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Combustion and Emissions Characteristics for DI Diesel Engine Run by Partially-Premixed (PPCI) Low Temperature Combustion (LTC) Mode

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ABSTRACT

This study discusses the partially-premixed combustion (PPC) concept. PPC is a combustion concept by which it is possible to get low PM and NOx concentrations simultaneously. Gasoline/diesel fuel blends as an alternative fuel with high cooled EGR levels accompanied with injection timings sufficiently early to extend the ignition delay. The air and fuel will be mixed extensively prior to combustion. These factors were used to determine the PCC mode operation effects on the performance and emissions characteristics of a DI four-cylinder diesel engine. Gasoline/diesel fuel blends containing 50% gasoline in volume basis were prepared and tested. Experiments were carried out at a constant speed (1500 rpm) and variable engine load. EGR was cooled using a heat exchanger system designed to reduce the EGR temperature. Three EGR rates (30, 40 and 50%) were used with gasoline-diesel blend. The results indicate that fueling the test engine with gasoline/diesel blends caused a reduction in the brake thermal efficiency, while the brake specific fuel consumption increased with proportion to EGR rates. The gasoline/diesel fuel blend properties affected the combustion and emission characteristics in addition to PPC operation used. They caused reductions in NOx and PM concentrations. However, unburned HC and CO concentrations were obviously increased.

Keywords: gasoline/diesel blend, partially premixed combustion, Performance, NOx, PM, emission.

1.INTRODUCTION

Environmental pollution and energy depletion created by transportation have made strict emission regulation, in the last two decades [16]. There is a progressive interest in the alternative fuel use in vehicles due to the impact of the transportation sector on greenhouse gases and human health, and limited petroleum sources [3]. Direct-injection diesel engines have proved to be an efficient option in heavy-duty applications like transportation or power generation. However, due to the natural conditions of high pressure and temperature in the combustion process, diesel engines emit considerable amounts of pollutants, especially nitrogen oxides (NOx) and PM (particulate matter) [10]. Hence there is a great deal of interest to developing engine combustion systems that offer the efficiency of a diesel engine, but with low PM and NOx. The emissions of NOx and PM produced by locally excessive combustion temperatures or fuel richness are a typical problem for diesel engine technology [11]. NOx includes the chemical species NO and NO_2 produced at high temperatures in the combustion chamber from both N_2 in the air used by the engine and sometimes from fuel-borne nitrogen. In the atmosphere, NO and NO_2 are in thermodynamic equilibrium depending on the amount of solar irradiation. NOx reacts with moisture in the air and other elements to eventually form nitric acid, one of the most water soluble gases found the atmosphere thus contributing to acid rain. NOx also reacts with VOCs via the OH radical in the atmosphere in the presence of sunlight to make troposphere ozone, more commonly known as smog. Ground level ozone has been definitively linked with respiratory disease in humans [30]. PM includes all solid and liquid-phase compounds, except water, in the atmosphere. Diesel engines emit PM as both carbonaceous soot and organic species forming mainly from rich partial combustion processes and from collection on established particle nuclei in the exhaust. The health effects of particulates are many and sometimes proceed through complex pathways. Although PM from engines is generally regulated on a mass basis, its health effects are more dependent on the size of the particle. The size ranges of particles are defined in many different ways. In the discussion of PM emissions, the terminology PM2.5 and PM10 are generally used to define particles of size 2.5 μm and smaller and 10 μm and smaller respectively. Nano-particles are defined as those with diameters less than 100 nm [5]-[8]. The HCCI (homogenous charge compression ignition) combustion technique has shown promising results in terms of near-zero NOx and PM emissions [9]. One promising approach is that of Partially-premixed Compression Ignition (PPCI) or Low Temperature Combustion (LTC) mode [29]. If standard diesel combustion is black and HCCI is white, PPC is some shade of gray. If it is light gray much of the fuel is mixed with air before combustion, and if it is dark gray combustion is more stratified

