8. CO and HC emission characteristics of diesel, PODE15 and PODE25 at different loads.

Fig. 9 shows that blending PODE can significantly reduce the soot emission compared to neat diesel. In PODE molecule, each carbon atom connects to an oxygen atom and there is no C–C bond. Such a molecular structure combined with high oxygen content has been demonstrated to be an efficient structure in reducing soot emission [21]. PODE have low boiling point and high volatility than diesel and its high density can also result in higher fuel spray momentum. These properties make it prone to produce more uniform air–fuel mixture than neat diesel. In addition, blending PODE can accelerate the combustion rate in final combustion phase, which is also beneficial for soot oxidation. Lastly, the diesel is diluted by PODE component, which can reduce the aromatics content and contribute to the reduction of soot emission. These aspects mentioned above make the diesel/PODE blends burn much cleaner than neat diesel.

According to Fig. 9, the soot reduction performance for diesel/PODE blends are very obvious at low excess air ratio conditions (such as high load and high EGR conditions). At low load, the soot emissions of all fuels are close to zero and EGR or fuel property has little effect on it. Because at this low load condition, the ignition delay is relatively long, resulting in more uniform mixture and less fuel-rich regions. At such low soot emission condition, the soot reduction ability of diesel/PODE blends cannot be revealed obviously. As the load shifts to the medium load, the soot emissions for all fuels are quite low when the EGR is below 20%, while when the EGR rate is increased up to 20%, all fuels exhibit a significant rising trend in soot emissions and the diesel/PODE blends show great potential to reduce the soot emission compared to diesel. At high load, due to the low excess air ratio, the presence of oxygen in PODE blends results in more remarkable reduction in soot emission compared to diesel. It is seen that when the EGR rate is higher

than 12%, the soot emission of diesel dramatically increases while the soot emission of diesel/PODE blends can still be maintained at very low level.

### 3.2.3. NO<sub>x</sub>–soot and NO<sub>x</sub>–BSFC trade off relationships

At low load, with the increase of EGR, NO<sub>x</sub> emission can be dramatically reduced, while the soot emission kept almost the same. Therefore, the NO<sub>x</sub>–soot trade off of all fuels are almost straight lines, which are not presented here. The NO<sub>x</sub>–soot trade off at high load shows the similar trend as at medium load condition. Hence, only the NO<sub>x</sub>–soot trade off at medium load is presented here, which is illustrated in Fig. 10(a). The fuel with higher PODE blending ratio can shift the NO<sub>x</sub>–soot curve closer to the origin point. In other word, when the NO<sub>x</sub> emissions of all fuels are kept at the same level by EGR, the soot can be effectively reduced with the increase of PODE blending ratio. For instance, when the NO<sub>x</sub> is kept at about 2 g/kW h, compared to diesel, the soot can be reduced by 88% and 95% when fueling PODE15 and PODE25, which is able to meet the Euro VI soot limit. This means that a SCR system with an average conversion efficiency of higher than 80% is sufficient to meet the Euro VI NO<sub>x</sub> emission standard. Meanwhile, the lower engine-out soot emissions of diesel/PODE blends have the advantage of reducing the fuel consumption related to the active regeneration of the DPF. Fig. 10(b) illustrates the NO<sub>x</sub>–BSFC trade off of diesel, PODE 15 and PODE 25. As the blending ratio increases, the NO<sub>x</sub>–BSFC trade off become worse. However, it should be noted that at low NO<sub>x</sub> levels, the BSFC of fuel with higher PODE blending ratio gets closer to that of low blending ratio fuel and diesel, which shows the potential of PODE to improve the thermal efficiency at very low NO<sub>x</sub> conditions.

