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Investigation exhaust emissions and performance characteristics of a diesel engine by using addition of nanoparticles to diesel fuel

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Abstract

Users of fossil fuels are facing a range of challenges such as long-term rising demand, climate concerns due to emission of greenhouse gases, ecological pollution, finite reserves and price fluctuations. Diesel fuel is similarly affected, though with its own subset of issues. Studies suggest that diesel fuel characteristics are affected by addition of nanoparticles. In this research, carbon nanotubes (CNTs) were blended with pure diesel as an additive at concentrations of 30, 60, and 90 ppm to assess the emission and performance characteristics of a single-cylinder compression combustion engine. The considered emission contents included CO, CO2, HC, and NO produced by an engine at 50% and 100% loads, at 1800, 2300, and 2800 rpm. Addition of CNTs to the diesel fuel considerably reduced the emission of CO, CO_2, HC, and NO compared to additive-free diesel fuel. Furthermore, with the addition of carbon nanotubes, the Exhaust Gas Temperature (EGT) and the Brake Specific Fuel Consumption (BSFC) decreased, while the power and Brake Thermal Efficiency (BTE) increased at all loads and speeds of the engine.

Keywords: Carbon Nanotubes, Diesel Fuel, Emission, performance, Engine,

1 Introduction

Diesel engines are mostly used in heavy applications in transportation, agriculture, maritime and power generation sectors. They have greater fuel-economy than petrol engines [1]; [2]; [3]; [4]; [5]. Despite their many advantages, diesel engines produce more pollutants, for example, NOx, CO, HC, particulates, smoke and harmful fumes. These cause dangers, such as acid rain, ozone depletion, greenhouse effects, climatic changes, and smog affecting plant, animal and human health [6]; [7]; [8]; [9]; [10]. On the other hand, since energy plays a significant role in global economic growth, the demand for fossil fuels has been increasing over the years [11]. Many governments have imposed restrictive measures on the automotive sector and customers regarding emission of pollutant gases, as energy consumption keeps growing and oil reserves are finite. In turn, this has driven research into diesel technology to reduce emissions, transform fuel characteristics, modify engine design and filter output gases [12]; [13].

Various projects are presently underway to reduce pollution. The use of fuel additives in engines is considered an effective method to improve fuel properties and reduce the emission of pollutants to fit the standards [14]. Currently, various nano-additives have been applied in compression ignition engines in the form of nano metal-organic additives, metal oxide, carbon nanotubes, and a mixture of nano-additives [15]. These additives complement diesel fuel to achieve combustions that are more complete and reduce exhaust productions. The reactive nature of these additives includes a catalyst effect on the combustion of hydrocarbons [3] and improves fuel characteristics in terms of the surface area-to-volume ratio and evaporation speed and reducing the ignition delay [16]; [17]. Combustion, performance, and emissions characteristics from a diesel engine were assessed using aluminum, iron, and boron nanoparticles [18]. The results indicated a 25-40% reduction in the emission of CO, accompanied by 8% and 4% reductions in the emission of hydrocarbons for nano-fuels containing aluminum and iron, respectively. Given the increased temperature, emission of NOx was increased by 5% and 3% in the combustion of fuels containing aluminum and iron, respectively. Gumus et al. used CuO and Al2O3 nanoparticles as additives to diesel fuel. The addition of Al2O3 reduced the emission of CO, HC, NOx and BSFC by 11%, 13%, 6%, and 1.2%, respectively, while these values were 5%, 8%, 2% and 0.5% when CuO was used as the additive [7].

