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GEM Ternary Blends: Testing emitted NOx-smoke trading off when EGR is applied to the engine

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Abstract

This paper presents a multi cylinder spark ignition engine fuelled with a three-component, (ternary) fuel consisted of gasoline, bioethanol and methanol. The ratio of these components (9.7:1) is selected to control the air-to-fuel ratio. This ratio is the same as the equivalence ratio of conventional alcohol E85. This work is a continuation of a previous project that aims to establish an alternative fuel for Iraqi gasoline. Iraqi gasoline is characterised with its high sulphur and lead contents and low octane number. This paper also discusses the addition of hot and cool recirculated exhaust gas (EGR) to suction manifold on the resulting NOx-smoke tradeoff.

Results indicate that the ternary blend offers relatively lower NOx and larger reduction in smoke when used alone than that with Iraqi gasoline. EGR addition to GEM blend reduces the NOx concentration remarkably and the smoke opacity rates at a lesser extent than those with gasoline and E85 blend. Cool EGR introduces good NOx-smoke tradeoff at the tested cases. Furthermore, the addition of hot and cooled EGR reduces the NOx concentrations by approximately 17.83% and 21.42% at variable speeds and by 44.9% and 62.57% at variable torques compared with those of Iraqi gasoline. Correspondingly, these additions also reduce the smoke opacity with about 22.24% and 14.83% at variable engine speeds and 21.44% and 14.11% at variable engine torques.

Keywords: Iraqi gasoline, Sulphur, Lead, Ternary blends, GEM, NOx-smoke tradeoff

INTRODUCTION

Iraqi gasoline is characterised with its low octane number (ON), which is below 83, and its high sulphur and lead contents [1]. Given the hazards related to lead and sulphur and the compounds resulting from gasoline combustion, an alternative to this gasoline should be determined.

The presence of sulphur in fuel contributes to the increased particulate matter (PM) emissions caused by combustion because the sulphur molecules in the fuel oxidise to sulphur dioxide (SO_2). Although the bulk of SO_x is SO_2, approximately 5% of the oxides are SO_3; when water is available, sulphuric acid is formed [2]. Sulphur in fuel is converted into sulphate, in which particles bind to form the particles; this process consumes 1%–3% sulphur in fuel [3, 4]. The interaction of sulphates, sulphuric acid, water vapour and hydrocarbons with relatively low vapour pressure in the tail pipe of the exhaust will condense on the soot when exhaust gases are cooled, thereby causing considerable growth in foaming PM [5]. The amount of sulphur in fuel is responsible for the mass of hydrocarbons, including hydrogenated hydrocarbons. The interaction of sulphuric acid on the soot surface with the hydrocarbon compound in the exhaust causes the formation of heavy hydrocarbons; this reaction is called the washing effect [6]. Reducing the sulphur content of fuel to the minimum possible limits will reduce the emitted particles; hence, three-component fuel with Iraqi gasoline can be used to reduce sulphur content to the maximum extent.

Three-component (ternary) blend of gasoline, bioethanol and methanol was used to fuel multi cylinder spark ignition engines (SIE). Results are promising, and the high useful compression ratio is increased from 8 in conventional Iraqi gasoline to 9.5 in ternary fuel case [7]. The use of ternary blends offers practical development step to reduce the dependence on fossil gasoline [8].

E85 fuel can be replaced with a ternary mixture consisting of gasoline, ethanol and methanol. Replacement is performed by selecting the volume part of each component separately so that the correct equivalence ratio of the resulting fuel is equal to that of the E85 fuel. Ternary blend fuels, which range from E85 to M56 (Figure 1), were created by Turner (2012) [9]. The air-to-fuel ratio (AFR) of E85 is 9.7:1, and the whole family of equivalents displays the same stoichiometric AFR [10].

