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Article

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Research paper

Performance and emission characteristics of a diesel engine fueled with functionalized multi-wall carbon nanotubes (MWCNTs-OH) and diesel–biodiesel–bioethanol blends



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ABSTRACT

Biodiesel is one of the renewable fuels which is similar to diesel fuel. Biodiesel fuel has more oxygen than diesel fuel and this leads to better combustion and thereby, decreases PM, CO, and UHC emissions. On the other hand, biodiesel has a higher viscosity and density than diesel fuel which increases the BSFC, NO_x and smoke emissions. One of the ways to solve this problem is using catalysts in the fuel which decreases the viscosity and density of the blend and as a result reduces the smoke and NO_x emissions compared to the diesel fuels. Carbon nanotubes are one of the nanoparticles which due to their unique properties such as aspect ratio (length-to-diameter ratio), mechanical strength and high thermal and electrical conductivity are considered as a topic of interest by researchers. Due to their hydrophobic surface, carbon nanotubes tend to accumulate. For better dispersion in solution, their surface is amended with different functional groups. In this study, the diesel–biodiesel fuel was prepared with 5% biodiesel and 95% diesel. The MWCNTs-OH with concentrations of 30, 60, and 90 ppm were mixed with bio-ethanol-based solution at concentrations of E4 and E8. The performance and emissions were recorded at the engine speeds of 1800, 2100, and 2400 rpm and full load. The results showed that, addition of the additive to diesel+biodiesel+ethanol blends (B5+E4 and B5+E8) improved the torque and power and decreased the BSFC. The emissions of UHC and CO also decreased but NO_x emission increased.

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1. Introduction

Diesel engines have a high brake thermal efficiency and durability compared to gasoline engines, so, diesel engines are used in the agricultural machinery and transportation (Jahanbakhshi et al., 2020; Jaliliantabar et al., 2020). On the other hand combustion of diesel engines causes emission of pollutants NO_x, PM, SO_x, UHC and CO (Heidari-Maleni et al., 2020b; Jaliliantabar, 2017). Due to the reduction of fossil fuels and the environmental pollution from the combustion of these fuels, renewable fuels have received attention (Salehi et al., 2020; Jahanbakhshi and Salehi, 2019; Jaliliantabar et al., 2018; Salehi et al., 2018).

Biodiesel is one of the renewable fuels which is similar to diesel fuel. Biodiesel fuel has more oxygen than the diesel fuel and that leads to better combustion and thereby, decreases PM, CO, and UHC emissions. On the other hand, biodiesel has a higher

viscosity and density than diesel fuel which increases the BSFC, NO_x and smoke emission (Seraç et al., 2020; Prabakaran and Udhoji, 2016). One of ways to solve this problem is using the ethanol and catalysts in the fuel which decreases the viscosity and density of the blend and as a result reduces the smoke and NO_x emissions compared to the diesel fuels (Prabakaran and Udhoji, 2016). Different catalysts are used as additives for fuels to enhance fuel quality, improve combustion and reduce the emissions. The use of catalysts during combustion leads to the acceleration of fuel reactions and improved engine performance (Hosseini et al., 2017a; Celik et al., 2015). Recent studies showed that adding nanoparticles to the fuels can improve the thermo-physical properties such as high surface area-to-volume ratio, thermal conductivity and mass diffusivity. Furthermore, it increases the flash point, fire point and viscosity. Adding nanoparticles to diesel–biodiesel and bioethanol blends affects engine combustion, performance and emission characteristics of the diesel engine (Heidari-Maleni et al., 2020a; Hoseini et al., 2020). Nanoparticle additives to biodiesel reduce the harmful pollutants and increase the combustion efficiency (Manigandan et al., 2020; Chen et al., 2018).

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Abbreviations

ASTM	American Society for Testing and
B	Biodiesel
B5	5% Biodiesel
E	Ethanol
D100	Pure Diesel
MWCNTs-OH	Multi-wall carbon nanotubes-OH
B5+E4+MWCNTs-OH 30	5% Biodiesel + 4% Bioethanol + 30 ppm MWCNTs-OH
B5+E4+MWCNTs-OH 60	5% Biodiesel + 4% Bioethanol + 60 ppm MWCNTs-OH
B5+E4+MWCNTs-OH 90	5% Biodiesel + 4% Bioethanol + 90 ppm MWCNTs-OH
B5+E8+MWCNTs-OH 30	5% Biodiesel + 8% Bioethanol + 30 ppm MWCNTs-OH
B5+E8+MWCNTs-OH 60	5% Biodiesel + 8% Bioethanol + 60 ppm MWCNTs-OH
B5+E8+MWCNTs-OH 90	5% Biodiesel + 8% Bioethanol + 90 ppm MWCNTs-OH
CI	Compressed Ignition
CO	Carbon Monoxide (vol. %)
CO ₂	Carbon Dioxide (vol. %)
kW	Kilo Watt
L	Liter
Mbar	Milli bar
MJ	Mega joules
Nm	Newton meter
NO	Nitrogen Oxides (ppm)
O ₂	Oxygen (vol. %)
ppm	Part per million
rpm	Revolutions per minute
MPa s	Mega Pascal second
g	Gram
h	Hour
cm	Centimeter
°C	Centigrade Degree
BSFC	Brake Specific Fuel Consumption
UHC	Unburned Hydrocarbons

So far, various metals and metallic oxide as additives in the fuel have been used (Knothe and Steidley, 2018; Gu et al., 2018). However, there are possible environmental hazards using metal oxide and metal nanoparticles. Generally, the development of nanotechnology and its different usage causes interactions between the environment and the nanomaterial. According to the results of previous studies, nanoparticles have a positive effect on the performance of different chemical systems, but the release of metallic oxide nanoparticles into the environment has caused a lot of concern (Reddy et al., 2016). There is a lot of concern about threats to human health and the environment with using metal nanoparticles (Joo and Zhao, 2017; Khan, 2014).

