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Particle Size Distribution Emitted from Combustion of Diesel- Waste Cooking Oil Biodiesel Blends

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ABSTRACT

Iraqi diesel is characterized by its high sulfur content, which causes the emission of high concentrations of particulate matter. This work focuses on the evaluation of these particle size distribution when the engine is fuelled by pure diesel fuel blended with biodiesel. The study focused on particulates matters mass concentration. The first goal consists of monitoring the percentage of particulate matter substances emitted by the diesel engine powered with pure diesel fuel and biodiesel-diesel blends. The emissions of particles of all sizes decreased from biodiesel blends with a significant effect on particles measured in nano and fine particles. Under constant engine speed and variable load and, PM2.5 was reduced by 7.2%, 16.7%, 32.2% and 42.8% for DB20, DB35, DB50 and B100 compared to diesel, respectively. For the same testing conditions, the TSP reduced by 4.98%, 12.07%, 21.54% and 26.53%, respectively. The use of biodiesel blends also resulted in a significant reduction in particulate matter compared to diesel when the engine run at variable speed and fixed load. The reduction rate for PM1 was 12.13%, 36.65%, 60.92% and 81.06% for DB20, DB35, DB50 and B100, respectively. The PM10 reduced by 9%, 25.98%, 43% and 61.3%, respectively.

1. Introduction

Among the significant environmental degradation, air quality is of prominent importance nowadays. A large portion of air pollution is related to transportation, with the majority of engines operated with fossil fuels. Therefore, engines are working on biodiesel fuel formulations that are more efficient, reduce emissions and are environmentally and economically acceptable [1]. There is global pressure to develop new energy technologies that would enable a significant reduction in the use of fossil fuels in electricity production and transportation, in order to reduce the emission of gases responsible for increasing greenhouse gases and improve the quality of breathable air. To date, biodiesel and gasoline are examples in terms of engine performance in comparison with other

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alternative fuels that can be used in diesel engines, but they present the worst emissions of pollutants during their combustion [2].

In the particular case of diesel engines, the burning conditions of diesel fuel tend to form soot, which introduces health issues because the soot has direct impacts on human health [3]. The World Health Organization has classified diesel soot as a Group One human carcinogen, capable of causing lung cancer, and several epidemiological studies suggest a relationship between diesel soot and lung cancer in people who are exposed to this pollutant [4].

The discovery of the harmful effects of diesel engine emissions promotes the development of diesel engines and leads to the search for new fuels that meet the required reduction in harmful emissions. The use of biodiesel, and blends of biodiesel and diesel specifically developed for these types of engines, has been shown to achieve this requirement [5]. One problem with these alternative fuels compared to pure diesel is the magnitude of particulate emissions [6].

All methods used to date to reduce emissions from the combustion of conventional diesel fuel affect engine performance or fuel efficiency. Various combustion systems have been implemented to reduce emissions typically associated with high-performance diesel engines [7]. The best way to use heat requires maximum burn rate in range of 5 and 12 degrees ATDC (after top dead centre); this provides a balance between heat transfer, production and energy [8]. Also, the best optimal thermal efficiency range necessitates the combustion phases to fall within 5 and 12 degrees ATDC, ensuring the equilibrium in energy distribution among work output, exhaust energy, and heat transfer [9]. To overcome the combustion restrictions related to feed gas emissions, peak combustion pressures, pressure rise rate and, combustion is delayed towards the end of the expansion stroke by control the injection timing of fuel, coupled with the utilization of exhaust gas recirculation (EGR) [10,11]. EGR stands out as a highly efficient method for NOx reduction, yet its applicability is constrained by diminished efficiency of the combustion, slower combustion rates, and heightened soot emissions, all of which contribute to diminished fuel efficiency [12,13].

The basic problem with diesel engine emissions is that they contain harmful gases which create health and environmental hazards [14]. The diesel combustion process leads to high levels of particulate matters (PM) and unburned hydrocarbons (UHC) [15]. Dramatic emission reductions are mandatory in order to comply with legal restrictions and to reduce the environmental impact [16]. To achieve the near future goals set by any environmental legislation, more effort should be undertaken for the assessment and modelling of new technologies associated with pollutant emissions [17].

