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The impact of equivalence ratio on performance and emissions of a hydrogen-diesel dual fuel engine with cooled exhaust gas recirculation

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Abstract— The employment of hydrogen as a fuel in a diesel engine or dual fuel engine researched since mid 70's of the last century. As an alternative fuel, many researchers suggested hydrogen for two aspects: fuel economy and emission.
In this study, the influence of cooled EGR on the engine performance and emissions of 4-cylinder duel fuel engine fueled with hydrogen and diesel investigated. The effect of the air-fuel ratio (AFR) at constant engine speed (1500rpm) and optimum injection timing is presented.
The acquired results show that the engine performance and emissions strongly influenced by air fuel ratio and optimum injection timing. Also, using cooled EGR has a significant effect on performance and emissions. The results indicate a trade-off between hydrogen and EGR addition. Adding hydrogen increased NOx concentrations and reduced PM, while adding cooled EGR reduced NOx and increased PM concentrations. The resulted NOx and PM concentrations were the product of these two parameters.

Index Terms— Direct injection engine, Injection timing, Engine performance, Air fuel ratio, Hydrogen fuel, dual fuel, cooled EGR, NOx, PM.

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1 INTRODUCTION

Both nitrogen oxide and smoke cannot be reduced simultaneously in diesel engines. This problem studied intensively for years. Using gaseous fuel was one of the solutions. The suggested procedure was to introduce gaseous fuel in the intake port, and the combustion starts by injecting light oil. This method is called dual fuel engine [1].

Most research in dual fuel engine has concentrated on defining the extent of dual fueling and its effect on emissions and performance [2], [3]. Natural gas in combination with diesel was tested and found to be very effective in NOx reduction. However, the engine operation suffered from high hydrocarbons (HC) emissions and poor performance, especially at high loads [4], [5].

Experimental investigation of an LPG–diesel dual fuel engine by [6], [7] illustrated that the brake thermal efficiency is always lower than diesel values at low loads, but it is better at high loads. Also, increasing the pilot quantity and intake temperature at low outputs improves the thermal efficiency. The HC and CO concentrations increased in the dual fuel mode operation.

A long history of studies investigated using hydrogen as a fuel for automotive internal combustion engines in academic and industry circles. Hydrogen distinguishes by its wide flammability limits compared to gasoline [8], [9]. Thus, the engines fueled with hydrogen can operate under extremely high levels of dilution (either ultra-lean or with high levels of EGR) – resulting in high efficiency and low emissions [10]. Table 1 illustrates diesel fuel, and hydrogen properties.

The effect of hydrogen addition on engine performance and emissions has been researched extensively [11], [12]. The engine performance was reported to increase slightly with the hydrogen addition at high load. Hydrogen greatly reduces emission levels but with reduced power [13]. In other hand, when hydrogen accompanied with diesel in dual fuel mode, the engine emits low NOx, CO and particulate matter emission levels while increasing engine efficiency by 13-16% [14], [15].

TABLE 1

PROPERTIES OF DIESEL AND HYDROGEN [12], [22]

Properties		Diesel	Hydrogen
Formula		Cn H1.8n C8-C20	H_2
Auto ignition temperature	(K)	533	858
Lower heating value	(MJ/kg)	42.5	119.93
Density	(kg/m^3)	833-881	0.08
Molecular weight	(g/mole)	170	2.016
Flammability limits in air	(vol %)	0.7- 5	4-75
Flame velocity	(m/s)	0.3	2.65-3.25
Boiling point	(K)	453-653	20.2
Cetane number		40-60	-
Octane number		30	130
Mass diffusivity in air	(cm^2/s)	-	0.61
Min. ignition energy	(mJ)	-	0.02
CO_2 emission percent	(%)	13.4	0

Previous investigations in dual-fuel combustion show that hydrogen enriched engines the achievement in fuel economy reached between 7% and 10% [16], [17]. However, a trade-off between improving fuel economy and managing nitric oxides (NOx) emissions exists in compression ignition engines [18].

EGR is used to reduce the large heat difference between peak pressure and intake pressure [19]. Adding EGR to the intake increases its temperature and certainly assists in the mixtures auto-ignition. EGR addition increases the engine brake thermal efficiency (BTE), and reduces the NOx formation as well [20]. Furthermore, EGR reduces the peak in-cylinder pressure that results in enhancing the fuel auto-

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ignition. EGR employment in a diesel engine resulted in 1.1% enhancement in engine efficiency. It advanced the auto-ignition by 10° CA and reduced the heat release rate by 11 % compared to diesel fuel [21], [22].

