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DIMINUTION OF AIR POLLUTION FROM NO_X AND SMOKE/SOOT EMITTED FROM ALCOHOLS/DIESEL BLENDS IN DIESEL ENGINE AND INFLUENCE OF THE EXHAUST GAS RECIRCULATION (EGR)

Mohammed A. FAYAD[1*], Waleed K. ALANI[2, 1], Hayder A. DHAHAD[3], Jing ZHENG[2]

[1]*Energy and Renewable Energies Technology Center, University of Technology- Iraq, Baghdad, Iraq*
[2]*Tribology Research Institute, Key Laboratory of Advanced Technologies of Materials, Ministry of Education, Southwest Jiaotong University, Chengdu, China*
[3]*Mechanical Engineering Department, University of Technology- Iraq, Baghdad, Iraq*

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Highlights

- Alcohol/diesel blends reduced NO_X emissions, smoke, and PM compared to the diesel fuel.
- Combined effect of oxygenated fuels and different EGR rates decreased NO_X emissions with less effect on smoke/soot emissions.
- Different EGR rates increases the carbonaceous gas emissions and smoke/soot emissions.
- Higher alcohol/diesel blends up to 20% in diesel engine enhance the combustion performance.

Abstract. In this study, the impact of butanol-diesel blends and exhaust gas recirculation (EGR) on engine performance, NO_X emissions, smoke, and particulate matter (PM) characteristics were experimentally investigated under fuel post-injection condition. The maximum peak of cylinder pressure is achieved under without EGR compared with applied different rates of EGR. Furthermore, the brake thermal efficiency (BTE) increased during the combustion of B20 and B10 by 4.25% and 2.61%, respectively, compared with diesel fuel combustion. Considerable reductions in carbonaceous gas emissions (CO and THC) and nitrogen oxides (NO_X) were achieved from combustion of B20 and B10 compared to the diesel fuel for with and without EGR. The NO_X emissions decreased with 30% of EGR compared with 15% of EGR for all fuels studied. The results indicated that the addition butanol to the diesel fuel significantly reduced smoke opacity and soot emissions by 31.3% and 35.26%, respectively, compared with diesel. It is observed that an effective reduction of the NO_X emissions to be higher during the combustion of B20 compared to the combustion of B10 and diesel for different EGR rates. The results of PM emission showed increase by 16% under 15% of EGR and 28% under 30% of EGR compared to the without EGR for all fuels tested. The number, concentration and size of PM decreased from combustion of B20 and B10 compared with diesel fuel combustion for with and without EGR.

Keywords: alcohols/diesel blends, combustion, gaseous emissions, EGR rates, smoke, soot.

Introduction

Normally, the particulate matter (PM), unburned hydrocarbons (HCs), carbon monoxide (CO) and oxides of nitrogen (NO_X) are emitted from raw exhaust of diesel engines, which they are negatively affect the environment and the health of people (Verma et al., 2020; Dhahad et al., 2021). An increasing in pollution emissions of diesel fuel leads to undesirable climatic changes, health problems and accelerate global warming. Therefore, the using oxygenated fuels, fuel injection strategies and aftertreatment technologies are needed for diesel applications to reduce the deteriorating air quality. The use of cleaner fuels in transport sector continues receiving high attention by researchers due to mitigate health and environment effects (Yilmaz et al., 2005b). It is reported that higher alcohols (n-butanol and 1-pentanol) is considered to be a good alternative to the diesel fuel in diesel engine. Also, alcohol fuels can be produced from non-edible sources and can be blended directly with diesel fuel, which is reflected positively on the economic and environmental sectors (Yilmaz & Atmanli, 2017; Atmanli & Yilmaz, 2018). Fayad et al.

