Experimental Investigation of the Effect of Exhausts Gas Recirculation (EGR) On Nox-Smoke Trade-Off for SIE Fueled With Blends of Gasoline/Bioethanol

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Abstract: *Iraqi bio-ethanol can be used as an alternative fuel to gasoline to reduce the total CO_2 emissions from internal combustion engines. This paper devoted to investigate the effect of usage of two blending ratios of 10 and 20% of bio-ethanol to gasoline with the addition of 10% hot and cool EGR. The experimental work was carried out on a multi-cylinders spark ignition engine at variable engine torque, speed, and spark timing conditions.*

The results show that adding bio-ethanol to gasoline reduced NOx and smoke opacity, and this influence alters with blends ratio complied with a certain pattern. EGR addition opposite smoke reduction consequence and limited it. Cool EGR resulted in lower NOx and higher emitted smoke. Retarding spark timing reduces

NOx concentrations highly but increases smoke opacity. Advancing spark timing increases NOx but reduces smoke opacity.

Keywords: Bioethanol, Nox, Smoke Opacity, EGR

Introduction

Any substance in the air harmful to humans and the environment considered as an air pollutant. Air pollution is a serious global problem. The emission emitted by vehicles engines is one of the most dangerous polluters. Pollutants can take the form of gases, liquid droplets, or solid particles. Besides, pollutants may be natural or manmade. Exhaust gases from engines primarily contribute to form air pollutants. Therefore, finding methods that reduce emissions from vehicles to meet more stringent requirements for terminating or reducing the air pollution is a crucial and imperative task for researchers, manufacturers, and regulators [1].

Alternative fuels used in a variety of vehicle applications; among these fuels, bioethanol that is employed most widely [2]. The use of bioethanol fuel in the transport sector can save significant amounts of fossil fuels and greenhouse gas (GHG) emissions. Bioethanol manufacturers are using hydrolysis to produce simple from sugar beet and wheat (in Europe), dates and grapes (in Iraq), corn (in the US) and sugar cane (in Brazil). Sugars are then fermented to produce bioethanol [3]. Blends called E5 and E10 with 5% to 10% ethanol, and the rest gasoline can fuel conventional gasoline vehicles without any modifications to the engine. Above these proportions, ethanol causes corrosion in certain parts of conventional vehicles. However, relatively inexpensive engine modifications avoid corrosion [4 & 5].

Ethanol blends in gasoline offer excellent benefits in spite of its low energy density, as it increases power density thanks to its high octane rating and latent heat of vaporization [6]. The high heat of vaporization of ethanol fuel causes a decrease in the peak temperature inside the combustion chamber resulting in a reduction in the emitted NOx concentrations and increased engine power [7].

Saleh reported that adding ethanol to gasoline by 10% vol. resulted in a reduction in NOx emissions. However, a further increase in ethanol content caused an increase in NOx emission, though no data gave on combustion phasing [8]. Wallner showed that as the ethanol blend ratio increased, the NOx emissions reduced due to the increment in enthalpy of vaporization [9]. Turner reported that ethanol addition to gasoline reduced hydrocarbon emissions. Generally speaking, the impact of ethanol blends on NOx emissions is not as decisive as for unburned hydrocarbon emissions [10]. The ethanol increased charge cooling can manifest itself in some engines with the result of lower in-cylinder temperatures and thus lower NOx emissions [11].

In Iraq, Habbo carried out a study with ethanol-leaded gasoline blends (E10, E20, E30, E40, and E50) at three different compression ratios (9:1, 10:1 and 11:1) for two different ignition timings (0º TDC- 30º BTDC), at fixed engine speed of 2000 rpm and an equivalence ratio=1. The experimental results showed a significant reduction in exhaust emission for high percentage ethanol-gasoline blend, i.e., for E30, E40, and E50 [12].

NO_X consists primarily of NO and NO_2, and it is a product of complete combustion. NO is the predominant nitrogen oxide formed inside the combustion chamber. The oxidation of atmospheric (molecular) nitrogen is the principal source of NO [13]. However, an additional source of NO comes from the oxidation of the fuel compounds that contained a significant amount of nitrogen. NO level can first be detected above around 1,900^{o}C. Overall, more than 90% of NOx emissions are nitrogen monoxide. A characteristic of NO is its reactivity with oxygen and particularly quick reactivity with ozone to form NO_2 [14].

