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Evaluation of Emitted Particulate Matters Emissions in Multi-cylinder Diesel Engine Fuelled with Biodiesel

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Abstract As an alternative fuel, biodiesel is receiving rising attention for diesel engines. The corn oil biodiesel was prepared from Iraqi produced corn oil through transesterification process, using methanol and sodium hydroxide in the present investigation. Neat corn oil biodiesel, as well as, the blends of varying proportions of it and diesel was used to run a 4-cylinders direct injection CI engine. The effects of some engine variables like load, speed, and injection timing on emitted particulate matters (PM) were studied. The aim was to evaluate the emitted particulate matters from a diesel engine when it fuelled with blends diesel and biodiesel. As the Iraqi conventional diesel has high sulfur content that release high rates of PM, it was taking as the baseline fuel in the tests. The results showed a significant reduction in PM when biodiesel was used. The maximum reductions in PM concentrations observed were 34.96 % in the case of biodiesel operation compared to diesel at full engine loads and constant speed. An increment in the PM concentrations as the timing retarded from the optimum injection timing. Biodiesel has a significant impact on smoke at idle mode with reductions of 8.6%, 18%, and 39.75% for B20, B50, and B100 respectively compared to diesel. The study concludes the possibility of more reduction of PM concentrations in the case of reducing sulfur content in Iraqi diesel fuel significantly.

Keywords: *biodiesel, particulate matters, transesterification process*

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1. Introduction

Diesel engines usually emit higher particulate matter (PM) compared to the spark ignition engines. The strict emission regulations in the world have placed design limitations on diesel engines. The worldwide growing trend towards cleaner burning fuel pushed towards many alternative diesel fuels that show better exhaust emissions than traditional diesel ([1,2]).

Biomass energy is considered as one of the renewable energies among these alternatives. Biomass energy includes liquid biofuels derived from vegetable oils with low environmental pollution impact, to replace petroleum-based fuels. Some of the well known liquid biofuels are ethanol for gasoline engines and biodiesel for compression ignition engines or diesel engines [3].

Vegetable oils were used as fuel for diesel engines to some extent since the invention of the compression ignition engine by Rudolf Diesel in the late 1800`s. During the early stages of the diesel engine, strong interest was shown in the use of vegetable oils as fuel, but this interest declined in the late 1950`s after the supply of petroleum products become abundant [4]. During the early 1970`s, oil shock, however, caused a renewed interest in vegetable oil fuels. This interest evolved after it became apparent that the world's petroleum reserves were dwindling. At present, to replace a part of petroleum-based diesel usage, the use of vegetable oil product biodiesel has been starting in some countries [5]. Biodiesel properties are comparable with those of conventional diesel fuels. Therefore, it added to diesel engines as neat or blended, without any engine modifications. However, the variations in fuels chemical nature result in differences in their fundamental properties affecting engine performance, combustion process, and pollutant emissions [6].

Biodiesel exhibits several merits when compared to that of the existing petroleum fuels. Many researchers have shown that using biodiesel as fuel reduced particulate matter, unburned hydrocarbons, carbon monoxide, and sulfur levels significantly in the exhaust gas. However, biodiesel employment increases the oxides of nitrogen levels as reported by [7]. Besides, biodiesel produces less detrimental to human health pollutants as it does not contain carcinogens materials such as polyaromatic hydrocarbons and nitrous poly-aromatic hydrocarbons [8].

The exhaust of diesel engines contains solid carbon soot particles or particulate matter (PM); these observed as smoke emission. Particulate matter (PM) is a primarily emitted emission by diesel engine compared with a gasoline engine. There is a clear consensus that biodiesel fuels result in significant reductions in PM [9,10,11]. The methyl esters current capability to reduce regulated or non-regulated emissions emitted from the engines have not fully cleared. In the same time, the impact of vegetable oils on the particulate formation and production have not well assessed yet. Some researchers claimed that a reduction in PM achieved when vegetable oils used [12]. While, other researchers demonstrated PM concentrations increased when biofuels employed [13]. However, most authors report decreases in aromatic and polyaromatic hydrocarbon emissions [14,15,16].

