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The Effect of Exhaust Gas Recirculation (EGR) on the Emission of a Single Cylinder Spark Ignition Engine

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Abstract
A single cylinder variable compression ratio spark ignition engine type PRODIT was used in this study. The experiments were conducted with gasoline fuel (80 octane No.)at equivalence ratio (Ø =1). This study examined the effects of exhaust gas recirculation on emission. It was conducted at engine speeds (1500, 1900, 2300 and 2700 r.p.m.).

The exhaust gases were added in volumetric ratios of 10%, 20% and 30% of the entering air/fuel charge. The results showed that the EGR addition decreases the CO_2 concentrations, in the same time CO and HC concentrations increase remarkably. NOx concentration decreased highly with the increase of EGR percentage at variable engine speeds and constant torque. Also, it decreased when the engine run at constant speed and variable engine torque. The exhaust gas temperature decreased with increasing EGR ratio.

Keywords: EGR (Exhaust Gas Recirculation), EGR Rate, NOx, CO, HC.

دراسة تأثير تدوير غاز العادم على ملوثات محرك احتراق داخلي احادي الاسطوانة يعمل بالشرارة

الخلاصة
تم استخدام محرك اشتعال بالشرارة احادي الاسطوانة يعمل بنسبة انضغاط مختلفة نوع (PRODIT) في هذا البحث، اجريت التجارب باستخدام وقود كازولين ذو العدد الاوكتاني (80) ولنسبة مكافئة (Ø =1)، و تمت الدراسة لبيان تأثير اعادة تدوير الغاز العادم على الملوثات الناتجه من عادم المحرك، لمدى واسع من سرع المحرك (1500, 1900, 2300, 2700 r.p.m.) .

تم إضافة غازات العادم بنسب حجمية 10%، 20% و 30% من نسبة شحنة الهواء/الوقود الداخلة. بينت النتائج أن إضافة الغاز العادم يقلل من تراكيز CO_2، وفي نفس الوقت، تزداد من تراكيز CO وHC بشكل كبير. كما قلت تراكيز NOx بنسبة كبيرة بزيادة الغاز العادم المدور عند عمل المحرك بسرع متغيرة وحمل ثابت، وتناقصت عند عمل المحرك بسرعة ثابتة وحمل متغير، وكذلك قلت درجات حرارة الغاز العادم بزيادة معدل تدوير الغاز العادم.

الكلمات الدالة: EGR (تدوير الغاز العادم)، معدل الغاز العادم المدورEGR، NOx، CO، HC

Introduction
The emission problem is now reached at alarming level. The toxic gases emitted to atmosphere by automobiles are liable to cause harm to human health, other living organisms, plants and environment by entering into bio-logical system [1]. One method to reduce emissions employs an exhaust gas recirculation system, both with and without a coolant. This system's positive

impact on emissions, particularly NOx, in both heavy-duty and light-duty engines has been verified in many investigations [2].

EGR is not a new technology. It has been in use in gasoline fueled passenger car engines since the mid-1970s [3]. Exhaust gas recirculation means recirculating the exhaust gas to the engine. The incoming air when intermixed with re-circulated exhaust gas lowers the adiabatic flame temperature and reduces the excess oxygen. The exhaust gas increases the specific heat of the mixture and lowers the peak combustion temperature. NOx formation progresses faster at higher temperatures. EGR serves to limit the formation of NOx [4].

EGR has been one of the key technologies due to its ability to reduce exhaust emission. EGR acts as an additional diluents to the unburned gas mixture inside combustion chamber, thereby reducing the peak burned gas [5,6]. In addition to the benefit of NOx emission reduction, EGR also brings out the benefit of fuel economy because of the increase of intake pressure corresponding to the EGR amount, especially in part load [7,8]. However, excessive amount of EGR would result in the deterioration of combustion stability due to the thorough mixing of inert gas and air-fuel mixture [9].

The effects of EGR on the reduction of thermal loading at exhaust manifold were also investigated, because the reduced gas temperature is desirable for the reliability of an engine in light of both thermal efficiency and material issue of exhaust manifold. The steady-state tests by Begg showed that decreasing EGR temperature by 180°C enabled the reduction of exhaust gas temperature by 15°C in cooled EGR tests at 1600 rpm / 370 kPa BMEP operation, and consequently the reduction of thermal load at exhaust [10].