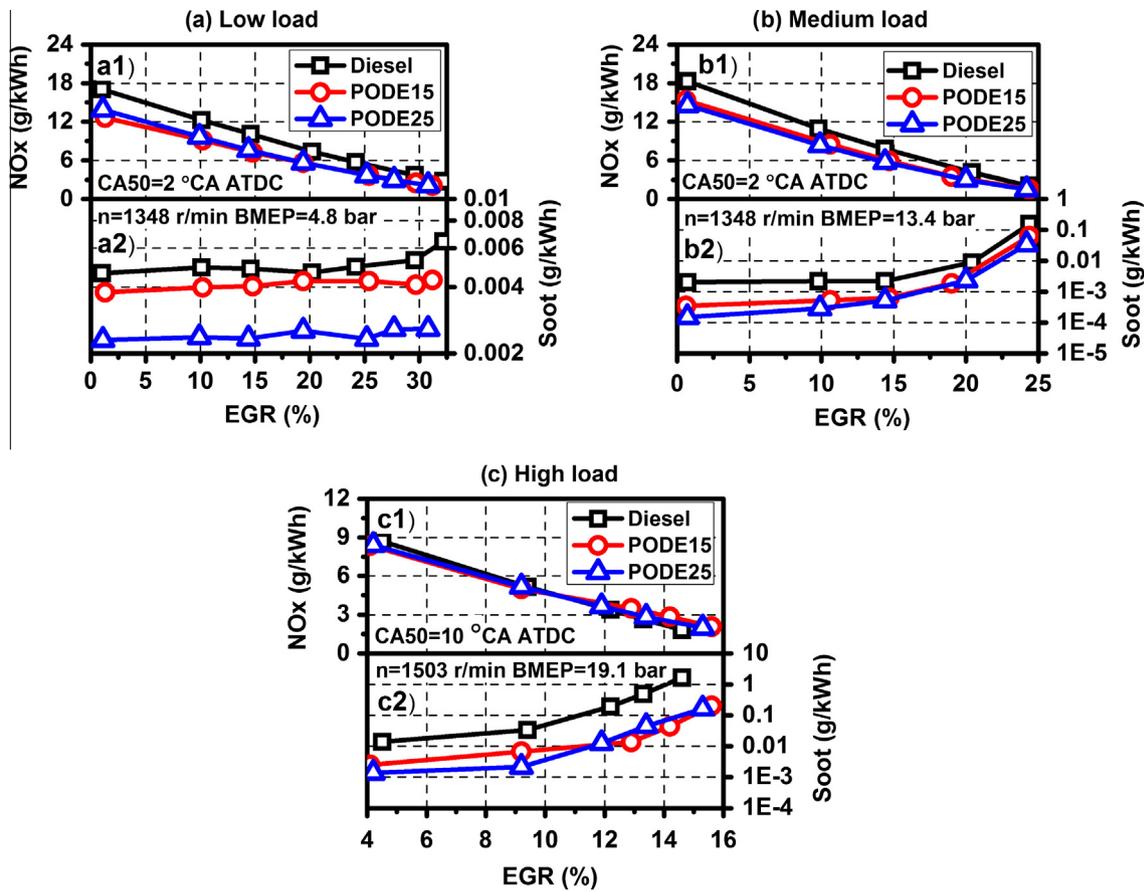


Fig. 9. NOx and soot emission characteristics of diesel, PODE15 and PODE25 at different loads.

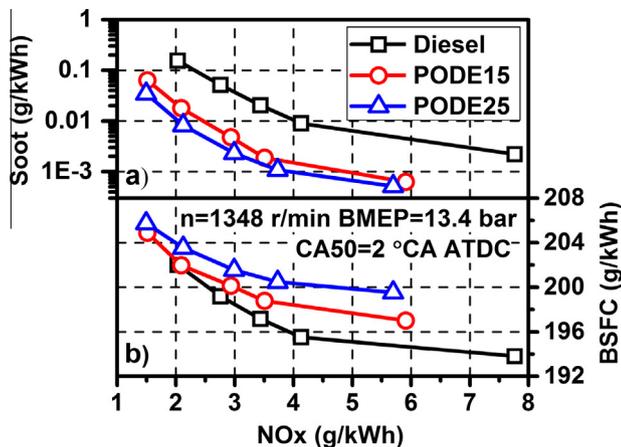


Fig. 10. NOx–soot and NOx–BSFC trade off at  $n = 1348$  r/min and  $BMEP = 13.4$  bar (medium load).