The majority of researchers worked in this field agreed that the reduction in PM emissions referred to the notable decrease in the insoluble fraction concentration, as a result of the increase in oxygen inside biodiesel structure and aromatic hydrocarbons absence in biodiesel fuels [17]. With the same air at the admission, the oxygen content of the ester molecule allows for a complete combustion. Even with fuel, intensive diffusion flames exist in zones of the combustion chamber, in addition to the support of the already formed soot oxidation. The aromatic hydrocarbons reduction in biodiesel involves a lack of the soot precursor species concentration in the combustion chamber [18,19].

Particulate matters are often fractioned in term of sulfate, soluble organic fraction (SOF) or volatile organic fraction (VOF) and carbon or soot [20]. In the diesel combustion process, some of fuel droplets may never vaporize, and thus never burn. However, the fuel does not remain unchanged; the high temperatures in the combustion chamber cause it to decompose. In the next steps, these droplets may be completely or partly burned in the turbulent flame. If any droplets not burned completely, they emit as a droplet of heavy liquid or carbon particles [21]. The conversion of fuel to PM is mostly occurring in the last part of the injected fuel in a cycle, or when the engine is running at high speed, and Iraq is a country distinguishes by large agricultural areas. Some of these fields are used, and the others are not. Corn is an Iraqi crop while corn oil produced in Iraq in large quantities. From this point of departure, the Mechanical Engineering Department- University of Technology, consider researchers about using corn oil and other Iraqi crops as alternative biodiesel fuels in future seriously.

The evaluation of the particulate matters concentrations emitted from a diesel engine fuelled with blends diesel fuel and biodiesel produced from Iraqi corn oil is the primary objective of this study. The Iraqi conventional diesel fuel was taking as the baseline fuel in the tests.

The method used to measure PM emissions for type approval tests is the filter samples gravimetric analysis. These filters fixed in a full exhaust flow dilution tunnel. Another notable characteristic of the particle is the particle size distribution or particle number since the particle diameter has an influence on the human health, especially nanoparticles [23,24]. Many studies conducted on the particle size distribution of diesel engine fueling conventional diesel [25,26]. Generally speaking, particle size distribution of diesel engine includes nucleation mode and accumulation mode, the division diameter of modes is 50 nm. Nucleation mode particles related to the soluble organic fraction and sulfate. The accumulation mode particles linked to soot [27,28].

2. Experimental Work

2.1. Materials and Transesterification Process

It is necessary to differentiate between fats and oils or the origin of biodiesel. The difference between a fat and oil is their physical state. The term fat usually defines the solid state, and oil in the liquid state. These terms are changeable depending on the temperature to which the compound exposed. When the state is unimportant, the term fat is usually used [3].

The transesterification process employed to convert the corn oil into its methyl ester. The transesterification is a chemical reaction used in the production of biodiesel. Fatty acid in vegetable oil reacts with an alcohol in a presence of a catalyst to form fatty acid alkyl ester. Simple alcohols like methanol or ethanol used in transesterification process and it is usually carried out in the complete absence of water with a basic catalyst (NaOH, KOH) [21]. In this work, methanol was used. Methanol takes high yield reaction quite easy. An excess of methanol needed to speed up the response, with the occurrence of a ready separation of methyl alcohol glycerol. In the transesterification process, the alcohol combines with the acidic triglyceride molecule to form glycerol and ester, which removed by density separation. The transesterification process decreases the oil viscosity, making its characteristics similar to diesel fuel [2,29]. The method of producing biodiesel illustrated in the block diagram of Figure 1.