and resembles diesel diffusion combustion [32]. PCCI (premixed charge compression ignition) combustion, which is a kind of HCCI, has recently drawn substantial attention [13]-[26]. The concept of PCCI combustion is to enhance the process of air and fuel mixing such that premixed combustion occurs simultaneously across the combustion chamber without diffusion flame [17]. Partially-premixed Combustion (PPC) is a combustion engine concept which is achieved through high EGR levels in combination with an injection timing adjusted to get an ignition delay long enough for the air and fuel to mix before combustion [20]. Injection strategies providing ignition delays sufficient for PPC can be found for retarded injection timing as in [21]-[27] or advanced injection timings seen in [12]-[15]-[22]-[33]. The ignition delay may also be extended by using lower cetane fuels as in [23] or lower compression ratio as in [24]. The PPC strategy is able to combine low smoke and NOx emissions while having a combustion controllability that is higher than that of Homogenous Charge Compression Ignition (HCCI). It is of interest to be able to use this combustion strategy in a large operating region in order to meet future emission legislations [2]. However, there are dramatic increases in unburned hydrocarbon (HC) and carbon monoxide (CO) emissions with ultra-high EGR and LTC [19]-[31]. In addition to the common sources of HC and CO emissions such as over-mixing of fuel during the ignition delay period in conventional diesel combustion, there are further causes contributing to the increases of HC and CO emissions in ultra-high EGR low temperature combustion. Firstly, bulk quenching of mixture during the gas expansion owing to lowered peak combustion temperatures with ultra-high EGR can be a significant source of HC and CO emissions [6]. Next, fuel-air over-mixing at the spray tails after the end of injection has been observed in experiments with both constant-volume vessels and optical engines under conditions simulating diesel LTC, and the mixtures here are too lean to support complete combustion, becoming a source of HC and CO emissions [14]. Moreover, owing to the increases in ignition delays with ultra-high EGR, advanced fuel injection is commonly necessary to avoid deterioration in the torque output; as a result, fuel missing the piston bowls and entering the squish zones can be considered as a further source of HC and CO emissions [25]. Thus, the main objective of this investigation has been to improve the knowledge of using gasoline/diesel blends and the influence of PPCC mode on NOx and PM simultaneous reduction, without efficiency being jeopardized much in a DI diesel engine. Major improvements were considered as the rates of cooled EGR on mixture formation, accompanied with the effects of advanced injection timing in low-temperature combustion conditions, in order to reduce PM-NOx engine-out emissions using better air-fuel mixing before the start combustion.

2.EXPERIMENTAL SETUP

2.1 Equipment

The experimental apparatus of the engine under study is a direct injection, water cooled four cylinders, in-line, natural aspirated Fiat diesel engine whose major specifications are shown in Table 1. The engine is coupled with a hydraulic dynamometer through which load is applied by increasing the torque. The Multigas mode 4880 emissions analyzer was used to measure the concentration of nitrogen oxide (NOx), unburned total hydrocarbon (HC), CO_2 and CO. Low volume air sampler type Sniffer L-30 was used to collect emitted PMs. Whatmann-glass micro-filters were used to collect PMs. These filters were weighted before and after the end of sampling operation which extended for half an hour. Each filter was kept in a plastic bag temporarily till the end of collecting samples operation. These filters then are weighted and analyzed. Particulate matters (PMs) concentrations were determined by the equation:

$$PM \;\; in \left(\mu g / m^3\right) = \frac{w_2 - w_1}{Vt} \times 10^6 \quad (1)$$

Where: *PM* = particulate matters concentration in (μg/m^3).
w_1 = filter weight before sampling operation in (g).
w_2 = filter weight after sampling operation in (g).
Vt = drawn air total volume (m^3)
Vt can be found by the equation:

$$Vt = Q_t \cdot t \quad (2)$$

Where: Q_t= elementary and final air flow rate through the device (m^3/sec).
t = sampling time in (min).

Overall sound pressure was measured by a precision sound level meter supplied with microphone type 4615, and the device was calibrated by standard calibrator type pisto phone 4220. The EGR system used in the present study was type Prodit; and consisted of a heat exchanger in which hot exhaust gas could be cooled to the desired temperature (70^{o}C in the present study) by circulating water. In each test, three EGR mass ratios of 30, 40 and 50 percent were investigated. It should also be noted that when the EGR is introduced, the engine load was slightly readjusted by the dynamometer to achieve the specified engine speed. The EGR rate is calculated as follows [7]:

$$EGR\ (\%) = \frac{\dot{m}_{EGR}}{\dot{m}_{EGR}+\dot{m}_a} \times 100 \qquad (4)$$

Where m_{EGR} is the mass flow rate of EGR and m_a is the mass flow rate of fresh air. In order to determine cooled EGR, the water valve should be opened to achieve a desirable EGR temperature.

