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Influence of Pentanol and Dimethyl Ether Blending with Diesel on the Combustion Performance and Emission Characteristics in a Compression Ignition Engine under Low Temperature Combustion Mode

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Abstract

Dimethyl ether (DME) and n-pentanol can be derived from non-food based biomass feedstock without unsettling food supplies and thus attract increasing attention as promising alternative fuels, yet some of their unique fuel properties different from diesel may significantly affect engine operation and thus limit their direct usage in diesel engines. In this study, the influence of n-pentanol, DME and diesel blends on the combustion performance and emission characteristics of a diesel engine under low-temperature combustion (LTC) mode was evaluated at various engine loads (0.2-0.8 MPa BMEP) and two Exhaust Gas Recirculation (EGR) levels (15% and 30%). Three test blends were prepared by adding different proportions of DME and n-pentanol in baseline diesel and termed as D85DM15, D65P35, and D60DM20P20 respectively. The results showed that particulate matter (PM) mass and size-resolved PM number concentration were lower for D85DM15 and D65P35 and the least for D60DM20P20 compared

with neat diesel. D60DM20P20 turned out to generate the lowest NO_x emissions among the test blends at high engine load, and it further reduced by approximately 56% and 32% at low and medium loads respectively. It was found that the combination of medium EGR (15%) level and D60DM20P20 blend could generate the lowest NO_x and PM emissions among the tested oxygenated blends with a slight decrease in engine performance. THC and CO emissions were higher for oxygenated blends than baseline diesel and the addition of EGR further exacerbated these gaseous emissions. **This study demonstrated a great potential of n-pentanol, DME and diesel (D60DM20P20) blend in compression ignition engines with optimum combustion and emission characteristics under low temperature combustion mode, yet long term durability and commercial viability have not been considered.**

Keywords: Low temperature combustion, EGR, Blended fuel, PM emissions, Combustion performance

Nomenclature

EGR	exhaust gas recirculation	BTE	brake thermal efficiency
LTC	low temperature combustion	CN	cetane number
THC	total hydrocarbon	ECU	electronic control unit
CO	carbon monoxide	BSFC	brake specific fuel consumption
TEOM	tapered element oscillating microbalance	SMPS	scanning mobility particle sizer
BMEP	brake mean effective pressure	LHV	lower heating value
DME	dimethyl ether	PM	particulate matter
EGT	exhaust gas temperature	BTE	brake thermal efficiency

1. Introduction

Despite an anticipated decline in the overall diesel market share in the years to 2030, demand for diesel is expected to remain above 50% in medium-upper car segments. Compression ignition engines are still facing the challenge of trade-off emission controls for oxides of nitrogen (NO_x) and particulate matter (PM), which are harmful to the environment and human health [1-3].

Low-temperature combustion (LTC) is one of the promising techniques to tackle this issue [4-8]. Flame temperature remains low during the combustion process in LTC mode, which may significantly suppress the formation of NO_x emissions. The LTC strategy provides a longer time for air-fuel mixing in the cylinder prior to compression ignition, which in turn reduces the soot and NO_x emissions [4, 9, 10]. LTC mode can be achieved by carefully adjusting exhaust gas recirculation (EGR) levels, fuel injection pressure, fuel reactivity and fuel injection timings,[11] among which EGR and late injection timing are generally deemed efficient techniques to realize LTC mode [5, 12]. High EGR levels reduce the in-cylinder combustion temperature which prolongs the ignition delay with more time available for better air-fuel mixture preparation and thus result in less NO_x emissions [5, 13, 14]. Rajesh et al.[5] used low EGR strategy, retarded injection timing, and alcohol/diesel blends to enable premixed low-temperature combustion in a compression ignition engine. They found that NO_x and PM emissions were reduced simultaneously in an LTC diesel engine. Fang et al.[15] utilized medium level EGR and protracted ignition delay to achieve LTC and reported that low temperature combustion elevated CO and HC emissions. However, Zhang et al.[16] found that LTC combustion mode had the potential of reducing NO_x formation as well as reducing CO and HC emissions noticeably. Apart from lower temperature, longer ignition delay and better mixture preparation **are key features of LTC mode** compared with conventional diesel engine combustion [15]. Alcohols are considered more favorable for LTC operation than neat diesel because they have greater resistance to auto-ignition, and hence provide longer ignition delay due to their lower cetane number (CN) and higher enthalpy of vaporization [5, 17].

Pentanol (long-chain alcohol) has gained much attention recently because of its advantages (higher energy density, greater cetane number, higher heating value, higher viscosity, and lower volatility) over short-chain alcohols and hence has been considered as a great potential candidate fuel for diesel engines [18-22]. Li et al.[23] evaluated the effects of pure pentanol on the combustion performance and emissions of a single-cylinder compression ignition engine. They reported that pentanol generated less soot and NO_x

emissions than diesel fuel and also exhibited smooth heat release rate curves. Wei et al.[24] examined the influence of n-pentanol-diesel blends on the gaseous and particulate emissions of a direct-injection compression ignition engine. They found that pentanol addition prolonged the ignition delay and substantially reduced particle number and mass concentrations. However, a slight rise in nitrogen oxides (NO_x) emissions was observed at high engine loads. Campos-Fernandez et al.[25] studied the effect of pentanol addition on the performance of a direct-injection diesel engine. They reported that pentanol blends could significantly improve the brake thermal efficiency and generate less PM number and mass concentrations than diesel fuel. Li et al.[26] observed a simultaneous decrease in both soot and NO_x emissions when n-pentanol was blended with diesel in a single-cylinder diesel engine at low and medium load, but an opposite trend of NO_x emissions was presented at high loads. There are a limited number of studies reporting the influence of pentanol and diesel blends on the performance and gaseous emissions of diesel engines [27-29] and even fewer focusing on particle size-resolved number concentrations, which become an increasingly crucial metric in the light of new PM number-based regulation and health concerns.

Although alcohols have superior emission characteristics than neat diesel, their low cetane number inevitably leads to poor ignitability, bad cold-start performance and even unsuitability for direct usage in diesel engines. **However, this deficiency** could be compensated by blending a component of high cetane number **fuel**. Dimethyl ether (DME) is one attractive candidate which has been regarded as a clean-burning, non-toxic, and potentially renewable fuel. Its high cetane value (55-60) and quiet combustion, as well as its inexpensive fueling system, make it a promising diesel alternative that could meet increasingly stringent emission limits. Because of its lack of carbon-to-carbon bonds, using DME as an alternative to diesel can virtually eliminate particulate matter emissions [15-18] and thus negate the need for costly diesel particulate filters. Ying et al. [30] investigated the influence of DME-diesel blends on the emission characteristics of a naturally aspirated diesel engine. They found that DME-diesel blends produced less smoke emissions compared to neat diesel, which attributed to the higher oxygen content of DME. NO_x emissions were observed to be lower by adding DME in diesel while HC and CO emissions exhibited an increasing trend. Ikeda et al.[31] found that DME addition in diesel reduced the NO_x emissions without increasing HC emissions in a compression ignition engine. Fang et al.[32] studied the impact of different EGR levels on emissions produced from heavy-duty compression-ignition engine fueled with DME. They concluded that high EGR level (up to 40%) could suppress the NO_x and smoke emissions simultaneously at low to medium engine loads. There is a gap existing in the literature concerning the emission characteristics and performance of compression ignition engines fueled with DME-alcohol blends.