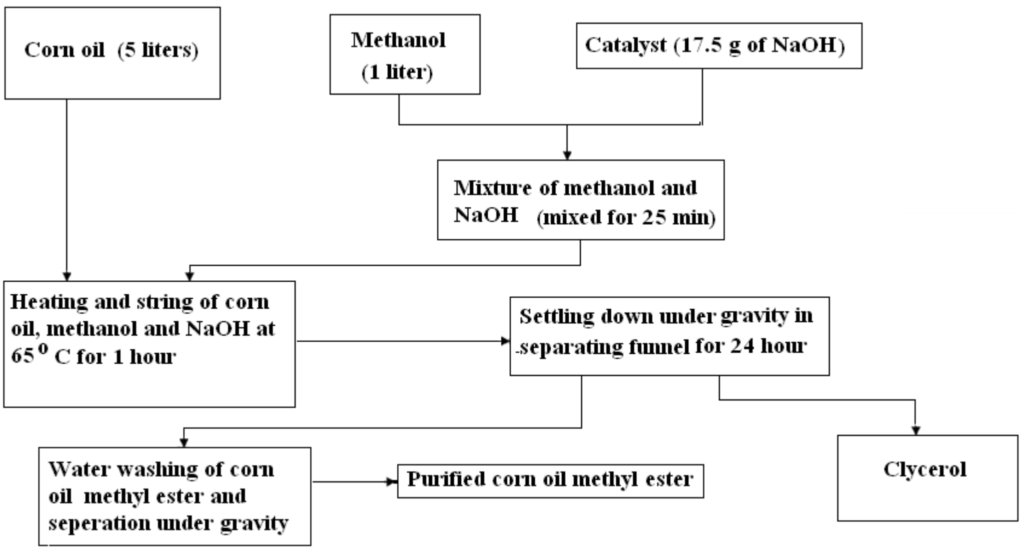

Figure 1. Block diagram for producing corn biodiesel by transesterification process

Several factors were found to affect the yield and quality of the ester significantly. The water content of all materials, including the catalyst and triglyceride, and the acid value of the triglyceride were required to be very low. Acid contents above 0.5% and water content of 0.3% were reported to cause a significant decrease in the ester yield. Other important factors for transesterification are reaction time and temperature. The time required to complete the reaction estimated about one hour. The reaction temperature depends on the used alcohol type and it temperature recommends to be below the boiling point of the used alcohols used with a few degrees (for examples of reaction temperatures for methanol was 60°C) [30].

2.2. Fuel-related Properties of Vegetable Oils

The related fuel properties of vegetable oil vary depending on the fuel fatty acid. The fuel-related tested properties of used biodiesel listed in Table 1. The viscosity of vegetable oils varies in the range of 14.38 to 65 mm^2/s at 27°C. The high viscosity of these biodiesel oils is due to the considerable molecular mass and chemical structure. Vegetable oils molecular weights range between of 550 to 900, which are triple or more times higher than diesel. The vegetable oils flash point is considerably high (236°C). The volumetric heating values of these blends are in the range of 39 to 41.6 MJ/kg that is low compared to diesel (about 44.2 MJ/ kg). The presence of chemically bound oxygen in vegetable oils lowers their heating values. The biodiesel blends cetane numbers are in the range of 38 to 42.9. The cloud and pour points of vegetable oils are higher than that of diesel fuels [31,32].

2.3. Experimental Setup

A four stroke, direct injection, naturally aspirated four-cylinder four-stroke diesel engine employed for the present study. The engine specifications listed in Table 2. The engine coupled to a hydraulic dynamometer, and the engine speed measured by a tacho-generator connected to the dynamometer.

The load and speed of the engine were controlled by adjusting the dynamometer resistance and the injection rate of the fuel pump. The determination of the engine fuel consumption was conducted by the measurement of the fuel level decrement in a scale container for a given period. The volumetric flow rate of the intake air was measured using orifice plate. The exhaust gas temperature measured using a thermocouple connected to the exhaust pipe just downstream of the exhaust manifold. The cooling water temperatures at the inlet and outlet of the engine were measured using calibrated thermocouples.