The utilization of thermal dilution techniques such as cooled exhaust gas recirculation (EGR) lessens the temperature of combustion, cools the hot spots [23], [24]. Cooled exhaust gas recirculation (EGR) is a common way to control in-cylinder NOx production and nowadays the most modern high-speed direct injection (HSDI) diesel engines using this technique. However, the variable impacts of EGR on combustion and emitted emissions are difficult to distinguish. It increases the intake temperature, delays the rate of heat release, and decrease the peak heat release. Also, it decreases the oxygen concentration (and thus of global air/fuel ratio (AFR)) and flame temperature). Thus the effects of EGR on NOx and particulate matter (PM) concentrations are not perfectly understood, especially under high EGR rates [25], [26].

In the present study, experiments were conducted on hydrogen–diesel dual fuel direct injection four cylinders engine using cooled EGR. The engine operated at variable speed, variable injection timing, and variable load conditions. The amount of primary fuel, i.e. diesel admitted was varied, and hydrogen substituted for each load. The objective was to determine in detail the performance, emissions and combustion characteristics of the engine.

2 EXPERMINTAL SETUP

2.1 Used Fuels

The diesel fuel used throughout testing was conventional Iraqi diesel supplied by Al-Doura Refinery. Iraqi diesel fuel contains at least about 10000 ppm sulfur particles that are very high [25]. Reducing sulfur levels to 30 ppm or less are necessary to achieve a particle trapping efficiency of 73 percent or higher in particulate filters [27]. Both sulfur reduction and aromatic saturation take place in hydrotreating units [28]. Hydrogen is necessary to accomplish the corresponding chemical reactions; therefore, hydrogen can be considered as an enabling agent to produce ultra-low sulfur diesel fuel that causes PM emissions reductions that are realized by particle filters [29]. The used hydrogen supplied in compressed gas cylinders provided by General Company for Vegetable Oils. The hydrogen was of research grade, meaning that the company certified the hydrogen purity at 99.99%.

2.2 Test Engine and Accessories

The engine used in this research was 4-cylinders, water cooled and direct injection diesel Fiat engine. The engine specifications listed in Table 2. A hydraulic dynamometer connected to the engine was used to control the speed and load put on the engine. A rotary air flow meter is used to measure the air flow entering the engine. A fuel mass flow meter was used to measure the precise mass of fuel supplied to the engine. The meter determines the mass of fuel supplied to the engine over a set length of time. Exhaust gas temperatures were recorded using many Standard K-type thermocouples.

In the present work, the exhaust gas was recirculated externally by using pipes to route it to the intake system. The EGR ratio is the ratio of the amount of EGR to the charge aspired into an engine cylinder. In this study, the EGR ratio was calculated with the following equation:

$$EGR = (\dot{m}_{EGR})/(\dot{m}_{air} + \dot{m}_{EGR}) \tag{1}$$

Where: $\dot{m}_{EGR}$ - is the mass flow rate of EGR air, and $\dot{m}_{air}$ - is the mass flow rate of fresh air.

TABLE 2
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= 160o
	Nozzle opening pressure=40 Mpa

The flow EGR rate must defined exactly to enable the calculation of EGR ratios correctly. However, this is very difficult because of the high temperature and contamination by ash, soot, and unburned hydrocarbon. The recirculated exhaust gas was allowed to pass through a heat exchanger to reduce its temperature to 50°C, city water used as the cooling fluid.

Hydrogen fueling system consisted of the high-pressure regulator on the gaseous hydrogen high-pressure vessel. The gas was fed to the engine through a choked nozzles assembly that performed as a flame arrester, besides to its primary serve as hydrogen flow measuring device. It was used to ensure the safety of the laboratory and the operator. The Hydrogen supplied at room temperature and ambient pressure so as to avoid a temperature or pressure gradient between the hydrogen and the intake air as they mixed. The hydrogen introduced to the engine immediately below the air filter to enable sufficient mixing of the air and hydrogen prior to entering the inlet manifold. Therefore, discrepancies in the supplied quantity of hydrogen to each cylinder were eliminated that resulted in a stable running of the engine. The introduced Hydrogen measured as a percentage of the intake air volume. A simple and low-cost air-hydrogen mixer device designed, fabricated, and used to mix hydrogen with the inlet air.