*Corresponding author. E-mail: *mohammed.a.fayad@uotechnology.edu.iq*

(2021) stated that biodiesel and alcohol fuels have significantly effect in reducing toxic emissions and soot particles in diesel engine. The ignition qualities can be improved when increasing the length of alcohol carbon chain, which makes more attractive to use in diesel engine than lower alcohols (Koivisto et al., 2015). Consequently, the formation of exhaust emissions and combustion from higher alcohols are necessary to understanding the development of their production processes. In addition, it is important to investigate the fuel properties of higher alcohols blends on the engine characteristics to obtain lower regulated emissions and semi-low temperature combustion in comparison to blends of waste oil methyl ester (Atmanli & Yilmaz, 2020; Yilmaz & Vigil, 2014). It is reported that the renewable fuels play a vital role in reducing both engine combustion and emissions characteristics under different operating conditions of engine (Kim & Choi, 2010; Shameer et al., 2017). Recent experimental studies (Liu et al., 2018; Ren et al., 2008) reported that the mixture of bioalcohol and diesel fuel significantly decreased the emissions of PM, CO and THC with keep NO_X emissions in moderate level, but another works documented the level of NO_X emissions are increased because of higher combustion temperature (Bugosh et al., 2011; Robbins et al., 2011). The PM emission has a major concern on human health and environment issues (Stone, 1999). Based to the previous studies, the particulate emissions were reduced during the combustion of butanol blends due to the less aromatic compounds and high oxygen content (Lapuerta et al., 2008; Fayad et al., 2020). The PM emission has variable size distribution and concentration in the exhaust (Fayad et al., 2021). It is documented that the size of PM decreased from biodiesel combustion compared to the diesel fuel combustion under various operating conditions of diesel engine (Neer & Koylu, 2006; Fayad, 2021). Prior work stated that the particulate size was smaller in diameter from the combustion of n-butanol blends compared to the biodiesel and diesel fuel (Yilmaz & Davis, 2016). Small nano-sized particulates have direct impact on human health and environment (Pan et al., 2020; Abood et al., 2021). Therefore, the nature of PM emission needed analysis to determine their effects and how its control. It is reported that using butanol blends is a good way to reduce the effect of PM emission through reducing the number and concentration of PM during the combustion process of diesel engine (Xu et al., 2020; Fayad & Dhahad, 2021). It is showed in the literature that the PM emitted from the combustion of oxygenated fuels has lower size compared to the diesel fuel combustion (Han et al., 2021; Ito et al., 2003).

Different technologies have been employed in diesel engines to control NO_X emissions such as EGR (exhaust gases recirculation) and injection strategies (Kim et al., 2005; Zheng et al., 2015; Fayad, 2019a). Furthermore, fuel injection strategies and fuel systems are linked with modern diesel engines to provide better engine efficiency with minimum level of exhaust emissions. The strategies of fuel injection offers the ability to control the pressure and combustion temperature, which in turn reduce the PM and NO_X emissions. Also, it was reported that the fuel injection strategies can be used to suppress combustion noise in diesel engine operated in conventional diesel fuel (Kondo et al., 2000). It is stated that low levels of PM and NO_X emissions in diesel engines is considered a formidable challenge for researchers. The use of EGR is an effective technology (among various strategies) for inhibition the NO_X emissions in diesel engines (Yu & Shahed, 1981; Zheng et al., 2015). Previous study by Asad and Zheng (2014) stated that no effecting combustion stability when the maximum EGR is limited to 20% in diesel engines. Another work by Abd-Alla (2002) reported that the EGR has good potential to reducing the NO_X emissions in diesel and gasoline engines. It was concluded that the 10–25% EGR has higher potential decrease in formation of NO_X with a penalty in combustion stability. To control fuel injection characteristics, the common-rail fuel injection system is considered effective way to control injection parameters (timing, duration, and quantity). Besides, another advantage of this system is select the number of injections and inject the fuel at high pressures, which result in enhance the combustion process and spray characteristics (Stone, 1999). Fuel injection strategies allow modifying the compression temperature and pressure under variable engine operating conditions result in clean combustion. The combustion noise, PM, and exhaust gaseous emissions can be reduced with employing electronic injection control (multiple injection events) (Fayad et al., 2017; How et al., 2018) in diesel engine. The high temperature combustion (HTC) leads to improve the thermal efficiency and emissions in diesel engines. It is typically linked with high engine loads and suitable fuels such as alternative fuels to use instead diesel fuel. The NO_X emissions and combustion characteristics was improved when engine fuelling with biodiesel compared to the diesel fuel under post-injection strategy (Nabi et al., 2004; Dhahad & Fayad, 2020). The levels of smoke opacity and NO_X emissions decreased with retarded fuel injection timing, while a significant increase in the levels of THC and CO (Payri et al., 2006). The PM formation decreased during the combustion of biodiesel (Menkiel et al., 2012) and in the same time promoted the oxidation rate of soot particles (Li et al., 2011). The concentration of PM and NO_X emissions decreased with delay fuel injection timing, but increased the carbonaceous emissions (Poorghasemi et al., 2012). It have been reported in previous studies (Desantes et al., 2006; O'Connor & Musculus, 2013) that the delay fuel injection timing can be contribute in reasonable reduction in the PM formation by 34.5%. The literatures presented a few articles discussing the effect of oxygenated fuels and EGR on combustion characteristics, engine emissions, and PM characteristics. Therefore, the purpose of this study is to investigate the combination effect of different butanol-diesel blends and EGR rates technology on engine performance, NO_X emissions, smoke, and soot emissions in a single cylinder CI diesel engine. Furthermore, study the effect of various rates of EGR (15% and 30%) and without

EGR technology on PM characteristics (number and size) fuelled by alcohol-diesel blends was also highlighted.