While DME and pentanol have been considered as low sooting propensity fuels due to their oxygenated molecular structure, their combustion may not necessarily depress NO_x emissions. In fact, increased combustion efficiency and an appreciable increase in NO_x emissions were observed at high engine loads [23, 26]. **The combination of low temperature combustion (LTC) and formulated blends of n-pentanol, DME, and diesel could potentially achieve low emission levels for both NOx and PM emissions from diesel engines, yet no existing literature were found reporting such work.** In this study, LTC mode was achieved by utilizing a strategy of moderate EGR level and alcohol/diesel blends. The objectives of this study were: (1) to quantify the effects of pentanol and diesel blends on LTC diesel engine emission characteristics with a focus on the trade-off between NO_x and PM emissions; (2) to assess the suitability of n-pentanol and DME blends with diesel under LTC mode by evaluating engine performances.

2. Experimental setup

2.1. Test engine and measuring techniques

The test was conducted on a naturally-aspirated, in-line four-cylinder compression ignition engine. Table 1 lists the key engine specifications. The engine is coupled with a common rail direct injection system and an eddy current dynamometer. An electronic control unit (ECU) is utilized to control the fuel injection pressure and timing. **The LTC mode with moderate EGR employs a single shot of fuel, delivered close to the TDC. The single injection event enables the desired coupling between the combustion and the fuel injection, thereby providing a method for controlling the engine**

performance. Since the heat release phasing is fully controllable via injection timing, therefore, high energy efficiency is attainable by modulating the combustion phasing [33, 34].

Table 1. Specifications of the test engine

Parameters	Value
Injection system	Common rail
Number of cylinders	4
Compression ratio	18.5:1
Displacement	3.168 L
Bore	98 mm
Stroke	105 mm
Rate power	62 kW
Rated speed	3200 rpm
Injection system	Common rail

The schematic of test rig is depicted in Figure 1. A TSI Scanning Mobility Particle Sizer (SMPS, Model 3071a) and a Tapered Element Oscillating Microbalance (TEOM, series 1105) were utilized to measure the particle-number size distribution and particle mass concentration respectively. The engine exhaust was diluted prior to entering TEOM and SMPS. The AVL CEB-II exhaust gas analyzer was used to measure the gaseous emissions (nitrogen oxides, carbon monoxides, and total hydrocarbons). Thermocouples were installed to measure the temperature of intake air, exhaust gases, and engine oil. **Table 2 shows the range and accuracy of instrument employed in this study**. An external cooled EGR system was employed to cool down the fraction of EGR which mixed with the incoming air in a mixing chamber before entering the engine cylinder. The EGR temperature was cooled to 35^{o}C. The EGR level was calculated using Eq. (1).

$$\text{EGR (\%)} = \left[\frac{(\text{CO}_2)_{intake}}{(\text{CO}_2)_{exhaust}}\right] \times 100 \qquad (1)$$

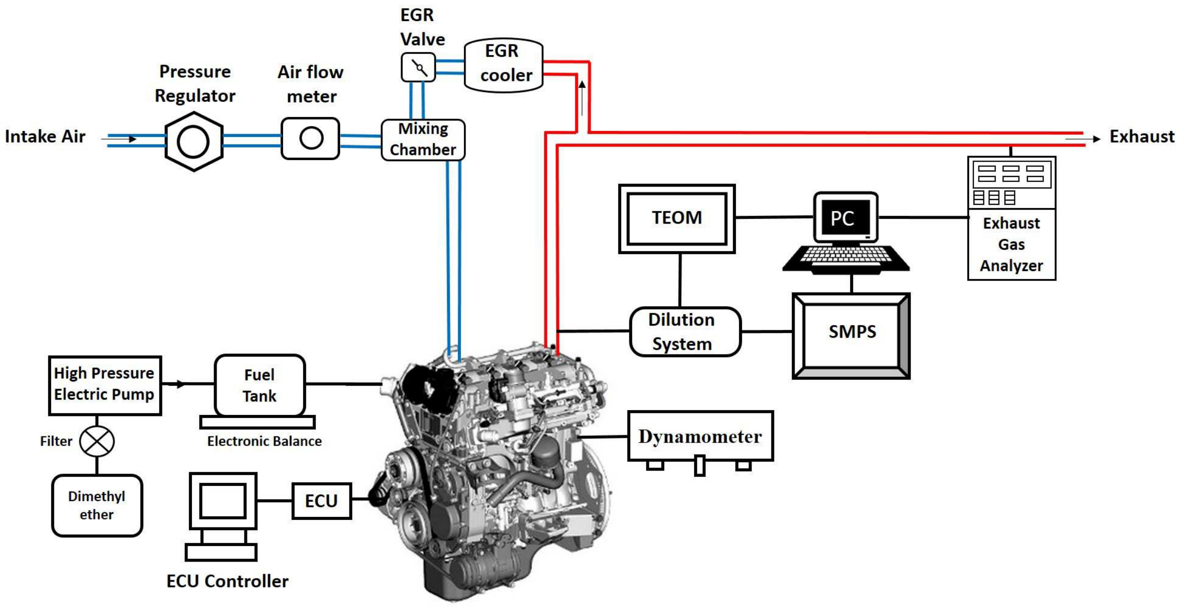

Figure 1. Schematic of test engine rig and measurement instruments

Table 2. Range and accuracy of instumetns used.

Instrument	Measured quantity	Range	Accuracy
Gas analyzer	**NOx**	**0-4000 ppm**	**± 1 ppm**
	THC	**0-20,000 ppm**	**± 1 ppm**
	CO	**0-20%**	**± 0.01%**
Pressure pickup	**Cylinder pressure**	**0-250 bar**	**± 0.1 bar**
Speed measuring sensor	**Engine speed**	**0-9999 rpm**	**± 5 rpm**
SMPS	**Particle size**	**2.5 to 1000 nm**	**-**
Crank angle encoder	**Cringle angle**	**0-360^{o}**	**± 1^{o}**
K-type thermocouple	**Temperature**	**0-1000 ^{o}C**	**± 1^{o}C**

2.2. Test procedure

All the experiments were performed at steady state conditions. The engine load was swept from 0.2 to 0.8 MPa at an interval of 0.1 MPa and the engine speed was maintained at 1600 rpm. Two EGR levels (15%, and 30%) were employed. The single injection strategy was adopted to demonstrate the sole effects of fuel properties. Apart from D85DM15, D65P35, **and** D60DM20P20 blends, neat diesel data was also recorded as a baseline value. The temperature of engine lubricating oil was maintained between 84 and 88^{o}C. The engine was run for 5 minutes to allow for stabilization and then the measurements were recorded. Each test was repeated three times for statistical analysis.