A hydrogen vessel was employed to supply the engine with hydrogen fuel. The hydrogen bottle was located outside the engine test cell, secured in a trolley. This texture was important as the operator needed to have control over the hydrogen supply at all times – to make adjustments or shut off if necessary. The hydrogen was controlled manually, using a regulator valve mounted on the pressure vessel. From the valve, the hydrogen flowed through a ¼″ copper line to the nozzle, which injected the nozzle directly into the air intake stream in the inlet manifold.

The Multi-gas mode 4880 emissions analyzer was used to measure the concentration of nitrogen oxide (NOx). The analyzer detects the contents of CO_2, CO, HC, and O_2. A probe is used to pick up the gasses from the engine exhaust pipe. The exhaust gasses separated from the contained moisture by condensation and separation filter, and then they are conveyed in the measuring cell.

A precision sound level meter used to measure the overall sound pressure. The meter supplied with microphone type 4615 Italy made. A standard calibrator type pisto phone 4220 calibrated the noise level meter. It measures overall sound pressure in disciple units (dP).

In this study, no direct measurements of PM size were attempted due to a lack of suitable equipment. However, a selection of particulate matter samples was obtained by exposing filter material to a diesel exhaust stream at the end of tailpipe dilution point. The emitted PMs collected by using low volume air sampler; type Sniffer L-30. Whatmann-glass microfilters used to collect the PMs; they were weighted before the sampling operation and after its end. The sampling operations extend for one hour. The equation determined the PMs' concentrations:

$$PM\ in\ (\mu g/m\text{^}3\ = (w_1 - w_2\ /V_t\ ) \times (10)\text{^}6 \qquad (2)$$

Where: PM = particulate matters concentration in ($\mu g/m^3$).
w_1 = filter weight before sampling operation in (g).
w_2 = filter weight after sampling operation in (g).
V_t = drawn air total volume (m^3)
The equation can find V_t:

$$V_t = Q_t . t \qquad (3)$$

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

Each filter preserved temporarily in a plastic bag until finishing the collecting samples operation, analyzing and studying the results using a light microscope.

Safety Features

Safety is one the major concerns when a large quantity of hydrogen used in a closed medium. Many research articles identified the following safety concerns associated with hydrogen application in the engine research laboratory:

(1) The leakage of H_2 into engine laboratory;
(2) Better ventilation to eliminate the accumulation of hydrogen in the laboratory especially the ceiling area;
(3) Preventing the occurrence of backfire and relief of pressure;
(4) Shut down of H_2 fuel system in case of emergency and
(5) The avoidance of over-dosing of H_2 flow, which may result in abnormal combustion such as backfire and the onset of knock.

In this research, the following safety approaches were developed and implemented during the tests:

Leakage Test

Detailed leakage test was conducted using soap bubbles approach, before and during the testing period. Also, leakage test was carried out for connectors and high-pressure hydrogen line after the switching of hydrogen tanks.

Better Ventilation

The hydrogen fuel cylinder installed in a shed outside the laboratory and open to atmosphere. Any hydrogen leaked from this system would ventilate into the air without accumulation around the hydrogen fuel system. The ventilation of the laboratory was maintained by turning on the ceiling ventilation fan in the lab prior to the start of testing. The ceiling fan was kept running for at least 30 minutes after the finishing of the test.

Purging of the H_2 Fuel System with Pure N_2 after Each Test: After all tests had been finished, the hydrogen system from the mass flow controller to the H_2 regulator was purged and filled with pressurized gaseous N_2. Such purging was necessary to eliminate the potential H_2 leaking source when the engine was not running. The pressurization of the fuel system with N_2 was also considered as a safety procedure to remove the possibility of air entering the H_2 fuel system.

Elimination of Backfire Damage

The damage of backfire was eliminated through the implementation of the following approaches: The relief of the high pressure established in the intake system once backfire occurs. A pressure relief valve installed between the intake manifold and flame arrestor. The relief valve would blow off once the intake manifold pressure reached 50 psi for any reason. This value was demonstrated to be effective in eliminating the backfire hazards. During this research, the backfire occurred two times without causing any damage to the intake system or blowing off the pressure relief valve. To minimize the amount of H_2-air mixture burned by backfire: the choked nozzles assembly was installed in the intake system and acts as flame arrestor and used to quench the flame initiated by a backfire.