Table 1: Tested engine specifications

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

2.2 Preparation of the used fuel

Commercial Iraqi diesel and gasoline fuels were used in this work. Iraqi diesel fuel is characterized by its high sulfur content (it was 10000 ppm in the present tested fuel) and moderate cetane number (49 in the present study). Also, Iraqi gasoline was characterized by its high sulfur content (500 ppm) and moderate octane number (82 in the present work).

Table 2: Properties of conventional diesel fuel and Gasoline

Property		Diesel	Gasoline
Density	(kg/m^3)	820	682
Cetane number		48.5	17
Lower heating value	(MJ/kg)	42.31	42.4
Viscosity	(cSt)	2.87	0.44
Final boiling point	(^oC)	369.8	78
Element analysis			
C%	(w/w)	86	85
H%	(w/w)	12.935	15
S%	(w/w)	1	-
N%	(w/w)	0.065	-
O%	(w/w)	-	-
Molecular weight	(g/mole)	211	105

The gasoline-diesel blended fuels were formed by blending together the following components: diesel fuel, gasoline and cetane number improver. Cetane number improver was used to compensate for the reduction in blend cetane number attendant to gasoline addition. The blending protocol was first to blend the cetane number improver (2% v/v for all gasoline–diesel blended fuels) into gasoline, and then blend this mixture into the diesel fuel, and then the gasoline/diesel blend was prepared. One tested blend was prepared; it consisted of 50% gasoline, 48% diesel fuel and 2% cetane number (CN) improver. The presence of gasoline generates different modifications of diesel fuel, notably reductions of the cetane number, lower heat content, viscosity, flash point, and pour point. These modifications changed the spray evaporation properties, combustion performance, and engine-out emissions.

2.3 Error analysis

Measurement accuracy represents the reliance potential extent of the study results. The error sources were defined through calibrating the measuring equipment used, and the uncertainty in this study was determined. Table 3 shows the measuring device and its calibration accuracy. The uncertainty can be defined as [4]:

$$e_R = \left[\left(\frac{\partial R}{\partial V_1} e_1\right)^2 + \left(\frac{\partial R}{\partial V_2} e_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial V_n} e_n\right)^2\right]^{0.5} \qquad (4)$$

Where:

e_R results uncertainty.

R function consists of variables or R=R (V_1, V_2, …, V_n).

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e_i variable uncertainty range.

The partial derivative $\frac{\partial R}{\partial V_1}$ represents results sensitivity for a single variable. Hence, the uncertainty for the present study results was:

$$e_R = \begin{bmatrix} (0.045)^2 + (1)^2 + (0.07)^2 + (0.95)^2 + (0.98)^2 + (1.24)^2 + (0.7)^2 \\ +(0.022)^2 + (1.09)^2 \end{bmatrix}^{0.5} = \mp 2.366\ \%$$

This result confirms that an uncertainty of less than 5% in measurement of the present study was achieved. For each condition, three tests were conducted to minimize random errors in the experiments. From the results of these experiments for each condition, the average value is reported along with more than 95% confidence intervals.

Table 3: Experimental Accuracies

Measurements	Accuracies in present study
Thermocouples	0.045
Volume measurement	1
Air flow meter	0.07
Fuel flow meter	0.95
Engine speed	0.98
Engine torque	1.24
Sound pressure level	0.7
Emitted exhaust gases concentrations	0.022
PM concentrations measurement	1.09

2.4 Tests Procedure

In the experiments, the gasoline/diesel blend was used to operate the engine on PPC mode, using three cooled EGR rates and advanced injection timing (50°BTDC). This injection timing was used depending on many references, such as [20]-[28]-[33]. The tests were conducted with variable loads at 1500 rpm engine speed. Meanwhile, performance and emissions characteristics were measured and analyzed. Furthermore, these parameters were compared with those of pure diesel combustion in order to clarify the effect of gasoline/diesel blend and LTC operation mode on combustion.