Exhaust gas recirculation (EGR) and lean burn utilize the diluents into the engine cylinder to control combustion, leading to enhance the fuel economy and reduce the emission. The proper stratification of mixture and diluents could improve the combustion stability under high diluents environment [11]. EGR stratification within the cylinder was made by adopting a fast-response solenoid valve in the midst of EGR line and controlling its timing and duty by Ref. [12]. The EGR in homogeneous mode and stratified mode, in-cylinder pressure and emissions, were measured [11]. The thermodynamic heat release analysis showed that the burning duration was decreased in case of stratified EGR. It was found that the stratification of EGR hardly affected the emissions. Almost same amount of nitrogen oxides (NOx) reduction was attained with and without the EGR stratification process [12].

The formation of pollutants and the engine performance were verified at full and partial loads by Ref [13]. The results showed that the combination of exhaust gas recirculation with turbocharger, or by increasing compression ratio, the relation between the engine performance and the emission of NOx will be enhanced. However, the turbocharger seemed to be more sensitive to the negative effects of the EGR technology.

In order to lower the nitrogen oxides (NO_x) concentration in the internal combustion engine emissions and to improve performance, Exhaust Gas Recirculation (EGR) and Scavenging mechanism are introduced. EGR recirculates a fraction of the exhaust gas back into the cylinders, thus diluting the intake air. This lowers the maximum combustion temperature and, since the formation of NO_x is heavily dependent on temperature, it results in a reduction of NO_x concentration [14]. Similarly, the Scavenging phenomenon is the air mass flowing from intake manifold directly to exhaust manifold, due to an overlap of intake and exhaust valves, without participating at the combustion. In Ref. [15], the authors present a mean value engine model, aimed at the challenging purpose of the analysis of EGR and Scavenging. The model is based on an innovative approach for engine dynamics conceived mainly on the analogy with electric systems.

Ref. [16] studied reducing short circuiting of fresh charge by admitting cooled exhaust gas to pass through reed valves fitted at the upper end of the transfer passage in a crank case scavenged two-stroke engine. This resulted in appreciable decrease in specific fuel consumption and in HC/CO emissions. The major work involved in this work was to design and fabricate aluminum flanges which accommodate the reed valves. An arrangement has been made at the upper end of the transfer passage in the engine cylinder to fasten the flange. A heat exchanger was fabricated in order to cool the exhaust gas at a temperature of about 400ºC to avoid the pre-ignition inside the engine cylinder. The performance of the engine was tested using eddy current dynamometer [17,18].

The aim of this investigation is to study the effect of EGR addition in variable volumetric rates (10, 20 & 30%) to suction induction on the exhaust gas emissions and exhaust gas temperatures. EGR affects the engine performance as well as its emissions, but due to its high influence on engine, emissions it was found that studying these effects can be the priority in this paper. Gasoline engine was used as a SI testing engine, it was fueled with conventional Iraqi gasoline produced by Al-Dura Refinery (80 Octane No.). All tests were conducted at stoichiometric air fuel ratio. Variable engine speeds (1500-2700) at constant torque (10 Nm) and variable engine torques (10-25 Nm) at constant speed (1900 rpm) were used in tests.

Experimental Setup

Experimental Apparatuses

Experiments were performed using petrol engine, type (PRODIT GR306/0001). The engine is a single cylinder, water cooled, four strokes and variable compression ratio engine. It is designed to be a spark ignition. The general arrangement of the experimental rig is shown in Figure (1), while Table (1) lists the engine specifications. The engine rig is coupled to the following equipment:

- The air providing system consists of air drawing tube, damping room and power converter of pressure. This set was calibrated in the laboratory by using a calibrated set, and the readings of the two sets were compared. Engine provided air was measured by using whole measurement device.
- A hydraulic dynameters was used to measure the output torque of the engine. This dynamometer was calibrated in the laboratory using calibrated weights.
- Exhaust gas temperatures were measured by using thermo-couples type K (Ni-Cr/Ni-AL) at the beginning of the exhaust tube. These thermocouples were calibrated in the laboratory by comparing their readings with that of a set of calibrated thermocouples.
- EGR System: In order to furnish the tested engine with EGR, a supply system was fitted to the engine, as shown in Figure (1). The exhaust gas was extracted immediately above an intermediate flange connecting between the exhaust gas manifold and exhaust pipe, which is 35cm downstream from confluence point. By this arrangement, the driving force for the EGR was the pressure difference between the exhaust and the intake manifold pressure. In case of hot EGR without cooling, the desired amount of EGR was controlled by a flow control valve, which was placed after a 50cm copper tube from the extraction point. The feedback point of the EGR was located at the end of a plenum chamber that is 3 cm downstream of the mixer in order to avoid the interaction between the recycled exhaust gas and residual gases at a valve overlaps as effectively as possible. EGR measurement was evaluated by:

$$EGR\ (\%) = \frac{\dot{m}_{EGR}}{\dot{m}_{EGR} + \dot{m}_a} \times 100$$

Where:

$\dot{m}_{EGR}$ is the mass flow rate of EGR.

$\dot{m}_a$ is the mass flow rate of fresh air.

In order to determine how far the EGR valve should be opened to achieve a desirable EGR mass ratio, different EGR rates were extracted from a simple computer code based on the equation of gas state and the method of trial and error.

- Exhaust gas analyzer infrared (gas analyzer is Flax 2000 microprocessor infrared designed to measure (CO, CO_2, HC and NOx) emitted from the engine).

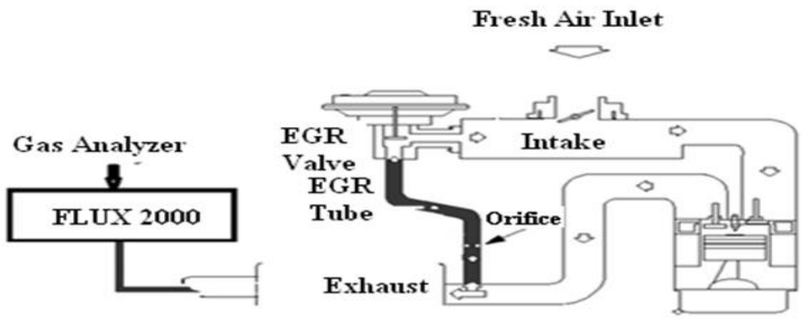

Fig. 1. A schematic diagram for EGR system

Table 1. Engine specifications [16]

Manufacturer	PRODIT	No load speed range	500÷3600 rpm (Otto cycle)
Cycle	OTTO	Load speed range	1200÷3600 rpm (Otto cycle)
Number of cylinder	1 vertical	Intake star	54^0 before T.D.C
Diameter	90mm	Intake end	22^0 after T.D.C
Stroke	85mm	Exhaust start	22^0 before T.D.C
Compression ratio	7/1	Exhaust end	54^0 after T.D.C
Max. Power	4kWat 2800 rpm	Fixed spark advance	10^0(spark ignition)
Max. Torque	28 Nm at 1600 rpm	Swept volume	$541cm^3$

Materials

Iraqi conventional gasoline (with octane No.= 80) was used in these tests. The octane No. was measured by Al-Doura refinery labs. This gasoline was used without any external additives.

Tests Procedure

The first set of tests was conducted to evaluate the engine higher useful compression ratio at which the fuel will give the lower brake specific fuel consumption and the higher brake power. In the second set of tests, the experiments were conducted on the engine without exhaust gas recirculation, i.e., (0% EGR), and the engine was run at HUCR, at this ratio, all experiments were performed. Stoichiometric air fuel ratio was used in all tests, because it is proposed to be the lower emitted emission. The engine emissions were measured at the following conditions:

1-The engine torque was constant at (10 N.m) and engine speed was varied (1100, 1500, 1900, 2300 and 2700 r.p.m.).

2-When engine speed was fixed at (1900 r.p.m.) and engine torque was changed (10, 15, 20 and 25 N.m.).

In the third set of tests, the tests were conducted with adding recirculating exhaust gas with volumetric ratios of (10%, 20% and 30% EGR) to the suction manifold. The engine emissions were measured and compared with the first case. Figure (1) represents a schemed of the used rig, while Figure (2) shows the used machine and its accessories.

Fig. 2 a, Engine fuel and air mass measuring devices

Fig. 2 b, Exhaust gases concentration measuring device type FLUX 2000

Results and Discussion

Figure (3) represents the effect of variable compression ratios on brake power at variable engine loads and constant speed. The results indicated that CR=7:1 is the higher useful compression ratio. The low octane number for Iraqi gasoline caused low engine compression ratio. Increasing compression ratio to 8:1 caused engine knock occurrence. At compression ratio= 7:1, all the remaining tests will be conducted.