The uncertainty analysis was performed based on the root mean square method [35, 36] using Eq. (2).

$$\mathrm{U}_R = \left[\left(\frac{\partial R}{\partial x_1}\mathrm{U}_{\mathrm{x}_1}\right)^2 + \left(\frac{\partial R}{\partial x_2}\mathrm{U}_{\mathrm{x}_2}\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n}\mathrm{U}_{\mathrm{x}_\mathrm{n}}\right)^2\right]^{\frac{1}{2}} \quad (2)$$

Where U_R denotes the uncertainty of the calculated quantity R; x_n represents the measurement uncertainties of the n_{th} independent variables, and Ux_1, Ux_2, Ux_n are the standard deviations of the parameters. The uncertainties of key parameters are presented in Table 3.

Table 3. Uncertainties of key parameters

Parameters	Uncertainties (%)
Engine load (MPa)	±0.5
Engine speed (rpm)	±1.0
Air flow meter (m^3/h)	±1.0
NOx (g/kW.h)	±0.2
CO (g/kW.h)	±0.15
HC (g/kW.h)	±0.2
BSFC (g/kW.h)	±1.0

2.3. Properties of test fuels

Three test fuels were used and their key properties are listed in Table 4. The fuel blends were prepared by adding 15% dimethyl ether (DME), 35% n-pentanol and 20% DME + 20% n-pentanol on mass basis into the baseline and labeled as D85DM15, D65P35, and D60DM20P20 respectively. The baseline diesel and n-pentanol were poured into the fuel tank and then mixed with DME which was pressurized by a high-pressure pump to keep it in a liquid state. DME passed through a filter in order to remove impurities before it enters the fuel tank. Adding n-pentanol and DME into diesel increases the oxygen content of the test fuel blends which would influence engine performance and emissions. DME and n-pentanol have a lower boiling point and higher volatility than diesel which leads to rapid evaporation and hence promotes spray atomization. The low cetane number of pentanol with poor ignitability could be compensated by the high cetane number of DME, which allows such blends to combust with comparable ignition delay to neat diesel and thus no change in engine combustion system is needed. DME has no carbon-to-carbon bonds in its molecular structure, thus generated little PM emission during combustion but it has a low viscosity which may cause leakage issue in the fuel injection system. Therefore, the percentage of n-pentanol was added into DME to improve the viscosity of their blends which makes it feasible to fuel in a diesel engine.

Table 4. Primary properties of test fuels.

Fuels	Density (kg/m^3)	Viscosity @40°C (mm^2/s)	Lower heating value (MJ/Kg)	Cetane number	Oxygen content (%,w/w)	Latent heat of vaporization (kJ/kg)	Surface tension @ 25°C (Nm^{-1})	C/H ratio
Diesel	827	3.1	42.68	40-55	0	256	0.027	6.8
DME	670	0.18	27.6	55-60	34.8	465	0.012	0.337
n-Pentanol	814.8	2.89	34.65	20-25	18.15	308.05	0.024	4.96
D85DM15	803.45	2.662	40.41	42.25-55.75[a]	5.22	-	0.0238	5.83
D65P35	822.73	3.026	39.862	33-44.5[a]	6.35	-	0.0259	6.15
D60DM20P20	803.16	2.474	38.05	39-50[a]	10.59	-	0.0234	5.13

Data obtained from reference.[37-39]; [a] Estimated by reference.[40, 41]

3. Results and discussion

3.1. Particulate matter (PM) emissions

3.1.1 Size-resolved PM number concentration

Figure 2 illustrates bimodal particle number distributions for neat diesel, D85DM15, D65P35, and D60DM20P20 blends at various engine loads and EGR levels. At a low load of 0.3 MPa BMEP, the particle size distributions of D85DM15, D65P35, and D60DM20P20 rendered a lower particle number concentration compared with neat diesel. This can be attributed to the higher oxygen content of dimethyl ether (34.8%) and n-pentanol (18.9%) that decreased the particle formation in the locally rich region [26, 42]. The intramolecular oxygen atoms in the test blends can further suppress the particle formation by promoting post-oxidation [43-45]. In addition, lower aromatic content in DME and n-pentanol is also beneficial in reducing particle number formation because of the reduction of soot precursor, namely, polycyclic aromatic hydrocarbons [24]. On the other hand, the PM number concentrations in the nucleation (less than 50 nm) and accumulation mode (50-200 nm) increased and the PM number size distributions moved towards larger particle size region as the engine load rose. At high load of 0.7 MPa BMEP, the PM number centration in the accumulation mode considerably increased to 13.2×10^7 (#/cm^3), 12.7×10^7 (#/cm^3), 12.0×10^7 (#/cm^3), 11.2×10^7 (#/cm^3) for neat diesel, D85DM15, D65P35, and D60DM20P20 blends, respectively. This was due to the availability of large rich air-fuel mixture at high engine load which caused inadequate fuel oxidation. The size-resolved PM number concentration reduction effect was more remarkable at low engine loads than at high engine loads.

PM number concentration in the accumulation mode generally increased with the addition of EGR levels which can be seen from Figure 2. For instance, the PM number concentration was 18.2×10^7 (#/cm^3) for neat diesel, 17.5×10^7 (#/cm^3) for D85DM15, 16.9×10^7 (#/cm^3) for D65P35, and 16.3×10^7 (#/cm^3) for D60DM20P20 blend at 30% EGR. The increasing trend of PM number concentration for binary and ternary blends can be attributed to the lower in-cylinder combustion temperature, slower soot oxidation rate and the reduction of oxygen concentration inside the engine cylinder when EGR was employed [46]. The PM number concentration in the nucleation mode decreased with increase in EGR levels and in contrast, more particles with large diameter were produced in the accumulation mode. The addition of higher EGR levels reduced the oxygen concentration and led to the formation of rich air/fuel mixture combustion zones which promoted soot formation, enhanced particle coagulation, accumulation, agglomeration process, and resulted in the larger sizes of accumulation mode particles [47-50]. D85DM15, D65P35, and D60DM20P20 blends demonstrated less PM number concentration than neat diesel at various EGR levels. This could be attributed to the elevated oxygen content of these blends. During the combustion process, the oxygen presence of these blends decreased the local air-fuel equivalence ratio and promoted the oxidation of soot particles [51-54].