2.3 Test Procedure

The ultimate aim of this investigation was to determine the advantages in engine performance and emissions by using combined hydrogen and diesel fuel. Since, as has been shown by many articles, the carbon monoxide emissions, and filter smoke number always decrease with hydrogen addition. The injection strategy used in this study relied on operating the engine at the optimum injection timing.

The engine started on diesel fuel and allowed to settle at a steady speed without load. The hydrogen supply pressure increased to the correct setting. As the hydrogen flow rate was increased, the speed of the engine also increased, so the flow rate of the intake air was increased to maintain a constant intake pressure. Once the engine was running steadily on the correct settings NOx, CO, CO_2, HC and noise were measured. Also, the Sniffer L-3 was exposed to exhaust gas for an hour. The filters weighted before and after the end of the sampling operation, and PM concentrations were determined.

Variable types of test carried out during this investigation. In the first set, the engine run at speed (1500 rpm) on diesel fuel alone, then with hydrogen and diesel fuel, lastly cooled EGR added to the engine suction manifold. Optimum injection timing (OIT) and full load used for each tested point. The engine performance was studied in details, using supplementary hydrogen to diesel fuel with cooled EGR, to find the impact of engine speed, equivalence ratio, and injection timing on the engine performance.

The equivalence ratio which was determined from the measured air and fuel flow rates to the engine, defined as:

$$\emptyset = \frac{\text{stoichiometric} \quad \text{fuel /air ratio}}{\text{actual} \quad \text{fuel /air ratio}} \qquad (4)$$

The engine performance parameters calculated using the following equations:

Brake power

$$\mathrm{bp} = \frac{2\pi * N * T}{60 * 1000} \quad \mathrm{kW} \qquad (5)$$

Brake mean effective pressure

$$\mathrm{bmep} = \mathrm{bp} \times \frac{2*60}{V_{sn} * N} \quad \mathrm{kN/m^2} \qquad (6)$$

Fuel mass flow rate

$$\dot{m}_f = \frac{v_f \times 10^{-6}}{1000} \times \frac{\rho_f}{\text{time}} \quad {}^{\mathrm{kg}}/_{\mathrm{sec}} \qquad (7)$$

Air mass flow rate

$$\dot{m}_{a,act.} = \frac{12\sqrt{h_o * 0.85}}{3600} \times \rho_{air} \quad \frac{\mathrm{kg}}{\mathrm{sec}} \qquad (8)$$

$$\dot{m}_{a_{theo.}} = V_{s.n} \times \frac{N}{60*2} \times \rho_{air} \quad \frac{\mathrm{kg}}{\mathrm{sec}} \qquad (9)$$

Brake specific fuel consumption

$$\mathrm{bsfc} = \dot{m}_f / \mathrm{bp} \times 3600 \quad \mathrm{kg/(kW.hr)} \qquad (10)$$

Total fuel heat

$$Q_t = \dot{m}_f \times \mathrm{LCV} \quad \mathrm{kW} \qquad (11)$$

Brake thermal efficiency

$$\eta_{(bth.)} = \mathrm{bp}/Q_t \times 100 \quad \% \qquad (12)$$

3 RESULTS AND DISCUSSIONS

Fig 1 represents the effect of adding hydrogen and EGR on resulted brake power (bp) for a broad range of equivalence ratios. The brake power used as an effective comparison tool to measure engine performance and the produced power output over the full engine speed range. The figure illustrates the advantage of regulating the power with the air-fuel ratio. Hydrogen addition increased bp by about 30.72% due to its high burning velocity that improved combustion. Also, it increased the range of working equivalence ratios due to its wide flammability limits. Adding EGR to hydrogen-diesel duel fuel caused 8.04% reduction in bp compared to diesel. EGR took a part of the inner air and reduced combustion temperatures.

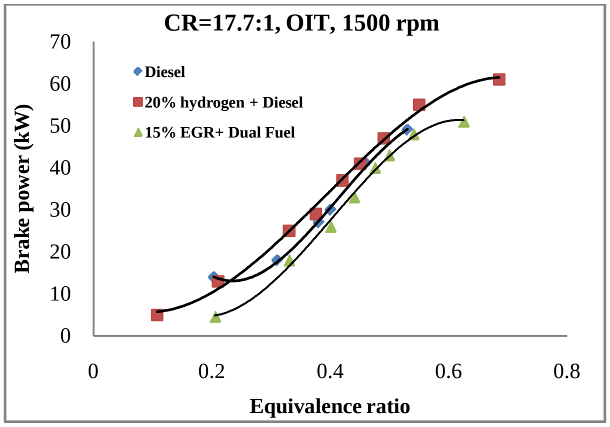

Fig. 1. The effect of hydrogen and cooled EGR addition on brake power for wide range of equivalence ratios