Table 1. Tested fuels specifications

Fuel type	Calorific value (kJ/kG)	Density (g/dm^3)	Viscosity (mm^2/s at 27°C)	Cetane No.	Flame point (°C)	Cloud point (°C)	Pour point (°C)
Diesel fuel	44227	810	4.23	49	59	-13.8	-29
Biodiesel (B100)	39873	906	65	38.6	239	-3.7	-12.4
B50	40368	877	44.7	40.6	179	-10.2	-17.833
B20	41654	829	14.38	42.9	112	-11.78	-24.68

The low volume air sampler (type Sniffer L-30) employed to collect emitted PMs. Whatmann-glass micro-filters used to gather PMs. The filters weighted before and after the sampling operation that extend for one hour. The PMs concentrations determined by the equation:

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

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).

Vt = drawn air total volume (m^3)

Vt found by the equation:

$$Vt = Q_t \cdot t$$

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

t = sampling time in (min).

The filters preserved in individual plastic bags temporarily at the end of collecting samples operation until analyzing and studying the results using a light microscope.

2.4. Experimental procedure

The amount of PM generated was measured using different engine variables strategies, as well as, the fuel impact on these strategies. Experiments were conducted on the engine using diesel fuel to provide baseline data. The engine was warmed up for half an hour. Engine cooling water temperature maintained at 70°C. Then, 20%, 50% and 100% blends of corn biodiesel were also tested. Physical characteristics of the tested fuels listed in Table 1. The first set of experiments conducted at the engine speed of 1500 rpm. The experiments performed at the designed injection timing of 38° BTDC for no-load, 50% load, and full load for all tested fuels. The injection timing varied from 20 to 45 ° BTDC, each step 5 degrees at constant 1500 rpm engine speed.

Table 2. Tested engine specifications

Engine type	4cyl., 4-stroke in line
Engine model	TD 313 Diesel engine rig
Combustion type	DI, water cooled, naturally 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° Nozzle opening pressure=40 MPa

In the second set of experiments, the engine speed varied between 1250 and 2500 rpm with intervals of 250 rpm while the engine operated at full load. The fuel delivery angle of the fuel injection system was kept constant at 38º BTDC with variable speed tests. Before each blend test, the fuel tank and fuel lines drained. Then, the engine left to operate at least 15 minutes to stable on the new blend. For each speed, the engine run for about 5 minutes until the steady-state conditions achieved, and then the data were collected in the sixth minute. The tests repeated three times to confirm repeatability, and the average of the results of the three trials counted in the study.

3. Results and Discussions

Figure 2 shows the PM concentrations for the tests fuels at a variable engine loads. The smoke contains solid carbon soot particles that generated when the fuel has no enough oxygen to react with all the carbon or in the fuel rich zone of combustion chamber during combustion process as Ref. [7] declared. From the experimental results, the smoke emission from corn biodiesel fuel and the diesel fuel have a few differences in 0% to 25% load level. However, at 50% to 100% load level the smoke emission from all biodiesel blends are lower than that of the diesel fuel. The smoke emission in case of various blends of biodiesel smoke emission is less as compared to diesel as Figure 2 declares. At full load, the maximum reductions in PM concentrations observed were 34.96 %, in the case of biodiesel operation when compared to diesel. There is an obvious reduction in PM emission for all biodiesel blends at all loads. This reduction referred to the soot free biodiesel fuel, and the complete combustion of it.

