PM and NOX emissions amelioration from the combustion of diesel/ethanol-methanol blends applying exhaust gas recirculation (EGR)

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Abstract. The fuel injection timings, equivalence ratio (Ø) and exhaust gas recirculation are considered the most important parameters can effect on combustion process and lower exhaust emissions concentrations. The influence of 15% EGR technology and operating parameters (Ø and injection timing) on NOX emissions and particulate matter (PM) using oxygenated fuel (ethanol and methanol) blends were investigated in this experimental study. The results showed that the NOX emissions concentrations with increasing the equivalence ratio (Ø) and applied EGR for all fuels studied. Besides, the E10 and M10 decreased the PM concentrations compared to the diesel fuel under various equivalence ratios (Ø). The applied EGR increased the PM concentrations, but when combination of oxygenated fuels and EGR leading to the decrease in the PM formation. The NOX emissions concentrations decreased from the combined effect of EGR and oxygenated fuels by 16.8%, 22.91% and 29.5% from the combustion of diesel, M10 and E10, respectively, under various injection timings. It is indicated that NOX emissions decreased with retarded injection timings, while the PM decreased under advanced injection timings.

Keywords: Oxygenated fuel, particulate matter, soot particles, EGR rate, BTE, NOX emissions.

1. Introduction

The transportation sector produces dangerous environmental pollutants that contribute to the increase in global warming and environmental pollution, despite the significant international strictness in fuel efficiency standards [1]. It is expected that the consumption of fossil fuels will increase in the future until the year 2050 [2] due to the high demand on use fossil fuel in energy and transportation if successful alternatives are not found [3]. Successful alternatives are environmentally friendly and green alternative fuels or fuel-burning technologies with low emissions rates [4]. Electricity is the most promising energy, but unfortunately it will not constitute more than 2% of the amount of fuel needed to be consumed in 2050 [3]. The diesel engine is still the mainstay in the production of power for medium and heavy vehicles and will continue to do so for the foreseeable future. To reduce emissions of greenhouse pollutants, numerous studies have found that the importance of improving diesel fuel by adding other types of fuels such as
alcohol fuels and biodiesel [4, 5]. These additives increase the amount of oxygen inside the combustion chamber and reduce the presence of areas with a rich fuel mixture, thus reducing particulate emissions (PM emissions). Oxygenated fuels also have a lower calorific value than diesel, so less heat is released from its combustion, which reduces the emitted nitrogen oxide (NO\textsubscript{X}).

Strict emissions regulations have forced diesel engine manufacturers to use the sophisticated technologies which in turn reduce the emissions from exhaust gases, especially NO\textsubscript{X} and PM emissions [6]. Since the beginning of the seventies of the last century, exhaust gas recirculation (EGR) technology has been used to control NO\textsubscript{X} emissions [7]. The reduction of these pollutants with the use of EGR results from that this addition causes a dilution to the fuel/air charge inside the cylinder cycle, which reduces the combustion temperature resulting in lower NO\textsubscript{X} formation [8, 9]. However, an excessive increase in the applied EGR rates causes a pronounced decrease in the oxygen concentration leading to increase PM emission [10]. Therefore, the effect is considered positive on one hand and negative on the other hand, and its final effect is complex. Consequently, when determining the added EGR, a trade-off should be made between NO\textsubscript{X} emissions and PM [11, 12, 13].

Ethanol and methanol can be produced from fossil petroleum and can be produced from agricultural crops which it’s considered promising fuels. Ethanol and methanol have a high percentage of oxygen in their chemical structure. Therefore, both alcohol fuels are considered good substitutes to fuel in spark ignition engines because of their high octane number. However, they can be used with diesel appropriately to reduce emissions of PM and toxic gas pollutants [14, 15]. In comparison between oxygenates (ethanol and methanol) fuels and diesel fuel, it was noted that these alcohols have a higher fuel/air stoichiometric ratio and high amount of oxygen in their chemical composition, which they have higher H/C ratio and lower viscosity than to the diesel. All of these properties are useful in improving the combustion of fuel inside the cylinder cycle and reducing the levels of pollutants emitted [16], [17]. For example, the oxygen content in alcohols causes a better reaction with the diesel spray, which results in a significant reduction in the concentrations of PM [18]. The latent heat of vaporization with high values of methanol and ethanol cause cooling of the fuel-air charge inside the combustion chamber [19], which leads to a decrease in NO\textsubscript{X} concentration. Therefore, the use of both of these alcohols fuels can contribute to solving the problem of PM – NO\textsubscript{X} trade-off in compression ignition engines [19, 0].