Fig. 2 shows the effect of adding hydrogen and EGR on brake specific fuel consumption (bsfc). Hydrogen extended the ultra lean limit equivalence ratio but at this limit bsfc increased. At this limit, the mixture combustion deteriorated because of small fuel quantity compared to air that produces low heating values. Adding EGR increased bsfc at very lean limits, but at the range of equivalence ratios that give the maximum bp it approached near diesel values. BSFC increased by about 25.85% with hydrogen addition, while it rose by 64.85% with adding EGR to duel fuel compared to diesel.

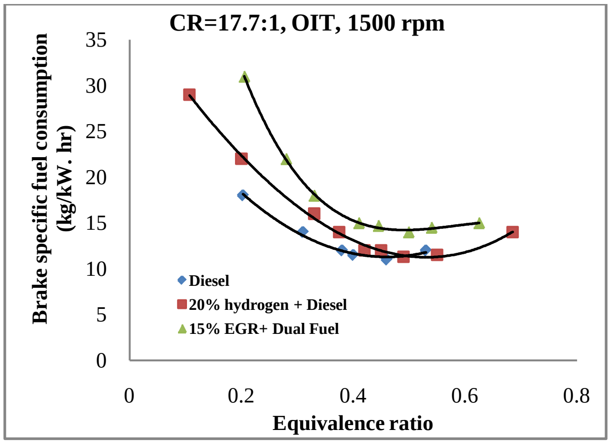

Fig. 2. The effect of hydrogen and cooled EGR addition on brake specific fuel consumption for wide range of equivalence ratios

Adding hydrogen to diesel reduced exhaust gas temperatures by about 5.44%, while adding cooled EGR to duel fuel reduced these temperatures by about 19.66%. This what Fig. 3 illustrates. Hydrogen heating value on a volume basis is lower than that for hydrogen causing this reduction in exhaust gas temperatures. Cooled EGR duty inside the combustion chamber is to reduce the resulted combustion temperatures. The results indicate the successes of added EGR in its duty.

Fig. 4 shows the effect of adding hydrogen to diesel fuel, and adding EGR to duel fuel on brake thermal efficiency. The engine brake thermal efficiency (BTE) is the ratio of brake power output to the power input and depicts the produced power by an engine with respect to the energy supplied by the fuel.

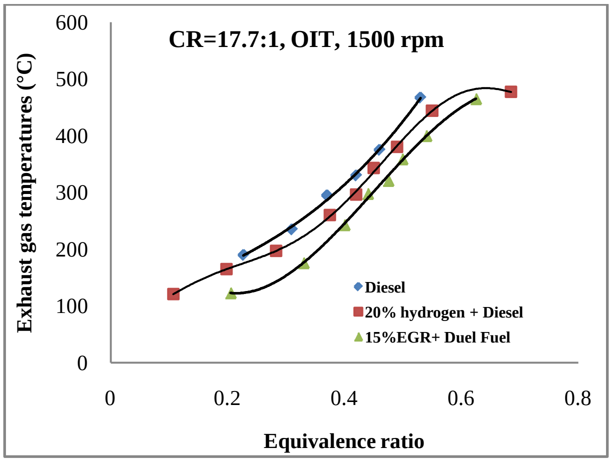

Fig. 3. The effect of hydrogen and cooled EGR addition on exhaust gas temperatures for wide range of equivalence ratios

Hydrogen addition effect appears at high equivalence ratios where the higher loads employed. Furthermore, hydrogen can operate with extremely lean mixtures and still maintain a relatively high efficiency compared to diesel engines.