In previous work, G37 E20 M43 was evaluated as an alternative to Iraqi gasoline [7]. In this blend, a part of gasoline is replaced with bioethanol and methanol. Adding ethanol or methanol is a good approach from an energy security viewpoint. Gasoline replacement with methanol, which is a renewable fuel, is beneficial from a carbon intensity perspective. The tested blend presents near-identical low heating value; this blend also practically presents a higher ON than that of conventional Iraqi gasoline. Turner indicated that the cost of a mixture of the three fuels, which contain a high proportion of methanol, may be less than that of gasoline on a cost-per-unit basis [10]. However, this fuel may also present defects, and the subject needs further research and testing [11, 12].

Several GEM characteristics, including phase separation, were reported later [8]. Alcohol fuels are highly aggressive towards certain commercial materials used in the construction of engine fuel systems [13, 14]. Chaichan reported that HC and CO levels are reduced by 25.16% and 30.5%, respectively, when GEM is used. The smoke opacity reduction is 46.49%, and the CO_2 and NOx levels are reduced by 5% and 1.75%, respectively [15].

Recirculated exhaust gas (EGR) has long been used as parameter to reduce or eliminate emitted NOx. The introduction of EGR inside the intake manifold to replace a part of oxygen with water vapour and carbon dioxide, which causes dilution of the incoming fresh charge, is an effective approach to reduce the engine's emitted NOx [16, 17]. Nevertheless, NOx is reduced on the expense of the engine thermal efficiency, which consequently decreases; high amount of PM is also emitted, and this condition is expressed as the NOx-PM tradeoff [18]. Turner (2018) indicated that at stoichiometric operation of a GEM blend, EGR causes a substantial reduction in soot mass emissions and in solid particle number emissions for a lesser extent [19].

Chaichan (2016) demonstrated that the addition of cool EGR to the suction manifold causes a decrease in nitrogen oxides and an increase in emitted smoke [16]. Many researchers who have investigated the use of alcohol mixed with gasoline in the SIE have explained that many challenges should be addressed in terms of the soot-nitrogen oxide tradeoff [20-25].

In the present study, the tradeoff between nitrogen oxides and PM will be studied by using a ternary mixture of gasoline, bioethanol and methanol as fuel. Experiments will be conducted on a four-stroke gasoline engine, which runs at variable speeds, loads and spark timing. All tests will be conducted without any modification to the engine, with the addition of 15% of the hot and cool EGR. This work aims to introduce an inexpensive, suitable and environment-friendly alternative fuel to the Iraqi gasoline.

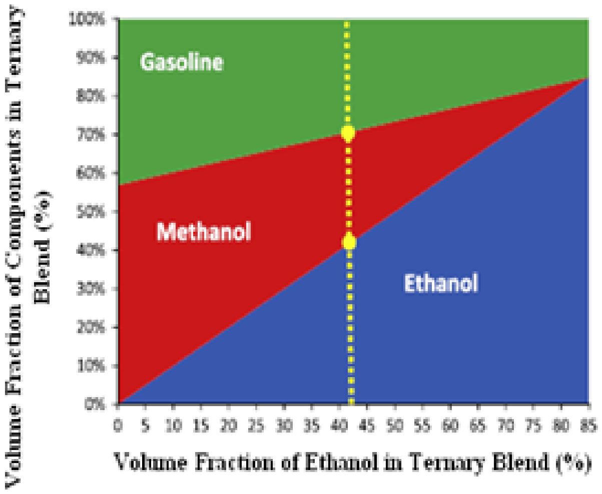

Figure 1. Isostoichiometric GEM blends equivalent to conventional E85 [10]

EXPERIMENTAL SETUP

Engine and accessories

Four-cylinder SIE type Mercedes-Benz was used. The engine torque was measured by means of a hydraulic dynamometer coupled to the engine. Table 1 introduces the primary engine specifications.

