Investigation the combined effects of exhaust gas recirculation (EGR) and alcohol-diesel blends in improvement of NOX-PM Trade-off in compression ignition (CI) diesel engine

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Abstract. The increasing demand to decrease the greenhouse gas emissions leads to find clean fuel and renewable fuel such as ethanol and methanol that good replacement of oil-derived transportation fuels. The combined effects of alcohols blends (ethanol-diesel and methanol-diesel) and with and without EGR on NOX-PM Trade-off in diesel engine were investigated under variable engine loads and speeds. The EGR is considered efficient technology to reduce the NOX emissions in compression ignition (CI) diesel engines. The current study highlighted on the trade-off between nitrogen oxides (NOX) and particulate matter (PM). The oxygenating content in the ethanol blend (E10) and methanol blend (M10) decrease the PM concentrations in the exhaust pipe compared to the diesel fuel for different engine operating conditions with keep NOX emissions in the moderate level. It was found that the NOX/PM concentrations significantly decreased from the combustion of E10 and M10 under variable engine loads and speeds.

Keywords: Trade-off, methanol, ethanol, EGR, NOX emissions, particulate matter, diesel engine.

1. Introduction

The high consumption of fossil fuels in various transportation sectors caused a significant increase in pollution rates in cities, especially those with a high population concentration [1]. This prompted towards finding alternatives that can be adopted to meet the strict requirements to reduce engine emissions, especially diesel engines, while providing clean fuels from renewable sources [2-4]. Bioethanol produced from sugarcane (Brazil) or from corn (USA) has gained worldwide acceptance and it is used as pure fuel or blended with diesel. Bioethanol is renewable and more environmentally friendly than fossil fuels [5]. Methanol fuel is made from the process of mixing fossil methane (from natural gas) with superheated water vapour at high temperatures [6]. It can be said that natural gas currently exists and has a lifespan more than oil [7]. The use of alcohol fuels into the diesel is better to using in diesel engine compared to the use biofuels produced from plant oils (methyl ester), which they are less harmful than to the biodiesel in terms of the consumption raw materials that extracted from the world's food.
Diesel engines are widely used in the industrial, transportation and power generation sectors. An environmental report by the Chinese government showed that the total emissions of only four types of pollutants resulting from burning fuel in cars in China alone in 2018 amounted to about 40.6 million tons. 70% of these emissions are nitrogen oxides (NO\textsubscript{X}) from diesel. Meanwhile, if PM emissions are added to these pollutants, their share will exceed 90% of the total emissions [2]. These two pollutants cause enormous harm to the environment, human, animals and crops. The emissions of PM and NO\textsubscript{X} have earned significant important part of the strictest regulations due to limit regular or irregular emissions [3]. The reduction of NO\textsubscript{X} and PM emissions should be achieved by reducing the burning of fossil diesel. Engine designs must also be optimized to simultaneously reduce the formation of high-temperature local areas and areas with a rich mixture. These two things can be contributing in reducing the NO\textsubscript{X} and PM emissions partially, but not at the same time due to the different conditions of their formation [10, 11]. NO\textsubscript{X} is formed in conditions of high temperature (above 950°C) and with an abundance of oxygen and the time available for formation. PM is formed in the event of a lack of oxygen as well as medium and low combustion temperatures.

Research directions are depending on three technical options to solve this dilemma relied, which are currently used to control these two types of pollutants. The first method adopted the installation of exhaust gas treatment systems outside the engine [12]. The second method adopted the technique of improving the quality of combustion inside the combustion chamber, such as using the homogeneous charge compression ignition technique (HCCI) [13]. The last method adopted the technology of using clean and environmentally friendly fuels in the sense of burning that emits less exhaust pollutants, especially NO\textsubscript{X} and PM [14]. Alcohols such as ethanol and methanol have received wide interest as alternatives to diesel because of their physical and chemical properties in addition to their combustion properties [15]. Alcohols are characterized by the presence of a high percentage of oxygen in their molecule structure of chemical composition, which causes an increase in the NO\textsubscript{X} emissions due to this abundance of oxygen. However, the lower calorific value of the two fuels causes less combustion heat to be released into the combustion chamber compared to the diesel, which leads to a reduction in NO\textsubscript{X} emission. Therefore, the resulting NO\textsubscript{X} concentrations are the sum of these two factors and the proportion of their mixing with diesel [16].