### 3.3. Comparison of fuel economy and emission characteristics between diesel, PODE15 and PODE25 over the WHSC test cycle

Taking the fuel economy into consideration, the SCR + EGR strategy shows advantages over the EGR + DPF strategy to meet the Euro VI standard [44]. In this paper, different SCR conversion efficiencies from 81% to 95% are assumed and taken into consideration, which correspond to the weighted raw NOx emissions of 7.7 g/kWh, 4.6 g/kWh, 3.4 g/kWh, 2.7 g/kWh and 2.1 g/kWh, respectively. The NOx raw control values except 2.7 g/kWh are

close to the NOx limits in Euro I, Euro III, Euro IV and Euro V standards.

Fig. 11(a1) depicts the comparison of fuel economy between diesel, PODE15 and PODE25 at different weighted NOx targets in the WHSC test cycle. The BSFC of all fuels increases with the decrease of the weighted NOx emission. In addition, blending PODE also results in the increase of BSFC. When the NOx is reduced from 7.7 g/kWh to 2.1 g/kWh by increasing EGR, the weighted BSFC of diesel increases more sharply than those of PODE15 and PODE25. If the weighted NOx is further decreased, the weighted BSFC of diesel has the possibility to exceed the weighted BSFC of diesel/PODE blends, which means that the diesel/PODE blends have the potential to improve the fuel economy under low NOx emissions conditions. The weighted BSFC reduction of PODE15 and PODE25 relative to diesel is illustrated in Fig. 11(a2). When the NOx is controlled at 7.7 g/kWh, the BSFC increased by 2% for PODE15 and by 2.8% for PODE25 compared to diesel. As the weighted NOx emission is further reduced to 2.1 g/kWh, the difference of BSFC between diesel, PODE15 and PODE25 is getting smaller. The weighted BSFC is only 0.4% higher for PODE15 and 0.7% higher for PODE25 compared to diesel.

The weighted soot emission comparison between diesel, PODE15 and PODE25 is exhibited in Fig. 11(b1) and the relative weighted soot reduction of PODE15 and PODE25 is illustrated in Fig. 11(b2). As the weighted NOx decreases, the weighted soot emission increases for all fuels. At different weighted NOx emission levels, the soot reduction percentages are different. Much lower soot can be obtained with higher PODE blending ratio. When the NOx is controlled at about 2.7 g/kWh, only the raw soot emission of PODE25 can satisfy the Euro VI soot limit. If the raw soot emissions of diesel and PODE15 are required to meet the Euro VI