3.RESULTS AND DISCUSSIONS

Brake specific fuel consumption (bsfc) of test fuels is shown in **fig. 1**. BSFC descends from lower to medium loads level then raises again from medium to high loads. BSFC increased for all tested EGR rates. The increments were about 4.68%, 7.7% and 14.37% for EGR rates equal 30, 40 and 50% respectively compared with neat diesel fuel. The rate of heat release was found to increase with increasing EGR rates. Experimental investigations showed that the mixture is better prepared due to prolonged ignition delay, but the extra cooling of the combustion chamber and the extra-dilution of the charge caused these increments in BSFC.

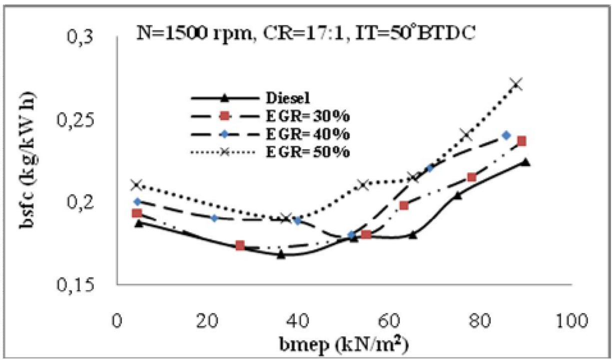

Figure 1 PPC mode operation effect on bsfc for variable range of loads

The diesel engine gave better brake thermal efficiencies for all tested loads, while gasoline/diesel blend engine records a decline in resulting brake thermal efficiencies for all tested loads, as **fig. 2** represents. Brake thermal efficiency deteriorates for gasoline /diesel blend because of mixture temperature reduction due to the effect of cooling concomitant with high rates of EGR, which reduced combustion chamber temperature and pressure, hence elongating the delay period, and this reduced the output power; and increased specific fuel consumption in addition to incomplete combustion.

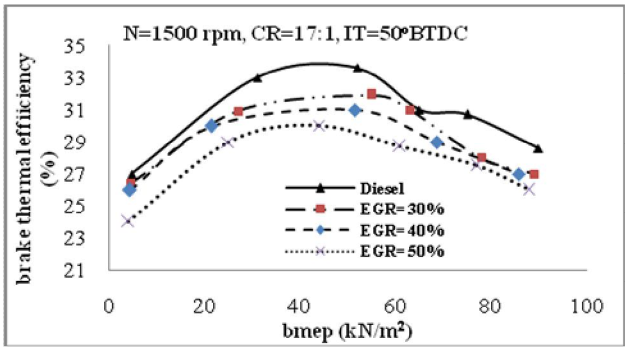

Figure 2 PPC mode operation effect on brake thermal efficiency for variable range of loads

Fig. 3 represents the resulting exhaust gas temperatures with PPC mode: these temperatures reduced for all tested EGR rates. The reduction was 21.3%, 33.44% and 40.43% for EGR rates equal to 30, 40 and 50% respectively compared to diesel fuel.

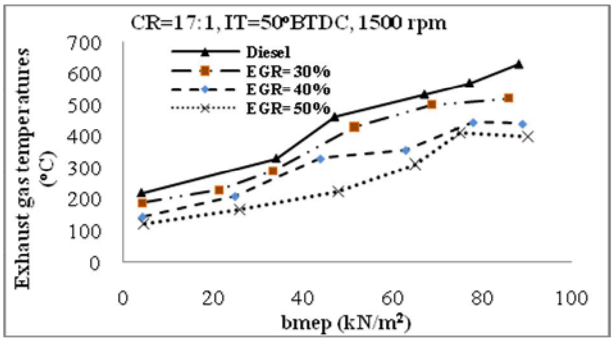

Figure 3 PPC mode operation effect on exhaust gas temperatures for variable range of loads

The variation of NOx formation with load is shown in **fig. 4** at constant engine speed and compression ratio for diesel combustion. NOx concentrations are increasing with load as the mass of fuel injection is increasing which gives higher flame temperature. The figure shows the NOx concentration rates with PPC and LTC mode. From the experimental results, it is found that 25.94, 50.9 and 84% of reductions in NOx concentrations are achieved with 30, 40 and 50% EGR rates compared with diesel respectively. The use of high EGR rate obviously leads to a reduction in the NOx emission rate. When EGR rate is increased above 40%, results show that the amount of NOx moves to nearly zero. As it has been found by many researchers, much of the NOx is formed in the zones up to the peak of the heat release rate. Hence, the heat release rate up to its peak value greatly affects the NOx formation. It is also known that the NO formation is very sensitive to the gas temperature during combustion.