Table 1. Specifications of the engine used in the tests

Engine model	Mercedes-Benz
Production year	1992
Cylinder number and type	4-cylinder-inline
The compression ratio	9.60:1
Fuel type	Gasoline
Stroke number	four-strokes
Displacement	2 liters
The piston stroke length	78.70 mm
the cylinder diameter	89.90 mm
Cooling	Water
Engine maximum torque	190 Nm at 4000 rpm
The maximum power delivered by the engine	100 kW at 5500 rpm

Exhaust gas recirculation system

Part of the exhaust gas emitted from the engine was recirculated, and its temperature was controlled using the Prodet EGR assembly system. This assembly contains a heat exchanger consisting of two tubes with thermocouples installed on the tubes to measure the working fluid temperatures. The fluids' flow direction (parallel or counter flow) can be controlled by arranging the inlet and outlet of each fluid. In the present study, the internal tube was used for the EGR, and the external tube was used for cooling water. EGR (%) is defined as the percentage of mass of the EGR (m_{EGR}) to the total intake mixture (m_a) [24].

$$\%EGR = \frac{m_a - m_{a+EGR}}{m_a}, \qquad (1)$$

where:

m_a: the mass of air entering the engine without EGR, and

m_{a+EGR}: the mass of air entering the engine with EGR.

Exhaust gas temperatures were measured using calibrated thermocouples (type K) at the entrance of the exhaust tube.

NOx analyzer

The HG-550 type gas analyser was used to measure the NOx levels. The analyser calibrations readings were produced by Hephzibah Co. Ltd. as a factory inspection sheet at November 11, 2016 because this device was used for the first time.

Smoke opacity Analyzer

The smoke opacity of the emitted exhaust gas was measured using a MOD SMOKY smoke-meter type. This smoke meter device contains an opacity measuring meter, control panel and probe. The device uses the optic absorption property of the smoke. The measuring process starts by inserting the probe into a straight section of the exhaust pipe; if not feasible, the exhaust pipe must be enlarged to confirm the ideal installation. The meter is equipped with a halogen lamp to provide a bright light. The optical sensor generates an electric signal where it is electrically adapted and processed by the microprocessor. Result is displayed as absorption % vol. This device was calibrated in the Central Organization for Measuring and Quality Control, Baghdad-Iraq.

Materials

Iraqi gasoline with two variable ONs (82 and 77), which was supplied by Iraqi Al-Doura Refinery, was used. This gasoline was characterised with its high content of lead compounds and low ON, and its properties were measured in the Fuel Laboratory in Al-Doura Refinery. Gasoline with ON of 82 was utilised as a reference fuel for comparison because it is the conventional fuel in Iraq. Gasoline with ON of 77 was used in the ternary blend because it is unleaded fuel. Bioethanol (99.7%) from Iraqi drink named Aaraq, which was distilled for several times to purify it from any residual, was used. Methanol was characterised with its phase separation: it can separate from the solution when blended with gasoline in the absence of any dedicated cosolvent. Ethanol addition can reduce the separation trend of methanol. Methanol was mixed first with ethanol and subsequently blended with gasoline. **Table 2** presents the typical properties of the used materials.

Table 2. Specifications of gasoline, ethanol and methanol [11]

Fuel component	Gasoline	Ethanol	Methanol
Formula	Various	C_2H_5OH	CH_3OH
Stoichiometric AFR	14.18	8.96	6.44
Density (kg/l)	0.732	0.789	0.791
LHV on mass basis (MJ/kg)	43.11	26.80	19.90
LHV on volume basis (MJ/l)	31.51	21.15	15.75
MON (to ASTM D2700)	85.0	89.7	88.6
RON (to ASTM D2699)	95.3	108.6	108.7
Sensitivity	10.3	18.9	20.1
Carbon intensity (gCO_2/l)	2297.2	1509.7	1088.0

Figure 1 shows that E85 contains no methanol. The E85 binary equivalent consisting of gasoline and methanol mixture occurs at M56. Turner described the first blend (G15 E85 M0), the second blend (G44 E0 M56) and the blend equivalent to E85 or the third blend (G29.5 E42.5 M28). In recent study, ethanol is possibly limited due to the use of nonflex-engines, which cannot resist its aggressive effects. Moreover, if the supplied bioethanol is constrained for any reason, then the feed stock supply is reduced, or legislations should be established to avoid the use of ethanol due to its interruption with the food chain. The limited amount of ethanol can be replaced with methanol in a ternary blend. The blend used in this study was G37 E20 M43, in which gasoline with an ON of 77was used. All these isostoichiometric ternary blends present embrace correspondent volumetric energy content (depending on the densities and masses of the components). The right- and left-hand edges demonstrate a stoichiometric AFR of 9.7:1 (i.e. E85 and M56, respectively). **Table 3** illustrates the compositions of E85 and the ternary blend used in this study and their properties. All these properties were measured in Al-Doura Refinery and Science Collage/Baghdad University Laboratories.