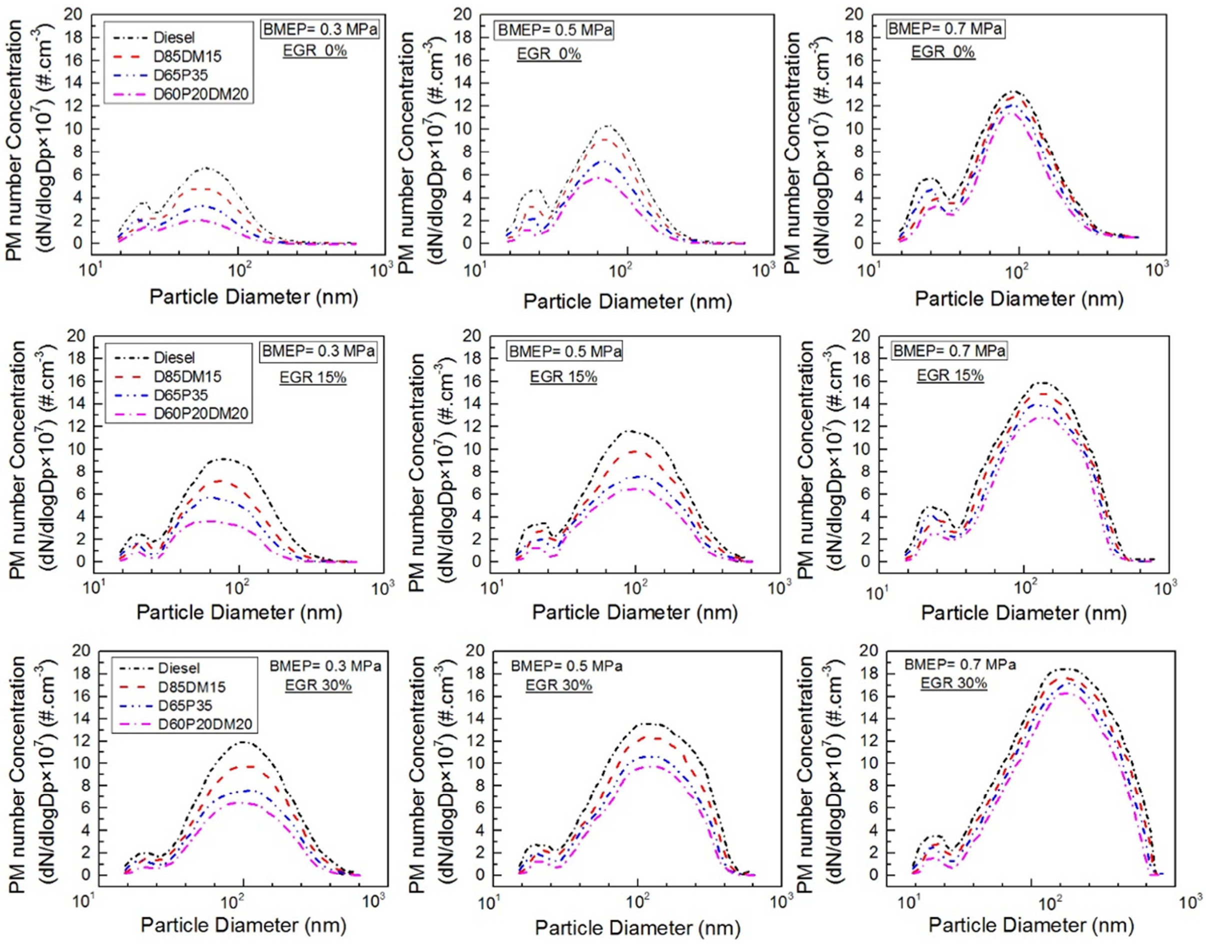

Figure 2. Size-resolved PM number concentrations of the four test fuels at different engine loads and EGR levels

3.1.2 PM mass concentration

Figure 3 demonstrates the effect of different engine loads and EGR levels on the PM mass concentration of binary (D85DM15 and D65P35) and ternary (D60DM20P20) blends. For engine loads from 0.2 to 0.4 MPa BMEP, a slight discrepancy in PM mass concentration was observed for all test fuels while a dramatic increase was noted at high engine load of 0.8 MPa BMEP. The reasons were threefold:

firstly, more fuel was combusted to attain high engine power with more carbon available for particle formation and higher temperature for promoting fuel thermal pyrolysis and soot precursor formation; secondly, the excess air ratio decreased at high loads which suppressed soot oxidation; thirdly, the ignition delay became shorter at high engine load which led to more diffusion combustion and consequently increased PM mass concentration. Similar results were found for other alcohol-diesel blends [55-58].

PM mass concentration**s** for D85DM15, D65P35, and D60DM20P20 blends **were** 38 (mg/m^3), 26 (mg/m^3), and 15 (mg/m^3) at low load (0.2 MPa BMEP) while **they** increased for all the test fuels as engine load rose. At high load (0.8 MPa BMEP), D85DM15, D65P35 and D60DM20P20 generated the PM mass of 158 (mg/m^3), 140 (mg/m^3), and 125 (mg/m^3) respectively. D60DM20P20 blend showed the lowest PM mass concentration which can be attributed to the high oxygen content, low aromatic content and low H/C ratio of n-pentanol and dimethyl ether [30, 59]. **EGR is essential to achieve simultaneous reduction in soot and NOx emissions from LTC without prohibitively high fuel consumption penalties due to poor combustion quality. Tuning the amount of EGR is the most commonly used technique to adjust the in-cylinder temperature, which controls the start of combustion, fuel burning rate and particulate emission characteristics of compression ignition engines [60, 61]. It has been well established that the increase in EGR level worsens the overall combustion quality and results in higher PM mass concentration.** As can be seen in Fig**ure.** 3, the PM mass concentration increased with the increase of EGR levels for all the test fuel blends. With 30% EGR level at high engine load of 0.8 MPa BMEP, the PM mass concentration of D85DM15, D65P35, and D60DM20P20 were 13%, 14%, and 16% higher than the results of binary and ternary blends without EGR addition. This can be attributed to the following two reasons: firstly, the oxygen concentration inside the combustion cylinder was inhabited with the addition of EGR which promoted soot formation; secondly, the increase in EGR levels lowered the in-cylinder temperature and resulted in incomplete oxidation.