Nowadays, studies on the use of biodiesel are increasing day by day and are carried out in the field of toxicology, economy, social awareness, microbiology, and heat and mass transfer [18]. Meanwhile the CO_2 gas emitted during the operation of the engine is part of the carbon cycle in nature, other hazardous emissions contribute to global environmental problems such as air pollution, acid rains, the development of photochemical and harmful effects on human health [19]. The increase in the effect of greenhouse gases observed in the world in recent years has caused the difficulties of global warming and climate change to be brought to the agenda [20]. The farms can only convert the solar energy into oilseed and then biodiesel energy, and releasing the same amount of CO_2 that they consume from the atmosphere, due to the fact that they are di-Carboxy plants [21]. Significant information on the engine power and power capacity of biodiesel, which plays an important role in agriculture and land transportation systems, has been determined. However, the development in the reduction of gases such as CO, hydrocarbon (HC), nitrogen oxides (NOx), and PM that positively affect human health also remains as a significant solution to the concern of increasing the emissions [22].

Biodiesel is an alternative autochthonous, regenerated fuel and is considered as a clean energy source [23]. Biodiesel is produced from various feedstock like the oil of various crops, or waste or used oil that is obtained in food process plants or from fryers [24]. The most common source of biodiesel is vegetable oil, such as rapeseed oil, soybean oil, sunflower oil, corn oil, peanut oil, and safflower oil [25,26]. However, some biodiesels used in the experiments were derived from animal fats [27]. Biodiesel has a high flash point and low sulfur content, and is a biodegradable and renewable fuel [28]. Biodiesel blends do not require modifications in diesel engines. Previous studies [29,30] on biodiesel blending with diesel fuel have shown not so different performances in terms of engine efficiency and emissions. The advantage of biodiesel is that it has a high cetane number and does not contain sulfur. However, the main disadvantage of biodiesel is having a higher viscosity and density compared to diesel and a significant reduction in its calorific value [31,32]. Many researchers [33,34] have tried to blend biodiesel with diesel in different techniques to overcome the problem of low combustion temperature and improve performance of the engine. Most of them have concluded that the best blending ratio is B20 (a mixture of 20% biodiesel and 80% diesel), which improves density, cooling, calorific value and flash point, as well as increasing engine performance [35,36]. Lawan *et al.*, [37] studied the effect of adding a biological material on the properties of biodiesel. The effectiveness of probiotic supplements depends on the level and type of phenolic compounds present in the additive and whether it contains antioxidants. Chaichan *et al.*, [38] used oxygenated additives (ethanol and methanol) to diesel to investigate the performance and emission of the engine. The researchers studied several effects such as using 15% EGR, changing the equivalent ratio and injection timing. The study focused on the effect of these variables on both NOx and PM emissions. NOx levels increased with increasing equivalent ratio. Adding both E10 and M10 to diesel caused a reduction in PM levels, while EGR was shown to increase PM levels. In the case of combining oxygenated mixtures with EGR, PM emission levels were decreased. Using biodiesel that produced from crude and refined cooking oils and cooking waste results in an engine exhaust emission often depend on the fuel combustion process inside cylinder [39]. The difference in engine tailpipe emissions, such as the combustion characteristics of biodiesel and diesel fuel, can be significantly different [40]. Therefore, there will be an urgent need to evaluate both cylinder pressures as well as engine exhaust emissions to optimize diesel engine fuelling with biodiesel. In general, both edible and non-edible crude oils contain a higher amount of carbon, due to the glycerol compound found in the oil chains. Using these oils in a diesel engine would increase particulate matter significantly [41,42].