Smoke results from the organic substances burn, it is a cloudy, hazy, emanations. Smoke consists of solid and liquid particles. Also, it consists of so small droplets that they tend to suspend in the air for periods of times extend from seconds to years. Smoke is visible to the human eye most the time; but a large part of it is not. The particles and droplets size and content comprise smoke highly, and it affects the human ability as well as the optical instruments ability to “see” it. Opacity (usually expressed as a percentage) is a measure of light reduction through a smoke column path [15].

Exhaust gas recirculation (EGR) is used mainly to provide a large reduction in oxides of nitrogen (NOx) emissions and to improve gasoline engine efficiency and its fuel economy. EGR causes an increase in soot emissions mass, and in solid particle number emissions. Many researchers who studied the usage of ethanol-gasoline blended in SIE highlight some challenges that face the soot-NOx trade off [16].

In this study, two ethanol–gasoline blend fuels are used to determine the NOx-smoke tradeoff for a four stroke SI engine running at variable speeds, loads, and spark timing. All the experiments performed without any modification on the engine at 10 and 20% EGR.

Experimental Setup

A spark ignition engine type Mercedes-Benz used in the recent study. This engine has two liters displacement volume, water cooled, four strokes and four cylinders. The engine coupled to a hydraulic dynamometer to measure the brake torque. Figure (1) shows the tests rig, and Table (1) lists the primary technical specifications of the used engine.

Measurement of the engine torque

A hydraulic dynamometer used to measure the engine torque using water as a friction fluid. The dynamometer has a rotating impeller coupled to the output shaft of the engine and rotates in a casing filled with water. The output load controlled by regulating the gates that moved in and out to obstruct partially or wholly the water flow between the casing and the impeller. The hydraulic dynamometer calibrated by using an electric generator dynamometer connected to the engine.

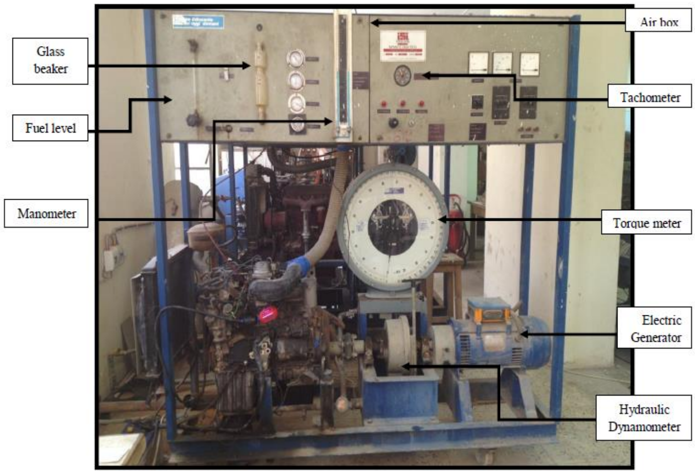

Figure 1: The experimental rig of SI engine

Table (1) The Main Technical Specifications Of The Engine

Item specification	
Engine	4-cylinder-inline engine (four-stroke)
Displacement	2 liters
Fuel System	Carburetor
Cooling	Water

Exhaust gas recirculation system

An EGR system fitted to the engine used to recirculate the engine exhaust gasses, as Figure 2 shows. EGR achieved by using Prodit EGR assembly illustrates in Figure 2. This assembly contains a two pipes heat exchanger with thermocouples fixed on it to measure working fluids temperatures. Inside this heat exchanger, a fluid flow can be controlled whether parallel or counter flow by arranging fluid cocks. The inside pipe used to recirculate exhaust gas while the outer pipe used for water used to cool the recirculated exhaust gas. EGR (%) defined as the mass percentage of the recirculated exhaust (m_{EGR}) in total intake mixture (m_a) [17].

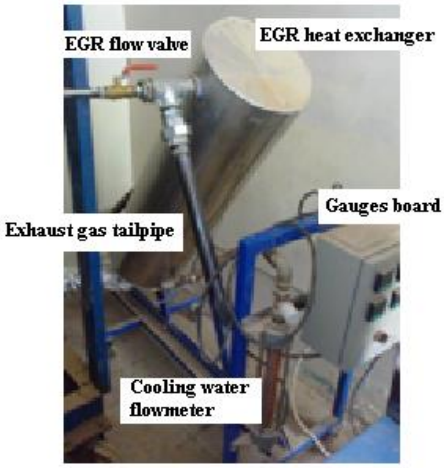

Figure 2: the EGR system type Prodit used in the recent investigation

The exhaust gas temperature measured using thermocouples type K fixed at the beginning of the exhaust tube. These thermocouples calibrated in the laboratory by comparing its readings with that of a set of calibrated thermocouples. EGR measurement evaluated by:

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

Where:
m_a: Mass flow rate of air admitted without EGR.
m_{a+EGR}: Mass flow rate of air admitted with EGR.