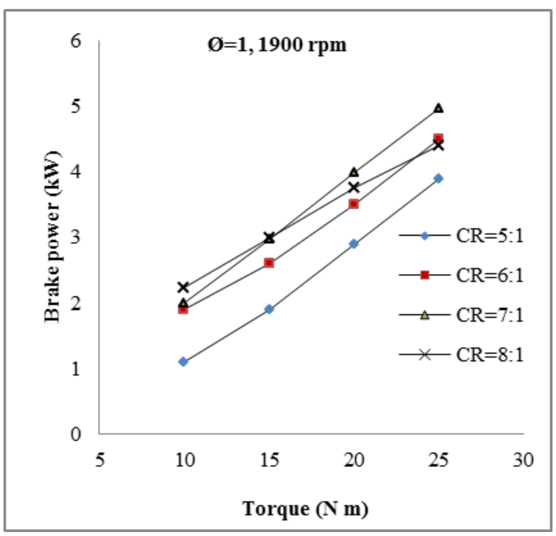

Fig. 3. Engine torque effect on brake power for variable engine compression ratios

Figure (4) shows the effect of the EGR with different ratios (10, 20 and 30%) on the CO_2 concentration for variable engine speeds and at constant torque. It is clear that the CO_2 concentration reduced with increasing EGR rate compared to the case of (0%EGR). The CO_2 concentration reduced about (10.0%) compared with case 1 when (10% EGR) was added. When (20% EGR) was used, the CO_2 concentration reduced more in comparison with the gasoline fuel of (0% EGR). This reduction in CO_2 concentrations with increasing EGR rates for the studied speeds resulted from the fact that the test was conducted with gasoline engine where, the fuel enters the engine with the air through the carburetor. Adding the recalculated exhaust gas will take a part of the combustion chamber volume, and hence affecting the entering air/fuel ratio. This affected the resulted CO_2 concentration.

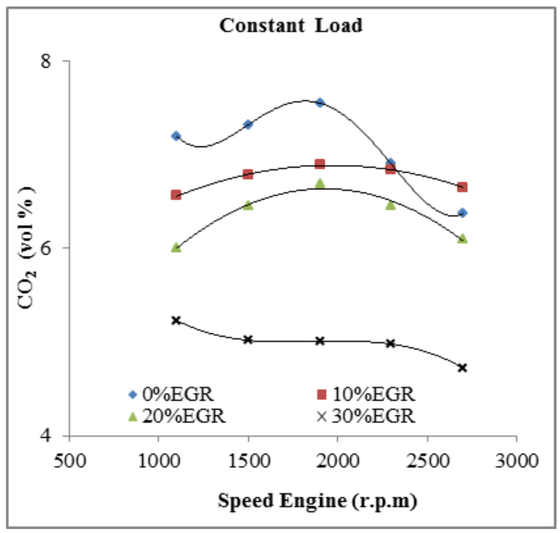

Fig. 4. EGR effect on CO_2 concentrations at variable engine speeds and constant load

This reduction in CO_2 concentration will be understood clearly by studying CO & HC concentrations. These emissions increased, as indicated in Figures (5) and (6). CO and HC concentrations increased on account of CO_2 concentration. This increment in CO and HC concentrations reflects the detrition in combustion and increasing partial fuel combustion due to existence of EGR. The increments in CO concentrations were 20.16, 51.28 and 114.64% for 10, 20, and 30% added EGR compared with 0% EGR, respectively.

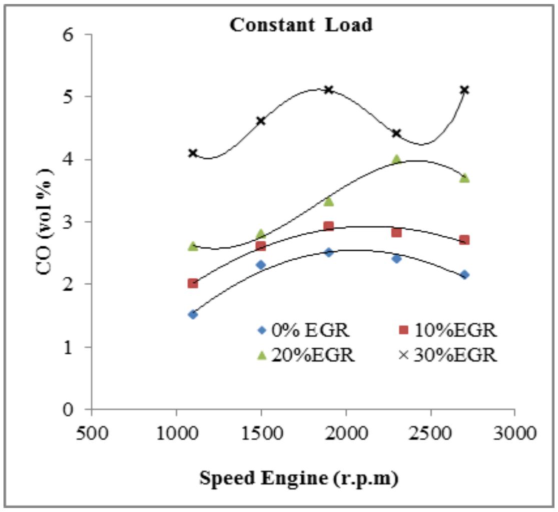

Fig. 5. EGR effect on CO concentrations at variable engine speeds and constant load