Carbon nanotubes are one of the nanoparticles which due to their unique properties such as aspect ratio (length-to-diameter ratio), mechanical strength and high thermal and electrical conductivity are considered as a topic of interest by many researchers (Aguilar-Bolados et al., 2020; Babaei-Ghaghelestany et al., 2020; Khan et al., 2019). These properties provide many applications for carbon nanotubes in actuators, chemical and biochemical sensors, catalytic applications, tools of optical electronics (Aguilar-Bolados

et al., 2020; Le Hoa, 2018). Many researchers studied the effect of adding carbon nanotubes to diesel–biodiesel fuel. For instance, Mirzajanzadeh et al. (2015) emphasized the effect of a new nanocatalyst on improving the performance and reduction of engine exhaust emissions. They investigated a hybrid nanocatalyst containing cerium oxide in the MWCNTs to be used for diesel–biodiesel blends (B5 and B20) at three levels (30, 60, and 90 ppm). The results of this study showed that, adding the coated catalyst at a concentration of 90 ppm to B20 (90 ppm) led to the development of optimal fuel. They reported that, B20 (90 ppm) blend exhaust pollutants such as NO_x, CO, UHC, and soot, respectively decreased by 18.9, 38.8, 71.4, and 26.3% compared to B20. Also, the results showed that, the performance parameters of the engine, i.e. power and torque increased up to 7.81 and 4.91%, respectively. Also, SFC reduced by 4.50%. In another study, Selvan et al. (2014) studied the effect of adding cerium oxide nanoparticles and carbon nanotubes to diesterol blends (at three levels of 25, 50, and 100 ppm concentration in diesterol blends) on the parameters of engine performance, combustion and exhaust emissions for a variable compression ratio engine. The results showed that, adding CNT and CERIA in diesterol blend improves brake thermal efficiency by 7.5% and also, the addition of CERIA and CNT to diesterol blends increases the CO emission to 22.2%, and reduces the UHC and smoke emission to 7.2 and 47.6% compared to the E20 blend, respectively. Chen et al. (2018) investigated the combustion, engine performance, and emission parameters of a diesel engine using nanoparticle–diesel fuel blends with aluminum oxide, carbon nanotubes and silicon oxide (at concentrations of 25, 50, and 100 ppm with pure diesel). The results showed that, the brake specific fuel consumption decreased by 19.8% and brake thermal efficiency increased by 18.8%. They found that, silicon oxide nanoparticle–diesel blends showed more favorable results than aluminum oxide–diesel blends in many aspects such as higher combustion pressure, lower brake specific fuel consumption, and lower carbon monoxide emissions.

Studies about carbon nanotube diesel–biodiesel blends showed that, the use of carbon nanotubes in fuels had a positive effect on exhaust emissions (Table 1). In addition, considering the possibility of toxic effects of metal oxide nanoparticles on living organisms, the use of bio-nanoparticles can significantly reduce this concern (Ettfaghi et al., 2018).

Considering the fact that carbon nanotubes tend to accumulate due to their hydrophobic surface, their surface must be amended with different functional groups for better dispersion in solution. Moreover, the outer wall of carbon nanotubes is neutral taking into account the chemical aspect and that is not desirable for nanotube applications. One of the ways to overcome this problem is functionalization of carbon nanotubes. Functionalization of carbon nanotubes improves their properties as well as their stability in solvents (Datsyuk et al., 2008).

Nanotubes functionalized with acids, oxygen-containing functional groups connected to the surface of carbon nanotubes that create negative charges on the surface of the nanotubes, cause the suspension stability of CNTs in solvents. Functionalized carbon nanotubes are used in various fields. Among applications of functional nanotubes are reinforcing polymers, their level with polar groups becomes functionalized and that improves their dispersion in the polymer matrix. In electrical applications, fluorine and nitrogen atoms on the surface of the nanotubes are connected and that alters the properties of the semiconductor. In biomedical applications, carbon nanotubes can be oxidized with polyethylene glycol or some biocompatible molecules to achieve good dispersion. Carbon nanotubes become connected with oxygen groups (OH or COOH) to form covalently. In covalent factorization, SP² carbon atoms are converted to SP³ carbon

Table 1
The effect of adding carbon nanotubes to diesel–biodiesel fuel.

Type of fuel blend	Engine type	Test condition	Performance		Emission results			Refs.
			Power	BSFC	CO	UHC	NO _x	
B100	1cylinder, Kirloskar/TV1 model, 3.5 kW	Different brake power	-	+++++	-	-----	+++++	Balaji and Cheralathan (2015)
B100+CNT100			-	↑+	-	-----	+++++	
B100+CNT200			-	++++	-	↓-	↑+	
B100+CNT300			-	+++	-	---	+++	
B100	1cylinder, Kirlosker model, 5.2 kW	Different brake power	-	↓-	-	++++	-----	Senthilkumar and Prabu (2015)
B100+CNT25			-	---	-	↑+	↓-	
B100+CNT50			-	-----	-	+++	↓-	
B100+CNT20	1cylinder model, 5.2 kW	Engine speed of 1500 rpm and different loads	-	-	↑+	↓-	nc	Basha and Anand (2011)
B100+CNT40			-	-	+++	---	nc	
B100+CNT60			-	-	++++	-----	nc	
B100+CNT80			-	-	+++++	-----	↑+	
B100+CNT100			-	-	+++++	-----	↑+	
D97+W5+Srf2	1cylinder, Kirloskar/TAF1 model, 4.4 kW	Different brake mean effective pressure	-	↑+	↓-	-----	↓-	Singh and Bharj (2015)
D97+W5+Srf2+CNT25			-	+++	---	---	---	
D97+W5+Srf2+CNT50			-	++++	---	↓-	---	
D83+W15+Srf2	1cylinder, Kirloskar/TV1 model, 5.2 kW	Engine speed of 1500 rpm and different loads	-	↓-	↓-	↑+	↓-	Basha and Anand (2014)
D83+W15+Srf2+CNT50			-	---	---	---	---	
D83+W15+Srf2+CNT100			-	-----	---	---	---	
D83+W15+Srf2+CNT150			-	-----	---	---	---	
B2+W5+Srf5+CNT25	1cylinder, Kirloskar/TAF1 model, 4.4 kW	Different brake mean effective pressure	-	↓-	-	-----	↓-	Basha (2018)
B2+W5+Srf5+CNT50			-	↓-	-	---	---	
B2+W5+Srf5+CNT100			-	↓-	-	↓-	---	
B91+W5+Srf4	1cylinder, Kirloskar/TAF1 model, 4.4 kW	Different loads	-	↑+	-	-	↓-	Le Hoa (2018)
B91+W5+Srf4+CNT50			-	+++	-	-	---	
B91+W5+Srf4+DEE50			-	+++	-	-	---	
B91+W5+Srf4+CNT50+DEE50			-	++++	-	-	---	

atoms. Therefore, transfer and electrical properties of the nanotubes change (Khalid et al., 2016; Ling et al., 2013; Ma et al., 2010).