NOx analyzing

NOx emissions measured using a gas analyzer type HG-550. The calibrations reading for this measuring device took from the factory inspection sheet produced by Hephzbah Co. Ltd at 16/10/2013 since it is a new appliance.

Smoke Analyzer

The smoke meter type "MOD. SMOKY" was used to measure smoke opacity in the recent study. The working principle of this device is the usage of optical absorption of the smoke. A halogen lamp provides the bright of light. The electric signal generated by an optical sensor electrically conditioned and computed by a microprocessor and then displayed as absorption % vol. The smoke meter consists of a command keyboard, probe, and the meter. At first, the probe inserted into the exhaust pipe, taking care that the extremity located in the straight section of the tube, if it were not possible, it would need to enlarge the exhaust pipe to check the proper installation. This device calibrated at the Central Organization for Measuring and Quality Control in Baghdad-Iraq.

Materials

The study tests carried out using the Iraqi conventional gasoline (with ON=82) as the baseline fuel. This fuel produced by Al Dora refinery/ Baghdad. Iraqi conventional gasoline characterized by its low octane number and high content of sulfur and lead. Two blends with the volume of 10% and 20% bioethanol with gasoline tested. Bioethanol (99.7% purity) employed in this work by distillate it from date juice after purifying it from the residuals. The used blends prepared by mixing the ethanol (10 & 20% by volume) with gasoline; these blends named E10 & E20 respectively.

The used fuels properties measured in the Fuel Laboratory of the Department of Chemical Engineering, UOT. **Table (2)** represents the measured properties of the used gasoline and ethanol.

Table (2) Properties of gasoline and ethanol fuels

Property	Gasoline	Ethanol
Chemical formula	various	C_2H_5OH
Oxygen content by mass [%]	0	34.8
Density at NTP [kg/l]	0.74	0.79
Lower heating value [MJ/kg]	42.9	26.95
Volumetric energy content [MJ/l]	31.7	21.3
Stoichiometric AFR [kg/kg]	14.7	9
Energy per unit mass of air [MJ/kg]	2.95	3.01
Research octane number	89-95	109
Motor octane number	85	89.7
Boiling point at I bar [ºC]	25-215	79
Heat of vaporization [kJ/kg]	180-350	838
Reid vapor pressure [psi]	7	2.3
Flammability limits in air [λ]	0.26-1.6	0.28-1.99
Laminar flame speed at NTP, Ø=1 [cm/s]	28	40
Adiabatic flame temperature [ºC]	2002	1920
Specific CO_2 emissions [g/MJ]	73.95	70.99

Error analysis

In experimental investigations measurement accuracy is imperative in evaluating reasonable results or not. The error sources are defined by calibrating the used measuring equipment. The uncertainty in the recent study was determined, and all engine and its accessories calibrated. Table 3 shows the measuring device and its calibration accuracy.

The result clarifies an uncertainty less than 5% in all measurements were achieved. The experiments random errors minimize in the conducted tests by repeating the tests three times. The average values of these experiments results for each condition reported along with more than 95% confidence intervals.

Table (3): Measurement type and accuracy for present study

Measurement	accuracy
Engine speed measurement	±1.30%
Engine torque measurement	±1.09%
NOx in exhaust gases concentrations measurement	±0.82%
Smoke meter measurement	±0.93%
EGR flow rate measurement	±0.98%

Tests Procedure

In the experiments, the three ethanol blends, E0 (100% gasoline), E10 (90% gasoline + 10% ethanol) and E20 (80% gasoline+20% ethanol)] were used to operate the engine. Hot and cold EGR used with a ratio of 10%. Meanwhile, the emitted NOx and smoke from the engine were measured and analyzed at the same load and engine speed. The tests conducted as the following:

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

Results and Discussions

All emissions are harmful, but the two studied (NOx and smoke) have a trade-off that makes its control tough. The smoke and PM reduce with increasing combustion temperatures, at the same time, NOx increases. NOx reduced by reducing combustion temperatures, but this decrease results in the rise of smoke. Most of the researchers study this trade-off relationship for diesel engines. In this study, the investigation conducted on spark ignition engine fueled by Iraqi gasoline. Iraqi conventional gasoline has high sulfur and leads content. These two materials are the nuclei that PM accumulated on it. From here, this study takes its importance.