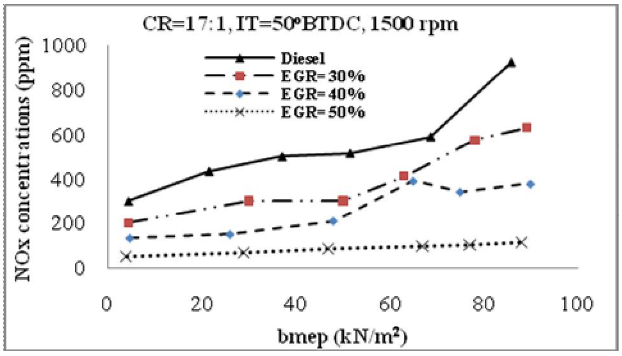

Figure 4 PPC mode operation effect on NOx concentrations for variable range of loads

PM concentrations reduced remarkably, as **fig. 5** demonstrates. Two factors contribute to this trend: First, the reduction in sulfur content (which assists in a higher probability of agglomeration of particulate matters) due to gasoline addition. Secondly, the lower exhaust temperatures due to high cooled EGR rates decelerate the PM formation process. The reductions in PM concentrations for the whole tested load range were 32, 41.7 and 70.97% for EGR rates of 30, 40 and 50% respectively compared with neat diesel. The figure clarifies that PM concentrations are insignificantly reduced at low loads, while at high loads the reductions are higher. The present results agree with [10]'s results.

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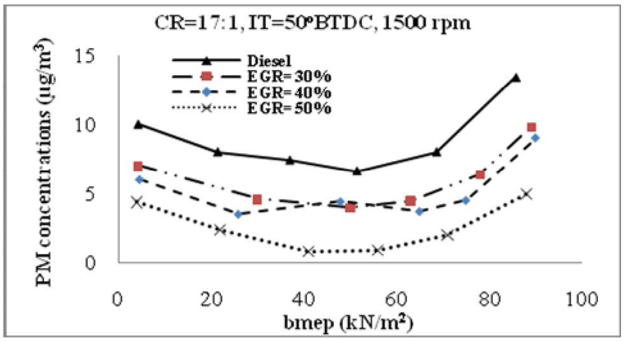

Figure 5 PPC mode operation effect on PM concentrations for variable range of loads

The effect of LTC mode and different EGR rates on the overall PM emission can be seen in Fig. 5. Firstly, high cooled EGR rates accompanied with intake charge dilution and reduction of in-cylinder oxygen concentration decrease air-fuel ratio. Hence, PM formation must be increased. However, when the EGR rates exceed a critical point, PM formation decreases sharply. As a result, it can be said that increasing cooling EGR rate to 50% decreases the PM emission level but it cannot totally eliminate it as the figure indicates. In order to explain this reduction in PM with increasing EGR rates, the effect of temperature on PM formation should be investigated. It has been investigated by [1]-[18] at very low load engine conditions. Further explanation of NOx and PM concentration reduction, can be seen in Figs. 4 & 5. It is well known that with oxygen availability and high temperature conditions satisfied NOx formation increases. However, high EGR level decreases the local high temperature regions and flame temperature due to reduction in oxygen flow rate to the engine, and increases the specific heat of the charge in conjunction with introducing exhaust gas. Therefore, NOx emissions are gradually reduced, especially for the conditions of combustion temperature below 2000 K. The maximum PM concentration can be found at intermediate flame temperatures (i.e., 1600 to 2000 K), where PAH (Polycyclic Aromatic Hydrocarbons) and tar formation and their transformation to PM particles exist. At low temperature flames, the rate of oxidation of PAH is very low, and because the temperature is too low to induce the coagulation of PAH into PM, the rate of PM formation is reduced and total incylinder PM concentrations decreases. The combustion condition of the 50% EGR case does not enter the high PM formation region as shown in Fig. 5. Namely, if the temperature is kept below approximately 1600 K, both the NOx and PM formation rates can be reduced. This concept is referred to as low temperature combustion (LTC).Fig. 6 shows that unburnt hydrocarbons (HC) increased for EGR rates with about 9.6, 27.04 & 40.02% for EGR rates 30, 40 & 50% respectively compared with neat diesel fuel. Connecting these results with the use of PCCI mode, it can be observed that with PCCI the HC emissions were typically higher. Even with a high percentage of gasoline in the blend, PCCI still produced higher HC concentrations. It should be noted that high levels of HC are an indicator of poor fuel efficiency. The early fuel injection accompanied with low temperatures inside the combustion chamber due to high EGR rates, caused higher concentrations of HC because of partial quenching in the squish area.