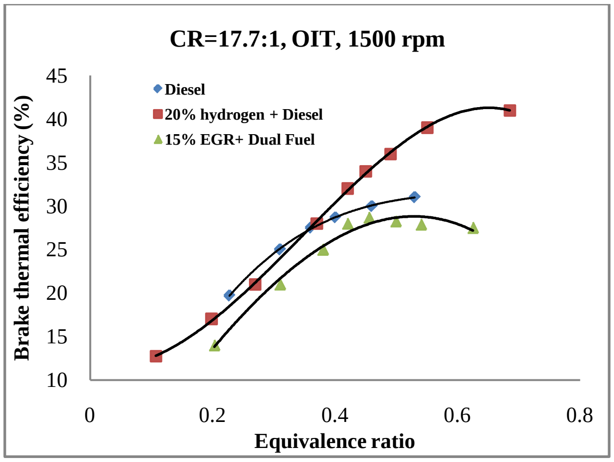

Fig. 4. The effect of hydrogen and cooled EGR addition on brake thermal efficiency for wide range of equivalence ratios

The increment in brake thermal efficiency was 21.78% with hydrogen addition. Szwaja and Grab-Rogalinski [30] found that the BTE was increased from 30.3% to 32% with 5% hydrogen. The lower BTE increment reason in the present study because the used fuel was Iraqi diesel fuel with high sulfur content [26]. Another reason is the used diesel fuel had CN=48.6 produced in Al-Doura refinery, Baghdad-Iraq. The cetane number (CN) expresses the readiness of the fuel to ignite spontaneously depending on the physical fuel properties (willing to evaporate). Also, it depends on the fuel chemical properties (speed of pre-flame reactions). The Cetane Number means a shorter ignition delay corresponds to a higher CN. The proper functioning of the engine needs a sufficiently high cetane number, greater than the used one [30]. The adding of cooled EGR reduced this efficiency with 6.76% compared to diesel fuel. Adding cooled EGR counteracts the effect of hydrogen addition. The resultant approaches diesel fuel act.

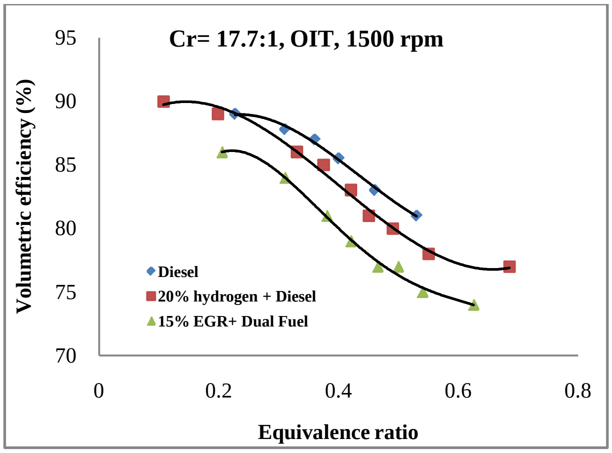

Fig. 5. The effect of hydrogen and cooled EGR addition on volumetric efficiency for wide range of equivalence ratios

Fig. 5 represents the effect of adding hydrogen and EGR on volumetric efficiency. Hydrogen (which is a very clean fuel because of the absence of carbon atoms) addition takes a part of air entering the combustion chamber, and that reduced the volumetric efficiency about 2.8%. While adding EGR to duel fuel reduced this efficiency about 6.5%.

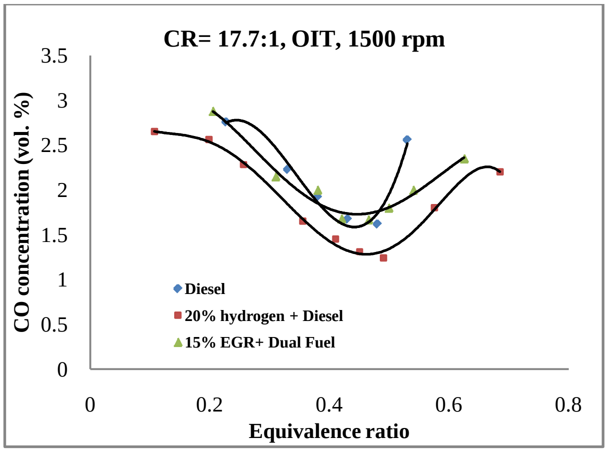

Fig. 6. The effect of hydrogen and cooled EGR addition on CO concentrations for wide range of equivalence ratios

Hydrogen addition reduced CO, CO_2 and unburnt hydrocarbon due to the increment in hydrogen molecules compared with carbon ones, also because of combustion improvement as a result of hydrogen addition. On the contrary adding EGR as all researchers approved increases these pollutants, as figures 6, 7 & 8 shows. The results indicate that the effect of hydrogen overcome EGR influence and the resulted CO reduction was 4.5%, the CO_2 reduction was 14.82%, and HC reduction was 11.14%.