Figure. 3 shows the effect of adding 10% hot and cool EGR on NOx and smoke emissions for E0, E10, and E20 at variable engine speeds. Adding 10% ethanol increased NOx concentration for engine speeds more than1600 rpm (Figure 3 A). The high combustion temperature with more available oxygen from ethanol led to these results. EGR reduced NOx concentrations apparently compared with E0 and E10. The reduction rates were 6.9 and 16% for hot and cool EGR respectively compared with emitted NOx from a gasoline engine. NOx concentrations reduced by using 20% ethanol due to the reduction in the blend heating value which reduced the combustion temperatures as Figure 3 B represents. The effect of EGR reduced NOx concentrations by 10.46 and 19.9% for hot and cool EGR respectively compared with emitted NOx from the gasoline engine. Figure 3 C illustrates that adding 10% ethanol to gasoline reduced smoke opacity by 13.1%. Adding ethanol increased the blend oxygen content that improved radicals' oxidations and reduced smoke. Adding EGR operated in opposite manner, it increased smoke opacity due to its dilution effect that reduced oxygen content.

Ethanol and EGR addition caused their influences to interfere, and the results appeared that adding hot EGR to E10 increased smoke slightly compared with cool EGR. The results show that E10 has great influence on smoke, where adding EGR in any mode cannot exceed the emitted smoke. Using E20 (as in Figure 3 D) enhanced smoke reduction while adding EGR opposite this effect. Figure 3 E declares The NOx-smoke tradeoff for variable engine speeds. E0 and E10 tradeoff has the same range of NOx concentrations between 600 and 750 while adding hot EGR to E10 creped to left for arranging between 550-650 ppm. Adding cool EGR caused the trade-off relationship to creep more and more to lift at in a range between 500-600 ppm indicating lower emitted NOx. All the cures Figure 3 F behaved the same as Figure 3 E with creeping to lower ranges representing lower emitted smoke opacities.