Oxygenated functional groups on the surface of the nanotubes have an important effect on the base surfaces in the same distribution (Mazov et al., 2012; Hou et al., 2010). It should be noted that, MWCNTs is not well dispersed in fuel as it quickly sediments into the fuel due to its hydrophobic properties. So, functionalization of nanotubes causes better dispersion and more sustainability of these nanotubes in fuel. Also, use of oxygen-containing functional groups improves the oxygenation of the fuel during combustion.

In this study, the performance and emission characteristics of diesel engine are reported using the functionalized Multi-Walled Carbon Nanotubes-OH (MWCNTs-OH) in the diesel–biodiesel (B5). Thus, the present study reported the properties of MWCNTs-OH mentioned above to fill the gap in the literature on the topic; lack of studies about the addition of MWCNTs-OH to biofuels.

2. Materials and methods

2.1. Biodiesel production

In this study, the biodiesel fuel was produced from fish oil using the transesterification reaction. Then, its characteristics were matched to the ASTM-D6751 standard. After ensuring the standard of biodiesel fuel, a mixture diesel–biodiesel fuel with 5% biodiesel fuel and 95% diesel was prepared. Properties of the fish oil and biodiesel are shown in Table 2.

2.2. Fuel samples preparation

The MWCNTs-OH was mixed with concentrations of 30, 60, and 90 ppm with B5 and then bioethanol was added at concentrations of E4 and E8 (vol. %). Fig. 1 shows the typical SEM image of MWCNTs-OH. The properties of MWCNTs-OH nanocatalysts are

Table 2
Properties of the fish oil and biodiesel.

Properties	Unit	Fish oil	Biodiesel
Density	(kg/m ³)	890	871
Viscosity (cst)	(mm ² /s)	32	4.12
Cloudy point	(°C)	-14	+9
Flash point	(°C)	260	71
Pour point	(°C)	-23	-2

Table 3
MWCNTs-OH nanocatalysts properties.

Parameter	Properties
Purity	>95 wt % (carbon nanotubes)
Content of -OH	1.76 wt % (XPS & Titration)
Outside diameter	20–30 nm (from HRTEM, Raman)
Inside diameter	5–10 nm
Length	10–30 μm (TEM)

Table 4
Properties of fuels used in this study.

Fuel type	Viscosity (40 °C)	Density (15 °C)
D100	2.67	827
B5	3.25	835
B5+E4+30 ppm MWCNTs-OH	3.10	833
B5+E4+60 ppm MWCNTs-OH	3.10	833
B5+E4+90 ppm MWCNTs-OH	3.00	833
B5+E8+30 ppm MWCNTs-OH	2.86	833
B5+E8+60 ppm MWCNTs-OH	2.86	833
B5+E8+90 ppm MWCNTs-OH	2.86	833

shown in Table 3. Table 4 shows the properties of the combination of fuels used. Table 5 shows the devices used for measuring the fuel properties. It should be noted that, the MWCNTs-OH was added to B5+E4 and B5+E8, and they were mixed in the ultrasonic for 30 minutes. Fig. 2 shows the combination of the fuels.

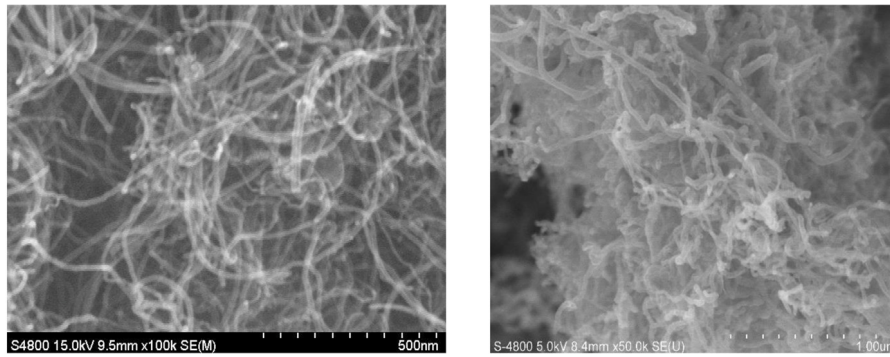


Fig. 1. Typical SEM image of Multi-walled carbon nanotubes-OH.

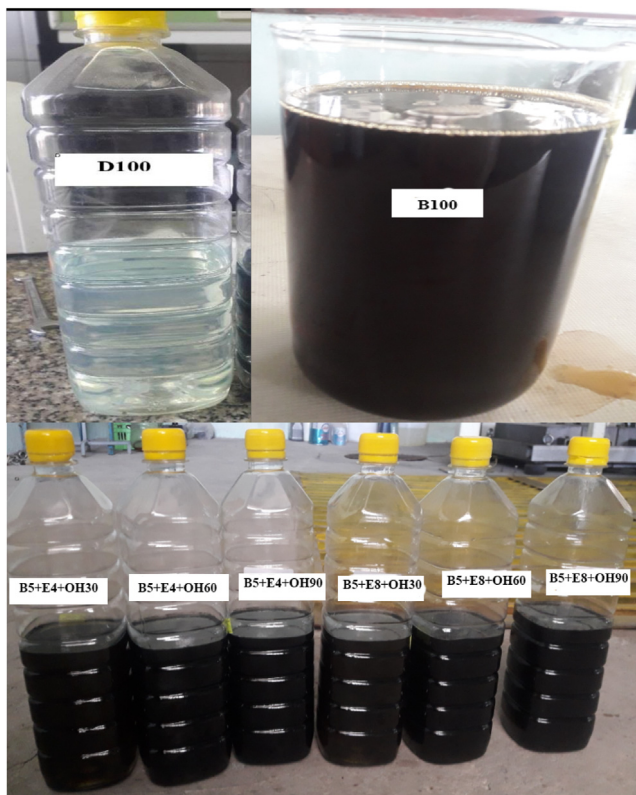


Fig. 2. Fuels used in the experiments.