Table 3. Compositions of the tested ternary blends fuels and their properties

Fuel component	Gasoline	E85	G37 E20 M43
Stoichiometric AFR	14.97	9.7	9.71
Density (kg/l)	0.732	0.780	0.768
LHV- on mass basis (MJ/kg)	43.12	29.09	29.56
LHV- on volume basis (MJ/l)	31.52	22.71	22.71
Carbon intensity (gCO_2/l)	2297.3	1627.9	1623.9
Carbon Intensity (gCO_2/MJ)	72.88	71.69	71.49
RON (to ASTM D2699)	82	97.4	96.4
MON (to ASTM D2700)	75.0	85.7	85.3
Sensitivity	10.3	17.7	17.1

Error analysis

In practical investigations, measurement accuracy becomes an important factor in evaluating the validity of results. Error sources are defined by calibrating the measuring instruments used. To determine uncertainty in the current study, all the engine and its accessorial measuring devices were calibrated. Table 4 provides a list of the calibration accuracies of the measuring device used. The system uncertainty can be evaluated by the following equation:

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

where:

e_R: results uncertainty,

R: function consisting of variables or R=R (V_1, V_2, …, V_n) and

e_i: variable uncertainty range.

The uncertainty for the current study is as follows:

$$e_R = [(0.97)^2 + (0.93)^2 + (0.78)^2 + (0.89)^2 + (0.96)^2]^{0.5} = 4.1279.$$

The uncertainty equation elucidated that the current study uncertainty is less than 5% for all measurements. To reduce the errors of randomised trials in the experiments and confirm the repeatability, each experiment was repeated three times, and the average values of the results of these experiments were obtained.

Table 4. Measurement method and calibration accuracy for the current study

Device	Accuracy
Tachometer (Engine speed)	±0.97%
Dynamometer torque measurement	±0.93%
NOx levels (ppm)	±0.78%
Smoke opacity (% vol.)	±0.89%
EGR flow rate measurement	±0.96

Tests Procedure

In the experiments, the Mercedes-Benz engine was fuelled with GEM blend. Hot and cool EGR with a ratio of 10% was also added to the air intake. The NOx emitted by the engine throughout the experiment and smoke opacity were measured and analysed at each tested engine's speed and load. The experiments were divided into sets as follows:

1. Constant load and spark ignition timing with variable speed;
2. Constant speed and spark ignition timing with variable load; and
3. Constant load and speed with variable spark ignition timing.

RESULTS and DISCUSSIONS

The effects of GEM blend and EGR on PM-NOx tradeoff were investigated in a multi cylinder SI engine with a compression ratio of 9.6. The EGR ratio was fixed at 10%, focusing on smoke-NOx tradeoff. NOx formation is a temperature-dependent process. NOx formation starts at temperatures higher than 1900 K and remains during cooling because the reverse reaction is considerably slow. Moreover, the soot particles formed in locally rich areas are composed of heterogeneous mixture in the combustion chamber; these particles contribute significantly to the level of particle concentrations emitted from the engine. High temperatures on the front of a flame sheath limit the soot formation, but these temperatures help in the formation of nitrogen oxides. Therefore, reducing the combustion temperature (by adding EGR) to reduce the level of NOx emissions causes an increased emission of smoke. This phenomenon is called the NOx-PM tradeoff.