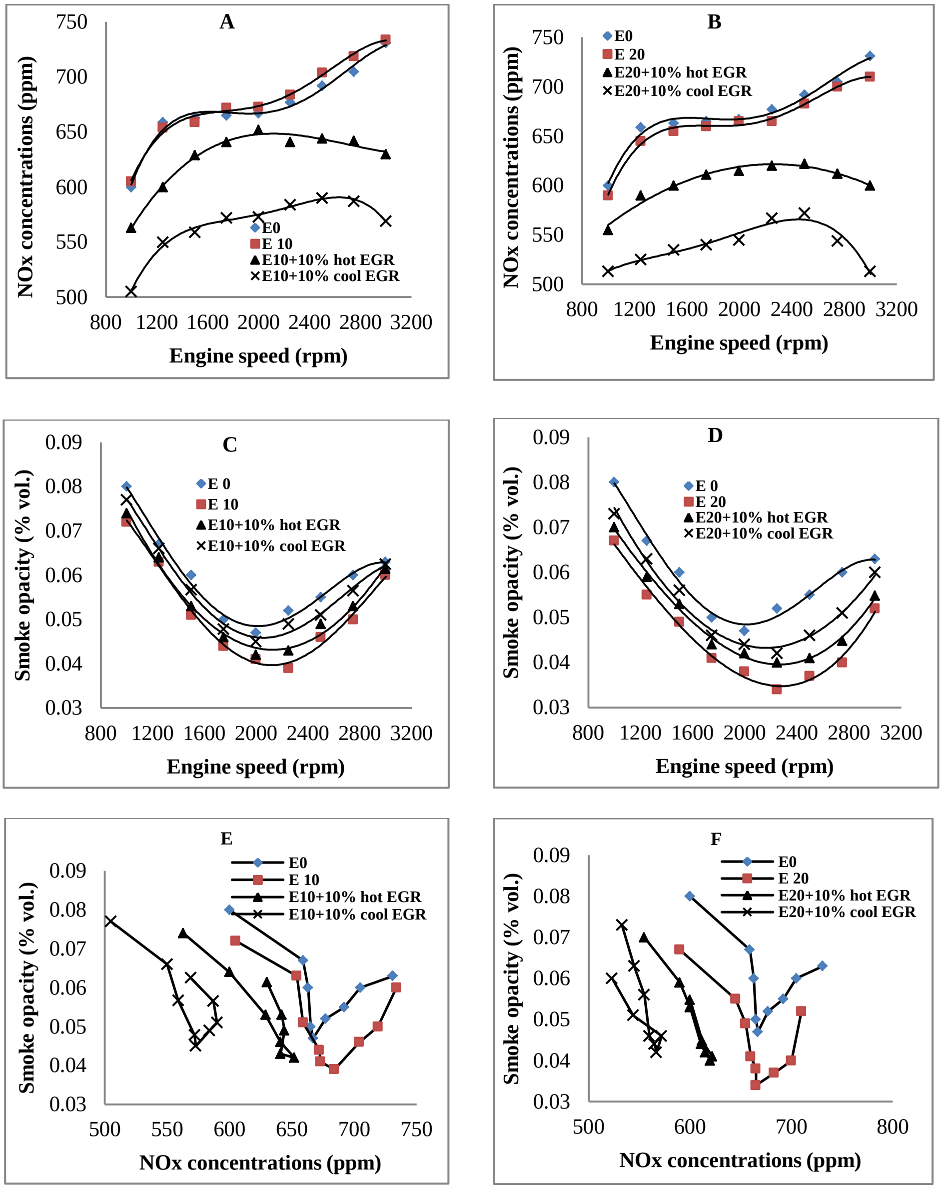

Figure 3: the effect of variable engine speed on NOx and smoke opacity of E0, E10 & 20 with and without adding hot and cool EGR

Figure 4 represents the effect of variable engine torques on NOx and smoke opacity of E0, E10 & 20 with and without adding hot and cool EGR. Increasing engine torque increases combustion temperatures by burning more fuel, which results in more NOx concentrations.

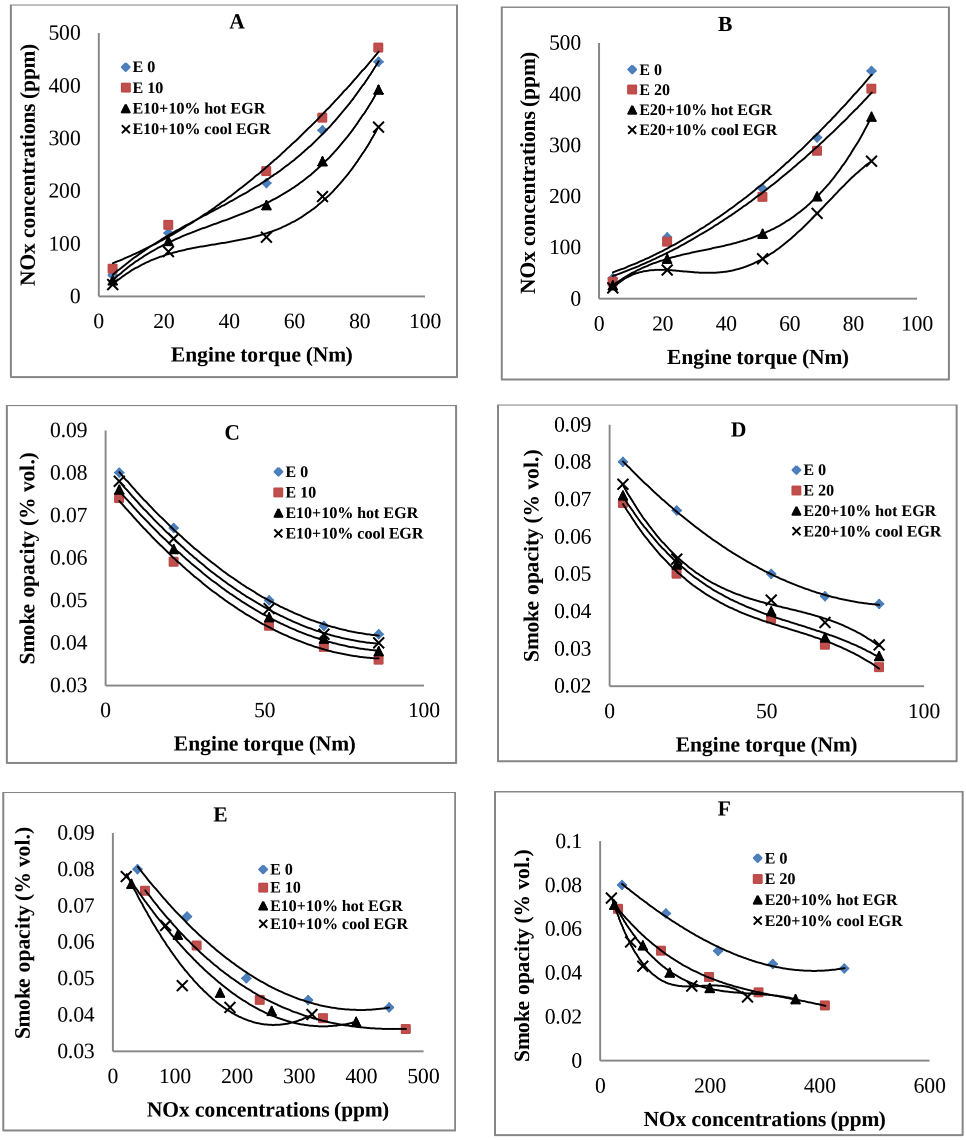

Figure 4: the effect of variable engine torques on NOx and smoke opacity of E0, E10 & 20 with and without adding warm and cool EGR