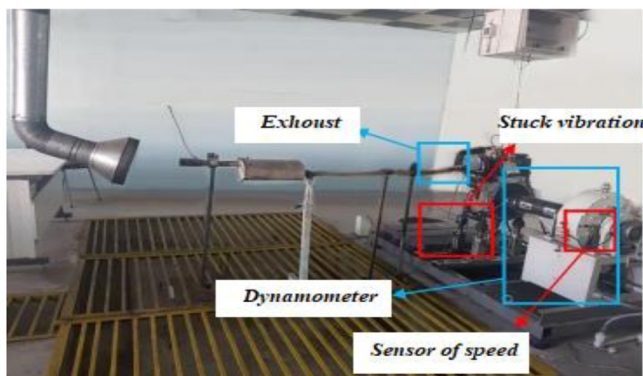


Fig. 3. Engine and dynamometer set-up.

Table 5

Technical specifications of the devices used.

Devices	Technical specifications
Viscometer	Measure viscosity of fuel, 3000-SVM stacker viscometer model manufactured by anton paar, used under the ASTM D 455 standard
Density (viscometer)	The 3000-SVM stacker viscometer made by anton paar based on 4052 ASTM standard with a precision of 0.0001 g/cm ³ at 15 °C
Flash point	According to 93 ASTM standard was used by the shanghai-shenkai flash Point I1002SKY device with a precision of ±2 °C

Table 6

Specifications of all devices used in the test.

Devices	Technical specifications
Engine test	Lombardini model 3LD510, single cylinder, four-stroke, direct injection, air-cooled, cylinder capacity 3530 cm, power of 9 kW at 2300 rpm, speed of 3000 rpm.
Dynamometer	MPA-40 model, vortex flow dynamometer, maximum torque of 110 N m. Max speed 8000 rpm.
Emission analyzer	Maha model MET 6.1 Detection of HC, CO, CO ₂ , O ₂ , NO and lambda emissions.
Other items and sensors	Ultrasonic Homogenizer: Hielscher UP400S, Germany. Fuel consumption meter: OVAL brand, Japan. Exhaust temperature sensor: Type K thermocouple (0 to 1000 °C). Humidity Sensor: (3% to 99%). Environment Pressure: (700 to 1100 mbar). Environmental temperature sensor: PT100 (10–60 °C).

2.3. Experimental set-up

The experiments were conducted under full load at different engine speeds of 1800, 2100, and 2400 rpm with three replications, on a four-stroke, single-cylinder, air-cooled diesel engine (Fig. 3), whose main parameters are presented in Table 2. Then, the performance parameters such as torque, power, BSFC and emissions such as NO, CO₂, CO, UHC, and exhaust gas temperature were recorded in each test using a computer. Specifications of all devices used in the test are shown in Table 6.

3. Results and discussion

This section shows the results for the effect of adding MWCNTs-OH with concentrations of 30, 60, and 90 ppm in the fuel blends (B5+E4 and B5+E8) on the performance parameters and exhaust emissions of a diesel engine.

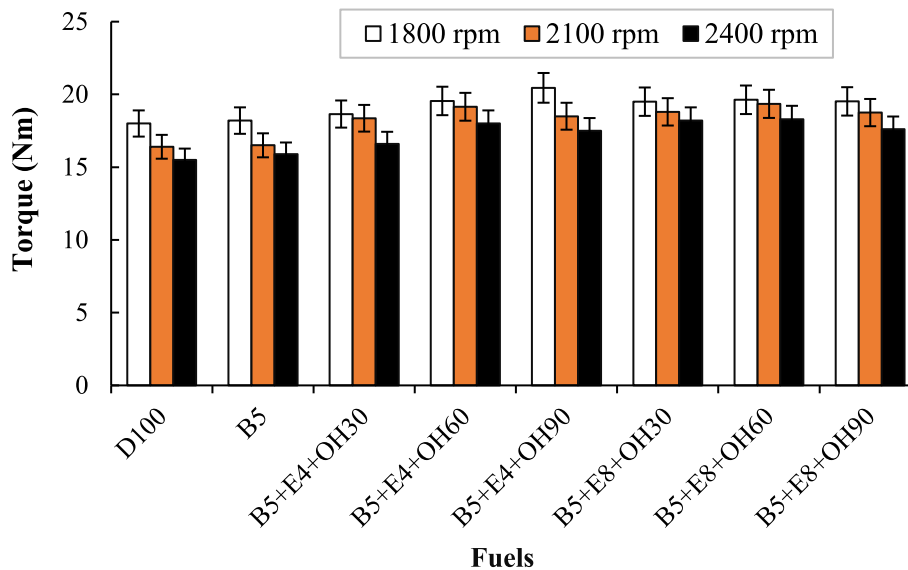


Fig. 4. The effect of engine speed and fuel type on engine torque.

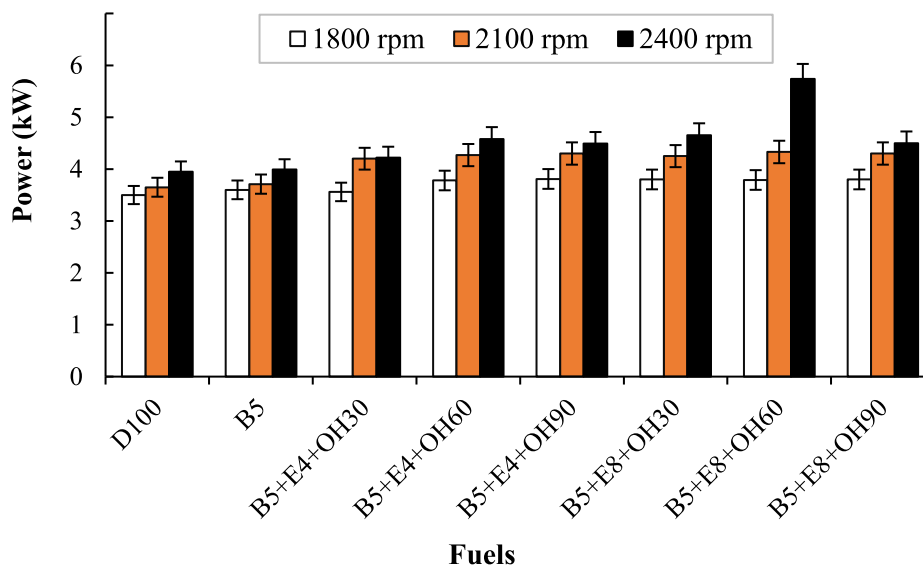


Fig. 5. The effect of engine speed and fuel type on engine power.