1. Experimental methods

1.1. Engine testing and fuels

The experimental tests were conducted on water-cooled, four-cylinders, direct-injection diesel engine as shown in Figure 1. The common-rail system was connected with cylinder head (see Figure 1) to control the injection events (pre, main and post-injection). The engine bore and stroke were 110 and 125 mm, respectively, with compression ratio 17:8. The maximum mean effective pressure (IMEP) and engine speed were 5 bar and 2500 rpm, respectively. The system of common-real fuel injection has three injection events (pre, main, and post injection). The engine speed and torque were controlled by an electric dynamometer. The variation results of cylinder pressure were plotted by the combined crank shaft position and pressure. The programme of LabVIEW was linked with engine to monitor the injector profile trace and the cylinder pressure.

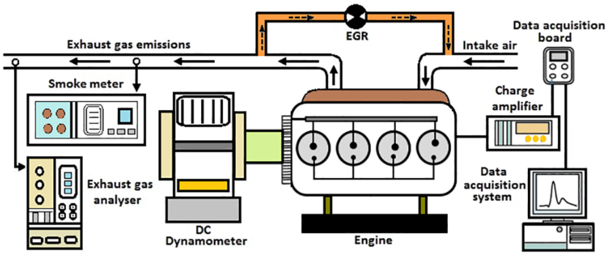

Figure 1. Schematic layout showing engine operation and experimental setup

The properties of diesel fuel, B10, and B20 used in this experimental study were presented in Table 1. The fuel of n-butanol was selected as oxygenated fuel with CAS number of 71-36-3 and the purity was 99.5% (Fayad et al., 2017). The fuel blends were prepared by mixing 10% and 20% by volume fraction of butanol with the base fuel (diesel fuel).

Table 1. Specification of tested fuel

Properties	Diesel	Butanol	B10	B20
Derived cetane number	50.2	17	40.23	41.98
Latent heat of vaporization (kJ/kg)	243	585	320	374
Bulk modulus (MPa)	1410	1500	–	–
Density at 15 °C (kg/m^3)	840.4	809.5	813.4	833.2
Upper heating value (MJ/kg)	45.76	36.11	41.63	43.5
Lower heating value (MJ/kg)	43.11	33.12	38.92	40.91
Water content by coulometric KF (mg/kg)	40	170	362.3	389.4
Kinematic viscosity at 40 °C (cSt)	2.564	2.23	2.24	2.27
Lubricity at 60 °C (μm)	424	571.15	432.4	444.5

The tested fuel prepared at the same time of tests to avoid any separation may be occurred in the fuel mixture. The fuel blends of B10 and B20 were prepared using blending (based on volume) and mechanical mixing. An electric magnetic stirrer was used to stirrer each of the mixture continuously for 30 minutes. To reach equilibrium at room temperature, the blend was left for 30 minutes before they were subjected to any test. Normally, the fuel lines cleaned before the real test by running the engine for 15 minutes without test to removing utilised fuel from earlier test. For start the tests, the fuel blends were prepared during test to keep the homogeneity of the fuel mixture.

1.2. Experimental conditions and equipment

The tests of diesel engine were conducted at constant parameters of engine speed, fuel injection pressure, and IMEP by 1800 rpm, 650 bar, and 4 bar, respectively. In this study, the fuel post-injection was carried out at 45 CAD after top dead centre (ATDC) for all fuels tested. The engine was warmed up for 30 min before collecting data in all engine tests. The engine test started with diesel fuel for the heating process to ensure that all the devices were worked in properly. The engine ran for 10 to 15 min as the fuel was being changed to clean the fuel line before starting a new test. The first test was performed on diesel fuel to record basic data for comparison with the other fuel tests. The results of three measurements in each test were averaged to avoid experimental error. To ensure the accuracy of the results, the same measurements were made on each fuel. The variation in the temperatures at the exhaust gas pipe was measured using thermocouples (K-type) and data Logger (Pico Technology, 2011). Three injection events of pre, main, and post injection quantity were fixed at 0.15, 0.48, and 0.1 mg/str, respectively. Different rates of EGR (0%, 15%, and 30%) were used to show the influence of EGR on particulate emissions. Exhaust gas analyser and smoke meter/scanning mobility particle sizer (SMPS) with model TSI/3080 were used to record the level of diesel emission (CO, THC, NO, NO_X) (Dhahad & Fayad, 2020) and particulate emissions (Fayad, 2020), respectively.