Carbon nanotubes can be used in a range of scientific fields due to their unique physical, chemical, mechanical, and electrical characteristics. An experimental study was applied in respect of a diesel engine with the

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emulsion of biodiesel and carbon nanotubes (CNTs). At full load, the NOx content and smoke opacity were 1288 ppm and 69% for pure Jatropha (JME), respectively, while these values were 910 ppm and 49% for JME2S5W100CNT fuel, respectively [19]. Selvan et al. tested the performance, emission, and combustion properties of a diesel engine with cerium oxide nanoparticles and carbon nanotubes added as additives to a diesel-biodiesel-ethanol (DBE) blend. Addition of CNTs and cerium oxide to BDE blend resulted to a cleaner combustion and meaningfully reduced emission of dangerous gases [20]. The effect of addition of carbon black to diesel fuel at ratios of 5, 10, 15, and 20% in an air-cooled single cylinder engine was tested. The outcomes indicated that the emission of NO and smoke from the blend containing 10% carbon black decreased by 6.2% and 11.5% compared to pure diesel, respectively [21]. In another study, the DBE blend and carbon nanotubes were used to conduct tests on a single-cylinder air-cooled diesel engine subject to different loads at an invariable speed of 1500 rpm. The outcomes indicated a reduction in emission of CO, HC, and smoke, while emission of NOx was augmented [22]. Basha examined the effect of CNTs and diethyl ether as additives for biodiesel emulsion fuel on a single-cylinder four-stroke engine and stated that emission of NO and smoke was lessened [23]. The performance characteristics and emissions of a single-cylinder water-cooled were assessed using a biodiesel of biodiesel with CNTs. The results showed an improvement in the thermal efficiency of the engine and decrease in NO, CO, HC, and smoke [24].

Based on the review of the literature, the effect of different nanoparticles have been mostly studied on pure diesel, diesel-water emulsion, and metal nanoparticles, while the blend of diesel and CTNs has been barely discussed. Moreover, the influence of nanoparticles on diesel fuel has rarely been studied in Iran, where diesel engines account for a large portion of the contaminants in large cities. Therefore, in this study, the influence of nanoparticles on emissions from a diesel engine was experimentally studied.

2 Materials

In this research, a blend of diesel fuel and CNTs was used to fuel a single-cylinder, air-cooled, four-stroke engine and the pollutants emitted were studied. The characteristics of the engine are given in Table 1. Since functionalized CNTs are greatly reactive and tend to react with many chemical elements, they can be applied to increase fuel quality [25]. The characteristics of the functionalized multi-walled carbon nanotubes containing carboxyl groups (MWCNTs-COOH) purchased from Iranian Nanomaterials Pioneers Co. are presented in Table 2. CNTs were combined with the diesel fuel at proportions of 30, 60, and 90 ppm (the ratios are in milligram per liter of diesel). The resulting solution was stirred for 30 min using a UP400A (400W, 20 kHz) ultrasonicator to prepare a homogeneous fuel blend. The specifications of the pure diesel fuel and its blend with CNTs were measured based on the ASTM standard and are shown in Table 3.

Table 1: Technical specifications of the test engine

Engine parameters	Specification
Engine model	Lombardini (3LD510)
Number of cylinders	1
Bore	85 mm
Stroke	90 mm
Crank length	34.5 mm
Rated torque	32.8 N.m at 1800 rpm
Displacement	510 cm^3
Compression ratio	17.5:1
Rated power	9 kW at 3000 rpm
Nozzle operation pressure	200 bar

Table 2: Details of multi-walled carbon nanotube

Item	Specification
Manufacturer	US Research Nanomaterials,Inc.
Chemical name	(MWNTs),-COOH
Surface area	233 m^2/g
Outside diameter	5-15 nm
Inside diameter	3-5 nm
Length	50μ
Content of –COOH	1.56 wt.%
Purity	95 wt.%
Appearance	Black
Density	0.27 g/cm^3
Thermal conductivity	3000 W/m.K
Manufacturing method	CVD

Table 3: Properties of diesel without and with MWCNTs sample fuels

Property	Unit	Standard	D	D+CNT30	D+CNT60	D+CNT90
Kinematic Viscosity in 40℃	mm^2/s	ASTM D-445	2.9320	2.9415	2.9499	2.9816
Flash point	℃	ASTM D-92	73.9	74	75.9	66.7
Cloud point	℃	ASTM D-2500	-3.9	-3.3	-2.8	-2.2
Density	gr/cm^3	-	0.8321	0.8307	0.8304	0.8407
Calorific value	MJ/kg	ASTM D-240	43.036	43.159	43.368	43.588