Figure 2 presents the effects of engine speed on emitted NOx concentrations for the studied cases at medium load. Medium torques were used because the Iraqi gasoline with ON of 82 will knock at high torques. Gasoline and GEM blend emitting NOx approach each other. Although GEM possesses higher oxygen content due to oxygenation, it displays lower heating value than that of gasoline. EGR application reduces NOx concentrations remarkably, but cool EGR is highly effective in this area. Hot EGR increases charge temperature and consequently increases thermal efficiency, whereas cool EGR reduces them. The reduction in NOx concentration of GEM, hot EGR and cool EGR is 0.7%, 17.83% and 21.42%, respectively, compared with that of Iraqi conventional gasoline.

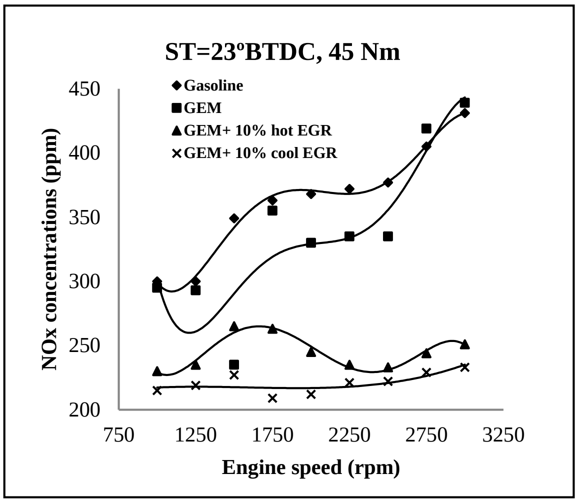

Figure 2. Effect of variable engine speed on emitted NOx concentrations for the tested fuels

The high oxygen content of the GEM blend causes the higher reduction in soot opacity than that of gasoline, as shown in **Fig. 3**. EGR addition increases the smoke opacity, which remains lower than that emitted by gasoline due to oxygenation effect. The reduction in smoke opacity is 43.49%, 22.24% and 14.83% for GEM, hot EGR, and cool EGR, respectively, compared with that of Iraqi conventional gasoline. The main drawback of the EGR method is the increased smoke emission. In all the test conditions, an increase of their value is observed with EGR addition due to the reduced AFR. Oxygen concentration is reduced, thereby affecting the oxidation process. The figure shows differences between hot and cooled EGR effects. When running with cooled EGR, smoke values are reduced compared with that of the hot EGR case. High EGR temperatures addition will ameliorate oxidation, which can consequently reduce the smoke opacity. With increased EGR temperature, the intake charge temperature increases, which compensates the negative effect of CO_2 and H_2O dissociations. Nevertheless, this increase cannot compensate for the lack of O_2 availability, which is compensated with oxygenated alcohols forming GEM.

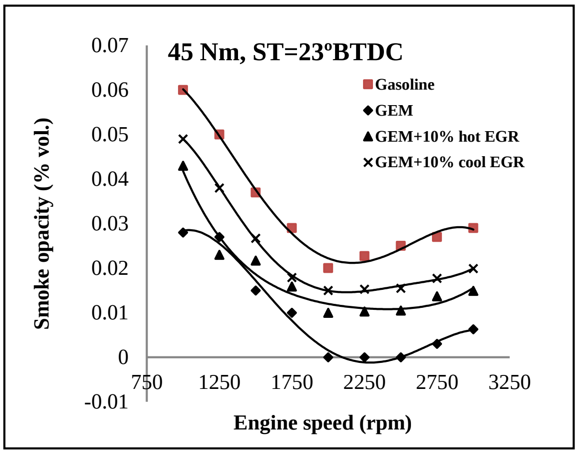

Figure 3. Effect of variable engine speed on smoke opacity for the tested fuels

Figure 4 illustrates the NOx-smoke tradeoff for the tested cases at variable engine speeds. Application of either hot or cool EGR shifts the curves to left, with low NOx and moderate smoke opacity. This result indicated that this technique is efficient and acceptable. EGR addition causes dilution effect, which decreases the combustion temperatures and oxygen concentrations at intake manifold. This effect will reduce NOx concentration, but its final effect on smoke is complex. This tradeoff between NOx and smoke is the result of contradictory phenomena. Practical EGR systems often suffer from unequal distribution of air in combustion chamber and among cylinders. This phenomenon has been studied by various researchers [27, 28]. Many studies have proposed to improve the design of inlet manifolds or air-EGR connections and the EGR distribution wither in combustion chamber or among cylinders [29, 30].