1.3. Experimental errors

The error is the difference between the actual and measured values. The uncertainties in the whole experiment could be attributed to different factors, such as the measurements by each device. Here, the uncertainty of the results was calculated according to the following equation (Line, 1986):

$$e_R = \left[\left(\frac{\partial R}{\partial V_1} e_1 \right)^2 + \left(\frac{\partial R}{\partial V_2} e_2 \right)^2 + \ldots + \left(\frac{\partial R}{\partial V_n} e_n \right)^2 \right]^{0.5}.$$

The sensitivity of a single variable of the result represents the partial derivative $\left(\frac{\partial R}{\partial V_1} \right)$. The uncertainty of the results and uncertainty intervals in the nth variable are represented by e_R and e_i, respectively. Table 3 lists the measurement accuracies of the various devices used in this study. Three times of each test were repeated and averaged these results to achieve the repeatability and accuracy of results as shown in Table 2. The devices were calibrated according to the quality control standards of Iraq (Dhahad & Fayad, 2020).

Table 2. Accuracy of the experimental measurements of the equipment used in this study

Equipment measurements		Accuracy %
Engine	Speed	±1.72%
	Dynamometer	±0.91%
	Torque	±1.24%
Flow meter	Diesel fuel	±0.56%
	Air flow	±1.10%
	Thermocouples	±1.20%
	Level of sound pressure	±0.66%
Emission analyser	Particulate matter (PM)	±0.1%
	(NO_X)	±0.70%
	(CO)	±0.18%
	(HC)	±0.14%

2. Experimental results and discussions

2.1. Combustion characteristics and BTE

Figure 2 shows the effect of B20, B10, and diesel fuel on the average cylinder pressure under different rate of EGR. The maximum cylinder pressure moves backward with increasing the rate of EGR for all fuels tested. Furthermore, the addition butanol to the diesel fuel plays a vital role by increasing the cylinder pressure under different EGR rates. This could have been because of the longer ignition delay result in an improving the combustion process (faster and shorter combustion). In addition, the main reason for that is the oxygen-bond in alcohol blends (B20 and B10) enhances the fuel mixture with air through better oxidation and reduced the duration of the combustion process compared to the diesel (Emiroğlu & Şen, 2018). Additional point is the extra fuel injects close the TDC which leading to move the average cylinder pressure backwards. In comparison of alcohol blends, Figure 2 shows that the average cylinder pressure increased more with B20 compared with B10 under various EGR rates. This has been reported due to the higher heat of vaporisation of B20 (Table 1) compared to the B10 and diesel fuel. Furthermore, the combustion of B20 advanced the start of combustion and premixed combustion phase (Fayad, 2019b), which result in an improvement of thermal efficiency (Qi et al., 2011; Fayad et al., 2017) and better combustion compared to the rest of tested fuels. It can be noticed that the peak pressure reduced with high rate of EGR for B20, B10, and diesel fuel. This can be justified that the insufficient time available for air-fuel mixing (slow burning) as presented in Figure 2. In addition, the combustion delay period further extends when ERG rate become high, therefore the combustion is shifted towards after TDC (Shi et al., 2017b). The cylinder pressure is significantly reduced with high EGR rate for three fuels studied, but this effect is clearer with diesel fuel combustion. This is because of the incomplete combustion of fuel caused from less air was used in combustion cycle to be burn completely.

Figure 3 shows the effect of various rates of EGR and alcohol blends on brake thermal efficiency (BTE). It can be seen that the BTE increased from the combustion of B10 and B20 compared to the diesel fuel combustion under variable EGR rates. The main reason for that is oxygen content in the alcohol blends which enhance the combustion efficiency and this agreement with previous studies (Fayad et al., 2017; Hajbabaei et al., 2013). Furthermore, the combustion of B20 and B10 increased the BTE by 4.25% and 2.61%, respectively, compared to the combustion of diesel fuel. The results indicated that the BTE reduced with applied EGR compared without EGR for all fuel tests (Figure 3). This may have been because the reducing the burning rate and impede combustion process (Saravanan, 2015). The results of this study are in good agreement with earlier report (Heywood, 1988) that EGR can effects on the thermal efficiency.

2.2. The influence of alcohol blends and EGR on gaseous emissions

2.2.1. Carbonaceous gas emissions (CO and THC)

The changes in the level of carbon monoxide (CO) and total hydrocarbons (THC) concentration in the exhaust are

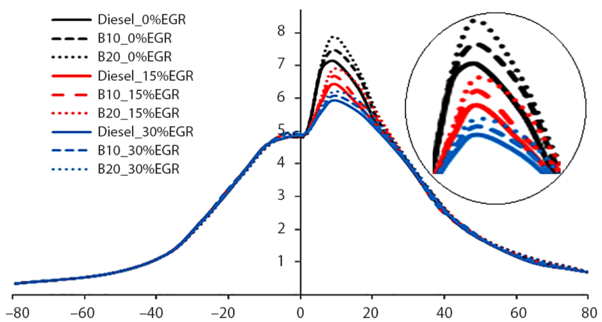

Figure 2. Effect of alcohol blends and EGR rates on the variation of cylinder pressure