Further improvement of the technical and environmental properties of diesel fuel consisting of 20-35% biodiesel will enable an increase in the share of biodiesel in the world, the total volume of private biodiesel, the quantities of bioenergy resources, and the number of raw materials used [43, 44]. The United Nations and other international organizations have set goals to develop the production of environmentally friendly engine fuel, which is produced based on bioenergy resource. One of these goals is to find ways and means to produce biodiesel from available renewable animal and plant raw materials [45,46]. Commercially available oils and fats are the most economical. A biodiesel formulation derived from used restaurant oil was blended with Iraqi diesel, which has a high sulfur content. The tests were conducted under constant engine speed and variable loads. The experimental results indicated that incorporation of biodiesel (using volume ratios of 20%, 35% and 50%) into neat diesel resulted in an increase in brake fuel consumption by 2.6%, 5.9% and 7.35%, respectively. Moreover, when operating with a 50/50 biodiesel/diesel blend, emissions showed a significant decrease compared to pure diesel. For example, carbon monoxide (CO) levels decreased by 18%, hydrocarbons (HC) by 23.4%, nitrogen oxides (NOx) by 3.5%, fine particulate matter (PM) by 46.4%, hydrogen sulfide (H2S) by 47.5%, and finally, sulfur dioxide (SO2) decreased by 27.2% [47].

Based on a review of the recently published literature on biodiesel-fuelled diesel engines, the motivation of the study is to find a solution to the issue of the effect of engine load as an operating parameter on soot emitted from an internal combustion engine. The uniqueness of the study comes from the attempt to study a specific problem, which is the types of fine particles and their nanoscale dimensions emitted from blends of biodiesel (renewable derived from spent cooking oil) with Iraqi diesel. Iraqi diesel is known to be a high-sulfur fuel. Sulfur in diesel causes higher emissions of fine particles with hazardous properties. Therefore, adding biodiesel that does not contain sulfur will reduce the final sulfur content in the mixture and thus reduce the resulting soot. In the present study, the effect of added biodiesel when the engine is operating at a range of different loads up to the maximum level on the distribution of emitted particles is investigated. This study also aims to contribute outside the existing literature and compare the emission performance of a diesel engine using this bio-oxygenated fuel produced by a conventional alkaline catalyst. The main objectives of the work are: to operate the engine under different engine loading conditions and to compare multiple measurements of emitted nanoparticles with those emitted from Iraqi diesel combustion.

2. Methodology

In this study, refined edible oils and residual edible oils were used. In this work, refined cooking oil is treated with a stratification process to get rid of glycerin and impurities. To evaluate the pros and cons of biodiesel in a diesel engine, PM emitted from the engine exhaust of B20, B35 and B50 mixtures was measured. In the present investigation, the diesel engine used was a four-cylinder, four-stroke, water-cooled, naturally aspirated DI diesel engine. Experimental work was carried out on an open test bed. The research test bed is composed of diesel engine, dynamometer and other accessory parts. Parameters of engine were effectively measured for different load conditions from low to maximum engine load using biodiesel extracted from used cooking oils with diesel. In this study, the authors carried out experimental work to evaluate the particles present in the engine exhaust pipe.

2.1 Production and Properties of Biodiesel

The biodiesel used in this study was produced using the transesterification process (usually in the production of methyl esters). In this method, methanol is added to vegetable oil or fat using a catalyst of sodium hydroxide). This method produces methyl ester plus glycerol (with mixture no more than 20%). Previous study [48] explains the process mentioned in this section with details and description. Laboratory-produced biodiesel is added to fossil diesel fuel in portions and the resulting mixture is named according to the amount of biodiesel added. The mixture consisting of 20% biofuel + 80% diesel is called DB20 and so on for the rest of the mixtures. Table 1 shows some of the most important mixed media. The sulfur content of the diesel fuel used in the study was very high (12,340 ppm), and the laboratory-prepared biodiesel mixture had a low sulfur content with a percentage equal to the amount of biodiesel in the mixture.