3 Methods

To collect the relevant data on engine contaminants, the fuel blends were tested at 50% and 100% dynamometer loads on an air-cooled, four-stroke, single cylinder, compression ignition engine at speeds of 1800, 2300, and 2800 rpm in the Engine Laboratory of the Agriculture Faculty in Tarbiat Modares University. To apply the loads, the test engine was attached to a WE-400 eddy current dynamometer manufactured by Mobtakeran Pars Andish Co. (MPA). Pure diesel was used to start the engine and warm it up. The warm-up period continued until the temperature of the cooling water stabilized, after which the data sampling started. After each test, the engine was kept operating on the new blend for 10 min to ensure all remnants of the previous blend in the engine fuel supply line were removed, after which the required data was recorded. The volumetric flow rate was measured with a Japanese OVAL flowmeter. The levels of pollutants in the exhaust gases were recorded using a calibrated AVL DITEST Gas 1000 gas analyzer device. The engine setup and the equipment used in the tests are shown in Fig. 1. Each test was conducted three times and the mean values of the results in steady-state conditions were recorded as the final values.

In this study, NO, CO, CO2, HC, power, BTE, SFC and EGT were assessed in terms of engine pollutants and performance characteristics. The percentage uncertainties of various parameters were calculated using the percentage uncertainties of different measuring instruments used in the experiment. The measurement accuracy, range, and percentage uncertainties of all used instruments are listed in Table 4.

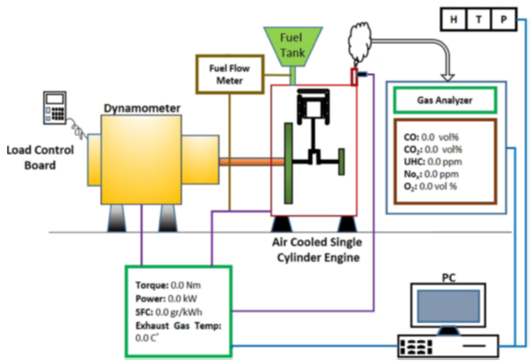

Figure 1: Measurement set-up and devices

Table 4: The accuracy of the measurements and the uncertainties in the calculated results

Parameters	Accuracy	Uncertainty(%)
Load	±0.1 Nm	0.5
Speed	±5 rpm	0.1
Power	±0.01 kW	0.2
BTE	-	0.2
BSFC	±0.01g/kWh	0.4
Tem.	±1℃	0.2
CO	±0.03 vol.%	1.6
CO_2	±0.3 vol.%	1.5
O_2	±0.02 vol.%	1.4
HC	±10 ppm	1.7
NO	±5 ppm vol.	1.3

4 Results and Discussion

In this study, the emissions from a single-cylinder, air-cooled, four-stroke engine were tested at two engine loads, three engine speeds, and four concentrations of CNTs. The measured and assessed pollutants included NO, CO, CO_2, and HC, and performance attributes were power, EGT, BTE and SFC. All the measurements were conducted under steady state and similar conditions.

4.1 Engine Power

Fig. 2 displays engine power versus engine speed, engine load, and fuel type. Comparison of the obtained mean values showed that increasing the engine load from 50 to 100 percent would almost double the mean power (from 2.29 kW to 4.47 kW). Increasing engine load also increases the fuel-to-air equivalent ratio. In fact, at higher engine loads, increasing fuel consumption would lead to a corresponding increase in engine power. The results also showed that by increasing speed to 2300 rpm, the output engine power first increased, but subsequently dropped as the speed was further increased to 2800 rpm. This can probably be attributed to the fact that combustion is incomplete at higher engine speeds (nominal speed = 3000 rpm).