Increased engine torques increase the combustion chamber temperatures, which results in increased NOx emission, as demonstrated in **Fig. 5**. The NOx concentrations of gasoline and GEM blend converge, and the emitted NOx in EGR cases diverges from them remarkably. The reduction in NOx concentrations are 5.5%, 44.9% and 62.57% for GEM, hot EGR and cool EGR, respectively, compared with that of Iraqi conventional gasoline.

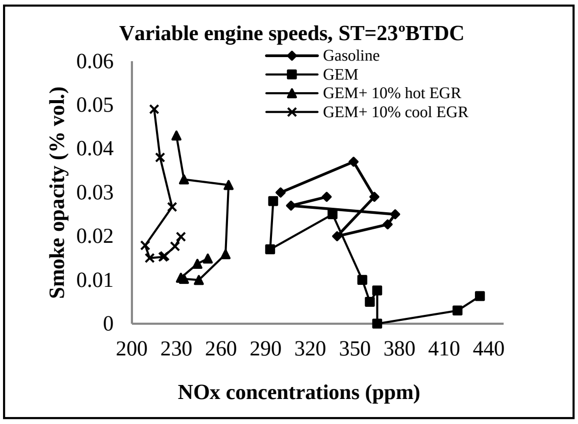

Figure 4. Effect of variable engine speed on NOx-smoke tradeoff for the tested fuels

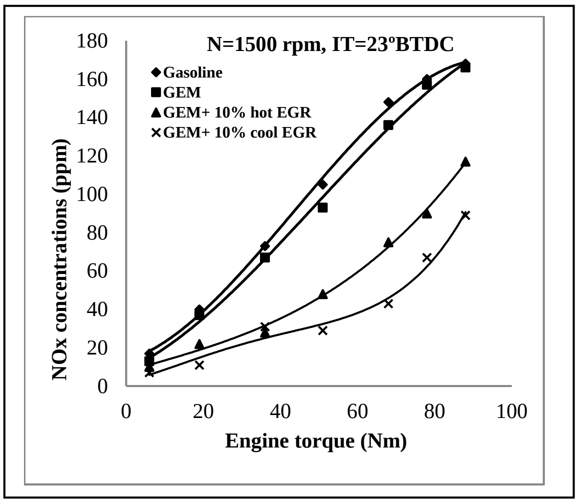

Figure 5. Effect of variable engine torques on NOx concentrations for the tested fuels

Increased engine torques, which increased the combustion chamber temperatures, also reduced the smoke opacity, as shown in **Fig. 6**. The smoke opacity of GEM blend diverges highly from the emitted concentrations of gasoline, depending on oxygen molecules in its formation. Cool EGR emits higher smoke amount than that of hot EGR due to its influence in reducing combustion chamber temperatures. The reductions in smoke opacity at variable engine torques were 45.64%, 21.44% and 14.11% for GEM, hot EGR and cool EGR, respectively, compared with that of Iraqi conventional gasoline. When GEM is formed from unleaded gasoline and alcoholic oxygenates, the oxygen in the intake charge is reduced due to EGR dilution effect. This reduction will be compensated with the high oxygen content. The reduction in temperature caused by EGR will be compensated with the high flame velocity due to the high methanol content of the blend. Notably, GEM contains less sulphur (approximately 63%) than that of conventional gasoline. This reduction exerts considerable influence on smoke opacity rates.