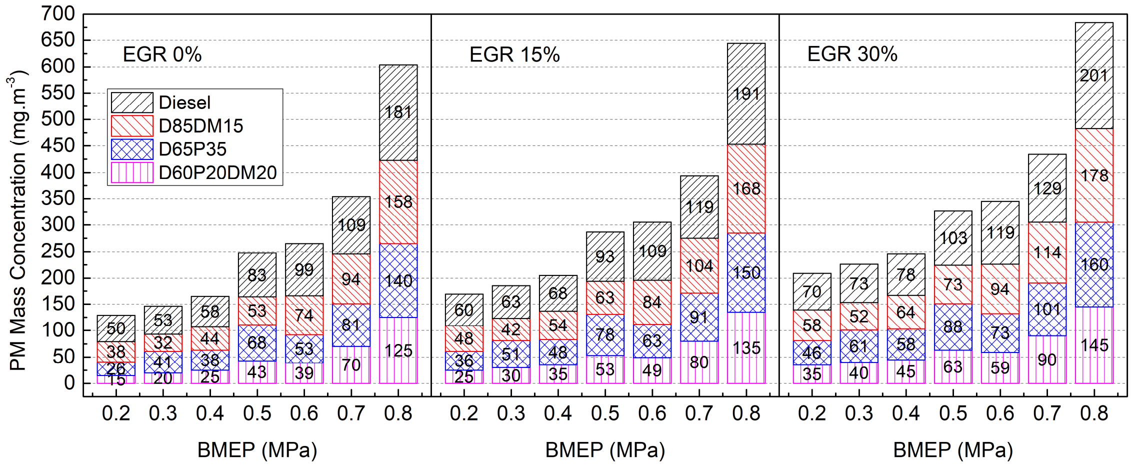

Figure 3. Variation in PM mass concentration of the four test fuels at different engine loads and EGR levels

3.2. Gaseous emissions

3.2.1 NO_x emissions

The NO_x emissions results of neat diesel, D85DM15, D65P35, and D60DM20P20 blends are shown in Figure 4. Thermal, Fuel and Prompt types are the three well-recognized mechanisms of NO_x formation,[62, 63] and among them, the thermal mechanism has been considered as the dominant one. Figure 4 illustrates that NO_x emission generally increased with increasing engine load for all the test fuels due to the rising in-cylinder gas temperature. At the engine loads of 0.2 to 0.4 MPa BMEP, D60DM20P20 generated the least NO_x emissions which mainly due to the lower heating value and higher latent heat of vaporization of blends that caused a reduction in combustion temperature. However, at high engine loads (0.7 and 0.8 MPa BMEP), D65P35 and D60DM20P20 exhibited a slightly higher NO_x emission than diesel which might be attributed to the higher volatility and oxygen content of blended fuels. Another reason is that the lower cetane number (CN) of pentanol caused longer ignition delay and hence more fuel was injected in premixed combustion phase [28]. Subsequently, more fuel oxidation elevated the combustion temperature and produced higher NO_x emissions. The NO_x emissions results obtained for D65P35 are in line with the findings reported in previous studies for pentanol-diesel [26, 64].

EGR is a well-established technique to suppress NO_x emissions [65-68]. NO_x emissions were reduced with the introduction of EGR for all the test fuels. The additional exhaust occupied some of the oxygen space as the diluent gas inside the engine cylinder and caused a reduction in flame temperature, which suppressed NO_x formation [69]. At low/medium loads with EGR, D85DM15, D65P35, and D60DM20P20 blends showed considerably lower NO_x emissions than diesel. This can be attributed to the higher latent heat of evaporation of those blends which reduced the combustion temperature and thus reduced NO_x emissions with respect to neat diesel. However, slightly more NO_x emissions were found for oxygenated blends than diesel at high loads, which might be because of additional oxygen presence in oxygenated fuel blends overwhelmed the NO_x decreasing effect caused by the initial temperature drop at high loads with high combustion temperature.

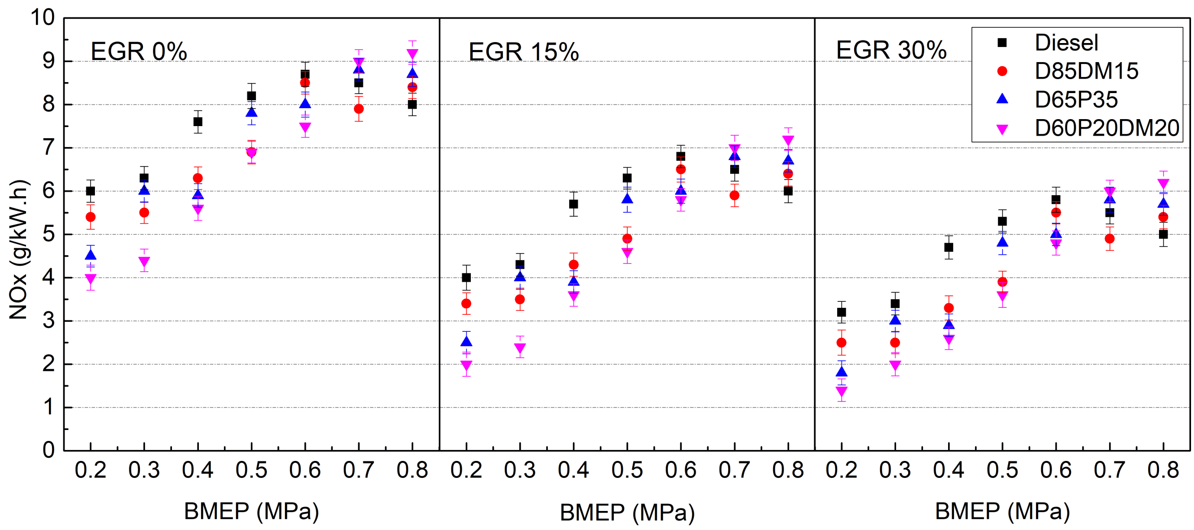

Figure 4. Effect of different engine loads and EGR levels on NO_x emissions

3.2.2 THC emissions

The total unburned hydrocarbons (THC) from the compression ignition engine are formed via incomplete combustion of locally over lean or over rich air-fuel mixture. In addition, fuel deposits on the cylinder wall, piston surface, and crevice area also account for the formation of unburned hydrocarbons [70, 71]. Figure 5 shows the comparison of THC emission for all the test fuels at various engine loads. In general, THC emissions reduced with the increase in engine load, owing to the increase in peak cylinder temperature, and the least THC emissions were observed at elevated engine loads. Over the test engine loads (0.2 to 0.8 MPa BMEP), D85DM15 demonstrated higher THC emissions than diesel due to its higher heat of evaporation and higher oxygen content of DME which formed over-lean mixture region [72, 73]. However, Ikeda et al.[74] studied the emission characteristics of DME-diesel blends in a diesel engine and found no considerable discrepancy in THC emissions for DME-diesel blends compared with baseline diesel. D65P35 showed higher THC emissions than neat diesel due to the higher latent heat of n-pentanol which generated the quenching effect in the lean combustion region. Additionally, the lower cetane number of D65P35 compared to diesel prolonged the ignition delay and provided more time for fuel vaporization, thus broader the lean outer flame zone and increased THC emissions [71]. Similar observations for pentanol/diesel blends have been reported earlier [75, 76]. The addition of DME and n-pentanol into diesel increased the latent heat vaporization of D60DM20P20 further which reduced the in-cylinder temperature and resulted in incomplete combustion. It can be deduced from Figure 5 that D60DM20P20 showed higher THC emissions among the oxygenated fuel blends on all the test engine loads.