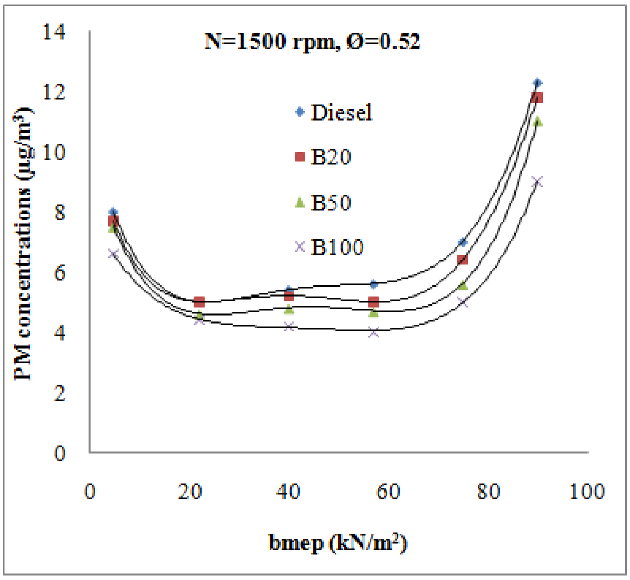

Figure 2. The effect of bmep on PM concentrations at 1500 rpm and constant equivalence ratio

Figure 3 represents the effect of equivalence ratio variation on PM concentrations at 1500 rpm engine speed and medium load. Increasing oxygen content in the fuel-air mixture reduced PM concentrations. Therefore, the PM concentrations are very low at ultra-lean equivalence ratios and increased highly by mixture enrichment with fuel. However, there are still recorded concentrations that mean using biodiesel reduces emitted PM but doesn't annihilate it completely.

Ref. [21] explained the reduction of PM with biodiesel fuelling is mainly caused by reduced soot formation and enhanced soot oxidation. Biodiesel has a nil content of sulfur and aromatic hydrocarbons that are considered soot precursors. The lower final boiling point of biodiesel, despite its higher initial boiling point and average distillation temperature (Table 1), provides a lower probability of PM formation from the inability to vaporize heavy hydrocarbon fractions. The oxygen bonded in the ester molecules structure allows for a complete combustion and promotes the oxidation of the already formed PM particles.

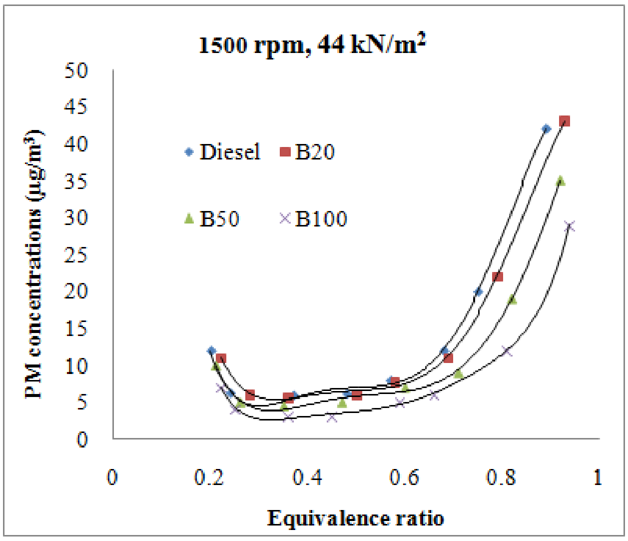

Figure 3. The effect of equivalence ratio variation on PM concentrations at constant load and speed

The injection timing is an important engine variable that has an impact on PM production. The primary cause to characterize is not only the fuel type but also the combustion mode used. Figure 4 illustrates the evaluation of the PM concentrations generated utilizing different injection strategies and the fuel impact on these strategies.

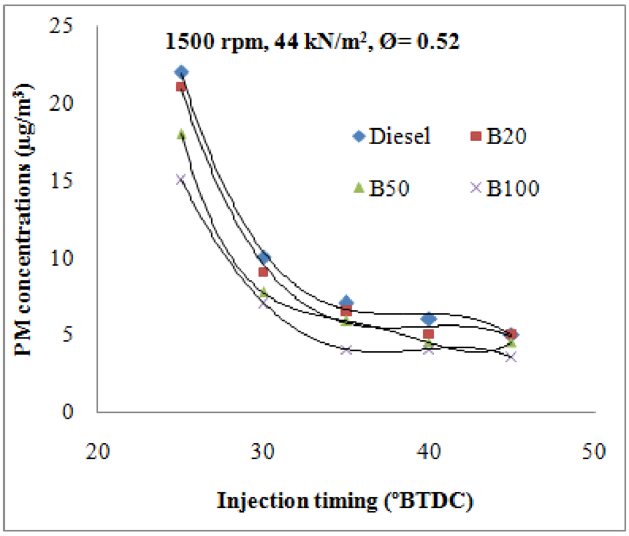

Figure 4. Injection timing variation effect on PM concentrations at constant load and speed