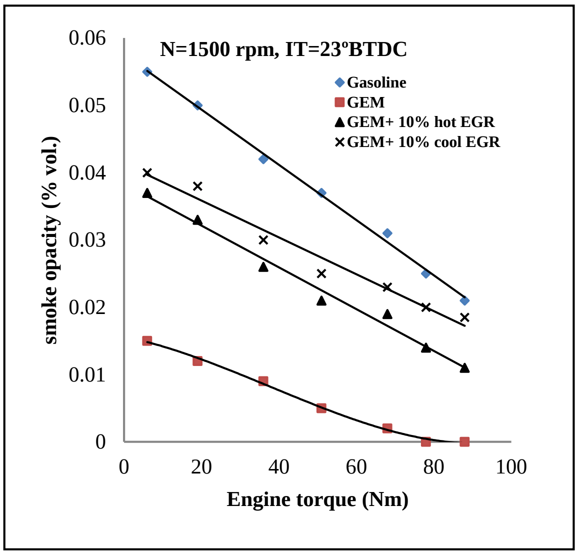

Figure 6. Effect of variable engine torques on smoke opacity for the tested fuels

Figure 7 displays the NOx-smoke tradeoff for the tested cases at variable engine torques. Cool EGR shows a narrow range of NOx, but GEM presents the lowest smoke opacity. Unfortunately, this substantial tradeoff between NOx-smoke causes the reduction in NOx, which results in negative effect on smoke. However, as a consequence, NOx-smoke tradeoff are better in the cooled EGR case than those in hot EGR.

Retarding spark timing is considered an efficient method to reduce NOx concentrations. EGR addition to retarded ST results in large NOx reduction, as shown in **Fig. 8**. Cool EGR application causes high reduction in NOx for the whole range of tested spark timings. Under considerably advanced ST (27°BTDC), GEM causes higher NOx concentrations than that of gasoline, depending on high methanol laminar burning velocity. Consequently, the blend velocity increases.

Decreased spark timing also increases the smoke opacity, whereas advanced ST reduces it, as depicted in **Fig. 9**. GEM blend still produces low smoke opacity, depending on its high oxygen content. Retarding ST indicates that a part of combustion will be initiated at expansion stroke with less combustion temperatures. Advancing ST increases the combustion chamber pressure and temperature and lowers the smoke rates.

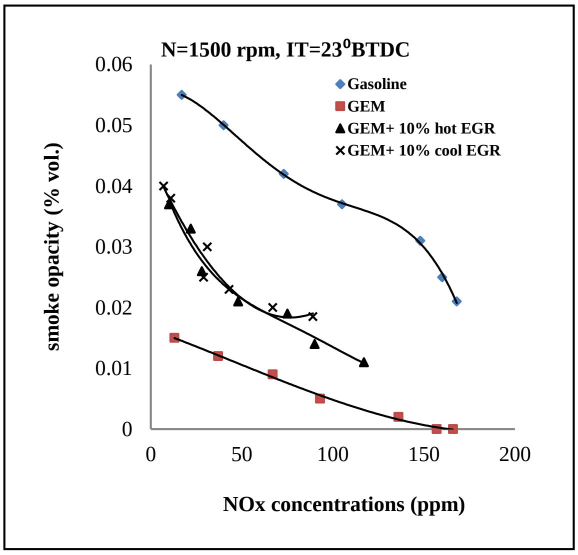

Figure 7. Effect of variable engine torques on NOx-smoke opacity for the tested fuels

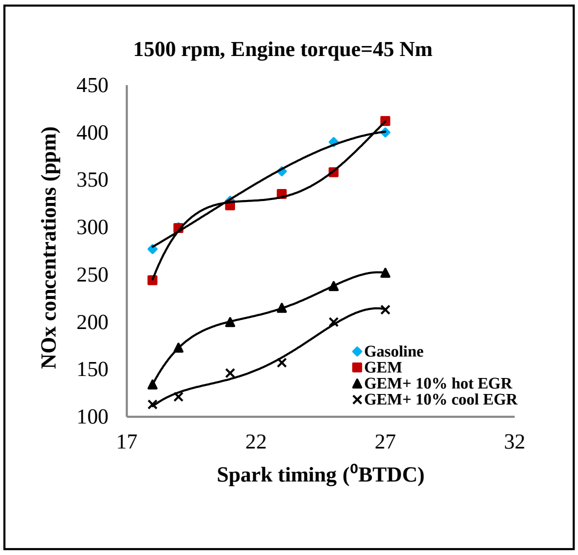

Figure 8. Effect of variable engine spark timing on NOx concentrations for the tested fuels