E10 blend emitted more NOx due to its higher oxygen content (Figure 4 A). Adding EGR resulted in lowering NOx concentrations. Figure 4 B shows the same trends but with a reduction in NOx concentrations with using an E20 blend.

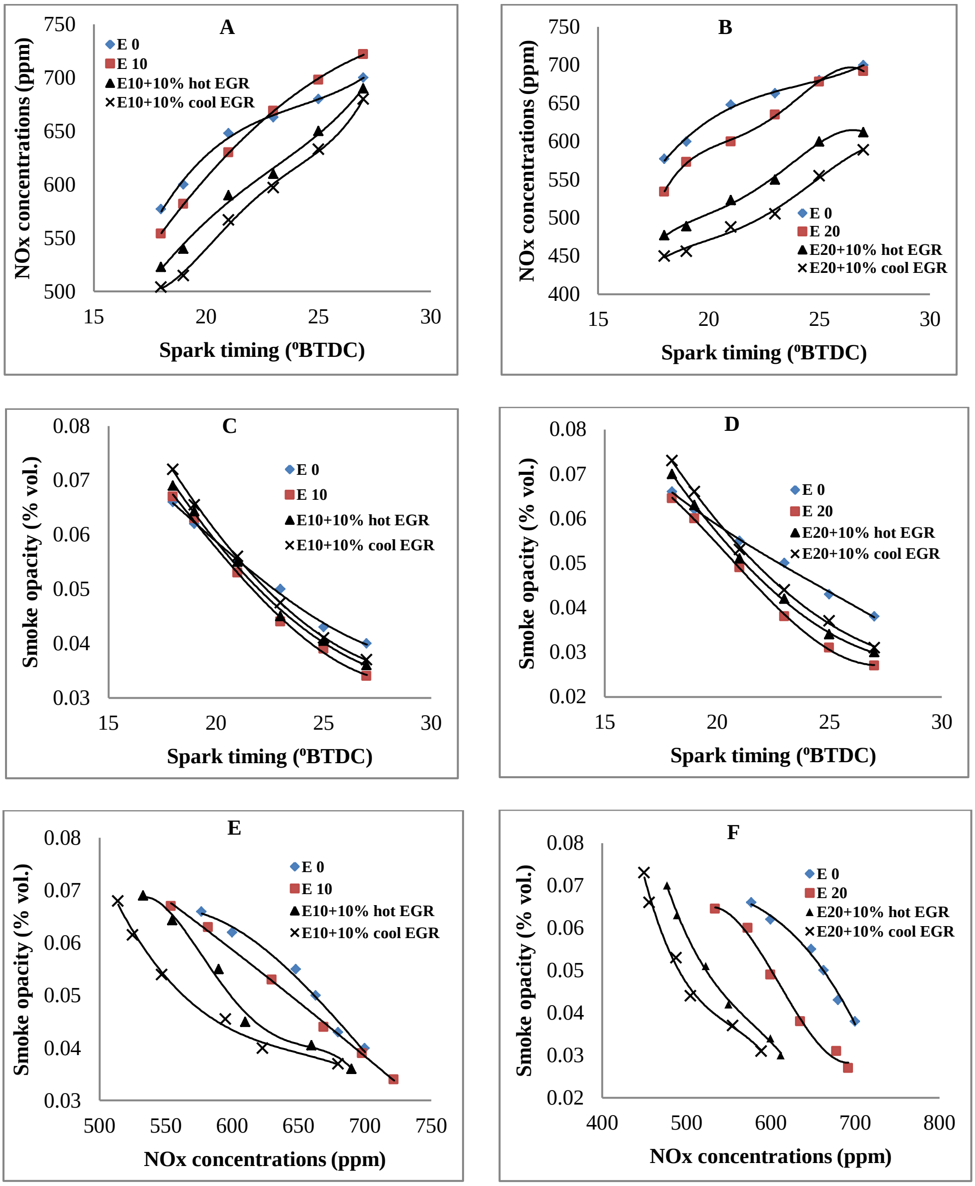

Figure 5: the effect of variable engine sparks timings on NOx and smoke opacity of E0, E10 & 20 with and without adding hot and cool EGR