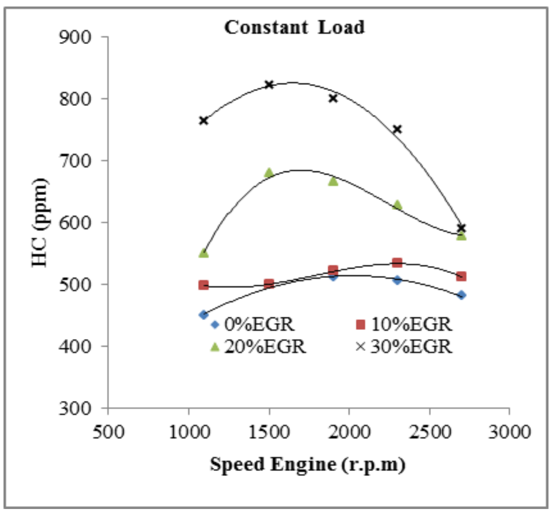

Fig. 6. EGR effect on HC concentrations at variable engine speeds and constant load

At same time, increasing the HC concentration is an evidence of the local inhomogeneousity that occurs due adding EGR. The increments in measured HC concentrations were 4, 26.2 and 52.28% for 10, 20, and 30% added EGR compared with 0% EGR, respectively

Figure (7) indicates the relation between the NOx concentrations and engine speed at constant torque. The main advantage of adding EGR to air-fuel mixture is to reduce NOx concentration. NOx concentrations were reduced by 13.43, 20.32 and 35.02% for 10, 20, and 30% EGR compared to 0% EGR, respectively. The recalculated water vapors and CO_2 are dissociated during combustion, modifying the combustion process and the NOx formation. In particular, the endothermic dissociation of H_2O results in a decrease of the flame temperature.

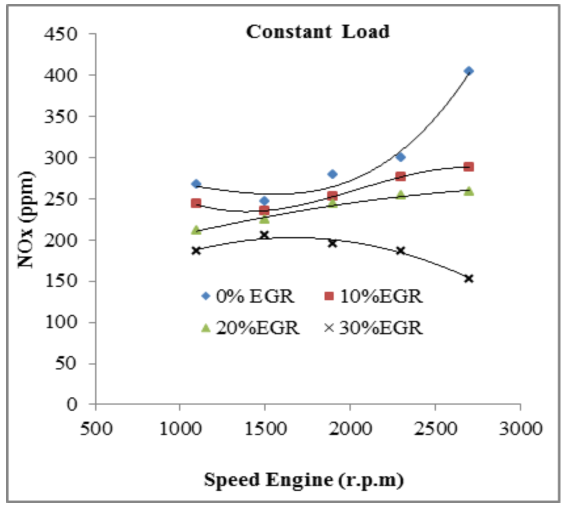

Fig. 7. EGR effect on NOx concentrations at variable engine speeds and constant load

Figure (8) depicts the effect of engine speed on the exhaust temperature at constant torque (10 N m). The exhaust temperature increased with increasing engine speed, which may be due to the increase in combustion temperature. As can be seen in this figure, the exhaust gas temperature decreased with increasing the EGR rate. Accordingly, a high EGR rate resulted in lower exhaust temperature, since a high EGR rate reduces the combustion temperature and prevents a late combustion. At an EGR rate of 30%, the exhaust temperature decreased by approximately 100°C at maximum under the engine operation of 2000 rpm and constant engine torque (10 N m).

Figure (9) shows the same previous effect of EGR on the CO_2 concentrations when the engine speed was fixed at (1900 rpm) with applying variable torques. Increasing the subjected torque causes a reduction in the engine speed. To return to the required engine speed, more fuel must be consumed on the account of air, which reduces the air percentage inside the combustion chamber, causing a reduction in CO_2 concentration. The reduction in CO_2 concentration was about (7.32%) in the case of (10%EGR), about (15.78%) in the case of (20%EGR) and about (26.74%) in the case of (30%EGR) in comparison with (0% EGR).

