The Effects of Hydrogen Addition to Diesel Fuel on the Emitted Particulate Matters

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Abstract— Particulate matter (PM) makes diesel engine exhaust contributes substantially to ambient air pollution. Many disease infections in the respiratory and the cardiovascular system are created by PM as proofed by several valuable articles. Particulate matters (PM) emitted from Automotives and stationary engines threaten the public health because PM carries polyaromatic carcinogenic hydrocarbons (PAHs). Several kinds of alternative fuels have been adopted and tested for diesel engines as an effort to reduce emitted PM from diesel engines.

The effects of load, speed, equivalence ratio and injection timing and hydrogen addition level on the exhausted particulate matter investigated in this article. The experiments performed on 4- cylinders, direct injection engine. Hydrogen induction was interred in three volumetric fractions 30, 50 and 70% vol. of the inlet charge. The addition of hydrogen dramatically altered the emitted particulate matter. The studied engine variables have appeared to have a large effect on resulted PM.

Keywords— PM, hydrogen, diesel fuel, injection timing, equivalence ratio, load, engine speed.

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1 INTRODUCTION

Diesel engines are the workhorses for commercial, industrial and personal transportation. Also, it plays a vital role in power generation. They are widely used in on-road and off-road vehicles because they are more efficient than its counterpart, the gasoline-fueled engine. Primarily, due to it has a greater compression ratio and operating temperature [1]. The diesel volumetric energy content (kW/liter) is higher than that of other liquid fuels, like gasoline, ethanol, methanol, and butanol. However, like the gasoline engine, the Diesel engine emits regular emissions like carbon monoxide (CO), hydrocarbons (HC) and oxides of nitrogen (NOx). Also, diesel engines produce high levels of particulate matter (PM) [2]. There is growing concern about these PM emissions since emerging evidence potentially links PM with acute health effects [3].

PM formed in diesel engines due mainly to the heterogeneous combustion characteristics of diesel engines. The presence of fuel rich mixture under high temperature and pressure enhances the formation of PM due to the lack of sufficient O_2 [4]. Particulate matter characterized by two distinct stages of development, particle formation or nucleation, and particle growth. The first phase is particle nucleation, where large numbers of spherical particles with diameters less than two-nm are formed in the combustion chamber [5]. Concurrently, stage two begins when the particles start to combine with one another due to phonetic forces (coagulation). Growth via coagulation depends strongly on the number of particles nucleated, increasing the number of nucleated particles [6]. The combined effect of soluble organic fraction (SOF) accumulation and particle coagulation is the increase in primary particle diameter as well as the formation of larger particulate structures [7].

Particulate emission and composition are greatly affected by engine operating conditions. Such as equivalence ratio, fuel injection timing in diesel engines, engine load, and engine temperature, exhaust gas re-circulation (EGR), and fuel composition. These conditions directly impact cylinder temperature and pressure, fuel vaporization, and the amounts of available hydrocarbons and oxygen, all of which influence PM formation, oxidation, and composition [8], [9].

Diesel PM is a subset of the total amount of particulate matter present in the atmosphere. Exposure to the mixture of gases and solids that compose diesel exhaust has been shown to result in serious health effects [10]. Diesel exhaust linked to diseases such as cancer, respiratory illnesses, and asthma symptom aggravation. Several premature deaths connected to high levels of particulate matter exposure [11]. Numerous studies have linked exposure to diesel exhaust as follows:

Effects related to short-term exposure: Lung inflammatory reactions, adverse effects on the cardiovascular system increase in medication usage, respiratory symptoms, increase in-hospital admissions, and Increase in mortality [12]. The related effects to long-term exposure are an increase in lower respiratory symptoms, reduction in lung function in children. Moreover, reduction in lung functions in infants and increase in chronic obstructive pulmonary disease. Also, reduce the life expectancy owing mainly to cardiopulmonary mortality and probably to lung cancer [13], [14].

Due to the increasing pressure to eliminate the production of greenhouse gases by governments and World leaders, the research for alternative fuels increased. Various alternatives examined and employed in conventional internal combustion engines without modifications or with minor ones were examined severely. There are many promising liquid alternative sources of energy as alcohols, vegetable oil. Also, many gases sources like compressed natural gas (CNG), liquefied petroleum gas (LPG), liquefied natural gas (LNG), producer gas, biogas, and hydrogen [15], [16]. Among these fuels, Hydrogen is a long-term renewable, recyclable, and non-polluting fuel. Hydrogen has a unique feature compared to hydrocarbon fuels that are the absence of carbon [17], [18]. Hydrogen burning velocity is very high that achieve a very rapid combustion. The limits of flammability of hydrogen vary from an equivalence ratio (Ø = 0.1 to 2.7), which allow the engine to operate with a broad range of air/fuel ratios [19].