Table 1
Properties of diesel fuel, biodiesel, and their mixtures

"Fuel type"	"Density" (kg/m^3)	"Viscosity" (cSt @ 40 °C)	"Heating value" (kJ/kg)	"Cloud point" (°C)	"Sulfur content"
"Diesel"	830	1.86	45,573	-41	12340
"DB20"	837	2.4	44,616	-31	9872
"DB35"	844.5	2.62	44,275	-22	8021
"DB50"	855.6	2.77	42,914	-19	6170
"B100"	881	4.2	40,296	-4	0

2.2 Experimental Setup

The engine used in this study is a Fiat diesel engine (TD 313 Diesel engine rig), the engine is water cooled, direct injection, natural aspirated one. The test engine is a European-made four-cylinder diesel engine and is equipped with a hydraulic dynamometer system to determine the load applied to the engine. This engine was selected because of its modular design and close resemblance to those used around the world. The maximum engine power is 60 kW, which is typical for some compact passenger cars. The engine is water-cooled, with a capacity of 3.66 litres and a compression ratio of 17:1. The engine is warmed up for 15 minutes before starting to measure the fuel mixture. To limit the test data, the first test phase was conducted at an average engine speed of 1,500 rpm (which represents the rotational speed of an urban engine at average speeds). The engine load was changed in steps, each equal to 10% of the total load of the maximum load. Engine load is adjusted using a hydraulic dynamometer. In the second part of the experiment, the engine rpm was changed by operating the engine load at a medium load. The measured speed indicates low, medium and high speeds. The engine is heated with diesel fuel and when the engine coolant temperature reaches to temperature of 90°C (which is the required), the engine switches to the type of mixture to be measured.

2.3 Analysis and Measurements of Emission

Five types of PM emissions are PM1, PM2.5, PM7, PM10, and TSP for five mixtures of diesel, DB20, DB35, DB50, B100, respectively. Emitted particle concentrations were measured using GT-521of Met One Model, which uses a laser photometer. The calibration of the device was approved by the Central Organization for Standardization and Quality Control in Baghdad, Iraq. A meter distance of the device from the exhaust outlet is placed to ensure emissions are reduced as required by the PM measurement conditions set by the manufacturer.

2.4. Uncertainty Analysis

Uncertainty analysis was utilized to perform a comprehensive evaluation of the statistical precision of the study and the empirical results. Through the application of this method, possible discrepancies observed in the calibration processes of instruments can be identified, thereby aiding in the prediction of data inaccuracies. The determination of uncertainty in the current research was based on the methodology proposed by Klein and McClintock. The following equation was employed to determine the various inaccuracies in experimental measurements:

$$W_R = \left[\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2\right]^{0.5}$$

W_R is a symbol denoting the overall uncertainty, with R representing the function of the independent variables (x_1, x_2, …, x_n) and (w_1, w_2, …, w_n) signifying the uncertainties of these independent variables. The uncertainty associated with the test reg can be found in Table 3. A total uncertainty of 2.83% was determined experimentally, indicative of a high level of accuracy and a low degree of uncertainty.

4. Results and Discussion

4.1 Engine Load Effect

Combustion is a very complex process and it is impossible to reduce the cause or effect of anything without dealing with its other effects. Two operating parameters were changing and studied in this study, such as speed and engine load, are measured for four types of emissions. PM emissions results are changing with varying engine load at constant speed as shown in Figure 1. Emission of PM1.0 is higher at both conditions (low and high loads) and it is lower at medium loads. Medium loads at medium speeds are used for testing and are good for mixing the fuel and allowing oxidation time. Using DB50 produced the lowest level of PM1.0 compared to the others. Reduction of PM1.0 compared to diesel: 4.2%, 14.2%, 24.78% and 34.63% for DB20, DB35, DB50 and B100. This study confirmed that reducing sulfur in oil has a significant impact on PM1.0 production.