As Figure 4 reveals, comparing the effect of advancing and retarding the timing on PM concentrations shows an increment in these concentrations as the timing retarded from the optimum injection timing. This trend is independent of the used fuel. However, for comparison the emitted PM by B20, B50 and B100 were less than that produced by diesel fuel by 7%, 18.8%, and 33%

respectively on average. The injection timing retardation means reducing available combustion time, and hence causing a higher concentration of PM. It is suitable to advance the combustion start since it enlarges the residence time of PM particles in a high-temperature environment and gives the oxygen presence to promote further oxidation.

Figure 5, Figure 6 and Figure 7 showed the tests when engine speed changed between 1250 and 2500 rpm at intervals of 250 rpm while the engine operated at no load, medium, and full loads. The engine injection timing kept constant at 38º BTDC. Constant equivalence ratio (Ø=0.52) was used, around this Ø the maximum brake power obtained.

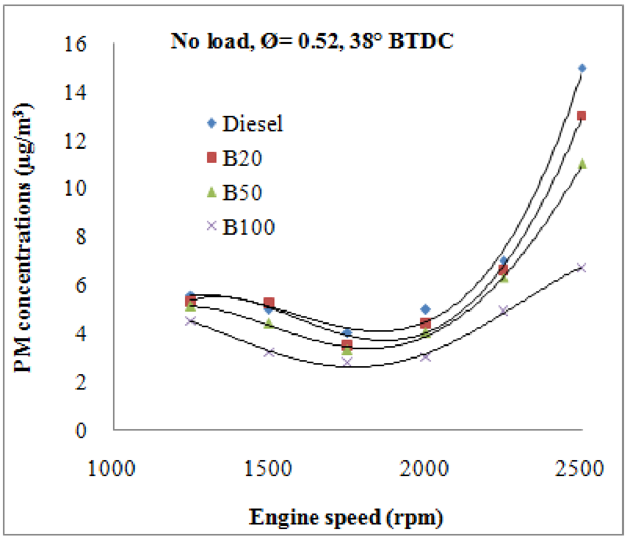

Figure 5. Engine speed effect at no load for Ø=0.52 and 38° BTDC

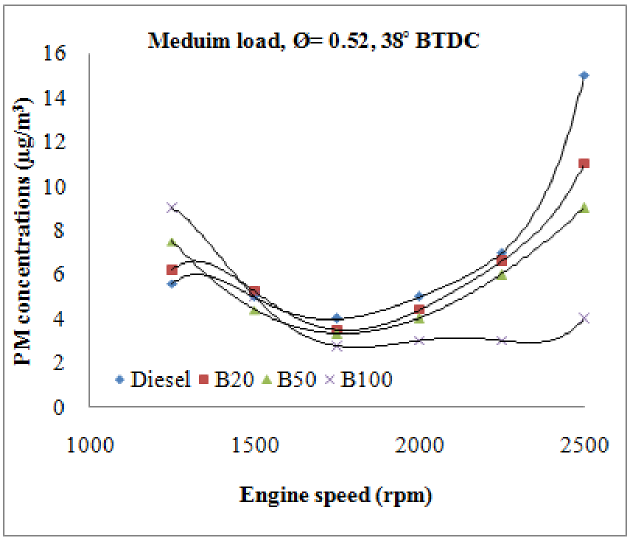

Figure 6. Engine speed effect at medium load for Ø=0.52 and 38° BTDC

The use of biodiesel reduced PM concentrations significantly. Biodiesel declared the greatest effect on smoke at no load mode where B20 reduced smoke by 8.6% and B50 reduced smoke by 18% while at B100 blend the reduction was 39.75%. In this study, biodiesel addition reduced particulate emission in all stage as seen in Figures.