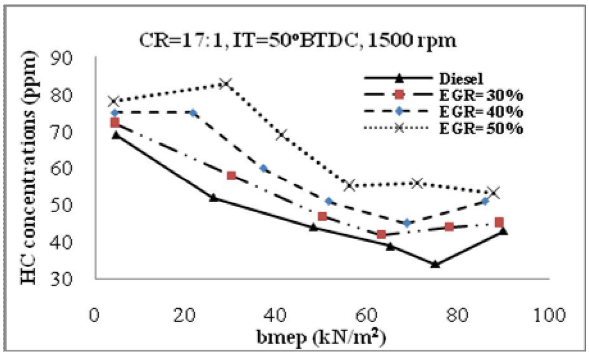

Figure 6 PPC mode operation effect on unburnt hydrocarbons concentrations for variable range of loads

CO concentrations increased for all EGR rates with PPC mode about 10.4, 21.69 and 40.4% for 30, 40 and 50% of EGR respectively. Increasing cooled EGR complicated the burning phenomena and reduced the combustion quality, causing these increments in CO concentrations, as **fig. 7** represent. Gasoline presence in the blend reduces the carbon-hydrogen percentage which must reduce CO concentration theoretically. Also working with lean mixtures as in compression ignition engines reduces CO concentrations. But high rates of cooled EGR as in PPC mode reduce the oxygen content in the entering charge. On the other hand, the reduction in combustion chamber temperatures makes part of the hydrocarbons oxidize partially producing higher HC and CO concentrations.

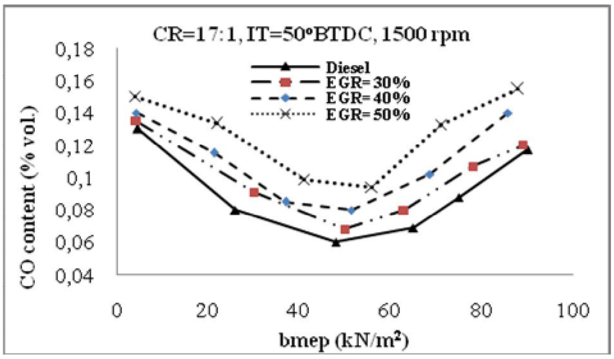

Figure 7 PPC mode operation effect on CO concentrations for variable range of loads

As mentioned in the last figures, low temperature with high EGR rates reduced CO_2 concentrations about 17.16, 18.6 & 29.75% for EGR rates of 30, 40 and 50% respectively compared to diesel fuel. This is reasonable because increasing HC and CO cause reduction in CO_2 concentrations, as fig. 8 represents, because the increment in HC and CO concentrations was brought forward from CO_2 quotient. The diesel engine is known to produce much more noise than that produced by a spark ignition engine. Noise is transmitted throughout the engine block as vibration, which can cause audible noise to the human ear at a different spectrum of frequencies. In the previous tests engine noise was measured, as fig. 9 shows. PPC mode operation reduced noise by 2.4, 4 and 8.7% for EGR rates of 30, 40 and 50% respectively compared with the neat diesel engine. Advancing the fuel injection timing is effective to extend the premixing time and improve the fuel-air mixing, but with the high intake oxygen concentration and high cetane numbers, this strategy significantly increases the maximum rate of pressure rise and the engine noise.