The use of hydrogen in dual fuel combustion as a premixed

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high octane fuel, ignited by a main injection of diesel investigated as a combustion improver [20]. Hydrogen can lead to lower particulate matter mass emissions, lower smoke emissions, lower CO and lower unburnt hydrocarbons. However, hydrogen produces higher NOx emissions, as is usually the case with diesel engines [21].

In a dual engine, H_2 can be burned in diesel engines as a supplemental fuel either by mixing it with air in the intake manifolds or injected directly into the combustion chamber prior to the injection of diesel. Prior to the injection of pilot diesel fuel, hydrogen and air have been mixed well and formed to some extent a homogeneous fuel-air mixture. Then, the mixture compressed to a high temperature, but not high enough to initiate the auto-ignition process of hydrogen in air. After the pilot diesel fuel had injected into the cylinder, it atomized, vaporized, mixed with the H_2-air mixture and ignited through auto-ignition [22], [23].

Under suitable conditions, the burning of diesel fuel serves as an energy resource to ignite the H_2-air mixture at multi-points. The H_2-air mixture either burned through flame propagation similar to that of an SI engine if the H_2-air mixture is rich enough to support the speed of the flame. Alternatively, the hydrogen may oxidize in the air if the H_2-air mixture is leaner than the flammability limit [24], [25].

Despite there are no specific authoritative studies for air quality in Iraq. Many studies reported that diesel engines handle for more than 65% of the air pollution, due to the enormous number of unmodified engines working as a part of electric generators. This paper discusses the effect of blending hydrogen with diesel in different proportions on PM. In this study, hydrogen was inducted into the cylinder of a diesel engine from an intake port, and the percentage of hydrogen substitution varied from 0% to 70%, simultaneously reducing the diesel percentages. Many engine variables studied, like equivalence ratio, engine speed, load, and injection timing effects on resulted PM.

2 EXPERMINTAL SETUP

2.1 Used Fuels

The tests used diesel fuel was conventional Iraqi diesel supplied by Al-Doura Refinery. Iraqi diesel fuel has high sulfur content that recorded at least about 10000 ppm that is a gigantic quantity [26]. It is necessary to reduce sulfur levels to about 30 ppm or less to maintain a particle trapping efficiency of 73 % or higher in particulate filters [26]. Particulate matter (PM) reduced to near zero when PM filters tested with the 150 ppm sulfur fuel. However, when PM filters tested with 350 ppm sulfur fuel, PM increased [1], [2], [6].

Both aromatic saturation and sulfur reduction take place in hydrotreating units. In this treating process, hydrogen is necessary to carry out the corresponding chemical reactions. Therefore, hydrogen is an enabling agent in the production of ultra low sulfur diesel fuel leads to reductions in PM emissions that are realized by particle filters. The used hydrogen supplied by a compressed gas cylinder delivered by General Company for Vegetable Oils. The company certified that the hydrogen was of research grade with purity of 99.99%. Table 1 represents the diesel and hydrogen specifications.

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2.2 Tests Engine and Accessories

The engine used in the tests was a four-cylinder, direct injection diesel Fiat engine. Table 2 lists the engine specifications. A hydraulic dynamometer connected to control the speed and load subjected on the engine. The engine was attached to the dynamometer by a rubber coupling to isolate the dynamometer from any high vibrations from the engine. A flow meter is used to measure the air mass flow entering the engine. A fuel mass flow meter used to measure the precise mass of fuel supplied to the engine. Many standard K-type thermocouples used to record exhaust gas temperatures.

TABLE 1

PROPERTIES OF FUELS USED

Property	Diesel	Hydrogen
Calorific value , kJ/kg	44500	48500
Self ignition temperature, °C	725	858
Boiling point range , °C	260-320	-252
Ignition delay period, s	0.002	-
Flame propagation rate, cm/s	10.5	265-325
Flame temperature, °C	1715	2316
Surface tension, dynes	32	-
Viscosity at 39 °C, centistokes	2.7	-
Specific gravity at 32 °C	0.83	0.43
Sulfur content by weight, %	0.8	0.0112