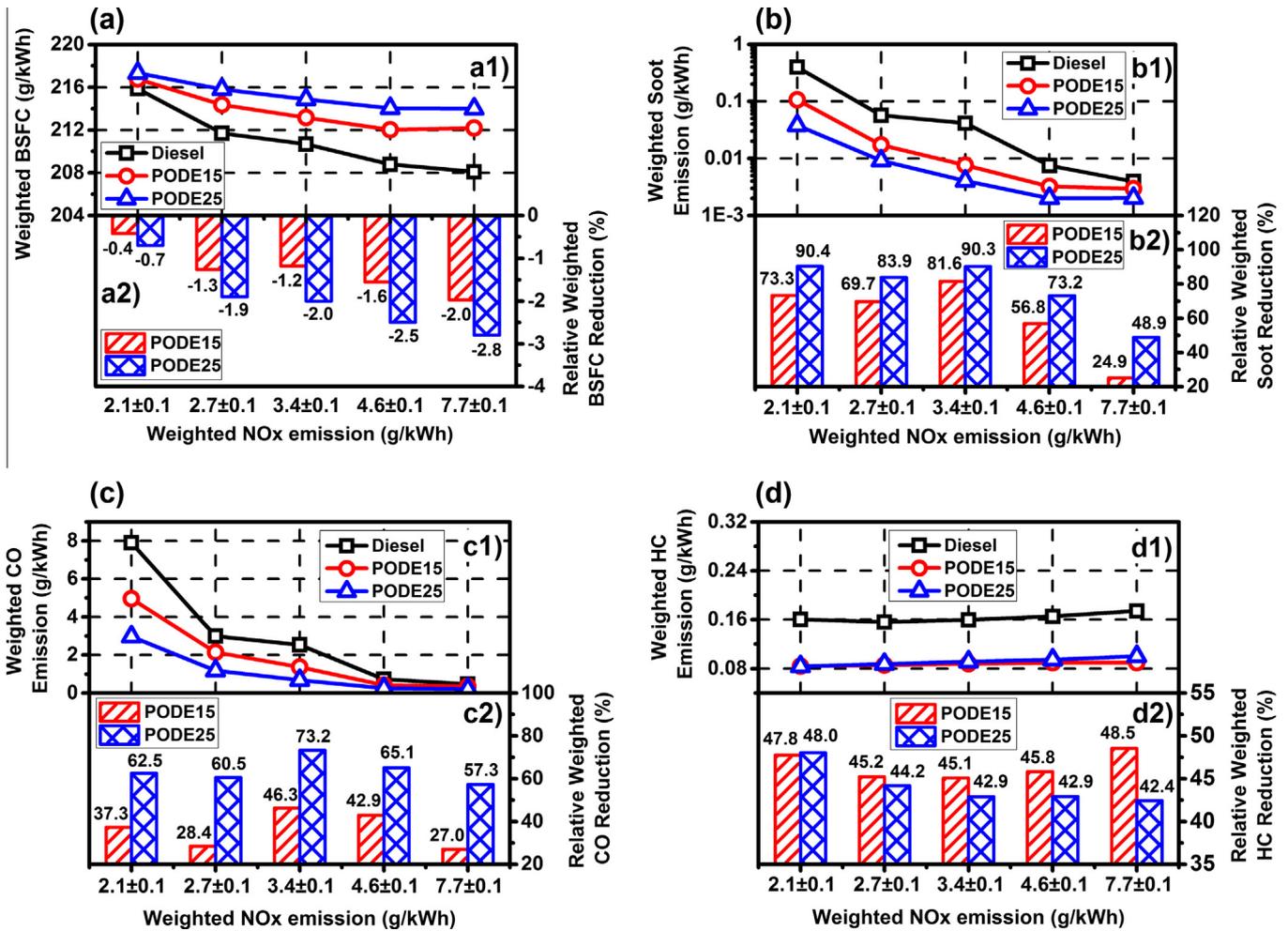


Fig. 11. Weighted BSFC, soot, CO, HC emissions and their relative weighted reduction percent at various raw weighted NOx emissions.

soot limit, the NOx should be kept at about 4.6 g/kWh and 3.4 g/kWh, respectively. In this case, a SCR system with conversion efficiency of about 92% and 88% are needed to meet the NOx limit in Euro VI. In conclusion, PODE blends can dramatically improve the NOx–soot trade off and show significant advantage in soot reduction under low NOx conditions.

The weighted CO emissions of diesel, PODE15 and PODE25 at various NOx control targets are shown in Fig. 11(c1) and their relative reduction ratio of PODE15 and PODE25 compared to diesel are depicted in Fig. 11(c2). The weighted CO can be dramatically reduced as the blending ratio increases and the reasons have been previously discussed. The weighted CO emission for all fuels increase with the decrease of weighted NOx emission. Moreover, when the weighted NOx emission decrease from about 2.7 g/kWh to 2.1 g/kWh, the CO emission increase rate of diesel/PODE blends are slower than that of neat diesel. That is to say, the diesel/PODE blends show better performance in CO reduction at lower NOx conditions, which is coincident with the observed trends for BSFC and BTE. From Fig. 11(c2), it is shown that at different weighted NOx emission, the CO reduction percent of diesel/PODE blends are different. The maximum CO reduction percent of PODE15 and PODE25 can reach 46.3% and 73.2% at the raw weighted NOx emission of about 3.4 g/kWh.