The THC emissions for neat diesel, D85DM15, D65P35, and D60DM20P20 blends at different EGR levels are presented in Figure 5. With an increase in EGR levels, THC emissions increased drastically at low loads (0.2-0.4 MPa BMEP) due to lower in-cylinder temperature and protracted combustion process. However, a slight increase in THC emissions was observed at high loads (0.7-0.8 MPa BMEP) implying that EGR was less sensitive in terms of THC emissions at high engine loads. At 30% EGR level and high engine load of 0.8 MPa BMEP, THC emissions for D85DM15, D65P35, and D60DM20P20 were noted 45.8%, 32.1%, and 34.6% higher than the results of oxygenated test blends without EGR addition because the increase in EGR levels reduced the flame temperature which formed a large flame quenching zone and caused incomplete combustion [70, 77, 78]. Combustion temperature was even lower in the vicinity of cylinder walls due to the larger heat losses. Thus, inadequate combustion of the air-fuel mixture in these areas may result in a further increase in THC emissions [79]. **The lower local flame temperature in LTC mode facilitated the reduction of the soot and NO_x emissions [80, 81] while it caused incomplete combustion and resulted in higher CO and THC emissions. The mixture trapped in crevices would be too cold to be ignited during LTC mode. The fraction of THC emissions increased with increasing compression ratio because the amount of mixture trapped in crevice volume increased [60].**

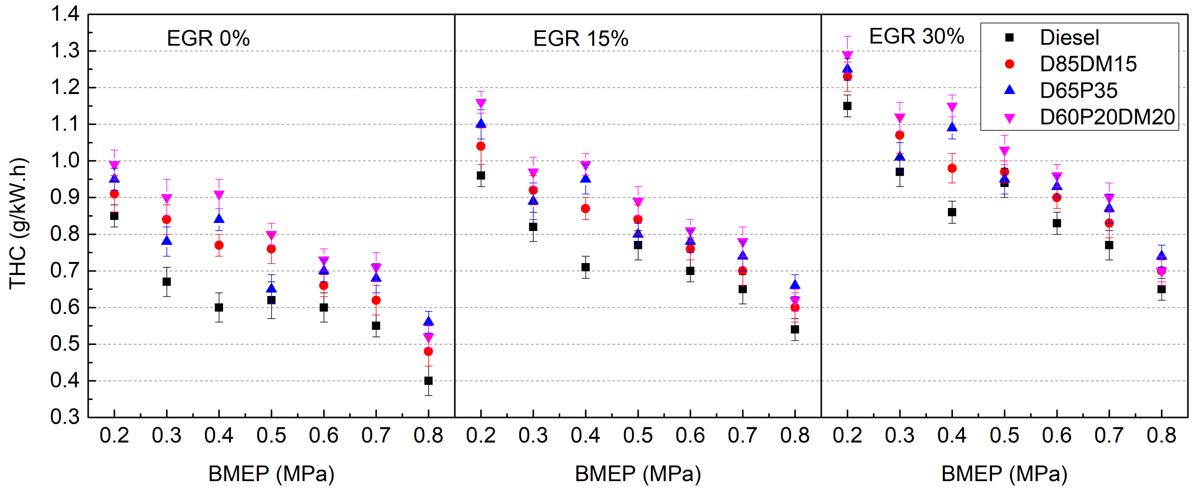

Figure 5. Effect of different engine loads and EGR levels on THC emissions

3.2.3 CO emissions

Carbon monoxide (CO) emissions from CI engine can be controlled primarily by the fuel-air equivalence ratio [70]. Lack of oxygen inside the combustion chamber and rich air-fuel ratio increased the formation of CO emissions [82, 83]. **In a LTC engine, CO is dependent on air fuel ratio λ and inlet**

air temperature. Little CO is generated in the engine when mixture is close to rich limit. While high amount of CO may be generated in the vicinity of lean limit [84, 85]. The CO emission of neat diesel, D85P15, D65P35, and D60DM20P20 blends are shown in Figure 6. The results followed similar trends to THC emissions. In general, CO emissions for all the test fuels were observed higher at low loads and reduced as load increased. This trend could be linked to the in-cylinder combustion temperature which fell at low loads and resulted in higher CO emissions. At high loads, combustion temperature considerably increased and caused lower CO emissions. D85DM15 had a higher heat of evaporation than diesel which generated the quenching effect inside the combustion chamber and impeded complete combustion, thus resulted in higher CO emissions [86, 87]. Another reason for higher CO emission of D85DM15 was the presence of **an** over-lean region **that was** formed due to the lower local equivalence ratio [88]. D65P35 showed generally higher CO emissions than other test fuels which could be attributed to the higher latent heat of n-pentanol which absorbed more heat during the combustion process and caused a reduction in in-cylinder gas temperature. Furthermore, the lower cetane number of D65P35 also contributed to the increase of CO emissions. Yilmaz et al.[89] and Rajesh et al.[5] also reported that pentanol/diesel blends increased CO emissions. At a high load of 0.7 MPa, the CO emissions for D85P15, D65P35, and D60DM20P20 blends were found to be 1, 1.2, and 1.4 g/kWh, respectively. The higher latent heat of D60DM20P20 blend caused a reduction in combustion temperature and promoted the formation of CO emissions.

Figure 6 shows that CO emissions increased with the increase in EGR levels. Oxygen concentration decreased in the engine cylinder with an increase in EGR percentage which hindered the oxidation of carbon monoxide (CO) and consequently increased CO emissions. At 30% EGR **level**, the oxygen concentration, and in-cylinder combustion temperature became lower which resulted in higher CO emissions. **CO emissions can also be related to the retarded combustion phasing, which resulted in slower chemical kinetics of fuel-air mixture, inhibiting CO to CO_2 conversion.** CO emission for D85DM15, D65P35, and D60DM20P20 blends increased from 1 to 1.8, 1.2 to 2, and 1.4 to 2.2 g/kWh respectively at 0.7 MPa. This trend was consistent with other studies, [90, 91] where CO emission increased at elevated EGR. CO emissions are normally enhanced in LTC mode because of inferior combustion temperature [11, 15] which caused incomplete combustion.