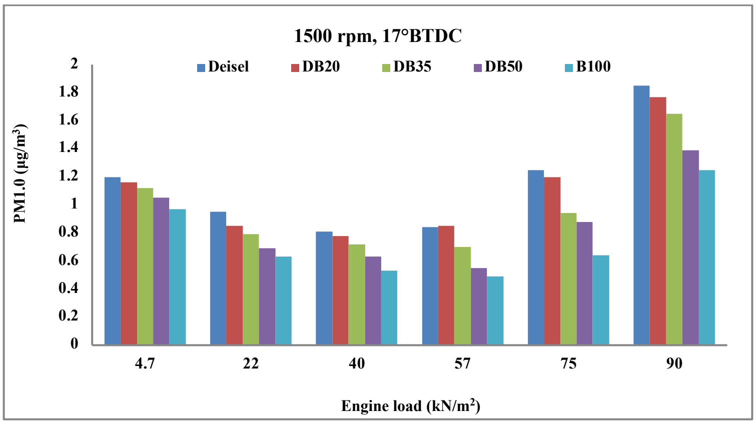

Fig. 1. Engine load effect on emitted PM1

The results in Figure 2 are approximately followed the same trend as Figure 1, with lower PM2.5 concentrations at medium loads and higher for both conditions of loads (low or high). The engine fed with biodiesel-diesel blends has given promoted results. Furthermore, the emissions of two types of PM (PM1.0 and PM2.5) in this study seem to be very small, counting the emissions of engines operating in many ways and shutting down these pollutants over days and weeks provides a real warning of the seriousness of these pollutants. The PM2.5 was reduced by 7.2%, 16.7%, 32.2% and 42.8% for DB20, DB35, DB50 and B100, respectively, compared to diesel.

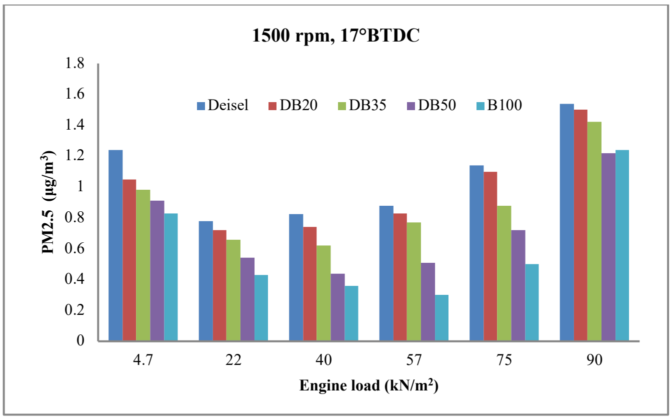

Fig. 2. Engine load effect on emitted PM2.5

Figure 3 presented the concentrations reduction of PM10 using biodiesel-diesel blends. The rates of reduction emitted the type levels of PM10 for DB20, DB35, DB50 and B100 in comparison with neat diesel were 12.93%, 21.11%, 31.64% and 42.73%, respectively.

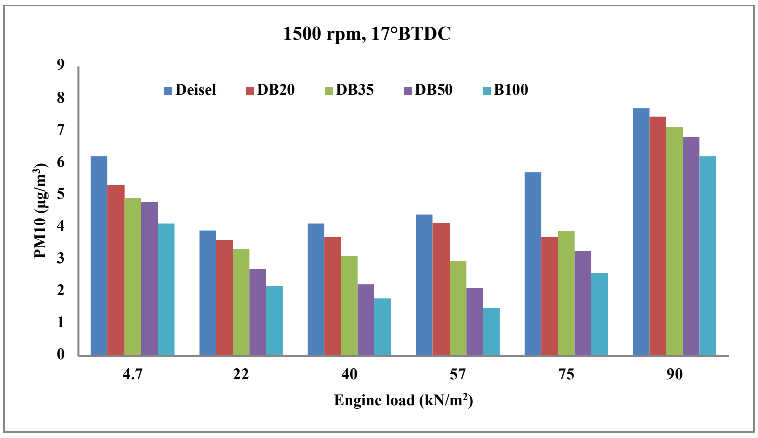

Fig. 3. Engine load effect on emitted PM10

Regarding the TSP released from the engine, the percentage reduction shown in Figure 4 is 4.98% for DB20, 12.07% for DB35, 21.54% for DB50 and 26.53% for B100 compared to diesel. The results showed that using biodiesel led to a reduction of particles in-cylinder in all directions, but the impact on nano- and PM was greater than the effect on particulate matter.