Fig. 11(d1) shows the weighted HC emission of diesel, PODE15 and PODE25 at different NOx control targets and Fig. 11(d2) exhibits the relative weighted HC reduction ratio of PODE15 and PODE25. At all weighted NOx emission targets, the weighted HC

for all fuels are all very low. The weighted HC can be reduced by adding PODE to diesel while it remains almost unchanged when the blending ratio increased from 15% to 25%. At different weighted NOx emission conditions, the relative weighted HC reduction percent has no significant difference, which can be seen from Fig. 11(d2).

According to all these weighted results over the WHSC test cycle, it is seen that the diesel/PODE blends have a distinct advantage in soot reduction. The NOx, CO and HC can also be reduced by adding PODE. Moreover, the BTE of diesel/PODE blends have the tendency to exceed that of diesel at low NOx regions. Therefore, it has the potential to achieve clean and high efficiency combustion by adding PODE.

#### 4. Conclusions

In this study, an experimental study has been conducted to explore the effects of diesel/PODE blends on the combustion and emission characteristics in a 6-cylinder heavy duty diesel engine. The potential to simplify the aftertreatment system (including both SCR and DPF) to meet the Euro VI emission standards has been studied and evaluated through fuel property and EGR ratio optimization. The mechanism of the PODE blends on emission reduction, especially the soot emission, has been discussed. Based on these experimental results, the main conclusions can be summarized as follows:

1. The peak HRR can be reduced by adding PODE at both low and medium loads because of the shorter mixing time and lower LHV. With the increase of load, the difference of peak HRR between diesel and diesel/PODE blends are getting smaller due to the superior volatility of PODE.
2. The combustion rate in late combustion phase can be accelerated by adding PODE because of its high oxygen content and high volatility. The combustion phasing loss caused by longer injection duration can be partially compensated by the fast combustion rate in the late combustion phase with PODE component.
3. NO<sub>x</sub>-soot trade off can be dramatically improved by adding PODE component. PODE with the properties of high oxygen content, no C–C bond, superior volatility and dilution effect are beneficial to soot reduction. Furthermore, the NO<sub>x</sub> emission from diesel/PODE blends can also be reduced because of the lower peak HRR and lower premixed combustion fraction at low and medium loads.
4. Blending PODE can reduce the HC and CO emissions. The high oxygen content in PODE make the CO and HC to be easily oxidized. Superior volatility of PODE can produce relatively better air–fuel mixture, the oxygen in the fresh air can then be fully utilized to oxidize CO and HC.
5. Blending PODE decreases the BTE because of lower premixed combustion ratio and probably higher heat transfer loss, while it has the potential to improve BTE under low NO<sub>x</sub> emission conditions due to higher combustion efficiency and higher combustion rate in the late combustion phase.

## Acknowledgements

The authors would like to acknowledge the financial supports provided by the National Nature Science Foundation of China through the project of 51506145 and the project of “Survey of ASEAN clean coal based liquid fuel and coal chemical industry”.