In addition, increasing nanoparticle concentration in the fuel increased the engine power. In general, CNT particles possess large surface areas and are highly reactive. Both these characteristics help trigger more chemical reactions, making these nanoparticles act as good potential catalysts [10]; [23]. These nanoparticle catalysts positively affect the physical properties of the fuel and reduce combustion delay, thus improving the combustion process [7]; [20]. The power increase due to CNTs is the result of improved combustion and the conversion of the effective fuel energy into useful work. Such increase can be attributed to the high surface to volume ratio of the CNTs, which leads to better atomization as well as more rapid fuel oxidation and evaporation rates, thus increasing the thermal conductivity of the same. This increase could also be due to the presence of oxygen in the functional CNTs used in the experiments. Using CNTs at 30, 60, and 90 ppm in the diesel fuel respectively increased engine power by 8.41, 11.97, and 16.99% on average compared to the diesel fuel. These results were in good agreement with those obtained in [5]; [7].

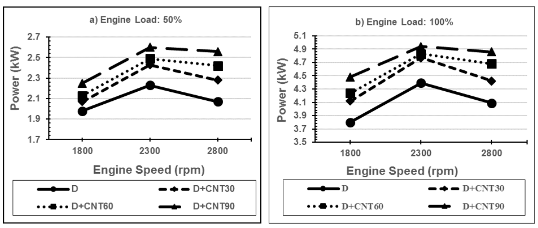

Figure 2: Variations of engine power with respect to engine speed and fuel blends at load a) 50%, and b) 100%.

4.2 Brake Thermal Efficiency (BTE)

Fig. 3 displays the brake thermal efficiency (BTE) values in the engine versus speed, load, and fuel blend. The brake thermal efficiency shows how efficiently the fuel energy is converted into mechanical output. BTE of neat diesel fuel and CNTs-diesel blends decline with the increase in engine load due to the increase in fuel consumption. In addition, the BTE value reduced with increasing engine speed. The most important reason for this decrease is the increase in BSFC values along with increasing engine speed (see Fig. 4). The results also showed that increasing the nanoparticle content of the diesel fuel would increase the BTE. The BTE increase was probably due to the improved combustion, atomization and rapid evaporation of the nanoparticles dispersed test fuel, resulting in better air fuel mixing, which allows more surface area of fuel to react with oxygen molecules. Furthermore, a shorter combustion period and relatively higher heat release rate through diffusion control phase of blends containing nanoparticles may be the reason for higher BTE compared to pure diesel [9]. Using CNTs at 30, 60, and 90 ppm in the diesel fuel respectively increased BTE by 4.95, 8.54, and 12.94% on average compared to the diesel fuel. It was observed that the maximum average BTE for D+CNT90 was 22.36%, whereas the lowest average BTE for diesel fuel was 19.78%.

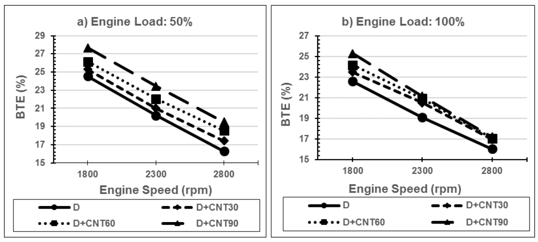

Figure 3: Variations of BTE with respect to engine speed and fuel blends at load a) 50%, and b) 100%