Exhaust gas recirculation (EGR) can be used as a control technology for NO\textsubscript{X} emissions so that the EGR rate does not exceed 30% only [17]. Adding EGR to the combustion chamber reduces the amount of oxygen inside the combustion chamber. However, when ethanol or methanol is added to diesel fuel, the effect of the oxygen amount from EGR will be reduced due to the oxygen available in the composition of the alcohol fuels. The addition of EGR inside the combustion chamber causes a dilation of the charge and results in increased combustion instability. However, EGR plays an important role in the heat released into the combustion chamber and in reducing NO\textsubscript{X} and PM emissions [4, 5]. In this experimental study, a specific percentage of methanol and ethanol was added to diesel (10%) separately, and the effect of some operational variables on NO\textsubscript{X} and PM emitted from the engine was studied. Furthermore, the differential relationship between NO\textsubscript{X} and PM emissions is evaluated to determine the best operating conditions that generate the least emissions of both pollutants.

2. Experimental setup and procedure

2.1. Fuel blends

According to the previous researchers, the ethanol blends (10% of ethanol and 90% of diesel fuel) and methanol blends (10% of methanol and 90% of diesel fuel) are selected to produce various exhaust concentrations of NOX emissions and particulate matter (PM). The preparation of ethanol blends (E10) and methanol blends (M10) were done at the same time of the experimental tests to avoid any fuel separation
before and after the tests. The main properties of diesel fuel, E10 and M10 are measured and calculated as listed in Table 1. The surface tension, liquid viscosity and oil density are measured at 20 °C. Three times at least are repeated the measurements to avoid any error and the average results are listed in the results section. In this study, a solvent consisting of oleic and iso-butanol was added to the methanol blend due to the low methanol solubility in the diesel fuel and to enhance the stability of the blend. Table 1 presented the fuel properties of diesel, ethanol and methanol fuel. High oxygen content was appeared in methanol fuel compared to the ethanol fuel as listed in Table 1. The emissions of NOX and PM emitted from the combustion of E10 and M10 are measured and compared with results produced from the combustion of diesel fuel to clarify how the oxygenated additives impacts on combustion process.

Table 1. Fuel properties of diesel, ethanol and methanol.

| Properties                          | Diesel  | Ethanol | Methanol |
|-------------------------------------|---------|---------|----------|
| Chemical formula                    | C\textsubscript{10}H\textsubscript{18.7} | C\textsubscript{2}H\textsubscript{5}OH | CH\textsubscript{3}OH |
| Mole weight (g)                     | 148.3   | 46.1    | 32       |
| Density (g/cm\textsuperscript{3} at 20°C) | 0.84    | 0.789   | 0.828    |
| Boiling point (°C)                  | 180-330 | 78      | 0.796    |
| Heat of evaporation (kJ/kg)         | 280     | 856     | 1110     |
| Lower heat value (MJ/kg)            | 42.5    | 27.0    | 19.68    |
| Liquid viscosity (cP at 20°C)       | 3.03    | 1.2     | 1.07     |
| Surface tension (mN/m at 20°C)      | 34.1    | 28.9    | 23.5     |
| Flash point (°C)                    | 78      | 13.5    | 11       |
| Stoichiometric air fuel ratio       | 14.4    | 9       | 6.4      |
| Cetane number                       | 45      | 5.8     | 2        |
| Auto-ignition (°C)                  | 235     | 423     | 588      |
| Carbon content (wt%)                | 87.4    | 52.2    | 77.98    |
| Oxygen content (wt%)                | 0       | 34.3    | 8.52     |