## References

- [1] Reitz RD. Directions in internal combustion engine research. *Combust Flame* 2013;160(1):1–8.
- [2] Johnson TV. Review of vehicular emissions trends. SAE paper 2015-01-0993.
- [3] Agarwal AK. Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines. *Prog Energy Combust Sci* 2007;33(3):233–71.
- [4] Lu XC, Han D, Huang Z. Fuel design and management for the control of advanced compression-ignition combustion modes. *Prog Energy Combust Sci* 2011;37(6):741–83.
- [5] Kumar S, Cho JH, Park J, Moon I. Advances in diesel–alcohol blends and their effects on the performance and emissions of diesel engines. *Renew Sust Energy Rev* 2013;22:46–72.
- [6] Han M. The effects of synthetically designed diesel fuel properties—cetane number, aromatic content, distillation temperature, on low-temperature diesel combustion. *Fuel* 2013;109:512–9.
- [7] Millo F, Debnath BK, Vlachos T, Ciaravino C, Postriotti L, Buitoni G. Effects of different biofuels blends on performance and emissions of an automotive diesel engine. *Fuel* 2015;159:614–27.
- [8] Barrios CC, Martín C, Domínguez-Sáez A, Álvarez P, Pujadas M, Casanova J. Effects of the addition of oxygenated fuels as additives on combustion characteristics and particle number and size distribution emissions of a TDI diesel engine. *Fuel* 2014;132:93–100.
- [9] Park SH, Lee CS. Applicability of dimethyl ether (DME) in a compression ignition engine as an alternative fuel. *Energy Convers Manage* 2014;86:848–63.
- [10] Moka S, Pande M, Rani M, Gakhar R, Sharma M, Rani J, et al. Alternative fuels: an overview of current trends and scope for future. *Renew Sust Energy Rev* 2014;32:697–712.
- [11] Sarathy SM, Oßwald P, Hansen N, Kohse-Höinghaus K. Alcohol combustion chemistry. *Prog Energy Combust Sci* 2014;44:40–102.
- [12] Surisetty VR, Dalai AK, Kozinski J. Alcohols as alternative fuels: an overview. *Appl Catal, A* 2011;404(1):1–11.
- [13] Jin C, Yao M, Liu H, Lee CFF, Ji J. Progress in the production and application of n-butanol as a biofuel. *Renew Sust Energy Rev* 2011;15(8):4080–106.
- [14] Chen Z, Wu Z, Liu J, Lee C. Combustion and emissions characteristics of high n-butanol/diesel ratio blend in a heavy-duty diesel engine and EGR impact. *Energy Convers Manage* 2014;78:787–95.
- [15] Hansen AC, Zhang Q, Lyne PW. Ethanol–diesel fuel blends—a review. *Bioresour Technol* 2005;96(3):277–85.
- [16] Serrano L, Lopes M, Pires N, Ribeiro I, Cascão P, Tarelho L, et al. Evaluation on effects of using low biodiesel blends in a EURO 5 passenger vehicle equipped with a common-rail diesel engine. *Appl Energy* 2015;146:230–8.
- [17] Coniglio L, Bennadji H, Glaude PA, Herbinet O, Billaud F. Combustion chemical kinetics of biodiesel and related compounds (methyl and ethyl esters): experiments and modeling – advances and future refinements. *Prog Energy Combust Sci* 2013;39(4):340–82.
- [18] Ku Y-Y, Tang T-W, Lin KW, Chan S. The impact upon applicability of metal fuel tank using different biodiesel. SAE paper 2015-01-0521.
- [19] Zhu L, Cheung CS, Zhang WG, Huang Z. Compatibility of different biodiesel composition with acrylonitrile butadiene rubber (NBR). *Fuel* 2015;158:288–92.
- [20] Jaronjitsathian S, Akarapanavit N, Sa-norh SS, In-ochanon R, Wuttimongkolchai A, Tipdecho C, et al. Evaluation of 5 to 20% biodiesel blend on heavy-duty common-rail diesel engine. SAE paper 2009-01-1894.
- [21] Westbrook CK, Pitz WJ, Curran HJ. Chemical kinetic modeling study of the effects of oxygenated hydrocarbons on soot emissions from diesel engines. *J Phys Chem A* 2006;110(21):6912–22.
- [22] Arcoumanis C, Bae C, Crookes R, Kinoshita E. The potential of di-methyl ether (DME) as an alternative fuel for compression-ignition engines: a review. *Fuel* 2008;87(7):1014–30.