Fig. 9 & 10 represented the interaction between NOx and PM concentration due to hydrogen and cooled EGR addition. Hydrogen addition opposed EGR addition, the first increased NOx and reduced PM concentrations. While the second reduced NOx and increased PM concentration. The resultant was the outcome of the interference between these two factors. For NOx emissions, it seems that cooled EGR effect dominated while hydrogen influences dominated on the resulting PM emissions. NOx concentrations compared to diesel fuel were reduced about 7.46%, while PM concentration reduced 2.53%.

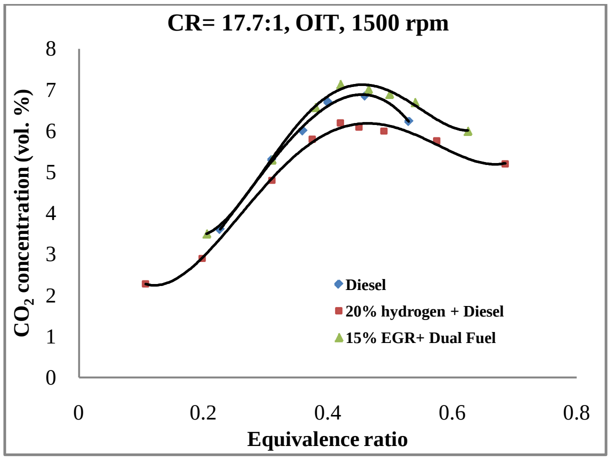

Fig. 7. The effect of hydrogen and cooled EGR addition on CO2 concentrations for wide range of equivalence ratios

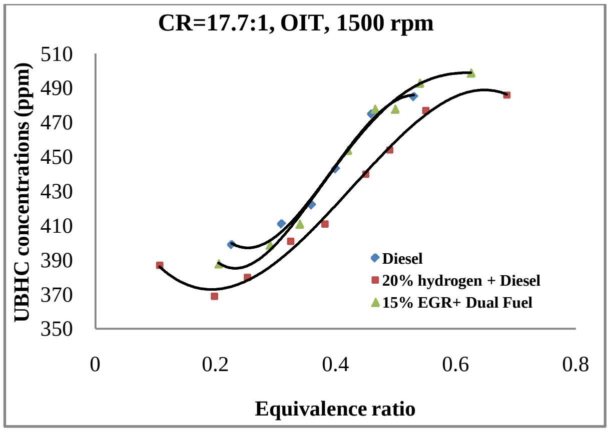

Fig. 8. The effect of hydrogen and cooled EGR addition on unburnt hydrocarbons concentrations for wide range of equivalence ratios

Fig. 11 showed the effect of hydrogen and cooled EGR addition on engine noise for a broad range of equivalence ratios. The presence of hydrogen inside combustion chamber improves combustion but makes it rough especially at high air-fuel ratios. Adding EGR decelerates combustion and makes it smoother in this range. This interference caused engine noise to reduce with about 3.79%.

4 CONCLUSIONS

Some effects of cooled EGR addition to a dual-fuel hydrogen diesel engine performance and emissions studied. An important conclusion from the work described above is that hydrogen as a fuel for ICE is rapidly gaining on traditionally fueled engines. Hydrogen increases the efficiency and it is very clean. Hydrogen mixed with air induced from the intake port and diesel injected into the cylinder in a direct injection diesel engine. The performance and the exhaust emissions were measured, and their relations discussed. The main results obtained in this study are as follows:

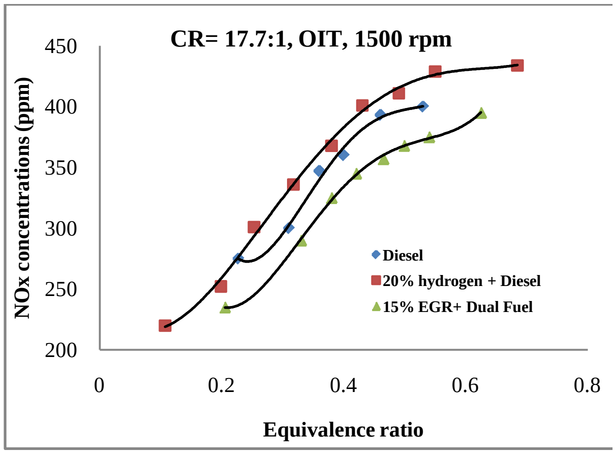

Fig. 9. The effect of hydrogen and cooled EGR addition on NOx concentrations for wide range of equivalence ratios