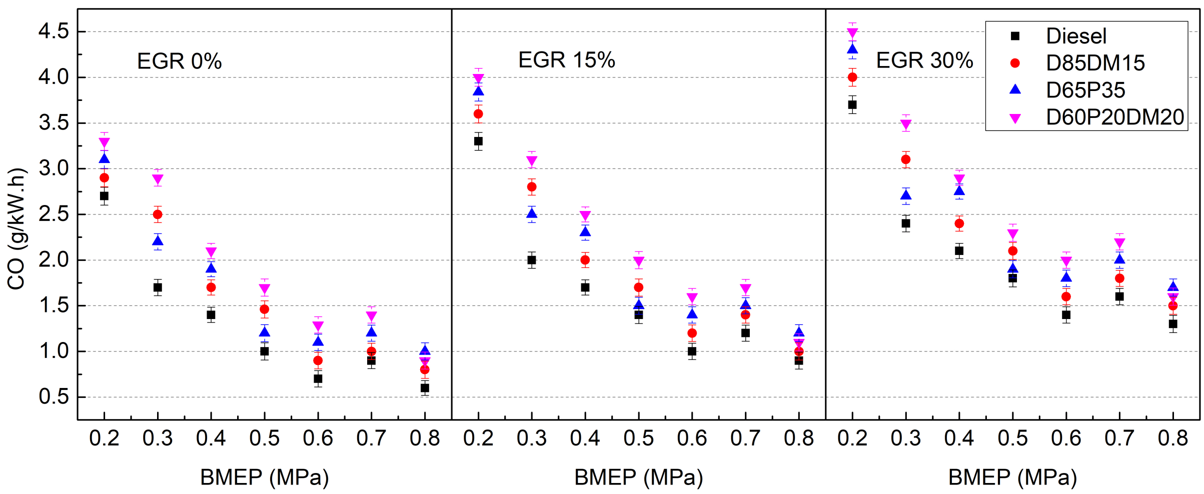

Figure 6. Effect of different engine loads and EGR levels on CO emissions

3. 3. Engine performance

3.3.1. Brake specific fuel consumption (BSFC)

BSFC is defined as the mass flow rate of fuel per unit brake power and it measures how efficiently an engine produced work with a specified amount of fuel [70]. Figure 7 illustrated the effects of oxygenated fuel blends on BSFC with and without EGR at various engine loads. BSFC for all the test fuels generally decreased with the rise in engine load, yet a slight increase of BSFC was observed at high loads, which might be attributable to higher oil temperature and lower excess air ratio deteriorating combustion quality and lubrication system. Similar trends for ethanol-diesel blends were reported earlier in the literature [92, 93]. At low engine load (0.2 MPa BMEP), the D85DM15 and D65P35 exhibited 12%, and 26% higher BSFC than diesel which can be attributed to the lower energy density of DME and n-pentanol, consequently, the more fuel quantity of these oxygenated blends injected to produce the equal power output to diesel. However, the BSFC of D85DM15 and D65P35 were considerably decreased at high engine loads but still remained higher than net diesel. Similar results for pentanol-diesel blends were reported by Wei et al.[24], Rajesh et al.[5] and Yilmaz et al.[89]. The addition of n-pentanol and DME into diesel resulted in a dramatic reduction of the lower heating value of D60DM20P20 and hence exhibited the highest BSFC among all the test fuels. At high load (0.8 MPa BMEP), D60DM20P20 showed 25% higher BSFC than neat diesel.

The effects of different EGR levels on the BSFC of four test fuels are demonstrated in Figure 7. BSFC generally escalated with increasing EGR levels for all the test fuels because the addition of exhaust in the combustion chamber exacerbated the oxidation kinetics and thus deteriorated the combustion quality. Furthermore, the low temperature of LTC mode caused incomplete burning of the fuel mixture and thus more fuel would be required to obtain the same power. At low load (0.2 MPa BMEP), the BSFC for D85DM15, D65P35, and D60DM20P20 blends was 10%, 21%, and 29% higher than neat diesel with the addition of EGR level (30%) and it was considerably reduced with the rising engine loads as shown in Figure 7. Rajesh et al.[64] also found similar trends for pentanol-diesel blends at different EGR levels.

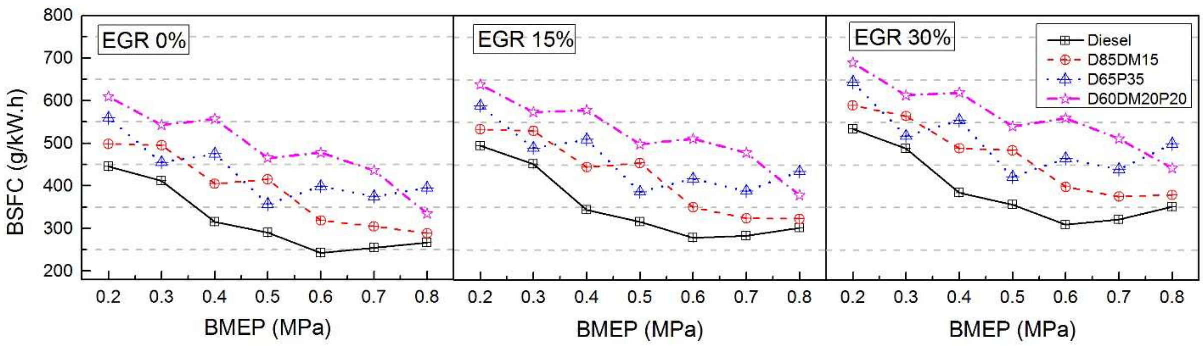

Figure 7. Comparisons of BSFC for four different fuels at different engine loads and EGR levels

3.3.2. Brake thermal efficiency (BTE)

The brake thermal efficiency (BTE) is basically the inverse of the product of BSFC and lower heating value (LHV) of the fuel [37, 94]. The effects of test fuel blends (D85DM15, D65P35, and D60DM20P20) on brake thermal efficiency at various engine loads are exhibited in Figure 8. In general, BTE showed a reverse trend to BSFC as shown in Figure 7. BTE generally increased with the rise in engine load and then slightly decreased at higher loads. This might be due to the low excess air ratio exist at high load which deteriorated the combustion [95, 96] and led to a slight drop in BTE. Compared to diesel, D85DM15, D65P35, and D60DM20P20 blends presented a lower performance over the **range of** engine loads **investigated**. The higher enthalpy of vaporization of n-pentanol and DME could lower the combustion temperature and caused a reduction in BTE of oxygenated test blends [64, 97].

By employing the EGR, a slight decrease in BTE was attained for all the test fuel blends because it protracted the combustion process due to the decrease in in-cylinder gas temperature and addition exhaust gas. At 30% EGR level and high load (0.8 MPa BMEP), the D85DM15, D65P35, and D60DM20P20 blends considerably decreased compared to neat diesel. The increase of THC and CO emission with the introduction of EGR also contributed to combustion energy loss and reduced the performance of D85DM15, D65P35, and D60DM20P20 blends.