Another variable interferes here that is ethanol lower heating value compared with gasoline, where its effect starts to introduce itself due to higher ethanol quantity in the blend. Operating the engine with E10 or E20 reduced smoke opacity while adding EGR in and mode increased it. Two parameters conflicted, ethanol addition with its high oxygen content and EGR addition with its dilution effect. The resulted emitted smoke is the production of this confliction. It is apparent from the figure that ethanol addition is more efficient than that for EGR. In Figs. 4 E and F, the NOx-smoke trade-off curves took more well-organized shapes than that for Figure 3. The figures show the same trends as this similar in Figure 3.

Retarding spark timing is considered as one of the most optimal methods to reduce NOx concentrations by all researchers. This effect is evident in Figure 5 A and B. At the same time, advancing spark timing gives increases combustion chamber pressure and temperatures resulting in more NOx concentrations as the figures declare.

NOx concentrations increased that emitted from gasoline at advanced spark timing due to high temperature and more oxygen content. EGR and retarding spark timing meeting caused a higher reduction in emitted NOx. This reduction reached 17.6 and 29.2% for hot and cool EGR respectively compared to gasoline. Spark timing retardation with cool EGR resulted in maximum smoke opacity followed by hot EGR then gasoline. Dilution effect of EGR causing oxygen decrements resulted in higher smoke opacity.

Retarding spark timing causes combustion delay, and a part of the fuel burns after the opening of the exhaust valve resulting in poor combustion followed by higher smoke opacity. Figs 5 E and F declare the NOx-smoke trade-off at variable spark ignition timing. The figures represent consistent behavior, as E10 is to the left of gasoline curve followed by hot EGR and cool EGR. This tendency resulted from lower NOx concentrations emitted for all the spark timing range.

Conclusions

The various NOx-smoke trade-off relations studied in a multi-cylinder spark ignition engine fueled with gasoline and two ethanol/gasoline blends. The effects of engine speed, torque, spark timing and blending ratio with 10% hot and cool EGR clarified. The main results are as follows:

1. Bio-ethanol can consider as a suitable alternative fuel for spark ignition engine without the need for any significant engine modifications.
2. As an oxygenated fuel, bioethanol usage leads to increase the NOx concentrations. A slight increase obtained for low-speed regimes when E10 used. Using E20 reduced the emitted NOx.
3. NOx concentrations give the highest value at maximum speeds and full load. The addition of EGR reduces NOx emission.
4. Adding 10% ethanol increased NOx concentrations at high speeds and torques and limited the EGR effect.
5. Adding 20% ethanol reduced NOx concentrations due to a lower heating value of the blend while it affected EGR influence highly due to the higher oxygen content of the mixture.
6. Smoke opacity increased with increasing engine speed and reduced with rising engine torque.
7. Smoke opacity reduced with adding ethanol while EGR opposite this consequence and limited the reduction.
8. Cool EGR resulted in lower NOx and higher smoke remittance.
9. Retarding spark timing reduces NOx concentrations highly but increases smoke opacity.
10. Advancing spark timing increases NOx but reduces smoke opacity.
11. Adding ethanol reduced NOx concentrations for all spark timing compared with gasoline, but for E10 at retarded ignition timing.
12. Adding EGR duplicated the NOx reduction while increased smoke opacity in the same time.

Notation

ST	spark timing	E0	gasoline
N	engine speed (rpm)	E1	90% gasoline+10% bio-ethanol
T	engine torque	LC	Lower calorific value
BTDC	before top dead centre	EGR	Exhaust gas recirculation

References

[1] Phong L Q, "Influences of alternative fuels and EGR on thermodynamic parameters and emissions of a heavy-duty engine," Internal Combustion Engine Ph.D. study in Institute of Mobile Systems, University of Magdeburg, Germany. 2007.

[2] Ghazikhani M, Hatami M, Safari B, DomiriGanji D, "Experimental investigation of exhaust temperature and delivery ratio effect on emissions and performance of a gasoline–ethanol two-stroke engine," Case Studies in Thermal Engineering, vol. 2, pp: 82–90, 2014.

[3] Radu A, "Experimental investigations of a S.I. Engine fueled with gasoline-bioethanol blends," Experimental Research Report no. 2, 2012.

[4] Balat M, Balat H, "Recent trends in global production and utilization of bioethanol fuel," Appl. Energy, vol. 86, pp: 2273–2282, 2009.