The objective of the current study is to evaluate the effect of some operational variables of a compression ignition engine running on diesel-ethanol and diesel-methanol blends on the NO\textsubscript{X} and PM pollutants emitted. The equivalence ratio of the incoming charge with changing the injection timing were tested to achieve the best operating conditions that reduce NO\textsubscript{X} and PM emissions together. The experiments were carried out using Iraqi diesel available in local fuel stations, which is characterized by containing a high percentage of sulphur. Several studies confirmed the negative role of the presence of sulphur in diesel in increasing PM formation [21, 22].

2. Experimental setup and procedure

2.1. Fuel blends

The ethanol blends (10% of ethanol and 90% of diesel fuel) and methanol blends (10% of methanol and 90% of diesel fuel) were chosen according to the previous researchers to produce various exhaust concentrations of NO\textsubscript{X} emissions and particulate matter (PM). At the same time of the experimental tests, the preparation of ethanol blends (E10) and methanol blends (M10) were done to avoid any fuel separation before and after the tests. Table 1 presented the main properties of diesel fuel, E10 and M10 and most of these properties were measured and calculated. The surface tension, liquid viscosity and oil density were
measured at 20 °C. Three times at least were 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 were 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_{10.4}H_{18.7} | C_{2}H_{5}OH | CH_{3}OH |
| Mole weight (g)                | 148.3    | 46.1      | 32       |
| Density (g/cm³ 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 equipment.

During this study, the diesel engine used is direct injection, four strokes, 4 cylinders equipped with EGR as shown in Figure 1. Table 2 listed the main specifications of the diesel engine. The engine speed measured by a tacho-generator that connected with hydraulic dynamometer. The dynamometer was used to adjust engine load and speed. The fuel consumption for a given period was measured by the level fuel decrease in a graduated container. The volumetric flow rate of the intake air was measured by an orifice plate. K-type thermocouples were used to measure the exhaust gas temperature which connected in different location in the exhaust manifold [3, 4]. The condensate separating filter was used to separate the exhaust gasses from the water and then they conveyed in the measuring cell. Cooling water temperatures was measured using calibrated thermocouples at the both of inlet and outlet of the engine. External EGR technology was 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 was 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       | 4 cyl., 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 |

Figure 1. Schematic of research diesel engine and tools.

The emissions analyzer (Multigas mode 4880) was used measure the NO\textsubscript{X} emissions concentrations. In addition, the emissions of CO\textsubscript{2}, CO, O\textsubscript{2} content and HC were also measured using the emissions analyser. Small a probe linked with the engine exhaust pipe to collect the exhaust gasses. Furthermore, the samples of PM were obtained at the end of the tailpipe by exposing filter material to a diesel exhaust gas. A scanning electron microscope was used to exam these filters. Whatmann-glass micro-filters were used to collect the PM emitted from diesel engine. Before and after test, filters samples were weighted. The following equation was used to determine the PM concentrations in the exhaust:
Where, the concentration of PM is µg/m³, \( w_1 \) and \( w_2 \) are represent the weight of filter sample before and after test (g) and \( v_t \) represent the total trailed air volume (m³). The following equation is used to calculate the \( v_t \):

\[
PM \text{ in } (\mu g/m^3) = \frac{w_2 - w_1}{v_t} \times 10^6
\]

Where, \( Q_t \) and \( t \) represent the final air flow rate (m³/sec) and pattern time in (min), respectively.

### 2.3 Test procedure

To evaluate the amount of PM and NOX emitted from engine, applied EGR and two oxygenated fuels were used in this study. About 30 min the engine was operating to warm the engine and reach the 80 °C of engine cooling water temperature. The ratio selected of EGR was 15% which represented the medium ration of the EGR used in the literatures. The first test of the engine was diesel fuel, and then with 10% methanol blends (M10), and followed with E10 under engine speed of 1500 rpm. These fuels were tested under variable equivalence ratio (\( \varnothing \)) and fixed the injection timing at 38 ° BTDC. In addition, these fuels were also tested under injection timing varied from 20 to 45 ° BTDC with constant equivalence ratio (\( \varnothing = 0.56 \)).