2.2. Engine setup and instruments

The diesel engine used in this study is direct injection, four strokes, 4 cylinders equipped with EGR as shown in Figure 1. Main specifications of the diesel engine are listed in Table 2. The engine speed measured by a tacho-generator that connected with hydraulic dynamometer. The dynamometer is used to adjust engine load and speed. The fuel consumption for a given period is measured by the level fuel decrease in a graduated container. The volumetric flow rate of the intake air is measured by an orifice plate. K-type thermocouples are used to measure the exhaust gas temperature which connected in different location in the exhaust manifold [6]. Cooling water temperatures is measured using calibrated thermocouples at the both of inlet and outlet of the engine. External EGR technology is used in this study by linked pipe between outer exhaust gas and intake system. The ratio of EGR was fixed at 15% to evaluate the effect of with and without EGR on the PM and NOX concentrations. The ratio of EGR is calculated in this study according to the following equation:

$$EGR = \frac{m_{EGR}}{m_{air} + m_{EGR}}$$
The mass flow rate of EGR represents the $m_{EGR}$, while the fresh air mass flow rate represents $m_{air}$.

Table 2. Diesel engine specifications.

| Engine type          | 4cyl., 4-stroke         |
|----------------------|-------------------------|
| Engine model         | TD 313 Diesel engine rig|
| Combustion type      | DI, water cooled, natural aspirated |
| Displacement         | 3.666 L                 |
| Valve per cylinder   | two                     |
| Bore                 | 100 mm                  |
| Stroke               | 110 mm                  |
| Compression ratio    | 17                      |
| Fuel injection pump  | Unit pump               |
|                      | 26 mm diameter plunger  |
| Fuel injection nozzle| Hole nozzle             |
|                      | 10 nozzle holes         |
|                      | Nozzle hole dia. (0.48mm) |
|                      | Spray angle= 160°       |
|                      | Nozzle opening pressure=40 Mpa |

The emissions analyzer (Multigas mode 4880) is used measure the NOX emissions concentrations. In addition, the emissions of CO2, CO, O2 content and HC are also measured using the emissions analyzer. Small a probe linked with the engine exhaust pipe to collect the exhaust gasses. Furthermore, the samples of PM are obtained at the end of the tailpipe by exposing filter material to a diesel exhaust gas. A scanning electron microscope is used to exam these filters. Whatmann-glass micro-filters are used to collect the PM emitted from diesel engine. Before and after test, filters samples are also weighted.

Figure 1. Schematic of research diesel engine and tools.

3. Results and discussion

The effect of EGR on NOX emissions for variable engine loads is shown in Figure 1. It can be noticed that the NOX concentrations decrease with applied EGR for all tested blends. The experimental results show that the combustion of M10 and E10 emitted higher rate of NOX emissions compared to the diesel fuel. According to the results, applied EGR produced significantly lower NOX emissions with oxygenated blends.
Therefore, the oxygenated blends are more sensitive to exhaust gas recirculation. Low cetane numbers and long delay period are the main properties of oxygenated blends [7, 8]. In addition, these properties intensified with addition EGR which result in lower NOX concentrations due to the lower flame temperature [9]. It can be noticed this effect of EGR with M10 combustion due to the lowest cetane number when compared to the E10 blend [10, 11]. The combination between EGR and fuels used in this study leads to reduction in NOX emissions by 56.22 and 43.59% and 36.27% from the combustion of M10, E10 and diesel fuel, respectively.

The effect of EGR on PM concentrations for E10, M10 and diesel under variable engine loads is shown in Figure 2. The PM concentrations increased by 17% with applied EGR. This could be due to the dilution mechanism affects the frustrated combustion and the flame temperatures. In addition, the overall air/fuel ratio decreased with EGR which result in increased the PM concentrations. The smoke level increased due to the recirculate exhaust gasses contains particulates [4, 12]. The oxygenated blends of E10 and M10 decreased the PM concentrations by 21.33% and 28.66%, respectively, due to the oxygen content inside the combustion chamber that preserved good combustion efficiency [13]. The higher reduction in PM concentration was from the combustion of E10. This is due to the higher oxygen born in E10 properties compared to the M10 and diesel fuel. Fayad et al. [14] reported that the increase the oxygen mass fraction in the fuel blend leads to increase the rate of PM oxidation and improve the exhaust processes [15].