3.1. Engine performance

3.1.1. Engine torque and brake power

The effect of adding MWCNTs-OH to B5+E4 and B5+E8 blends on the engine torque is shown in Fig. 4. The maximum torque of fuel blends was at the speed of 1800 rpm. In addition, by increasing the engine speed from 1800 to 2400 rpm, the torque decreased on average by 5.04 and 5.60%, respectively. Addition of MWCNTs-OH to B5+E4 and B5+E8 caused an increase in the torque compared to D100 and B5 under different engine speeds at full load. The fuel blends of B5+E4+MWCNTs-OH90 and B5+E8+MWCNTs-OH60 showed the highest torque, while D100 and B5 had the lowest torque. Addition of MWCNTs-OH to B5+E4 and B5+E8 at the speed of 1800 rpm led to increase in torque which was 8.61 and 7.41% on average compared to D100 and B5. Similarly, at 2400 rpm, adding MWCNTs-OH to B5+E4 and B5+E8 fuels caused average increase in the torque of 14.19 and 11.32% compared to D100 and B5, respectively. Addition of nanoparticles in the fuel blends caused more complete combustion of the engine (Heidari-Maleni et al., 2020a;

Hosseini et al., 2017b). In addition, using the oxygenated fuel blends (biodiesel+ethanol) caused an increase in the excess air ratio compared to neat diesel, thus more oxygen was available in comparison with the D100 and B5 fuels, consequently leading to better and more complete combustion (Heydari-Maleny et al., 2017; Prabakaran and Udhoji, 2016).

Fig. 5 shows the effect of adding MWCNTs-OH to B5+E4 and B5+E8 on the engine brake power. At the speeds of 1800 to 2400 rpm engine brake power increased. The power raised on average 11.29 and 9.31%, respectively. The fuel blends of B5+E8+MWCNTs-OH60, B5+E8+MWCNTs-OH30, and B5+E4+MWCNTs-OH60 had the highest power and B5 and D100 had the lowest power. In general, the addition of MWCNTs-OH to B5+E4 and B5+E8 caused an increase in power compared to D100 and B5. Addition of MWCNTs-OH to B5+E4 and B5+E8 at the speed of 1800 rpm led to an average increase of 7.33 and 4.35% in power compared to D100 and B5, respectively. Similarly, at the speed of 2400 rpm, the addition of MWCNTs-OH to B5+E4 and B5+E8 caused 18.90 and 17.71% increase in power, respectively. This increase could be explained by the fact that, oxygenation

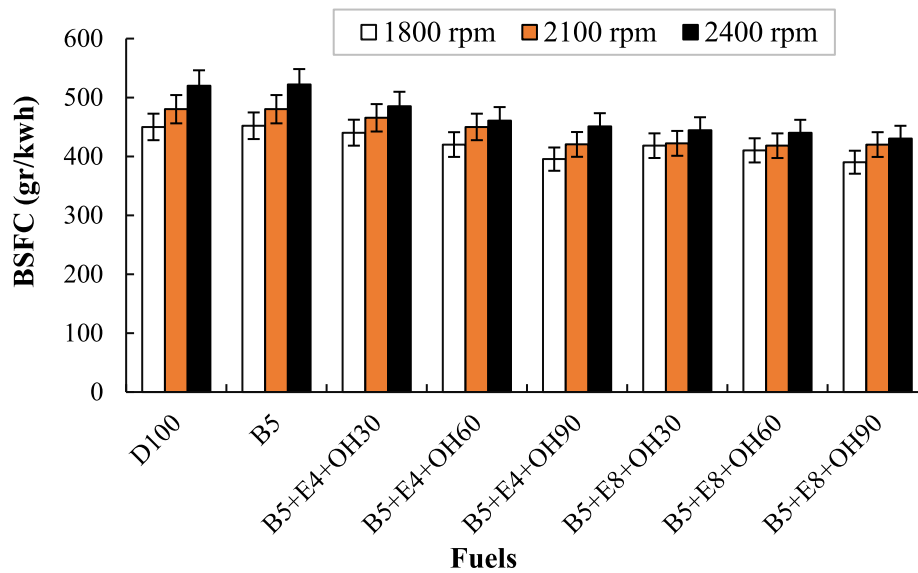


Fig. 6. BSFC at different engine speeds for different fuels.

of ethanol in fuel blends as well as the energy produced in the cylinder increased the heat transfer coefficient, which in turn increased the surface-to-volume ratio in the nanotubes (Heydari-Maleney et al., 2017). Moreover, the addition of a catalyst caused higher peak cylinder pressure and a faster heat release rate because of reducing the ignition delay and combustion duration of fuel in the engine (Zhu et al., 2012; Kannan et al., 2011).

3.1.2. Analysis of brake specific fuel consumption (BSFC)

The effect of adding MWCNTs-OH to B5+E4 and B5+E8 fuel blends on the BSFC is shown in Fig. 6. By increasing the engine speed from 1800 to 2400 rpm, the BSFC raised on average 5.32 and 11.10%, respectively. Fuel consumption increased by increasing the engine speed. That is due to the fact that when engine speed increases, the friction power increases at a rapid rate leading to more fuel consumption, as a result of which the BSFC increases (Appavu et al., 2019; Hosseini et al., 2017a; Alahmer et al., 2010).

The results showed that, by adding MWCNTs-OH to B5+E4 and B5+E8, the BSFC decreased compared to D100 and B5 under different engine speeds. The fuel blends of B5 and D100 had the highest BSFC, and the B5+E8+MWCNTs-OH90, B5+E4+MWCNTs-OH90, and B5E8+60MWCNT-OH had the lowest BSFC. Further, the addition of MWCNTs-OH to B5+E4 and B5+E8 at the speed of 1800 rpm led to a decrease in the BSFC by 8.35 and 8.76% on average compared to D100 and B5, respectively, and at the speed of 2400 rpm, adding MWCNTs-OH to B5+E4 and B5+E8 caused a decrease in the BSFC by 13.10 and 13.44% on average compared to D100 and B5, respectively. Generally, the BSFC decreased by increasing the share of MWCNTs-OH in the fuel blends. Addition of nanoparticles in the fuel blends resulted in a faster burning rate, more heat release rate, as well as causing positive effects on the physical properties of fuel and decreasing the ignition delay time leading to the additional complete combustion (Hosseini et al., 2017b). These findings were in line with those of other studies (Chen et al., 2018; Selvan et al., 2014).