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

Hydrogen fueling system composed of the high-pressure regulator on the gaseous hydrogen high-pressure bottle. A choked nozzles assembly used to feed the gas to the engine. Besides, it to its primary serves as hydrogen flow measuring device and to arrest backfire flames. The chocked nozzles assembly used to ensure the safety of the laboratory and the operator. The hydrogen supplied at room temperature and pressure to avoid a temperature or pressure gradient between the hydrogen and the intake air as they mixed. The hydrogen gas introduced to the engine immediately below the air filter. The air and hydrogen mixed sufficiently prior to entering the inlet manifold. Therefore, this procedure eliminated any discrepancies between the supplies to each cylinder to confirm a stable running of the engine. The supplied hydrogen measured as a percentage of the intake air volume. A simple, low-cost air-hydrogen device designed and used to mix hydrogen with the inlet air.

A pressurized hydrogen vessel employed to supply the engine with hydrogen fuel. The hydrogen bottle located secured in a trolley outside the engine test room. This procedure used to help the operator needs for controlling 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; the nozzle injected directly into the intake air stream in the inlet manifold.

Particulate matter samples obtained by exposing filter materials to a diesel exhaust stream at the end of tailpipe dilution point. Whatmann-glass micro-filters examined using a scanning electron microscope. Low volume air sampler type Sniffer L-30 used to collect emitted PMs. The filters weighted before and after the end of sampling process that extend for one hour. PMs' concentrations 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 ($\mu g/m^3$).

w_1 = the weight of the filter before sampling operation in (g).

w_2 = the weight of the filter after sampling operation in (g).

Vt = the total volume of the drawn air (m^3)

The equation can determine Vt:

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

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

t = the sampling time in (min).

Each filter was preserved in a plastic bag temporarily at the end of collecting samples process until analyzing and studying the results using a light microscope.

2.3 Safety Features

The employment of a large quantity of hydrogen in the closed medium needs safety precautions to become of the primary concern. Many hydrogen specifications require former determination with the hydrogen application in engines. The leakage of hydrogen into engine laboratory prevented through better ventilation to eliminate the hydrogen accumulation in the engine room, especially at the ceiling areas. The occurrence of backfire is ordinary abnormal hydrogen combustion that needs preparations by relieving the resulted pressure and shutting down the hydrogen fuel system. Also, in case of emergency the avoidance of over-dosing of the hydrogen flow that may lead to abnormal combustion such as backfire and the onset of knock.

The following safety prospects developed and implemented during the tests of this research:

Leakage Test: Soap bubbles approach used to confirm detailed leakage test after the hydrogen system construction, before and during the testing period. Also, after the switching of hydrogen tanks; the leakage test was conducted for connectors and high-pressure hydrogen line.

Better Ventilation: The hydrogen fuel bottle installed in an open to atmosphere shed outside the laboratory. Any leaked hydrogen from this system ventilated to air without any accumulation around the hydrogen fuel system. The ventilation of the engine room was maintained by running the ventilation fan prior to the tests start. The ventilation fan kept run for at least 30 minutes after the end of the test.

Purging of the hydrogen Fuel System with Pure Nitrogen after Each Test: After the end of all tests, the hydrogen system was purged and filled with pure pressurized Nitrogen. Such purging was necessary to eliminate the potential hydrogen leaking source when the engine was not running. The pressurization of the fuel system with Nitrogen considered as a safety procedure to remove the possibility of air entering the H_2 fuel system.

Elimination of Backfire Damage: The hazards of backfire eliminated through the implementation of the following approaches: Once backfire occurs, the high-pressure relief established in the intake system with the aid of a pressure relief valve installed on the intake manifold and flame arrestor. As soon as the intake manifold pressure reached 50 psi for any reason, the relief valve would blow off. This pressure value verified to be efficient in eliminating the backfire hazards. During this study, the abnormal backfire combustion occurred twice without causing any damage to the intake system or blowing off the pressure relief valve. The choked nozzles assembly installed in the intake system and acts as flame arrestor and used to quench the flame initiated by backfire combustion.

2.4 Test Procedure

The ultimate aim of this investigation was to determine if there was an advantage in terms of the PM 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 was operating the engine at the optimum injection timing.

The engine started with 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 increased, the engine speed also increased, so the flow rate of the intake air was increased to maintain a constant intake pressure. Once the engine was running steadily with the correct settings, 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 PMs' concentrations were determined.