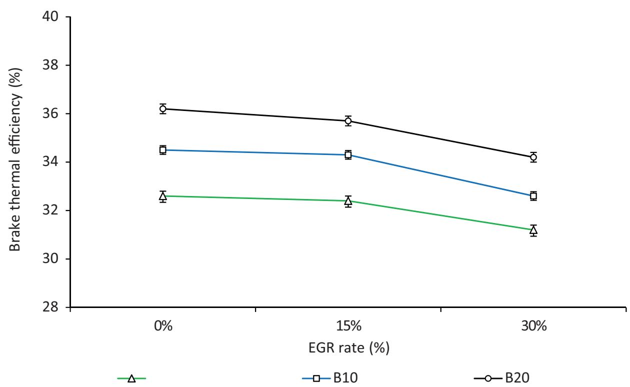

Figure 3. Effect of alcohol blends and different EGR rates on BTE under 1800 rpm

shown in Figure 4 and Figure 6. Lower CO concentration and unburnt THC emissions emitted from B20 and B10 combustion compared to the diesel combustion as shown in Figure 4 and Figure 6, respectively. Higher level concentration of CO and THC produced under post-injection for all fuels tested. This is due to the late fuel injected inside combustion cycle, which result the quantity of fuel tested isn't combusted. The combustion of B20 and B10 produced lower CO and THC emissions by 16.43% and 21.35%, respectively, compared to the diesel fuel as shown in Figure 4 and Figure 6. The main reason for this trend is better combustion resulted from the availability of inherent oxygen in the oxygenated fuels (B10 and B20). In addition, this can be due to the increases the time availability for oxidation both THC and CO emissions. For alcohol blends tests, Figure 4 shows that the increases addition of butanol to the blends (B20) decreased the CO emissions more than lower addition of butanol (B10). This is could be because of the lower C/H ratio in case of B20 compared to the B10.

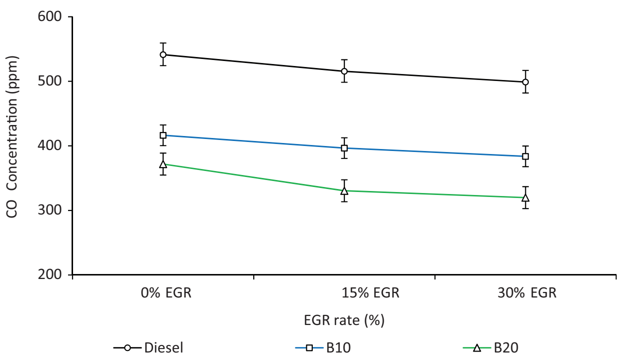

Figure 4. Effect of alcohol blends and different EGR rates on CO concentration in the exhaust gas under 1800 rpm

All hydrocarbon fuels combustion produces Carbon dioxide (CO_2) emissions. The level of CO_2 emissions refer to the improvement in the combustion process and complete fuel combustion (Ekaab et al., 2019). Figure 5 shows the level concentration of CO_2 during the combustion of B20 and B10 under different EGR rates. It can be seen that the high concentration of CO_2 emitted from the combustion of oxygenated fuels in comparison with diesel fuel under different EGR rates (Figure 5). Furthermore, these results agree with previous studies by Chaichan (2018) and Fayad (2021) which indicates that the improvement in combustion can be noted with oxygenated fuels. The findings of Figure 5 are due to the homogeneous air-fuel mixture of oxygenated fuels and most of the carbon is converted into CO_2 (Shi et al., 2017a). On the other hand, it can be observed that the CO and THC concentration increased 11.4% and 28.4%, respectively, when high rate of EGR is applied (Figure 4 and Figure 6). This could have been because of poor combustion, which result in an increasing the material that has less self-ignition. The high rate of EGR (30%) reduced the oxidation reactions, thus increased the level of CO concentration. Interestingly, the slight reduction of CO and THC emissions can be found in the case of 15% EGR rate compared to the without EGR and 30% of EGR for all fuels tested. This benefit could be due to the homogeneous mixture making better combustion process. The effect of 15% of EGR and high oxygen-bond in B10 and B20 decreases the CO and THC emissions compared to the diesel fuel. The multiple injections could be another reason with alcohol blends to enhance the combustion process and reduced the effect of EGR compared to those with diesel fuel as shown in Figures 4 and Figure 6. This trend is different under high rate of EGR for all conditions and fuels. This is because of reducing the level concentration of oxygen in the combustion chamber from the effect of high rate of EGR. A comparison of fuels, it can be seen that less effect of post-injection on CO and THC emissions during combustion of B10 and B20 compared to the diesel combustion.