3.2 Engine Speed Effect

Figure 5 shows the effect of varying motor speed on PM1.0 molecules. PM1.0 is affected by engine speed because it is higher at lower speeds due to lower combustion chamber temperatures. In addition to the cold walls of the combustion chamber, this also increases pollution and prevents oxidation. PM1.0 has the lowest value at medium speed because there is enough time for the fuel to breathe and mix the fuel with air, there is enough heat in the combustion chamber to oxidize the fuel, and there is enough space for oxidation. PM1.0 concentration is increasing at a high rate. Although more heat is supplied to the combustion chamber, mixing time with the same oxide will decrease and molecular density will increase. Blending biodiesel into the diesel reduced the concentration of PM1.0 by 12.13% and 36.65% for DB20 and DB35, respectively, than to the diesel.

However, the combustion of DB50 and B100 decreased these pollutants by 60.92% and 81.06% compared to diesel. The findings in this study confirm the significant effect of sulfur content in used oils. Moreover, the presented of biodiesel decreased the sulfur content of the diesel and improved the oxygen content of the mixture, emissions from biodiesel-diesel blends were lower due to the lower sulfur content.

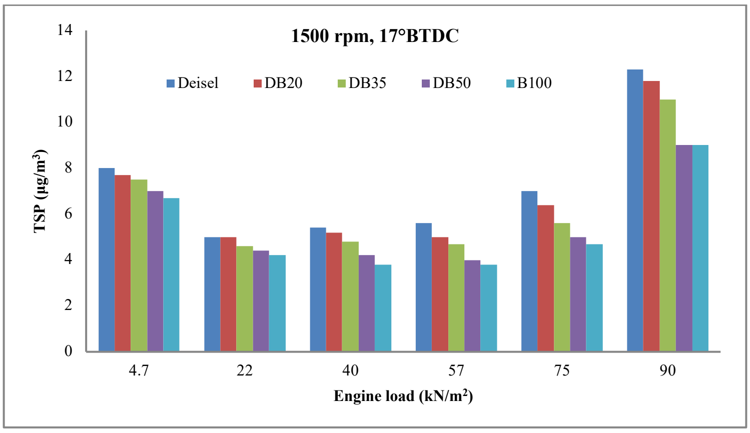

Fig. 4. Engine load effect on emitted TSP

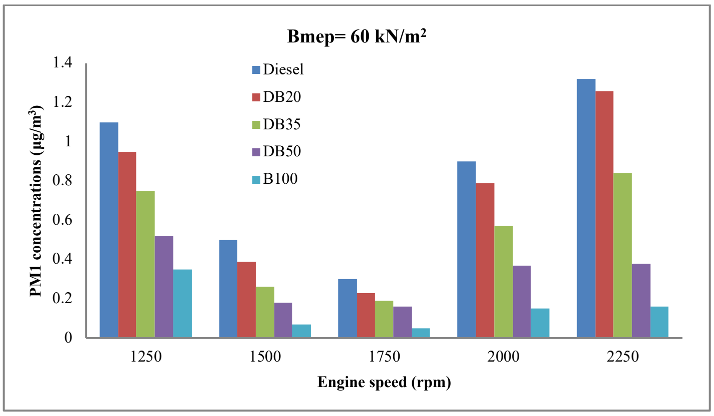

Fig. 5. Engine speed effect on emitted PM1

PM2.5 concentration in Figure 6 followed the results as PM1.0, decreasing at engine speeds with medium and increasing at low and engine speeds with high condition for the same reasons mentioned above (Figure 5). The addition of biodiesel resulted in a reduction of 21.29% and 25% for DB20 and DB35, respectively. However, when DB50 and B100 were used, the concentration decreased to 41.43% and 51.85%, respectively, compared to diesel. We believe that the decrease in the distribution of PM2.5 when adding biodiesel is not comparable to the case of PM1.0 due to the process of oxidation nearby and related molecules becomes difficult despite the oxygen effect that presented in the biodiesel.