3 RESULTS AND DISCUSSIONS

Fig. 1 represents the effect of load on PM concentration at a constant speed. Diesel fuel PM concentrations reduced for low and medium loads. For loads between 20 to 60 kN/m², the concentrations tend to be stable. At loads above 60 kN/m², PM concentrations increased highly. The figure shows the effect of hydrogen addition in three volumetric fractions to diesel. Hydrogen addition reduced the emitted PM. This reduction increased highly with 70% H2 volume fraction.

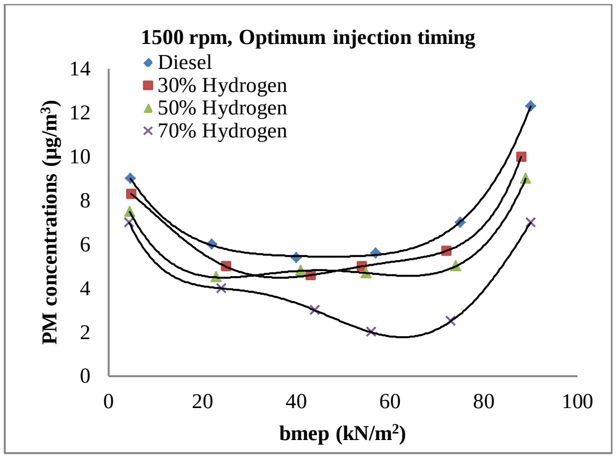

Fig. 1. Load effect on PM concentrations for variable volumetric hydrogen fractions

The lowest recorded PM emissions at 1500 rpm and optimum injection timing are with 70% vol. Hydrogen addition, as is shown in Fig. 5. Hydrogen addition with (70% vol. fraction) indicated a significant reduction in the PM concentrations approached about 43.7%. The lowest achievable PM emissions occur at 50% vol. Hydrogen addition was about 21.63%. Hydrogen addition with 30% volume achieved for about 14.79% reduction in PM concentrations

The combustion chamber temperature is low at low loads that lead to poor combustion especially for the hydrocarbon molecules with higher C molecules, resulting in higher PM concentration. At medium loads, the combustion chamber temperature is suitable that leads to an adequate combustion and approximate stability. At high loads, more diesel fuel injected to maintain engine speed, accompanied by higher combustion chamber temperatures resulting in a higher PM concentrations.

At low loads engine operation, the hydrogen addition did not improve exhausted PM significantly. At medium loads, the addition effect was evident due to improvement in combustion quality. The reduction in PM is due to the absence of carbon in hydrogen and also hydrogen forms a homogeneous mixture during combustion rather than a heterogeneous mixture like diesel. Hydrogen assists diesel during the combustion process to have a greater reduction in the PM concentrations. At very high loads PM reduced in a lesser form compared with medium loads. In this case, the combustion chamber's temperatures became high causing rapid combustion, putting in mind that the tests conducted at optimum injection timing for each instance. Adding hydrogen forced the injection timing to be retarded. It may conclude that the optimum injection timing operation gave the best PM concentrations reduction.

PM concentration increased at low and high speeds and reached it minimum values at medium speeds, as Figs. 2, 3 & 4 represent. The high concentration of PM is due to the volumetric efficiency reduction at low speeds. At high speeds, the preparation time of the air-fuel mixture reduced highly, leading to higher PM concentrations.

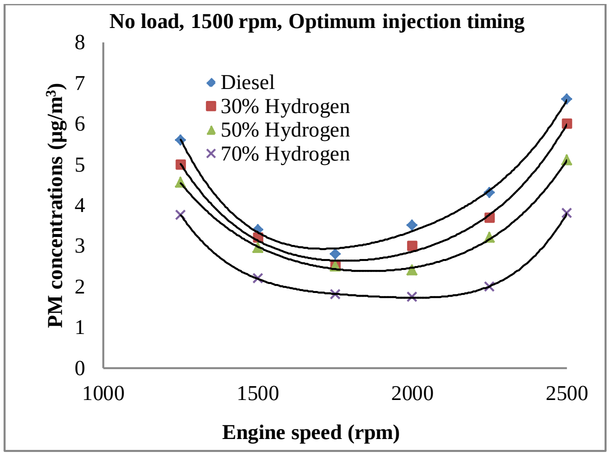

Fig. 2. Engine speed effect on PM concentrations for variable volumetric hydrogen fractions at no load

Hydrogen addition takes a part of inner air reducing volumetric efficiency more and more. In the same time, its addition changed the C to H rate inside combustion chamber together with changing combustion behavior. The resulted PM concentrations were the consequence of these factors. PM concentrations also increased at no load and high loads. At no loads, the combustion chamber temperatures are low causing the hydrocarbon particles near the chamber wall cannot participate. At high loads, the volumetric efficiency reduction due to higher fuel injection accompanied by hydrogen addition.