4.3 Brake Specific Fuel Consumption (BSFC)

Fig. 4 displays the changes of the BSFC in the engine versus speed, load, and fuel blend. As an important parameter in an engine, BSFC provides an idea of how efficiently fuel is converted into work by that engine. Lower BSFCs are always favorable; as a result, researchers are continually trying to reduce it to the maximum extent [1]. BSFC is particularly influenced by the fuel injection system as well as density, viscosity, and the higher heating value of the fuel [3]. Our results showed that increasing engine speed increased the BSFC. Increasing speed would lead to a corresponding increase in fuel injection frequency. Therefore, at higher speeds, fuel concentration inside the combustion chamber increases, leading to a corresponding increase in BSFC. The reason for this is probably the rapid increase of friction losses at higher speeds. The lowest BSFCs were associated with D+CNT90 blend, which at speeds of 1800, 2300, and 2800 rpm were 312.74, 361.045, and 479.77 gr/kW.h respectively. Whereas higher values for pure diesel fuel at the aforementioned speeds were by 348.2, 425.99 and 503.57 gr/kW.h. A further decrease in BSFC was observed at all speeds and engine loads upon increasing the CNTs concentration in the fuel. Nanoparticles improve combustion by enhancing fuel atomization, air-fuel mixing, and the diffusion of fuel into the engine cylinder, through their catalyst effect on the physical properties of the fuel and by reducing the combustion delay. This is surmised as the possible reason for the reduced BSFC after the addition of CNTs to the fuel, which is consistent with the results of previous studies [2]; [7]; [3]; [13]; [14]. When CNTs with proportions of 30, 60, and 90 ppm in the diesel fuel were utilized, BSFC decreased by 5.33, 8.86, and 12.56% on average compared to the neat diesel fuel.

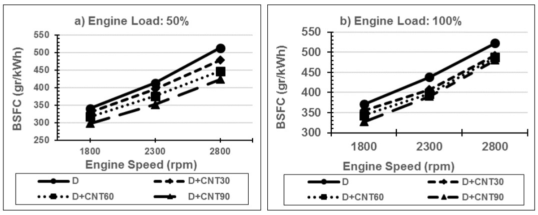

Figure 4: Variations of BSFC with respect to engine speed and fuel blends at load a) 50%, and b) 100%

4.4 Exhaust Gas Temperature (EGT)

Fig. 5 displays the changes of EGT in the engine versus engine speed, load, and fuel blend. The results showed that increasing engine load from 50% to 100% would lead to a significant increase in te temperature of the exhaust gases. This can be attributed to the increase in fuel consumption, which produces greater heat at higher loads. Increasing engine speed from 1800 rpm to 2300 rpm and from 2300 to 2800 rpm increased the exhaust gas by 16.52% and 11.50%, respectively. It was observed that exhaust gas temperature decreased at all speeds and engine loads as a result of using CNTs. The addition of CNTs reduced the BSFC as discussed above and consequently reduced the energy content, which in turn reduced the exhaust gas temperature. Another cause is that the addition of CNTs decreases the rich mixture zone to the diffusion mechanism, which results in reduced exhaust gas temperature [4]. These results were in good agreement with [10].

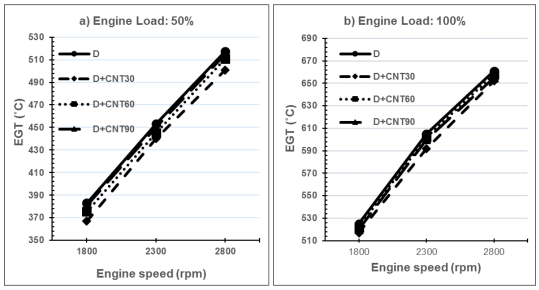

Figure 5: Variations of EGT with respect to engine speed and fuel blends at load a) 50%, and b) 100%