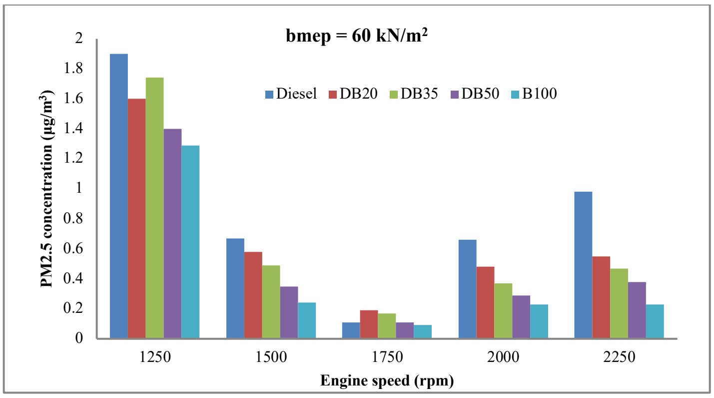

Fig. 6. Engine speed effect on emitted PM2.5

Figure 7 shows that the concentration of emitted PM10 is higher than that of other pollutants; This confirms that the larger the molecular size, the more difficult the oxidation process is. Biodiesel-diesel blends still offer a slight advantage over diesel; PM10 rates are 9%, 25.98%, 43% and 61.3% lower for DB20, DB35, DB50 and B100. Figures 5 to 7 show that the concentration of PM1.0 is increase more than PM2.5 and PM10 when presented B100, because the particulate matters are formed at the beginning as PM1.0 and then aggregated to form the rest of the particulate's sizes like both PM2.5 and PM10.

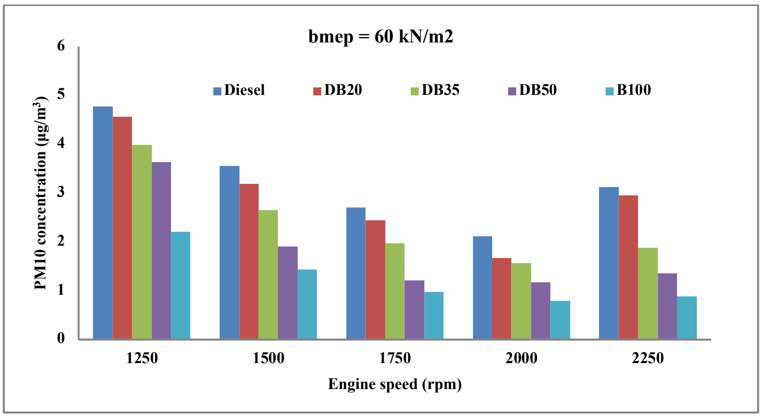

Fig. 7. Engine speed effect on emitted PM10

The effect of engine speed (Figure 8) on total suspensions particles (TSP) measured. The particles measured in device were mostly high and decreased at a moderate rate, and when biodiesel-diesel blends were used, the use of B100, DB50, DB35, DB20 lead to decrease of 51.9%, 35.2%, 19.6% and 9.37% compared to diesel. The above results confirm that reducing the sulfur content and increasing the oxygen content in fuel is very effective and significantly reduces total PM emissions.