3.1.3. Analysis of exhaust gas temperature of fuel blends

The results of the exhaust gas temperature of the fuel blends are presented in Fig. 7. In general, at the speeds of 1800 and 2400 rpm, exhaust gas temperature increased on average by 9.86 and 8.47%, respectively. Furthermore, addition of MWCNTs-OH to B5+E4 and B5+E8 in general caused an increase in the exhaust gas temperature at the speed of 2100 rpm on average by 2.25 and 1.95%, compared to D100 and B5, respectively.

3.2. Analysis of emissions

3.2.1. Carbon monoxide (CO)

The change in CO emissions at different speeds is shown in Fig. 8. The CO emission increased with an increase at all engine speeds, which is due to increase in the temperature of the gases causing an increase in the rate of CO oxidation reaction. Addition of MWCNTs-OH into B5+E4 and B5+E8 reduced CO emission. The maximum reduction in CO at all speeds was related to the presence of B5+E4+MWCNT-OH30. For B5+E4+MWCNTs-OH30, the CO emissions at the speeds of 1800, 2100, and 2400 rpm were 10.65, 8.52, and 3.42% lower than D100 and were 9.16, 4.83 and 0.71% lower than B5, respectively. The decrease in the CO emissions can be attributed to high oxygen content of bioethanol and cetane number of biodiesel. Addition of MWCNTs-OH into B5+E4 and B5+E8 also had a considerable positive effect on the CO emissions. This may be due to the shortened ignition delay and the improved ignition characteristics of fuel as a result of adding MWCNTs-OH. The higher surface to volume ratio of these nanoparticles caused high catalytic activity, as a result of which the fuel-air mixing in the combustion process was improved. On average, for B5+E4+MWCNTs-OH30, the reduction of CO emission was equal to 7.53 and 4.49% compared to D100 and B5, respectively.

3.2.2. Carbon dioxide (CO₂)

The results obtained on CO₂ emission of B5+E4 and B5+E8 with different concentrations of MWCNTs-OH under various engine speeds are shown in Fig. 9. By increasing the engine speed from 1800 to 2100, and then 2400 rpm, carbon dioxide emission increased. Addition of MWCNTs-OH into B5+E4 and B5+E8 in general caused higher CO₂ emission compared to D100. The addition of MWCNTs-OH to B5+E4 and B5+E8 at the speeds of 1800, 2100, and 2400 rpm led to increase in the CO₂ emissions on average by 2, 9.61, and 5.37%, compared to D100, respectively. Addition of MWCNTs-OH into B5E4 and B5E8 increased the CO₂ emission. Maximum increase in CO₂ at the speed of 1800 and 2100 rpm is related to the presence of B5+E8+MWCNTs-OH90, and maximum increase in CO₂ at the speed of 2400 rpm is due to the presence of B5+E8+MWCNTs-OH30. For B5+E4+MWCNTs-OH, the CO₂ emissions at the speed of 1800 and 2100 rpm are 8 and 11.53% higher than the net-diesel (D100), and were 8 and 22.72% higher than B5, respectively. For B5+E8+MWCNTs-OH30, the CO₂ emissions at the speed of 2400 rpm were 6.45 and 9.67% higher than the net-diesel (D100) and B5, respectively.

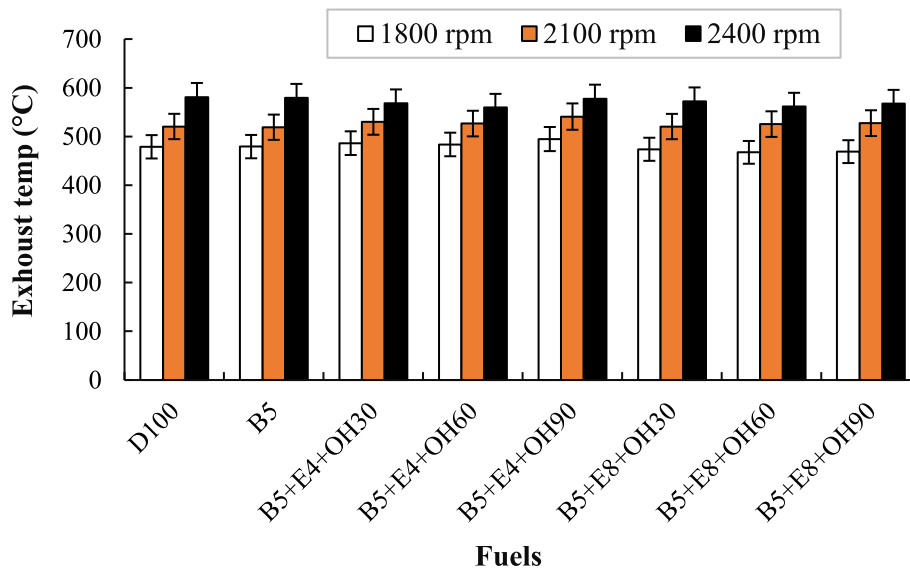


Fig. 7. Exhaust gas temperature at different engine speeds for different fuels.