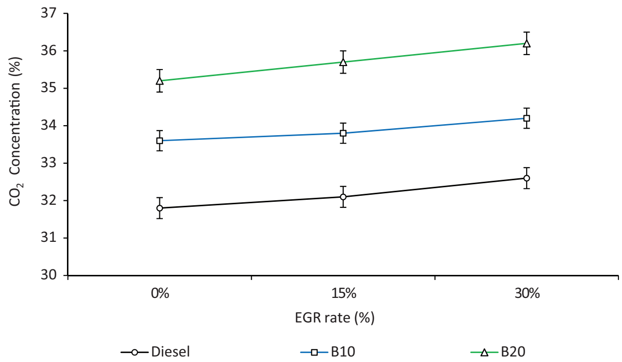

Figure 5. Effect of oxygenated fuel and different EGR rates on CO_2 concentration in the exhaust gas under 1800 rpm

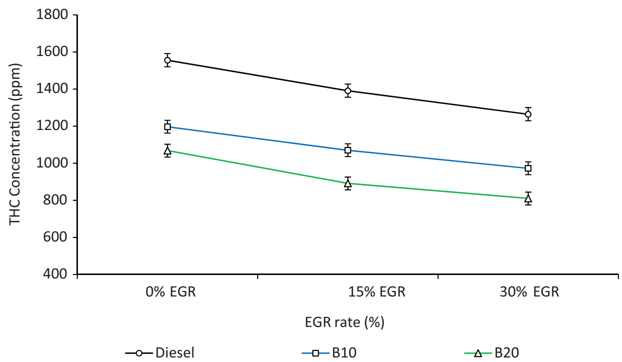

Figure 6. Effect of oxygenated fuel and different EGR rates on THC concentration in the exhaust gas under 1800 rpm

2.2.2. Nitrogen oxides (NO_x)

The variation of NO_X ($NO+NO_2$) concentration in the exhaust gas pipe was measured for B20, B10, and diesel fuel under different EGR rates as depicted in Figure 7. The NO_X emissions were lower under high rate of EGR for all fuels studied. This is could be due to the reducing the oxygen concentration from in-cylinder flame temperature as well as decreasing the temperature during combustion. The results of current study are in good agreement with previous studies by Shi et al. (2017b) and Koder et al. (2018). A significant decrease in the NO_X emissions during the combustion of B20 and B10 by 41.6% and 31.3%, respectively, compared to the diesel (Figure 7). This is related to the many reason such as oxygen content, lower viscosity, large flammability, and greater heat of vaporisation of butanol, which enhances the combustion (faster combustion) and reduces the NO_X emissions. It is reported in the study by Emiroğlu and Şen (2018) that adding ethanol to the diesel fuel leads to decrease the formation of NO_X and CO emissions, while increased the BSFC. In contrast, it is stated that the use of butanol blend slightly increased the NO_X emissions and reduced carbonaceous gas emissions (Fayad et al., 2018). The combination effect of EGR and butanol-diesel blends leads to reduce the oxygen concentration and temperature of combustion, which result in inhibits the NO_X formation. In addition, this can be justified due to the reduction of NO_X with some of the HCs post-injected and because the hydroperoxy radical (HO_2) that formed during post-combustion (Lyon & Cole, 1990) help in oxidise a portion of NO to NO_2. Therefore, it can be seen that the combined effect of increase EGR rate and introduce post-injection leads to decrease the NO_X formation during combustion. The nitrated-hydrocarbon formation with post-injection could be also reduce the NO_X emissions by enhance reacting the radical HC with NO_X emissions (Fayad et al., 2017).

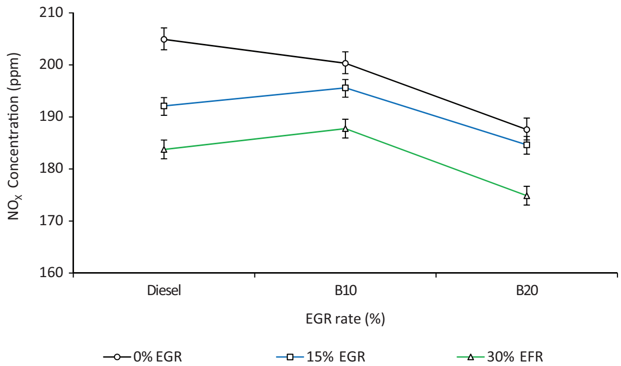

Figure 7. Effect of oxygenated fuels and different EGR rates on the NO_X emissions concentration under 1800 rpm