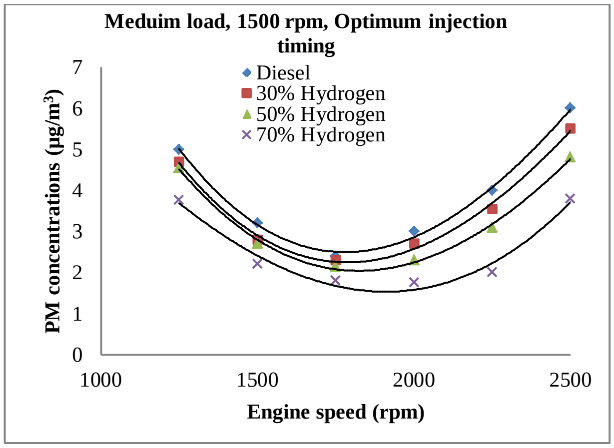

Fig. 3. Engine speed effect on PM concentrations for variable volumetric hydrogen fractions at medium load

At no burden, adding the hydrogen caused a decrease in PM concentrations of 10.68, 21 and 41.56 for hydrogen volume fractions (HVF) of 30, 50 and 70% respectively. At medium loads, adding hydrogen caused reduction of 4.4, 9 and 28.95% for HVF 30, 50 and 70% respectively. At high loads adding hydrogen caused reduction of 9.4, 17.46 and 35.22 for HVF 30, 50 and 70% respectively.

The reductions were calculated and compared for the whole engine speed tested range. A comparison of PM concentrations between no load conditions to medium load demonstrated reductions of 17.74, 11.9, 15.3 and 15.5% for diesel, 30%, 50% and 70% HVF respectively. On the contrary, moving from medium to high loads caused increments in PM about 67.8, 66, 64.5 and 64.7 for diesel, 30, 50 70% HVF respectively.

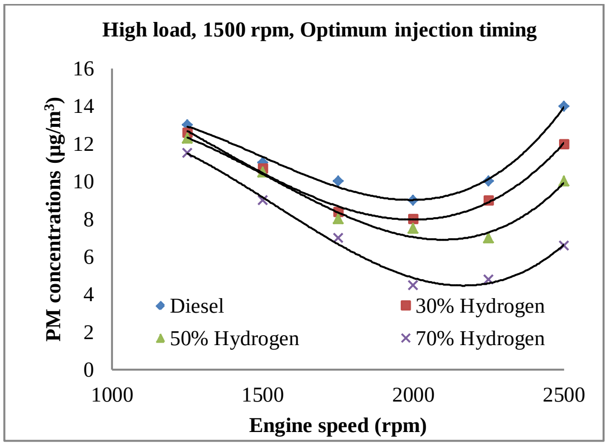

Fig. 4. Engine speed effect on PM concentrations for variable volumetric hydrogen fractions at high load

The reduction percentages mentioned above are low compared with reductions referred to by other researchers. High sulfur content characterizes Iraqi diesel fuel. Sulfur with aromatic compounds is the main chemical compound for smoke and particle nucleation. In this situation reducing sulfur content in diesel fuel caused a PM concentration reduction largely, also hydrogen effect enlarged.

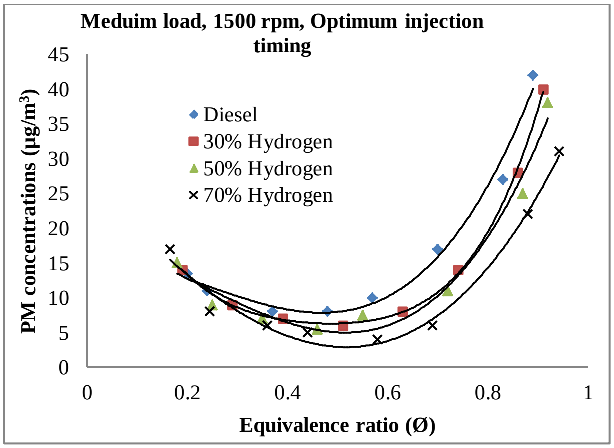

Fig. 5. Equivalence ratio effect on PM concentrations for variable volumetric hydrogen fractions at medium load

Fig. 5 shows the effect of the equivalence ratio and hydrogen addition on PM concentrations at medium load (44 kN/m²) and a constant speed (1500 rpm). Emitted PM was high at very low equivalence ratio (Ø≤0.3). Adding hydrogen extended the ultra lean equivalence ratio. At these ratios, the emitted PM was high. The minimum PM concentration existed between (0.3≤Ø≤0.6) where the maximum brake power produced. At equivalence ratios (Ø≥0.6) PM concentrations increased highly because of incomplete combustion resulted from improper mixing due to fuel quantity increase. Hydrogen addition reduced PM concentrations with about 7.69, 13.55 and 27.47 for HVF 30, 50 and 70% respectively.