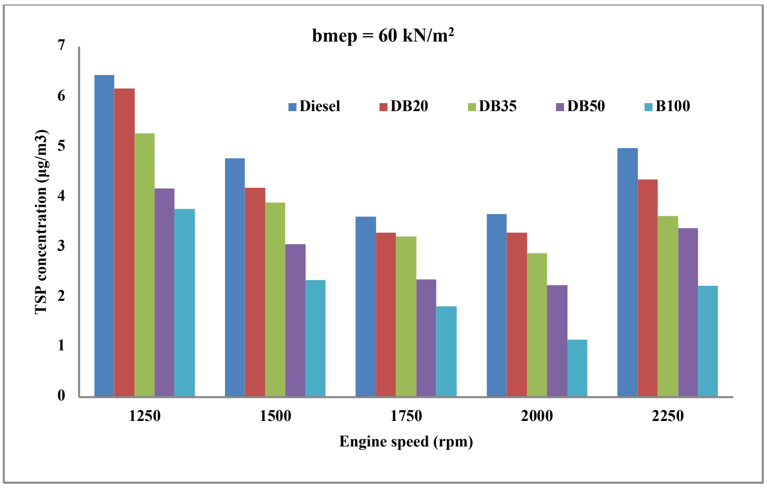

Fig. 8. Engine speed effect on emitted TSP

Figure 9 shows a comparison between some experimental studies that used biodiesel or mixtures of biodiesel and diesel or kerosene as fuel. The use of biodiesel with a high oxygen content reduces the emitted PM concentrations as is the case with the results of Refs. [50] and [52]. Ref. [48] introduced gaseous hydrogen with air and ignited it with biodiesel (pilot fuel) and the resulting PM concentrations were very low, reaching 3.8 µg/m^3. Ref 38 reduced PM concentrations by adding ethanol with a high oxygen and hydrogen content and recirculating the exhaust gas. Ref. [49] added biodiesel produced from waste restaurant oil (50%) to diesel with ultra-low sulfur content; the emitted PM was about 17 µg/m^3 at part load and speed of 1500 rpm. Refs. [3] and [51] added biodiesel to Iraqi kerosene, which has a much lower sulfur content than Iraqi diesel, so PM emissions reached 3.7 and 4 µg/m^3, respectively. In the present study, good mixing and use of suitable surfactant played an important role in achieving the lowest PM emissions, which was 3.07 µg/m^3.

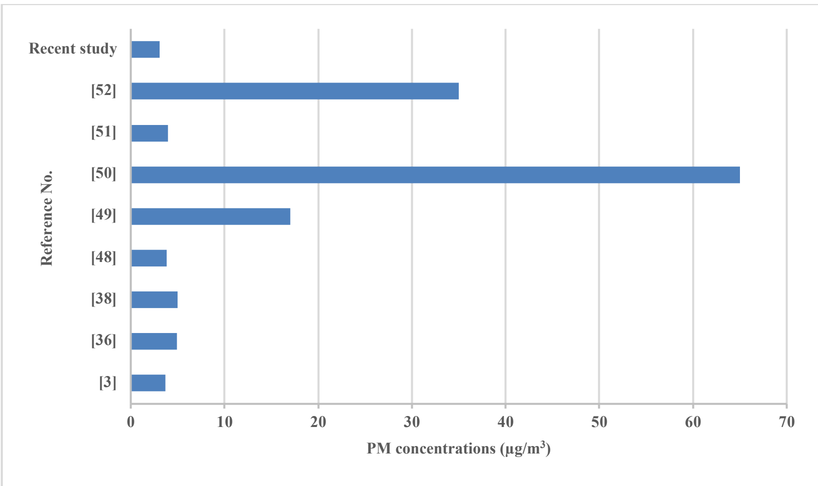

Fig. 9. Comparison between resulted PM concentrations for several studies from literature

4. Conclusion and Future Directions

The sulfur content of Iraqi diesel is high (between 10,000 and 25,000 ppm) and another alternative is used (especially in summer) to reduce the content: biodiesel. Biodiesel has no or very low sulfur content in its composition, making it the most acceptable additive to diesel fuel in Iraq, which suffers from high and dangerous pollution levels. The results showed that the use of biodiesel-diesel blends reduced particulate emissions of all sizes and had a significant effect on the measured nanoparticles and fine particles.

1- Compared to diesel at constant load and variable engine speed, the significant reduction in PM1.0 was 81.06% for B100, while PM2.5 for DB20 decreased by 51.85%.
2- The use of biodiesel blends resulted in a significant reduction in particulate matter compared to diesel, where TSP was reduced by 51.9% when using DB50, while a good reduction was found in DB20 by 19.6%.
3- Most of the reductions in output units were at medium engine speeds and loads.
4- The variable PM measurements increased at both (low and high) engine speeds and loads.
5- There are two main reasons for the reduction in PM emissions in diesel and biodiesel blends: The high oxygen content in biodiesel leads to complete combustion and soot oxidation. The second reason is the presence of less sulfur in bio-oil.

The present study confirms that the emitted PM was significantly reduced using biodiesel and diesel blends. In addition to measuring different groups of emitted PM, this study indicates that PM needs further investigation due to its impact on the surrounding environment and human health. This research will allow for a better and easier understanding of the basic components and their differences within PM particles. Therefore, future work should investigate the chemical and physical effects of PM and how they affect PM formation and its impact on diesel engine performance and emissions in detail. Also, a clear revision for PM variable measures effects on human health should be conducted.

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