### 3. Results and discussion

It is reported that the initial pressure and temperature, fuel properties, injection pressure and the combustion chamber shape determine the combustion process and engine emissions [3, 5, 6]. The equivalence ratio (\( \varnothing \)) also considered the important factor that decides whether an engine’s combustion process. The \( \varnothing \) can be also contributing to decrease the engine emissions [7]. The effect of various equivalence ratios on NOX concentrations is shown in Figure 2 under 44 kN/m² of engine load and 38 ° BTDC of injection timing. It can be noticed that the equivalence ratio decreased NOX emissions with applied EGR for all fuels tested as presented in Figure 2. Shorten ignition delay can be occurred due to decreasing the equivalence ratio [8].

![Figure 2](image_url)

**Figure 2.** Effect of equivalence ratio (\( \varnothing \)) and EGR on NOX emissions concentrations for diesel and ethanol/methanol blends.
The effect of various equivalence ratios on PM concentrations emitted from diesel engine is shown in Figure 3. It is clearly that the PM concentrations decreased from the combustion of E10 and M10 blends compared to the diesel fuel. These results are in agreement with previous work by Fayad et al. [9]. Furthermore, M10 and E10 decreased the PM concentrations by 17.3% and 21.68%, respectively. In contrast, higher PM concentrations were found from diesel combustion under with and without EGR (Figure 3). The increasing the equivalence ratio leads to increase the PM concentrations. Applied EGR reduce the oxygen in the combustion cycle which result in an increase the in the PM formation and decrease the NO\textsubscript{X} emissions [10]. The combination of 15% EGR and oxygenated blends contributed to decrease the NO\textsubscript{X} and PM emissions.

![Figure 3](image-url)  
**Figure 3.** Effect of equivalence ratio (\(\Phi\)) and EGR on PM concentrations for diesel and ethanol/methanol blends.

Figure 4 shows the effect of various fuel injection timings and fuel on NO\textsubscript{X} emissions at 15% EGR and fixed equivalence ratio. It can be observed that the retarding fuel injection timing is a powerful procedure for decreasing the NO\textsubscript{X} concentrations. The change in the location of the start of combustion and an increase in ignition delay resulted from the existence of diluents such as CO\textsubscript{2} and H\textsubscript{2}O in the exhaust [11, 12]. Therefore, the combustion process shifted toward the expansion stroke. Thus, lower combustion products exposed to high-temperature conditions and leading to lower level of NO\textsubscript{X} emissions [13, 14]. According to the Figure 4, the cylinder pressure decreased with applied EGR compared to the without EGR. The combined effect of EGR and oxygenated fuels caused to decrease in the NO\textsubscript{X} emissions concentrations by 16.8%, 22.91% and 29.5% from the combustion of diesel, M10 and E10, respectively.
The effects of EGR and fuels on PM concentrations under various fuel injection timings are shown in Figure 5. The results showed that the advanced injection timing decreases the PM concentrations. This is due to the increasing the oxygen and available time for oxidation. The maximum heat release rate resulted from the applied EGR [15, 16]. Another reason could be due to the lower-aromatic and lower-sulphur from E10 and M10 blends produces less particulate matter emission compared to the Iraqi diesel fuel that content high sulphur particles about 10000 ppm.

Figure 6 and Figure 7 show the effect of EGR and oxygenated fuel on NOX emissions and PM concentrations under different engine loads. The results indicated that the NOX emissions decreased with applied EGR for...
various engine loads and fuels tested. Furthermore, it can be seen that the NO\textsubscript{X} concentrations are more decreased from the oxygenated fuel compared to the diesel. For all fuels, the low condition of engine load produced lower level of NO\textsubscript{X} emissions compared to the other conditions of engine loads [17, 18]. The lower concentrations of NO\textsubscript{X} emissions were from the combustion of M10 compared to the E10 and diesel fuel under various engine loads and applied EGR (Figure 7). On the other hand, the PM concentrations decreased with applied EGR from the combustion of M10 and E10 compared to the diesel fuel for various loads. In addition, the PM concentrations decreased with increasing the engine loads due to the high combustion temperatures for PM oxidation inside the combustion cycle [19-21].