4.5 NO emissions

Variations of NO emission with regard to speed, engine load, and nanoparticles concentration are depicted in Fig. 6. The NO emission was significantly increased by increasing the speed at full engine load. The rise in NO emission at high loads might be ascribed to the high fuel-air ratio, which causes rich combustion, increased cylinder temperature and, consequently, increased NO content. Moreover, it can be stated that the burning temperature in the combustion chamber along with the cylinder pressure are increased at high loads, facilitating the emission of NOx gases based on the Zeldovich thermal mechanism [15]; [18]. However, it was observed that NO emission was reduced by increasing the engine speed at 50% load. Formation of NOx is affected by the utmost flame temperature, residence time of the high burning gas temperature, ignition delay, and the accessible oxygen and nitrogen contents in the reacting blend. While increasing the engine speed increases the pressure and temperature of the burning gas, the ignition delay decreases at the same time, which in turn decreases the maximum temperature residence time of the burning gas, ultimately decreasing the NO emission [6]. The results indicated that CNTs decreased the NO emission. At all engine speeds and loads, all the fuels containing nanoparticles achieved lower emissions compared to pure diesel. The lowest NO content was associated with D+CNT30, decreasing the NO emission at speeds of 1800, 2300, and 2800 rpm by 14.05%, 19.56%, and 20.41%, respectively, compared to pure diesel at full load. In addition, the lowest decrease at 50% load was related to D+CNT30, achieving reductions of 14.64%, 20.67%, and 24.04% at speeds of 1800, 2300, and 2800 rpm, respectively. High surface to volume ratio of nanoparticles cause improving atomization and better mixing of air and fuel and speeding up evaporation, which result in optimizing combustion [5]; [23]. The reduction in emission of NOx is possibly because of the full combustion of the fuels modified using the catalyst effect of nanoparticle additives that assist the convection heat transfer in the combustion chamber [25] and reduce the temperature (see Fig. 5), as a result it decreases NOx formation. Similar effects regarding emission of NO are observed in other studies [7]; [8]; [10]; [13].

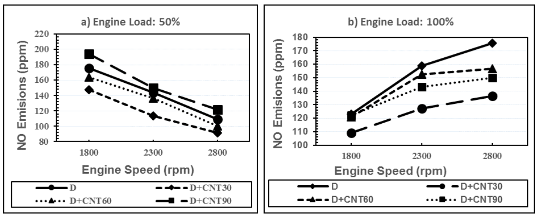

Figure 6: Variations of NO Emissions with respect to engine speed and fuel blends at load a) 50%, and b) 100%

4.6 HC emissions

Variations in HC emissions with respect to fuel type, engine speed and load are shown in Fig. 7. Unburnt or incompletely burnt hydrocarbons are produced during fuel combustion due to insufficient air supply [13]. By increasing the load, the emission of HC for all fuels was increased, possibly owing to the higher fuel content during combustion as the load rises. By increasing the engine speed, the HC emission increased for all fuel blends. HC emissions are created due to incomplete combustion in the combustion chamber of the engine. Increasing engine speed reduces the operating cycle time of the engine and consequently the combustion time, preventing a portion of the injected fuel from being fully or sometimes even partially oxidized. Therefore, this phenomenon might explain the increase in HC emission [25]. The lowest HC emissions were 34.36 ppm and 103.79 ppm associated with the D+CNT30 fuel blend at a speed of 1800 rpm obtained at 50% and 100% loads, respectively. The highest HC emission at 100% load was 275.24 ppm associated with pure diesel fuel at a speed of 2800 rpm, while at 50% load, the highest emission was 132.31 ppm associated with the D+CNT90 fuel blend at a speed of 2800 rpm. The results (on average) showed that CNTs significantly reduce the HC emissions, in the sense that the concentration of HC emissions for pure diesel was 152.80 ppm, while this value decreased to 108.17, 115.94, and 129.59 ppm when CNTs with proportions of 30, 60, and 90 ppm were utilized, respectively. The highest decreases in HC emission were 38.15%, 29.91% and 35.49% at speed of 1800, 2300, and 2800 rpm associated with D+CNT30 fuel at full load respectively. At 50% load, the largest reductions were 27.75%, 15.97% and 9.62% associated with D+CNT30 fuel at speeds of 1800, 2300 and 2800 rpm, respectively. The reasons for the reduced HC emission might be: the decreased ignition delay, enhanced combustion properties of CNTs, high catalyst effect of nanoparticles caused by their greater surface area-to-volume ratio, and the improved air-fuel mixture in the combustion housing [4]; [7]. At 50% load, the emission of D0CNT90 was significantly higher than that of pure diesel, which might be due to quick evaporation of fuels blended with nanoparticles, which decreases the temperature inside the combustion chamber and increases HC emission. The results on reduction of HC emission are consistent with those reported [2]; [3]; [7]; [13]; [18].