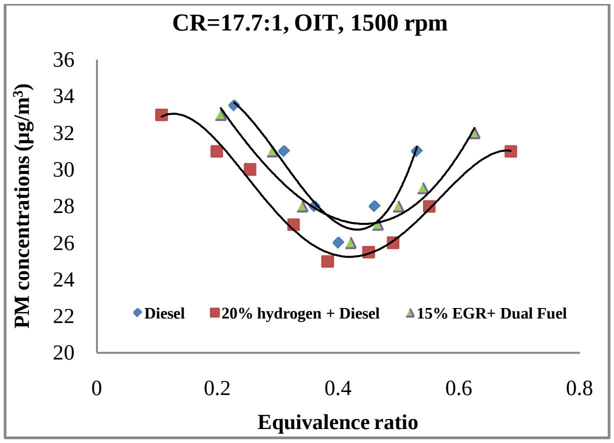

Fig. 10. The effect of hydrogen and cooled EGR addition on PM concentrations for wide range of equivalence ratios

1. Hydrogen can employed as a supplementary fuel in a diesel engine due to its conservation of diesel oil and reduction of exhaust pollutants. The results indicated clearly that the addition of diluents (EGR) reduced engine NOx emissions remarkably.
2. The performance can be improved by using hydrogen in the dual fuel mode with a significant reduction in emissions. Hence, the hydrogen fuelled engine can be operated smoothly in the dual fuel mode by optimizing the injection timing and duration.

3. The emissions of HC, CO, and CO_2 decreased when hydrogen added to the inlet air. However, brake thermal efficiency is slightly higher than that in ordinary diesel combustion.
4. At lean air-fuel ratio conditions, very low-NOx and PM emissions can obtain with cooled EGR accompanied by an increase in BSFC (that can be higher that 10%). CO, CO_2, and unburnt hydrocarbon emissions are at its minimum values.
5. Dilution can be used to increase specific power and control NOx. EGR extends higher load output over the normal operation and reduces NOx.

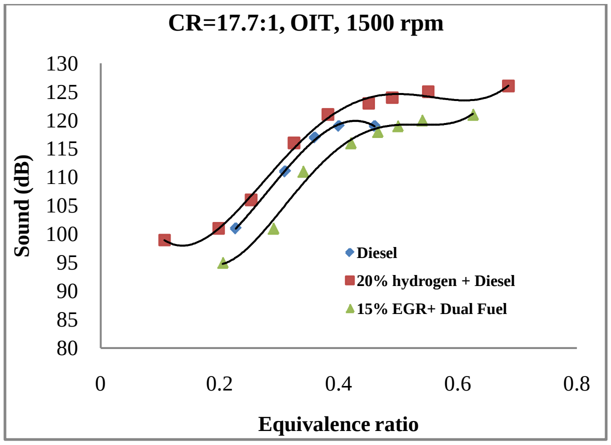

Fig. 11. the effect of hydrogen and cooled EGR addition on noise concentrations for wide range of equivalence ratios

6. An appropriate system designed specifically on the basis of hydrogen's combustion characteristics and cooled EGR addition can ensure smooth engine operational characteristics without any undesirable combustion phenomena. Lower engine noise can achieve.
7. An overall impression is that hydrogen has to be considered a future alternative CI fuel, because it has low engine-out emissions, which can improved further with emission control. The employing a modern fuel injection system that is capable of treating each air fuel ratio with its optimum injection timing can improve the hydrogen diesel dual fuel mode engine design.
8. Particles emitted from CI engines controlled with appropriate diesel particulate filters (DPFs) in the future. If hydrogen is added to diesel fuel, lower particle emissions from older engines, not equipped with DPFs may be possible. NOx emissions seem to be harder to control. Adding cooled EGR is, probably capable of achieving low NOx emission levels.

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NOTATIONS

bmep	brake mean effective pressure
BTE	brake thermal efficiency
CO_2	carbon dioxide
CO	carbon monoxide
CN	cetane number
CR	compression ratio
CA	crank angle
°BTDC	degree before top dead centre
DI	direct injection
N	engine speed (rpm)
T	engine torque
N	engine speed (rpm)
dB	decibel
IT	Injection timing
LCV	Lower calorific value
NOx	nitrogen oxides
PM	particulate matter
Vsn	swept volume
UBHC	unburnt hydrocarbon