Figure 10 demonstrates the NOx-smoke tradeoff at variable engine spark timing. Cool EGR results in low NOx and smoke opacity. In this study, the NOx-smoke tradeoff among variable tests was compared. A reduced emission causes an increase in other emissions. Therefore, the tradeoff remains unimproved. In **Fig. 10**, the NOx-smoke tradeoff at moderate torques suggests a hyperbolic behaviour, i.e., at the peak smoke and NOx points, the smoke and NOx levels are significantly changed with EGR.

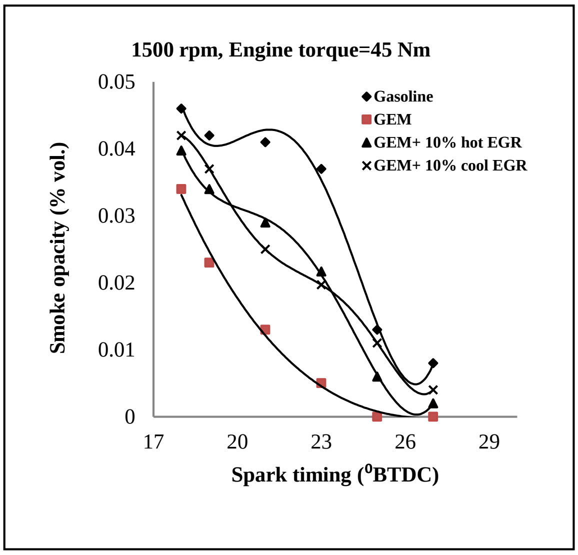

Figure 9. Effect of variable engine spark timing on smoke opacity for the tested fuels

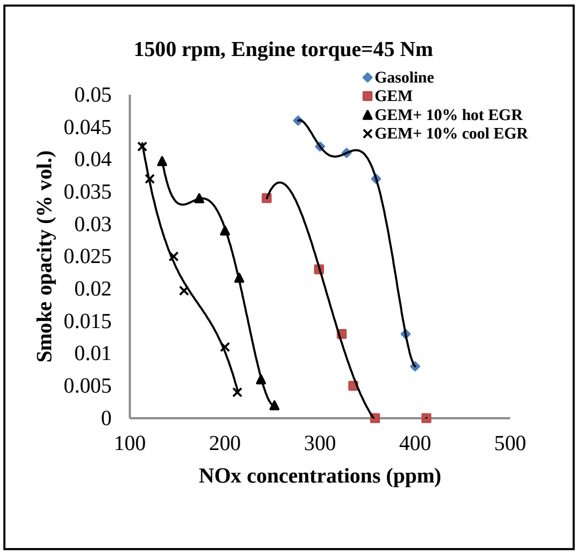

Figure 10. Effect of variable engine spark timing on NOx-smoke opacity tradeoff for the tested fuels

CONCLUSIONS

Ternary blend (G37 E20 M43) is evaluated in terms of NOx-smoke tradeoff when hot and cooled EGR are added to intake manifold with fixed percentage (10%). The tests indicated that ternary blends offer relatively lower NOx and larger smoke reduction when used alone than those of Iraqi gasoline. The NOx concentration is also reduced by 0.7% and 5.5% at variable engine speeds and torques, respectively. Furthermore, the smoke opacity is reduced with about 43.49% and 45.64% at variable engine speeds and torques, respectively. Addition of EGR to GEM blend reduces the NOx concentration remarkably and the smoke opacity rates at a lesser extent. Cool EGR introduces improved NOx-smoke tradeoff at the tested cases. Results suggested that the addition of hot and cooled EGR reduces the NOx concentrations by about 17.83%

and 21.42% at variable speeds and 44.9% and 62.57% at variable torques, respectively, compared with those of Iraqi gasoline. Correspondingly, these additions reduce the smoke opacity by approximately 22.24% and 14.83% at variable engine speeds and 21.44% and 14.11% at variable engine torques, respectively.

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