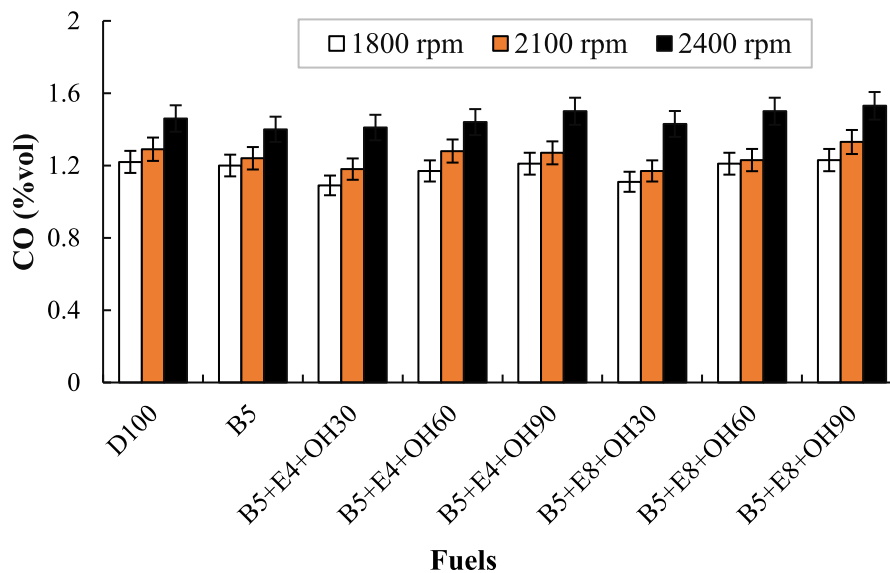


Fig. 8. CO emission at different engine speeds for different fuels.

3.2.3. UHC emission

The change in UHC emissions for fuel blends of MWCNTs-OH is shown in Fig. 10. By increasing the engine speed from 1800 to 2100 and then 2400 rpm, UHC emission increased. In general, adding MWCNTs-OH into B5+E4 and B5+E8 caused lower HC emission compared to D100 and B5 under different engine speeds. The B5E8+ MWCNTs-OH30 at the speed of 1800 and 2400 rpm, and the B5+E4+MWCNTs-OH60 at the speed of 2100 rpm had the lowest HC emission. For B5+E8+MWCNTs-OH30, UHC emissions at the speed of 1800 and 2400 rpm were 22.58 and 19.31% lower than D100 and 16.92 and 13.41% lower than B5, and for B5+E4+MWCNTs-OH60, UHC emission at the speed of 2100 rpm was equal to 19.75 and 13.3% compared to D100 and B5, respectively. For B5+E4+MWCNTs-OH60, UHC emissions on average was 11.06 and 13.51% lower compared to D100 and B5, and for B5+E8+MWCNTs-OH30, the UHC emissions were 19.66 and 13.51% lower compared to D100 and B5, respectively. Moreover, addition of MWCNTs-OH improved secondary atomization and fuel distribution in the combustion chamber, thereby causing

hydrocarbon and CO oxidation during combustion (Basha and Anand, 2014).

3.2.4. Nitrogen oxide (NO)

NO emissions depend on peak combustion temperature, decrease in speed and increase in temperature. The combustion temperature is also related to fuel quality and cetan number. Nitrogen oxide is produced at high temperatures. As the temperature drops, emission of nitrogen oxides reduces. Also, nitrogen oxide is produced in parts of the combustion chamber, where there is poorer fuel blend. At the speed of 1800, B5+E8+MWCNTs-OH60, and at the speeds of 2100 and 2400, B5+E4+MWCNTs-OH30 have the lowest NO emission. For B5+E8+MWCNTs-OH60, the NO reduction is 0.83 and 1.65% at the speed of 1800 rpm compared to D100 and B5, and for B5+E4+MWCNTs-OH30, the NO reduction is 3.75 and 2% at the speed of 2100 and 2400 rpm compared to D100 and it is 3.75 and 2.64% compared to B5, respectively. For B5+E4+MWCNTs-OH30, decrease in the NO emission on average was 1.98% compared to D100 and B5 fuels. At the speeds of 1800, 2100, and 2400 rpm, NO emission on

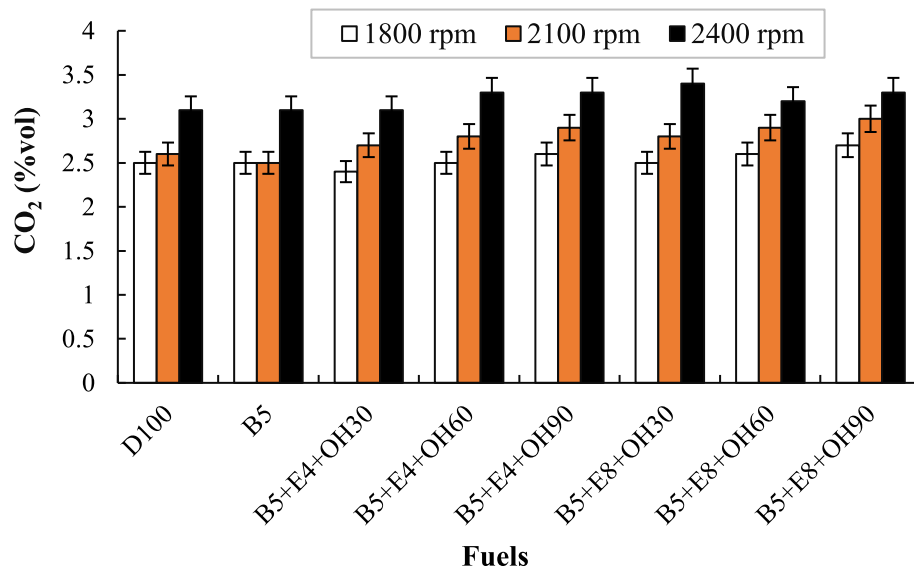


Fig. 9. CO₂ emission at different engine speeds for different fuels.

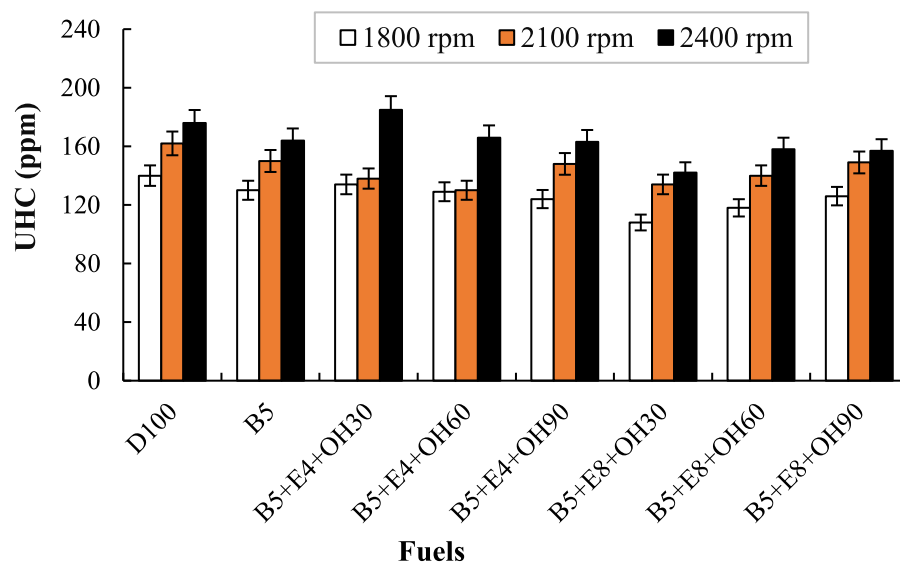


Fig. 10. UHC emission at different engine speeds for different fuels.