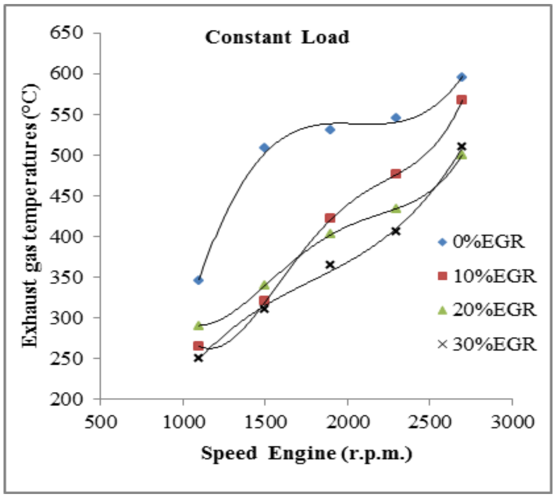

Fig. 8. EGR effect on exhaust gas temperatures at variable engine speeds and constant load

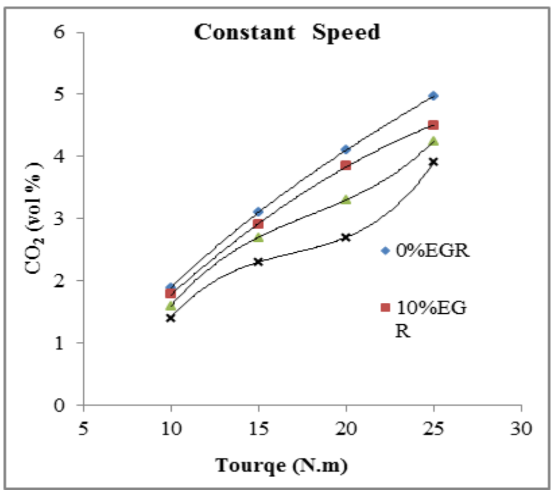

Fig. 9. EGR effect on CO_2 concentrations at variable engine loads and constant speed

EGR effect on CO & HC concentration at constant speed and variable engine torques is shown in Figures (10) and (11). Increasing torque increased CO & HC concentrations. In order to reach the required speed and torque, the fuel in the entering charge must be increased, which means increasing fuel consumption. The CO and HC increased with increase in load and EGR rate. Because of lower oxygen content available for combustion, the lower excess oxygen concentration results rich mixture which causes incomplete combustion and results higher hydrocarbon and CO emissions. CO concentrations increased about (15.83%) in case of (10% EGR), about (51.23%) in case of (20% EGR) and about (84.8%) in case of (30% EGR) in comparison with (0% EGR) case. While HC concentration increased by (3.7, 7.91 and 15.77 %) when (10, 20 & 30%) EGR were added, respectively. As the EGR ratio increased, the HC emission is also found to be increased.

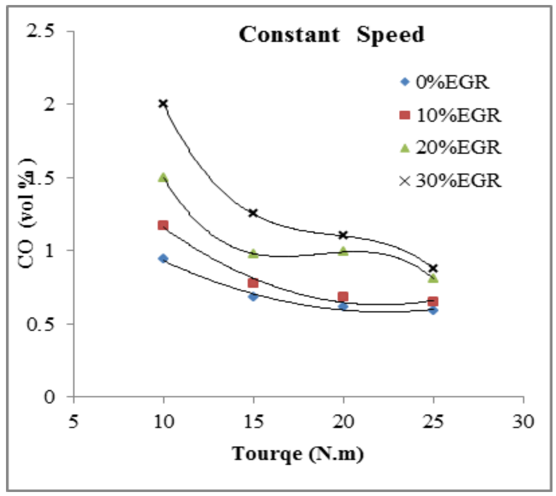

Fig. 10. EGR effect on CO concentrations at variable engine loads and constant speed

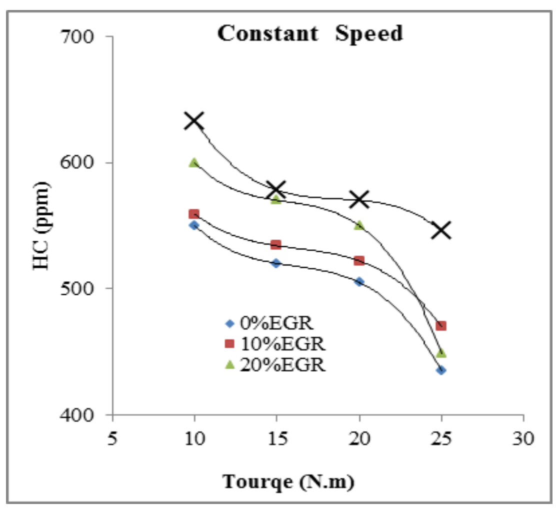

Fig. 11. EGR effect on HC concentrations at variable engine loads and constant speed