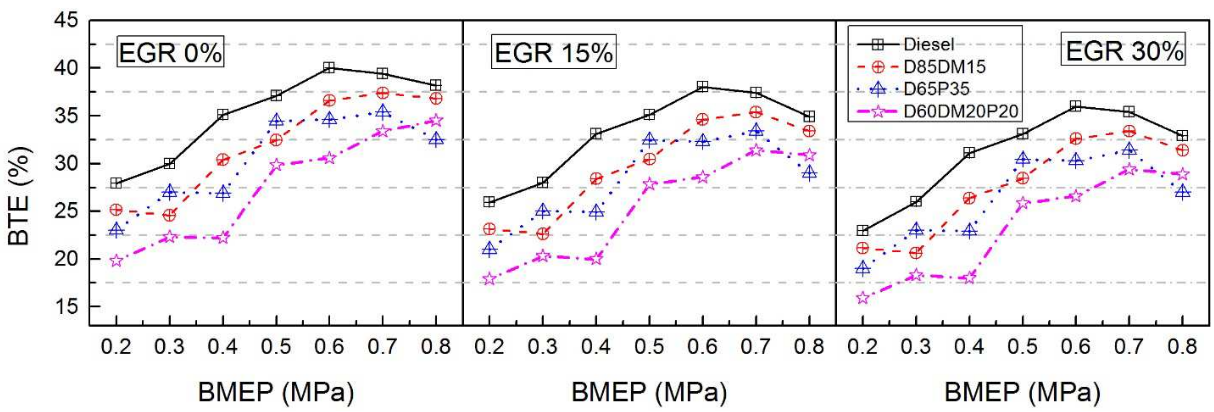

Figure 8. Comparisons of BTE for four different fuels at different engine loads and EGR levels

3.3.3 Exhaust gas temperature (EGT)

The exhaust gas temperature reflects the heat released inside the combustion chamber and has an appreciable influence on the formation of pollutants, [43] especially NO_x formation which is primarily thermally-driven. Figure 9 illustrates the variations in EGT results of four test fuels at different engine loads and EGR levels. In general, the EGT increased with engine load for all the test fuels. Compared with neat diesel, oxygenated blends featured noticeably lower EGT with the D60DM20P20 showing the lowest EGT. The lower LHV of oxygenated components (DME and n-pentanol) implied that more fuel quantity was injected to achieve the same power compared with diesel. Furthermore, the higher latent heat of vaporization of oxygenated fuels adsorbed more energy to evaporate the fuel inside the cylinder prior to combustion. The syngestric effects from both LHV and latent heat of vaporization on the energy adsorbed by the air-fuel mixture determined that oxygenated fuels would have lower initial combustion temperature and hence lower EGT. The energy required for complete fuel vaporization for DME and n-pentanol is estimated to be 2.8 and 1.5 times that for diesel.

The addition of EGR levels resulted in an appreciable decline of the EGT for all the test fuels which implied that a relatively low-temperature combustion was achieved. The unanimously decreasing trend of the EGT can be associated with the additional EGR which diluted the concentrations of reactants, and caused a suppressing effect on oxidation reactions and decelerated the burning rate [79]. Close inspection of Figure 9 also demonstrates that at higher loads, EGR addition reduced the EGT more significantly as compared to low loads which might be attributable to the fact that the exhaust addition at low engine loads would increase the cylinder temperature which promoted better mixture preparation and combustion to compensate the adverse effect from chemical kinetics perspective, yet the depressing kinetics dominated the overall combustion quality at high engine loads with high in-cylinder temperature.

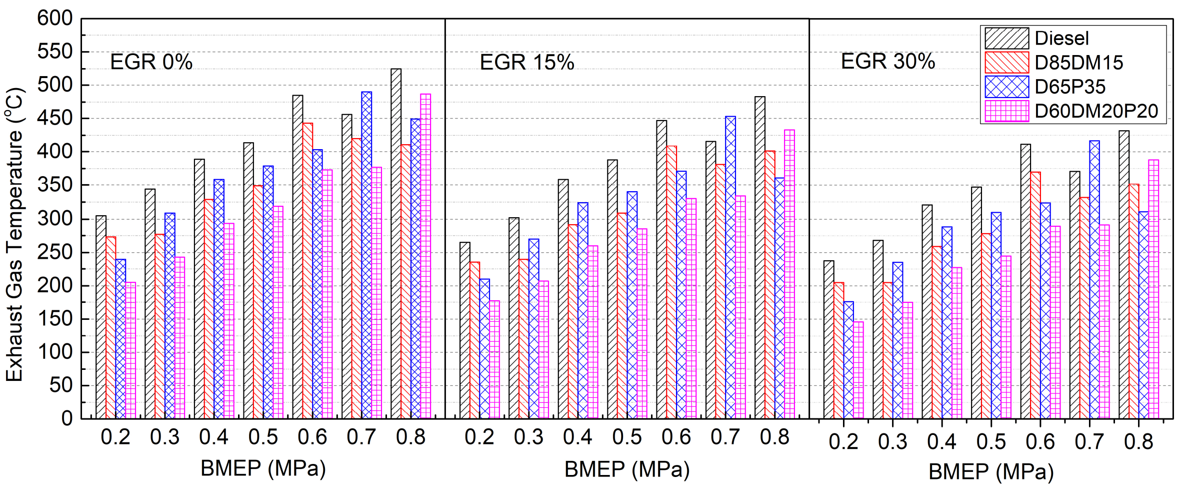

Figure 9. EGT as a function of engine load for four different fuels with and without EGR levels

4. Conclusion

The usage of alternative biofuels in compression ignition engines is promising from the ecological and economic point of view. With the aim of achieving the simultaneous mitigation of NO_x and PM emissions, dimethyl ether (DME) and n-pentanol were blended with diesel, and their influence on engine performance and emission characteristics of a direct-injection compression ignition engine under LTC mode was investigated. Main findings can be drawn as follows:

1. PM mass and PM number concentrations decreased for D85DM15 and D65P35 blends with the reduction being higher for D60DM20P20 blends compared with neat diesel. Increase in EGR levels decreased the PM number concentration in the nucleation mode while more particles with large diameter generated in the accumulation mode.

2. NO_x emissions at 30% EGR level decreased by 56% and 32% for D60DM20P20 blend for low and medium loads compared with neat diesel.

3. PM mass and PM number emissions increased for oxygenated test blends while NO_x emissions considerably decreased under LTC mode with EGR level being 30%. The combination of medium EGR (15%) level and D60DM20P20 blends generated lower NO_x and PM emissions with a slight decrease in engine performance.

4. CO and THC emissions were higher for binary (D85DM15 and D65P35) and ternary (D60DM20P20) blends compared with neat diesel. These gaseous emissions increased further when EGR was employed under LTC mode.

5. Binary (D85DM15 and D65P35) and ternary (D60DM20P20) blends demonstrated higher BSFC than neat diesel due to the lower energy density of the blends. The addition of EGR level further deteriorated the fuel economy and brake thermal efficiency.

Although the unique physiochemical properties of alcohols and DME limit their direct use in diesel engines, the blends of DME and pentanol with diesel could be considered as a promising alternative fuel for compression ignition engines with a potential of reducing hazardous emissions such as NO_x and PM. However, their durability in operation and commercial viability are also critical factors for the usage in diesel engines.

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Notes

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Highlights

- Suitability of n-pentanol/DME/diesel blends in a LTC diesel engine was examined.
- LTC mode was enabled by utilizing moderate EGR level and alcohol/diesel blends.
- Engine performance drops slightly by blending oxygenated fuels and EGR induction.
- PM/NOx trade-off can be control with suitable oxygenated blends fuel in LTC mode.