average increased by 6.66, 9.64, and 7%, respectively compared to D100. Also, adding MWCNTs-OH into B5+E4 and B5+E8 in general caused higher NO emission values compared to B5 under different engine speeds. This increase could be explained by the fact that, biodiesel has higher NO emission because of its higher oxygen content (~11%) leading to complete combustion and higher combustion temperature, as a result of which NO emission increases (Devan and Mahalakshmi, 2009; Cheung et al., 2009). Moreover, by adding MWCNTs-OH into the tested fuels, the combustion temperature increased, which accordingly increased the NO emission (see Fig. 11).

4. Conclusion

In the current study, the engine performance and emission characteristics were evaluated after adding MWCNTs-OH nanoparticles with the concentrations of 30, 60, and 90 ppm into diesel–biodiesel–bioethanol fuel blends (i.e., B5+E4+MWCNTs-OH30, B5+E4+MWCNTs-OH60, B5+E4+MWCNTs-OH90, B5+E8+MWCNTs-OH30, B5+E8+MWCNTs-OH60, and B5+E8+

MWCNTs-OH90). The experiments were conducted on a single-cylinder diesel engine at three speeds of 1800, 2100, and 2400 rpm under full load mode. The major conclusions obtained from the experiments could be summarized as follows:

- Addition of MWCNTs-OH into fuel improved the torque and power.
- Addition of MWCNTs-OH into B5+E4 and B5+E8 at all the three engine speeds led to a decrease in the BSFC, compared to D100 and B5. Generally, the BSFC decreased by increasing the concentration of MWCNTs-OH in the fuel blends.
- On average, for B5+E4+MWCNTs-OH30, the reduction of CO emission was equal to 7.53 and 4.49% compared to D100 and B5, respectively.
- Addition of MWCNTs-OH to B5+E4 and B5+E8 at the speeds of 1800, 2100, and 2400 rpm led to 2, 9.61, and 5.37% increases in the CO₂ emission on average, compared to the additive-free D100, respectively. Also, the addition of MWCNTs-OH to B5E4 and B5+E8 at the speeds of 1800,

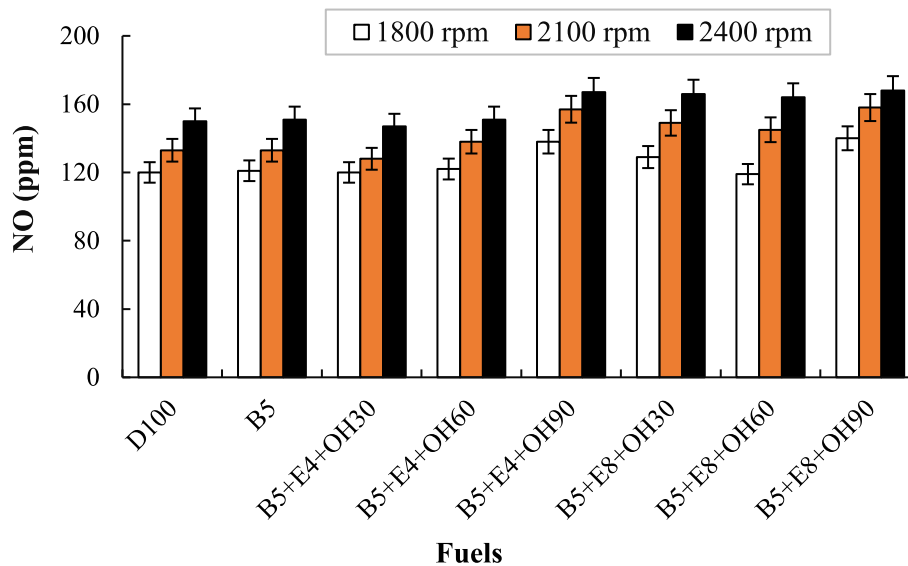


Fig. 11. NO emission at different engine speeds for different fuels.

2100, and 2400 rpm led to 2, 14, and 5.37% increases in the CO₂ emission on average, compared to B5, respectively.

- Addition of MWCNTs-OH to B5+E4 and B5+E8 at all speeds led to 12.02, 13.68, and 8.04% decreases in HC emission on average, compared to D100, respectively.
- For B5+E4+MWCNTs-OH60, on average the decrease in the UHC emission was equal to 11.06 and 13.51% compared to D100 and B5, and for B5+E8+MWCNTs-OH30, the decrease in UHC emission was equal to 19.66 and 13.51% compared to D100 and B5, respectively.
- Addition of MWCNTs-OH to B5+E4 and B5+E8 at all speeds led to 5.25, 6.77, and 1.32% decreases in HC emission on average, compared to B5, respectively.
- Addition of MWCNTs-OH to B5+E4 and B5+E8 at all speeds led to 6.66, 9.64, and 7% increases in NO_x emission on average, compared to D100, respectively. Also, the addition of MWCNTs-OH to B5+E4 and B5+E8 at all speeds led to 5.78, 9.64, and 6.29% increases in NO_x emission on average, compared to B5, respectively.

CRedit authorship contribution statement

Mohammad Shekofteh: Investigation, Methodology, Writing - original draft. **Tarhom Mesri Gundoshmian:** Supervision, Writing - review & editing. **Ahmad Jahanbakhshi:** Conceptualization, Methodology, Investigation, Data curation, Writing - review & editing. **Aram Heidari-Maleni:** Project administration, Methodology, Investigation, Resources, Supervision, Formal analysis, Writing - original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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