According to the figures, the PM concentrations decreased with biodiesel blends fuelling at practically all loads and engine speeds. At full load, this indicator of PM emissions was 12.7%, 25% and 52.38% lower for B20, B50 and B100 respectively than for diesel fuel, depending on engine speed. However at partial loads, this difference was attenuated. The impact of the operation mode of the engine on PM concentrations seemed to be fuel sensitive. For biodiesel blends, smoke compartment trend was similar at all loads and engine speeds; it was always less than diesel fuel. Higher loads require more fuel consumptions and higher engine speeds drive to shorter residence times of fuel-air mixture in the combustion chamber leading to higher PM concentrations.

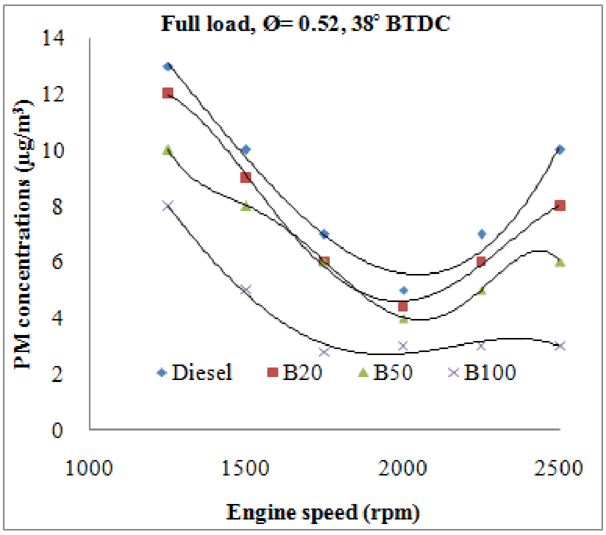

Figure 7. Engine speed effect at medium load for Ø=0.52 and 38° BTDC

Many works of literature attested that PM emissions increase or decrease according to the sulfur concentration. Sulfur in the fuel caused the formation of sulfates that are absorbed on soot particles and increase the PM emitted from diesel engines. Besides, fuel oxidation complete due to the oxygen content increase in the fuel. Oxygen increases even in locally rich zones resulting in a significant decrement in PM as References [33] and [34] revealed. Many researchers record higher reduction in PM concentrations with other types of biodiesel compared with this study. The reason for this difference is the amount of sulfur content in the tested fuel. The Iraqi conventional diesel fuel contains about 10000 to 15000 ppm sulfur [35] in comparison with the free sulfur diesel fuel employed in the other articles.

4. Conclusions

Biodiesel oil manufactured in a laboratory using Iraqi produced corn oil. Biodiesel production conducted using transesterification process. Three blends of biodiesel and diesel were prepared, B20 (contains 20% biodiesel and 80% diesel), B50 (contains 50% biodiesel and 50% diesel and B100 contains 100% biodiesel. The three blends used in operating 4-cylinder direct injection diesel engine and the emitted PM concentrations of these operation modes compared to diesel fuel operation. The tests conducted on several engine variables. The results show:

1. There is a significant reducing in the PM concentrations for all biodiesel blends at the part and full loads. PM concentration reduced with an increase in the blending of biodiesel.

2. PM concentrations reduced by increasing biodiesel percentage in fuel for all range of equivalence ratios.
3. The injection timing retardation increased PM concentrations while advancing it reduced these concentrations. Injection timing has a significant influence on emitted PM.
4. The increasing speed increases PM concentrations due to a reduction in available reaction time for the fuel's molecules with higher weight.
5. Increasing load increased the fuel consumption and hence the emitted PM.
6. At all tested engine variables, using neat biodiesel and its blends reduced PM concentrations for the safe range.
7. It is possible to reduce PM concentration and reach the percentages reported by other researchers if sulfur contents in Iraqi diesel fuel could be removed, or at least reduced.

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