- [23] Sasaki S, Kato M, Yokota T, Konno M, Gill D. An experimental study of injection and combustion with dimethyl ether. SAE paper 2015-01-0932.
- [24] Lacey P, Naegeli D, De La Cruz J, Whalen M. Lubricity of volatile fuels for compression ignition engines. SAE paper 2000-01-1804.
- [25] Pellegrini L, Marchionna M, Patrini R, Florio S. Emission performance of neat and blended polyoxymethylene dimethyl ethers in an old light-duty diesel car. SAE paper 2013-01-1035.
- [26] Pellegrini L, Marchionna M, Patrini R, Beatrice C, Del Giacomo N, Guido C. Combustion behaviour and emission performance of neat and blended polyoxymethylene dimethyl ethers in a light-duty diesel engine. SAE paper 2012-01-1053.
- [27] Liu HY, Wang Z, Wang JX. Performance, combustion and emission characteristics of polyoxymethylene dimethyl ethers (PODE 3-4)/wide distillation fuel (WDF) blends in premixed low temperature combustion (LTC). SAE paper 2015-01-0810.
- [28] Lumpp B, Rothe D, Pastötter C, Lämmermann R, Jacob E. Oxymethylene ethers as diesel fuel additives of the future. *MTZ Worldwide* 2011;72(3):34–8.
- [29] Burger J, Siegert M, Ströfer E, Hasse H. Poly(oxymethylene) dimethyl ethers as components of tailored diesel fuel: properties, synthesis and purification concepts. *Fuel* 2010;89(11):3315–9.
- [30] Liu H, Wang Z, Wang J, He X, Zheng Y, Tang Q, et al. Performance, combustion and emission characteristics of a diesel engine fueled with polyoxymethylene dimethyl ethers (PODE3-4)/diesel blends. *Energy* 2015;88:793–800.
- [31] Heywood JB. Internal combustion engine fundamentals. McGraw-Hill Inc.; 1988.
- [32] AVL. The specification of AVL 415S filter smoke number meter. AVL list GMBH, Graz, Austria; 2007.
- [33] Marchionna M, Sanfilippo D. High quality components for clean transportation fuels. *Hydrocarb Eng* 2002;7(7):49–51.
- [34] Sanfilippo D, Patrini R, Marchionna M. Use of an oxygenated product as a substitute of gas oil in diesel engines. US patent app. 10/716,501; 2003.
- [35] Zhao Q, Wang H, Qin Z-F, Wu Z-W, Wu J-B, Fan W-B, et al. Synthesis of polyoxymethylene dimethyl ethers from methanol and trioxymethylene with molecular sieves as catalysts. *J Fuel Chem Technol* 2011;39(12):918–23.
- [36] Patrini R, Marchionna M. Liquid mixture consisting of diesel gas oils and oxygenated compounds. US patent app. 10/373,781; 2003.
- [37] Yanowitz J, Ratcliff M, McCormick R, Tay J, Murphy M. Compendium of experimental cetane numbers. NREL report: NREL/TP-5400-61693; 2014.
- [38] Li T, Okabe Y, Izumi H, Shudo T, Ogawa H. Dependence of ultra-high EGR low temperature diesel combustion on fuel properties. SAE paper 2006-01-3387.
- [39] Mangus M, Kiani F, Mattson J, Tabakh D, Petka J, Depcik C, et al. Investigating the compression ignition combustion of multiple biodiesel/ULSD (ultra-low sulfur diesel) blends via common-rail injection. *Energy* 2015;89:932–45.
- [40] Padala S, Woo C, Kook S, Hawkes E. Performance improvement of a compression ignition engine by ethanol and diesel dual-fuelling. In: 18th Australasian fluid mechanics conference, Launceston, Australia; 3–7 December; 2012.
- [41] Francqueville L, Michel J-B. On the effects of EGR on spark-ignited gasoline combustion at high load. SAE paper 2014-01-2628.
- [42] Lü XC, Yang JG, Zhang WG, Huang Z. Effect of cetane number improver on heat release rate and emissions of high speed diesel engine fueled with ethanol–diesel blend fuel. *Fuel* 2004;83(14):2013–20.
- [43] Ruggero A, Tonetti, M., Gioannini, A., Pelassa, M. Combustion technologies to meet Euro 6 emissions standards on a diesel D-segment passenger car. In: Proceedings of the SIA international conference: le moteur diesel/diesel engine, Rouen-INSA Rouen, France; 2008.
- [44] Cloudt IR, Baert IR, Willems IF, Vergouwe M. SCR-only concept for heavy-duty Euro VI applications. *MTZ Worldwide* 2009;70(9):58–63.