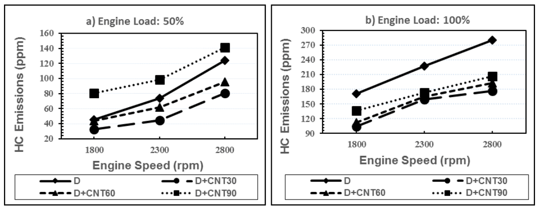

Figure 7: Variations of HC Emissions with respect to engine speed and fuel blends at load a) 50%, and b) 100%

4.7 CO emissions

Emission of CO is caused by defective combustion owing to either insufficient air in the air-fuel blend, or inadequate cycle time for the combustion. Variations in CO emissions with regard to fuel type, engine speed and load are presented in Fig. 8. By increasing the load, CO emission was increased for all fuel blends. At lower loads, a lower amount of fuel is supplied, which forms a leaner fuel blend that generates a lower amount of heat and flame temperature [23]. When there is insufficient oxygen to convert carbon to CO2, a portion of the fuel remains unburnt and a portion of the carbon remains as CO. Note that the emission of CO augmented by increasing engine speed might be due to the low amount of oxygen available.

CO is formed owing to defective combustion, which is intensified by deficiency of oxidizers, low temperature, and short residence time [20]; [21]. Considering the results, CNTs significantly reduced the CO emissions, as was the case for the HC emissions. Nanoparticles can improve the combustion process through secondary break-up of the fuel and as well as by reducing the combustion delay in the fuels blended with nanoparticles. These effects can increase the mixing of fuel and air, allowing the CNT-containing fuels to undergo complete combustion. The decrease in CO emissions might be related to the combustion characteristics improved by nanoparticles, which in turn causes a high catalyst effect due to the high surface area-to-volume ratio and improved mixing of air and fuel in the combustion chamber [10]; [22]; [23]. As shown in Fig. 8, at full engine load, all nanoparticle-containing fuels produce a lower amount of CO compared to pure diesel. The highest decreases in CO emission were 40.41%, 25.22% and 25.51% at speed of 1800, 2300, and 2800 rpm associated with D+CNT90 fuel at full load, respectively. Nanoparticles reduce the intra-molecular attraction (adhesion) of the fuel. Additionally, increasing the percentage of the nanoparticles involved reduces the homogeneity of the base fuel, consequently accelerating the breakup and decomposition of the fuel during injection. More decomposition of the fuel improves its mixing with air and reduces the equivalence ratio, which can eventually further reduce the emission of CO from D+CNT90 fuel [13]. At medium loads, the largest reductions were 33.91%, 32.83%, and 27.99% at the speeds of 1800, 2300, and 2800 rpm for D+CNT30 fuel. The results on reduction of CO emission are in line with those studies employing nanoparticles in the fuel blend [3]; [10]; [7]; [13].

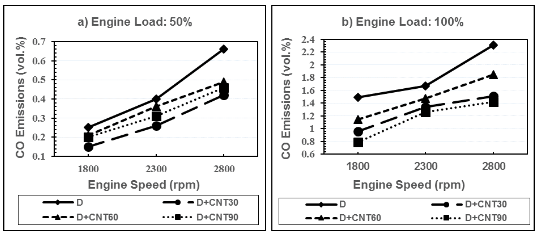

Figure 8: Variations of CO Emissions with respect to engine speed and fuel blends at load a) 50%, and b) 100%