2.3. Smoke opacity and soot emissions

The influence of different rates of EGR and butanol-diesel blends on smoke opacity and soot emissions are shown in Figure 8 and Figure 9. The level of smoke opacity increased with increasing the EGR rates (from 0% to 30%) for all fuels tested (Figure 8). Less efficiency mixture between air/fuel and incomplete combustion with high rate of EGR are the main reasons to increase the unburned HCs and smoke opacity. It has been reported that the applied EGR increased the level amount of smoke and reduces the NO_X emissions formation (Banerjee et al., 2015). In general, the current results suggested that the smoke opacity decreased from the combustion of butanol blends even with increasing the EGR rates compared to the diesel fuel under post-injection strategy. The interaction between post-injection strategy and oxygenated fuels could be the main reason for the smoke opacity reduction despite of increasing the EGR rates. Furthermore, the high reduction in smoke opacity from B20 and B10 under various rates of EGR is certainly due to enhance the premixing combustion resulted from the oxygen content in the butanol blends. It is stated in the earlier literatures that the alcohol blends improve the combustion and reduces the pollutants emissions (Fayad et al., 2018; Emiroğlu & Şen, 2018). According to the butanol-diesel blends results, it is clear from Figure 8 that the combustion of B20 produce low level of smoke opacity compared to the B10 for various EGR rates. The effective hydroxyl group of B20 are the main reason to explain the reduction in smoke level compared to the B10. The presence of oxygen-bond in B10 and B20 blends is playing a vital role with EGR to create a real balance in reducing the smoke level. In addition, B20 and B10 can compensate the low oxygen concentration during the combustion process resulted from applied EGR technology. It can observed that the smoke opacity reduced by 31.3% and 23.6% from combustion of both B20 and B10, respectively, compared to the diesel fuel as presented in Figure 8.

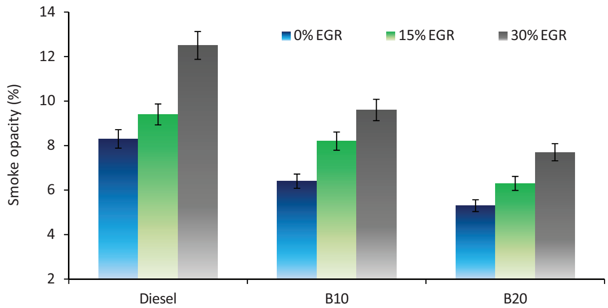

Figure 8. Effect of alcohol blends and different EGR rates on level of smoke opacity (%) under 1800 rpm

Figure 9 shows that B20 and B10 produced lower soot emissions compared than those emitted from diesel fuel for different EGR rates. Polycyclic aromatic hydrocarbons (PAHs), considered to be building blocks for soot emission, are associated with rich and lean combustion conditions (Yilmaz & Donaldson, 2005a; Yilmaz, 2007). The absence of aromatic compounds and presence oxygen content of butanol fuel leads to increase the oxidation rate of soot emissions, and these results are agreement with (Koivisto et al., 2015; Zhang & Balasubramanian, 2016; Fayad, 2019b). In addition, the butanol-diesel blends produces more complete combustion result in lower soot emissions formation as well as oxidation any newly particle that already formed during combustion process. Another reason could be due to shorten the residence time for soot growth as depicted in Figure 9. The addition butanol to the diesel fuel improve the particulate emission oxidation under various engine operating conditions (Sayin & Canakci, 2009; Fayad, 2021). The combustion of B20 and B10 result in lower level of soot emissions by 35.26% and 28.34%, respectively, compared to the diesel combustion under various EGR rates. A comparison of butanol blends showed that B20 decreased the soot emissions more than to the diesel fuel (Figure 9). The effective atom of oxygen content of B20 could be promotes the reduction in the formation of soot emissions as well as enhance the soot oxidation during the combustion process. The different fuel molecules structure also could be the advantage reason for the B20 fuel to inhibit the soot formation. Regarding to the EGR rates, Figure 9 shows that the soot emissions increased with applied EGR compared to the without EGR for B20, B10, and diesel. This effect is due to the insufficient time available for soot oxidation with applied EGR technology. The lower soot emissions were more evidenced with combustion of B20 compared to the combustion of B10 and diesel for different EGR rates. The combination of B20 and low rate of EGR application plays an important role to diminish both smoke opacity and soot emissions. Consequently, it can be noticed in Figures 8 and Figure 9 that the gaseous and solid emissions from the combustion of B20 are all reduced.