Figure (12) indicates the relation between the NO_x concentration and torque at a constant engine speed. The NOx emissions are found to be lower for EGR. With the exhaust gas recirculation, the NOx emissions are reduced as compared to that without EGR. As the percentage of oxygen is one of the factors affecting NOx formation, NOx is greatly suppressed when the O_2 concentration in the combustion chamber is reduced with the exhaust gas recirculation. The combustion takes place in regions, where the oxygen–fuel ratio is within the flammability limits. Even though the tested EGR rates showed higher NOx emissions, especially at the part load, it is found to be decreasing at higher loads. The figure reveals the main advantage of adding EGR to air-fuel mixture. NO_x concentration reduced by (8.69, 11.59 and 16.26%) for 10, 20, and 30% added EGR compared with 0% EGR, respectively.

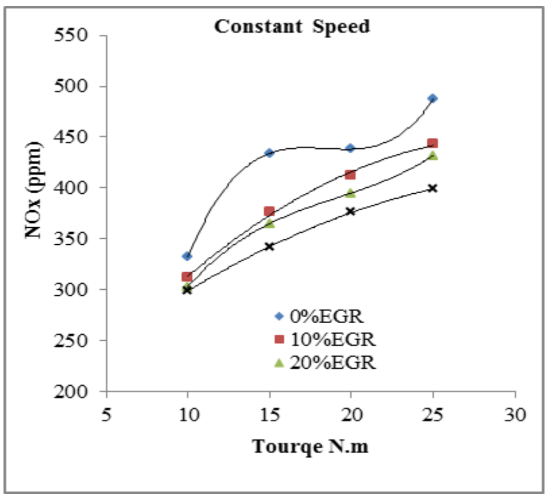

Fig. 12. EGR effect on NOx concentrations at variable engine loads and constant speed

Figure (13) shows the effect of adding EGR on the exhaust gas temperatures when the engine runs at the constant torque and variable speeds. Adding EGR means adding inert gases with a high temperature which relatively increases the change temperature before combustion. After combustion, the EGR takes a part of combustion heat, reducing the generated energy and causing a reduction in the resulted exhaust gas temperatures, as the figure shows the exhaust gas temperature increased with increasing engine torque, while it decreased with increasing EGR ratio. The decrements in exhaust gas temperatures were (10.56, 18.4 and 25.77%) for (10, 20 & 30%) added EGR compared to 0% EGR, respectively.

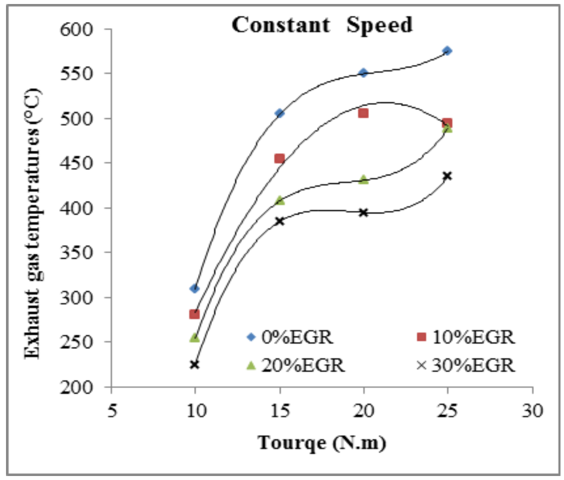

Fig. 13. EGR effect on exhaust gas temperatures at variable engine loads and constant speed

Conclusions

Tests were conducted using a single cylinder spark ignition engine operated with adding variable rates of EGR, to evaluate the effect of this addition on the emitted engine emissions. The results clarified that:

1. CO_2 concentration increased with speed and torque increase, while it decreased with increasing EGR ratio.
2. NOx concentration decreased highly with increase EGR percentage at variable engine speeds and constant torque. Also, it decreased when the engine run at a constant speed and variable engine torque.
3. EGR addition increased the CO& HC concentration significantly, for all added rates.
4. The exhaust gas temperature increased with increasing of engine speed and torque, and it decreased with increasing EGR ratio.

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