[5] Delgado R C O B, Araujo A S, Fernandes Jr V J, "Properties of Brazilian gasoline mixed with hydrated ethanol for flex-fuel technology", Fuel Process. Technol., vol. 88, pp: 365-368, 2007.

[6] Moore W, Foster M and Hoyer K, "Engine efficiency improvements enabled by ethanol fuel blends in a GDi VVA flex fuel engine," SAE paper No. 2011-01-0900, 2011.

[7] Yousufuddin S, Venkateswarlu K and Sastry G R K, "Effect of compression ratio and equivalence ratio on the emission characteristics of a hydrogen-ethanol fuelled spark ignition engine," International Journal of Advanced Science and Technology, vol. 40, 2012

[8] Saleh A M and Chaichan M T, "The effect of alcohol addition on the performance and emission of single cylinder spark ignition engine", proceeding to Najaf Technical collage international scientific conference, Najaf, Iraq, 2010.

[9] Wallner T, Miers S A, "Combustion behavior of gasoline and gasoline/ethanol blends in a modern direct-injection 4-cylinder engine", SAE paper No. 2008-01- 0077; 2008.

[10] Turner D, Xu H, Cracknell R F, Natarajan V, Chen X, "Combustion performance of bio-ethanol at various blend ratios in a gasoline direct injection engine", Fuel, vol. 90, pp: 1999–2006, 2011.

[11] Price P, Twiney B, Stone R, Kar K, Walmsley H, "Particulate and hydrocarbon emissions from a spray guided direct injection spark ignition engine with oxygenate fuel blends", SAE paper No. 2007-01-0472; 2007.

[12] Habbo A R, Hammodi H S, "The effect of adding ethanol to leaded gasoline on the performance of spark ignition engine", Al-Rafidain Engineering Journal, vol.18, No.4, pp. 33-43, 2010.

[13] Heywood J B, "Internal Combustion Engine", Mc Graw–Hill, New York, 1998.

[14] Chaichan M T, "Experimental evaluation of the effect of some engine variables on emitted PM and Pb for single cylinder SIE," Association of Arab Universities Journal of Engineering Science, vol. 2, No. 20, pp: 1-13, 2013.

[15] Chaichan M T, "The impact of engine operating variables on emitted PM and Pb for an SIE fueled with variable ethanol-Iraqi gasoline blends", IOSR Journal of Mechanical and Civil Engineering (IOSRJMCE), vol. 12, N0. 6-1, pp: 72-79, 2015.

[16] Abdul-Khalek I, "Particle emission from direct injection gasoline engines", Technology Today, summer 2011.

[17] Rajan K, Senthilkumar K R, "Effect of exhaust gas recirculation (EGR) on the performance and emission characteristics of diesel engine with sunflower oil methyl ester", Jordan Journal of Mechanical and Industrial Engineering, vol. 3, No. 4, pp: 306 – 311, 2009.

دراسة عملية لتأثير تدوير الغاز العادم (EGR) على العلاقة بين NOx- الدخان لمحرك اشتعال بالشرارة يعمل بخلائط جازولين-ايثانول حيوي

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المستخلص:

يمكن استخدام الايثانول الحيوي العراقي كبديل عن الجازولين النفطي لغرض تقليل ملوثات CO_2 الكلية المنبعثة من محركات الاحتراق الداخلي. كرسّت هذه الدراسة لبحث تأثير استخدام نسبتي خلط 10 و20% من الايثانول الحيوي الى الجازولين مع اضافة 10% من الغاز العادم المدّور الساخن والمبرد. تم العمل التجريبي على محرك اشتعال بالشرارة متعدد الأسطوانات عند ظروف عزم وسرعة وتوقيت شرر متغيرة.

أظهرت النتائج أن اضافة الايثانول الحيوي الى الجازولين قللت NOx وعتومة الدخان، ويتغير هذا التأثير اعتمادا على نسبة الخلط متبعا نمطا معينا. تعاكس اضافة EGR نقصان الدخان وتحد منه. ويسبب EGR المبرد تراكيز أقل من NOx مع زيادة انبعاث الدخان. يقلل تأخير توقيت الشرر من تراكيز NOx بشكل كبير ولكنه يزيد من عتومة الدخان، بينما يزيد تقديم توقيت الشرر من تراكيز NOx ويقلل من عتومة الدخان.

الكلمات الرئيسية: إيثانول حيوي، أكاسيد النيتروجين، عتومة الدخان، تدوير الغاز العادم.