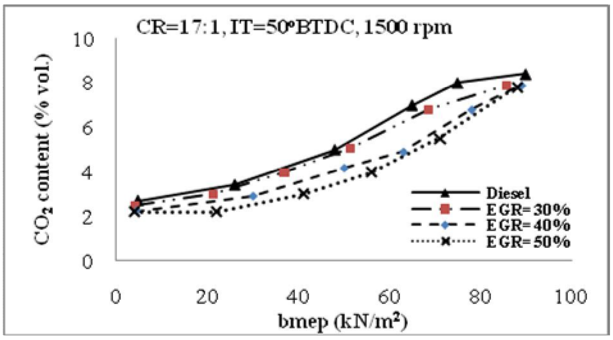

Figure 8 PPC mode operation effect on CO_2 concentrations for variable range of loads

This is not the situation here; gasoline existence reduced blend cetane number despite the addition of CN improver, which improved blend cetane number somewhat. LTC mode operation reduces combustion chamber temperatures, and then it reduces the maximum of pressure rise. These conditions meet together resulting in lower engine noise.

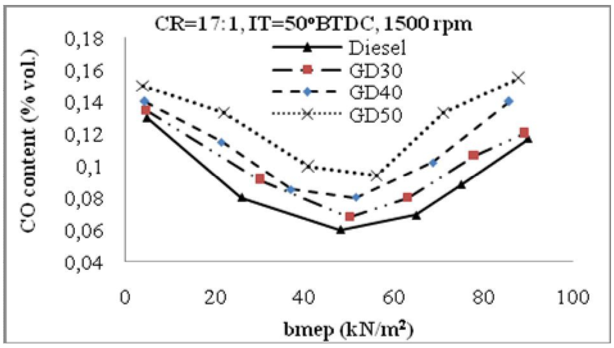

Figure 9 PPC mode operation effect on engine noise for variable range of loads

4.CONCLUSIONS

In the present work, partially-premixed compression ignition (PPCI) and low temperature combustion (LTC) modes concepts were studied. The effects of low temperature combustion conditions, advanced injection timing and adding gasoline to diesel fuel, combustion and emissions characteristics have been investigated for the DI Fiat diesel engine at constant engine speed (1500 rpm) and variable loads. Based on the above results one can conclude:

1-Using PPC mode increases BSFC, and the increment percentage was proportional with EGR rates. The increase in BSFC is compensated by decreasing of NOx and PM concentrations.
2-High EGR rates increase ignition delay due to lower in-cylinder temperature.
3-Increasing EGR rate to 50% reduces PM formation rate because in-cylinder temperature has been kept lower than 1600 K.
4-50% cooled EGR rate reduces the PM concentrations but cannot totally eliminate it, because some portions of rich mixture existed.
5-NOx emission is reduced to nearly zero associated with lower peak value of premixed combustion at 50% EGR rate. The peak value of in-cylinder pressure and temperature is decreased at higher EGR rates. This is because of slow heat release rate in conjunction with higher dilution effect and heat capacity effect at higher EGR rates.
6-Increasing EGR rates results in a distinct increase in HC and CO emissions but a slight reduction in engine noise.

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NOMENCLATURE

TDC	top dead centre
BMEP	brake mean effective pressure
BSFC	brake specific fuel consumption
BTE	brake thermal efficiency
CA	crank angle
IT	injection timing
UBHC	unburned hydrocarbons
NOx	nitrogen oxides
PM	Particulate matters concentration in (μg/m^3)
w_1	filter weight before sampling operation in (g).
w_2	filter weight after sampling operation in (g).
Vt	drawn air total volume (m^3)
Q_t	elementary and final air flow rate through the device (m^3/sec).
t	sampling time in (min).
e_R	Uncertainty in the results
R	a given function of the independent variables $V_1, V_2, \ldots, V_n$ or $R=R(V_1, V_2, \ldots, V_n)$.
ei	Uncertainty interval in the nth variable.

AUTHOR

Miqdam Tariq Chaichan received the B.S. in Mechanical Engineering from Baghdad University in 1982 and M.S. degrees in Power Generation from University of Technology in 1989. Since 1999, he tough in several universities and investigated in many fields like fuel and combustion, ICE, alternative fuels, Solar and Sustainable Energy. He is now Assistant Professor in Mechanical Engineering Dept., University of Technology; Baghdad, Iraq.