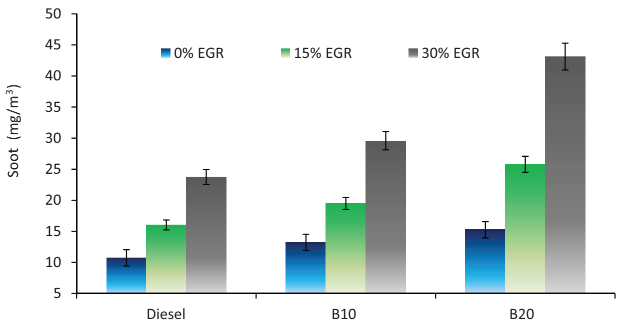

Figure 9. Effect of alcohol blends and different EGR rates on soot emissions under 1800 rpm

Figure 10 shows effect of B20, B10, and diesel on particulate size distribution of PM under different rates of EGR. It can be observed that B20 and B10 decreased number and concentration of PM in the exhaust by 33% and 22%, respectively, compared to the diesel fuel under different rates of EGR. This could have been due to the oxygen-bond in the alcohol blends which enhances the oxidation rate of PM emission (Emiroğlu & Şen, 2018; Zhu et al., 2016). It is reported in earlier works (Liu et al., 2012; Eveleigh et al., 2015) that the oxygenated fuels inhibited the particle number formation of PM emission by increasing the oxidation rate of soot primary particles. A significant increase was found in the concentration of PM by 33% and 22% with 15% and 30% of EGR, respectively, compared to the without EGR for all fuels studied (Figure 10). This is due to the increase randomly attached and collisions between soot particles of PM emission with increasing the EGR rates (Fayad, 2020). The combustion process improved from the combustion of B20 and B10, which in turn promote the PM oxidation and inhibit the formation of soot precursors. A slight decrease in the PM was observed with high addition of butanol to the diesel fuel (B20) compared to the low addition of butanol (B10) under variable rates of EGR (Figure 10).

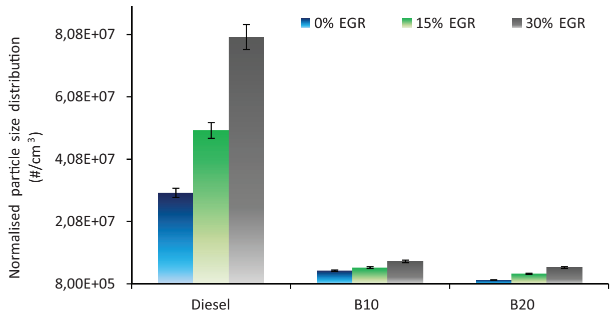

Figure 10. Effect of alcohol blends and different EGR rates on particle size distribution under 1800 rpm

Conclusions

The effects of butanol-diesel blends and different rates of EGR on the engine performance, NO_X emissions, smoke opacity, soot emissions, and PM emission were investigated. The effect of post-injection strategy on regulated and unregulated pollutants in common-rail diesel engine was also examined in this study. It was observed that peak cylinder pressure and BTE increased during the combustion of B20 and B10 compared to the diesel fuel. The addition of butanol into diesel fuel reduced the formation of carbonaceous gas emissions (CO and THC) by 24.6% compared to the diesel fuel. Furthermore, it was found that the blends of the B20 and B10 provided more benefits in decreasing the NO_X emissions by 41.6% and 31.3%, respectively, compared to the diesel fuel for different EGR rates. The levels of smoke and soot emissions decreased together when adding butanol to the diesel fuel under various rates of EGR technology. It can be concluded that the combustion of B20 and B10 reduced the smoke opacity by 31.3% and 23.6%, respectively, compared to the diesel fuel for different rates of EGR. Besides, the soot particles reduced by 35.26% and 28.34% from the combustion of B20 and B10, respectively, compared to the diesel fuel. It was found that the number and concentration of PM emission decreased by 33% and 22%, from the combustion of B20 and B10, respectively, under various rates of EGR. The results revealed that the addition 20% of butanol into the diesel fuel is enough to improve the engine performance and to alleviate the negative effect of high EGR rate on combustion. The incorporation between oxygenated fuel and EGR has a positive effect to inhibit the emissions formation of NO_X emissions and reducing the smoke opacity. The potential implications of the results could be increasing the PM under high rate of EGR, but the utilising the oxygenated fuels reduced the effect of these implications. According to the present paper, it is recommended that the manipulating in the injection strategies, EGR rates and various oxygenated fuels could be an engaging topic and will be addressed in future work. Also, it is suggested that the including low and high level of fuel injection pressure, EGR and oxygenated fuels under various operating conditions will be interesting for the next study.

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Abbreviations

ATDC = after top dead centre;
BTE = brake thermal efficiency;
B10 = butanol 10%, and Diesel 90%;
B20 = butanol 20%, and Diesel 80%;
CI = compression ignition;
CO = carbon monoxide;
HCs = hydrocarbons;
IMEP = indicated mean effective pressure;
NO_X = nitrogen oxides;
PM = particulate matter;
TDC = top dead centre;
THC = total hydrocarbons.

Conflict of interests

The author confirms and declares that there is no conflict of interests regarding the publication of this paper.

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