**Figure 6:** Effect of various engine loads and EGR on NO\textsubscript{X} emissions concentrations for diesel and ethanol/methanol blends

**Figure 7:** Effect of various engine loads and EGR on PM concentrations for diesel and ethanol/methanol blends
4. Conclusions

The influence of EGR ratio and oxygenated (E10 and M10) on the NOX emissions and PM concentrations under various equivalence ratio (Ø) and injection timing was studied. The present study showed that the NOX emissions and PM decreased from the combination of EGR and oxygenated fuels. In addition, it was found that the NOX emissions decreased with increasing the equivalence ratio (Ø) for all fuels studied, but slightly higher reduction in case of E10 and M10. It was observed that the PM concentrations decreased with medium equivalence ratio (Ø), while the PM increased with increasing the equivalence ratio (Ø) for diesel, E10 and M10, but the reduction of PM was clearly with oxygenated fuels. It can be concluded that the PM concentrations decreased under advanced injection timing from the combustion of oxygenated fuels compared to the diesel fuel. Furthermore, retarded fuel injection timings and applied EGR decrease the NOX emissions concentrations from the E10 and M10 more that to the diesel fuel under various engine loads.

NOMENCLATURE

BTDC = Before top dead centre
CO = carbon monoxide
E10 = Ethanol 10 %, and Diesel 90%
EGR = exhaust gas recirculation
HCS = hydrocarbons
THC = Total hydrocarbon
PM = particulate matter
Ø = Equivalence ratio

References:

1. Chaichan, M.T., Kazem, H.A., Abed, T.A., Environment, Development and Sustainability, 2018. 20(2): p. 589-603.
2. Dhahad, H.A., Chaichan, M.T., Thermal Science and Engineering Progress, 2020: p. 100535.
3. Fayad, M.A., Journal of Engineering Research, 2021. 9(2): p. 296-307.
4. Jung, Y., Hwang, J., Bae, C., Fuel, 2016. 165: p. 413-424.
5. Geng, L., Li, S., Xiao, Y., Xie, Y., Chen, H., Chen, X., Journal of the Energy Institute, 2020. 93(6): p. 2148-2162.
6. Dhahad, H.A., Fayad, M.A., Chaichan, M.T., Jaber, A.A., Megaritis, T., Fuel, 2021. 306: p. 121589.
7. Benajes, J., Novella, R., Garcia, A., Domenech, V., Durrett, R., SAE International Journal of Engines, 2011. 4(2): p. 2590-2602.
8. Dhahad, H.A., Chaichan, M.T., Megaritis, T., Energy, 2019.
9. Fayad, M.A., AL-Salihi, H.A., Dhahad, H.A., Mohammed, F.M., AL-Ogidi, B.R., Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 2021: p. 1-15.
10. Liang, J., Zhang, Q., Chen, Z., Zheng, Z., Yang, C., Ma, Q., Fuel, 2021. 298: p. 120843.
11. Zhou, Q., Wang, Y., Wang, X., Bai, Y., Journal of Environmental Sciences, 2022. 112: p. 218-230.
12. Fayad, M.A., Dhahad, H.A., Fuel, 2021. 286: p. 119363.
13. Zhang, Z., Balasubramanian, R., Applied Energy, 2016. 163: p. 71-80.
14. García, A., Gil, A., Monsalve-Serrano, J., Sari, R.L., Fuel, 2020. 275: p. 117898.
15. Fayad, M.A., Thermal Science and Engineering Progress, 2020: p. 100621.
16. Duan, X., Xu, Z., Sun, X., Deng, B., Liu, J., Energy, 2021. 231: p. 121069.
17. Dhahad, H.A., Fayad, M.A., Fuel, 2020. 279: p. 118384.
18. Varatharajan, K., Cheralathan, M., Fuel processing technology, 2013. 106: p. 526-532.
19. Attia, A.M.A., Kulchitskiy, A.R., Nour, M., El-Seesy, A.I., Nada, S.A., Energy, 2021: p. 121951.
20. Zhu, G., Chen, T., Hu, Y., Ma, L., Chen, R., Lv, H., Wang, Y., Liang, J., Li, X., Yan, C., Nano Energy, 2017. 33: p. 229-237.
21. Fayad, M.A., Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 2019: p. 1-11.