**Figure 2.** Effect of engine loads and EGR on NOX concentrations for diesel and alcohol blends.
The effects of EGR and engine speeds on the concentrations of NO\textsubscript{X} emissions under three conditions of engine loads are shown in Figures 4, Figure 5 and Figure 6. According to these Figures, it can be observed that the NO\textsubscript{X} emissions concentrations increased with increasing the engine loads and the same trend was found with increasing the engine speed [16-18]. The NO\textsubscript{X} emissions concentrations also increased from the oxygenated fuel under medium and high engine speeds. The combustion of E10 and M10 slightly decrease the NO\textsubscript{X} emissions compared to the diesel fuel [19-21]. The concentrations of NO\textsubscript{X} emissions decreased with applied EGR under low load condition compared to the high engine load. The applied EGR technology changes the temperatures inside in-cylinder under high engine load. Therefore, the effect of EGR significantly more with increasing the engine load.

**Figure 3.** Effect of engine loads and EGR on PM emissions for diesel and alcohol blends.
Figure 4. Effect of engine speeds and EGR on NOX concentrations for diesel and alcohol blends under low engine load.

Figure 5. Effect of engine speeds and EGR on NOX concentrations for diesel and alcohol blends under medium engine load.
Figure 6. Effect of engine speeds and EGR on NO\textsubscript{X} concentrations for diesel and alcohol blends under high engine load.

The engine burns 99.5% of the injected fuel with high combustion temperatures under conventional diesel operation. The burn fraction of engine decreased to 95% due to the incomplete combustion, when applied EGR with lower temperature conditions of engine. An undesired reduction in fuel efficiency can be occurred from this incomplete combustion which result in an increase PM concentrations [22]. The effect of engine speed and engine load on PM concentrations is shown in Figures 7, Figure 8 and Figure 9. These Figure also showed that the addition of ethanol and methanol to the diesel fuel leads to significantly decrease the PM concentrations under various conditions of engine loads and speeds. These results are agreement with previous study [23, 24] that the oxygenated blends decrease the PM due to increase the post-flame oxidation to the PM and decrease the rich spray region. The oxygen content in the E10 and M10 enhance the PM reduction and improve the diffusive burning phase. To be more remarkable, the reduction of PM was with high engine speed from 1500 to 2250 rpm. This can be justified due to reduce excessive rich-spray region and improve the fuel-air mixing. A remarkable reduction in PM was found from the combustion of oxygenated blends with and slightly increases in NO\textsubscript{X} emissions. A simultaneous reduction in both NO\textsubscript{X} and PM was achieved with the addition of EGR technology [25].
Figure 7. Effect of engine speeds and EGR on PM concentrations for diesel and alcohol blends under low engine load.

Figure 8. Effect of engine speeds and EGR on PM concentrations for diesel and alcohol blends under medium engine load.
4. Conclusions

The influences of oxygenated blends (E10 and M10) and exhaust gas recirculation (EGR) on NO\textsubscript{X}-PM emissions in multi-cylinders diesel engine were investigated in this study. Employing ethanol or methanol accompanied with EGR leading to the low NO\textsubscript{X} and PM emitted from a diesel engine. The main interesting point from the results is the trade-off between NO\textsubscript{X}-PM emissions can be achieved from the combustion of Iraqi diesel fuel blended with ethanol and methanol fuels. It was found that the oxygen-bond in the fuel properties of ethanol and methanol fuel plays a vital role in improve the combustion which and has beneficial influence in reduce the PM concentrations and in the same time enhances the rate oxidation of PM. For engine emissions, it can be concluded that the simultaneous reductions were registered of the NO\textsubscript{X} and PM emissions from the combustion of oxygenated-diesel blends compared to the diesel fuel with applied EGR under medium loads.

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