Injection timing effects on emitted PM was studied as Fig. 6 shows. Hydrogen has a high flame speed that affect combustion. For retarding injection timing of the diesel fuel, the available time for air-fuel mixture preparation reduced leading to a high PM concentration. Advancing injection timing increased the time preparation for the contained fuel, as well as, its delay period, originating a better combustion with less PM concentration. Engine knock appearance limited advancing injection timing. Adding hydrogen forced the optimum injection timing (OIT) to be retarded. Advancing injection timing away from OIT cause rough combustion and increased PM concentrations. The retardation of injection timing away from OIT caused combustion to continue at exhaust stroke increasing PM concentrations. In this work, the knock phenomenon impacts on PM concentration were not examined. The total reductions in PM concentrations were 6.8, 19.78 and 29.47% for HVF of 30, 50 and 70% respectively.

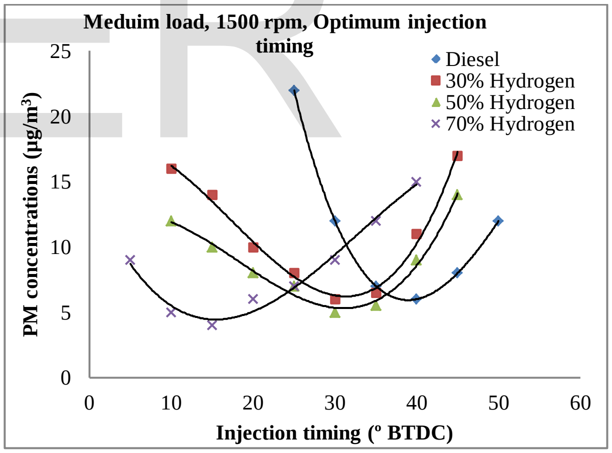

Fig. 6. Injection timing effect on PM concentrations for variable volumetric hydrogen fractions at medium load

4 CONCLUSIONS

The effect of the addition of hydrogen, equivalence ratio, engine load and speed on emitted PM concentrations in the exhaust gas of a FIAT diesel engine investigated experimentally. The engine fuel injection strategies were modified so that each case operates in optimum injection timing. The following conclusions obtained from this research:

1- The study demonstrates the effect of equivalence ratio, engine speed, load and injection timing on PM concentration.

2- The addition of hydrogen to diesel fuel in dual engine reduced the emissions of PM. The extent of reduction in PM emissions depends on the amount of hydrogen added and engine load. The maximum PM reduction of 43.7% obtained with hydrogen addition up to 70%, at 20%-80% of the engine load.
3- Adding hydrogen caused high reductions in PM concentration, but less than that mentioned in other articles that used sulfur free or ultra low diesel fuel.
4- Hydrogen addition to diesel engines could be used in the future to meet ever stricter engine carbon emission regulations.
5- Working at equivalence ratios that give the maximum brake power values produce lower PM concentrations. Also, hydrogen addition at these ratios made higher reduction of PM compared to other equivalence ratios.
6- Engine operation at ultra-low or very high equivalence ratios produced higher PM concentrations with or without hydrogen.
7- Engine operation at very low or very high loads gives higher PM concentrations with and without hydrogen addition.
8- Low and high speeds produce higher PM concentrations compared to medium speeds that produce lower concentrations.
9- Hydrogen addition always accompanied with injection timing retarding. The injection timing retardation away from OIT causes the maximum PM concentration in case of hydrogen addition and for diesel fuel also. On the contrary, for diesel fuel, advancing injection timing resulted in lower concentrations. Advancing injection timing increased PM concentrations in the case of hydrogen addition. Minimum PM concentration approached with optimum injection timing when hydrogen added to diesel.
10- High sulfur content that characterized Iraqi diesel fuel can cause a disaster if it is not treated as an urgent problem. This high content caused very high emitted PM concentration.
11- Hydrogen addition effect on PM concentration can be greater whenever sulfur content limited to its minimum acceptable levels, as in Europe, Japan, and USA.

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