4.8 CO_2 emission

Variations of CO_2 emissions with regard to fuel type, engine speed and load is shown in Fig. 9. As a rule, the most effective, economical usage of fuel takes place when the CO_2 concentration in the exhaust is at its maximum value [25]. By raising the engine load from 50% to 100%, the CO_2 emission increased for all fuel blends. The comparison between the mean values showed that this increase in engine load increased the CO_2 amount from 3.18 to 3.78%, since an increase in load increases fuel entry and the temperature inside the cylinder. As the engine speed increased, the CO_2 emissions also increased. CO_2 emission is dependent on the air-fuel ratio and concentration of CO emission. The results indicated that CNTs increased the CO_2 emission. The mean CO_2 emission from pure diesel fuel was 3.2%. As suggested by the results, the measured CO_2 contents at different nanoparticle concentrations of 30, 60, and 90 ppm were, respectively, 3.56, 3.42, and 3.64% in average. This can be attributed to the probability that nanoparticles decrease the intra-molecular attraction of the fuel, leading it to decompose more easily into small droplets, increase the fuel surface exposed to O_2 oxidizer, and consequently produce a larger amount of CO_2 [13]. The results revealed that at full engine load, the largest increases in CO_2 emission from D+CNT90 fuel were 11.04%, 9.17%, and 16.08% at engine speeds of 1800, 2300, and 2800 rpm. At medium loads, the largest increases were 19.31%, 12.01% and 6.81% at engine speeds of 1800, 2300 and 2800 rpm for the D+CNT30 fuel, respectively. Other studies using nanoparticles as additives to diesel fuel also confirmed the increase in CO_2 emission [2]; [13]; [3].

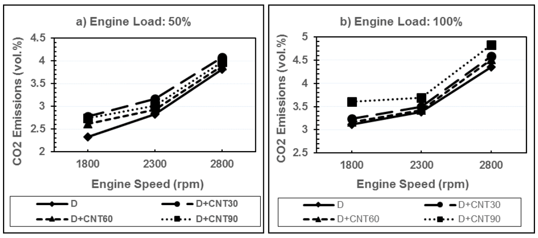

Figure 9: Variations of CO_2 Emissions with respect to engine speed and fuel blends at load a) 50%, and b) 100%

5 Conclusions

This study led to the following conclusions:

- When CNTs with proportions of 30, 60, and 90 ppm in the diesel fuel were utilized, power increased by 8.41, 11.97, and 16.99%, and also BTE increased by 4.95, 8.54, and 12.94% on average, respectively, compared to diesel fuel.
- At all speeds and engine loads upon increasing the CNTs concentration by 30, 60, and 90 ppm in the diesel fuel, further decrease in SFC by 5.33, 8.86, and 12.56% on average compared to the diesel fuel was observed. Also, by using CNTs in the diesel, the exhaust gas temperature marginally decreased.
- CNTs reduce the emission of NO content. At full engine load, all the fuels containing nanoparticles emitted a lower NO content compared to diesel fuel. The lowest NO content was associated with

D+CNT30 blend, reducing the NO emission by 14.64%, 20.67%, and 24.04% at engine speeds of 1800, 2300, and 2800 rpm at full load compared to pure diesel, respectively.

- The largest decreases in HC emission were 38.15%, 29.91% and 35.49% at speeds of 1800, 2300, and 2800 rpm associated with D+CNT30 fuel at full load respectively. At 50% load, the largest reductions were 27.75%, 15.97% and 9.62% associated with D+CNT30 fuel at speeds of 1800, 2300 and 2800 rpm, respectively.
- The largest decreases in CO emission were 40.41%, 25.22% and 25.51% at speeds of 1800, 2300, and 2800 rpm associated with D+CNT90 fuel at full load respectively. Whereas at medium loads, the largest reductions were 33.91%, 32.83%, and 27.99% at speeds of 1800, 2300, and 2800 rpm for D+CNT30 fuel.
- The results revealed that at full engine load, the largest increase in CO_2 emission from D+CNT90 fuel was 11.04%, 9.17%, and 16.08% at engine speeds of 1800, 2300, and 2800 rpm. Whereas at medium loads, the largest increases were 19.31%, 12.01% and 6.81% at engine speeds of 1800, 2300 and 2800 rpm for D+CNT30 fuel, respectively.

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