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Research Article

Influence of Renewable Fuels and Nanoparticles Additives on Engine Performance and Soot Nanoparticles Characteristics

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Abstract. The fuel combustion in diesel engines can be improved by adding nanomaterials to the fuel which result in an reduction in pollutant emissions and enhance the quality of fuel combustion. The engine performance and soot nanoparticles characteristics were evaluated in this study with adding nanoparticles of copper oxide (CuO_2) to the rapeseed methyl ester (RME) and diesel under variable engine speeds. The addition of CuO_2 to the RME significantly improve brake thermal efficiency (BTE) and decline the brake specific fuel consumption (BSFC) by 23.6% and 7.6%, respectively, compared to the neat RME and diesel fuel. The inclusion CuO_2 nanoparticles into the RME and diesel led to decrease the concentration and number of particulate matter (PM) by 33% and 17% in comparison with neat RME and diesel without nano additives, respectively. Moreover, PM is significantly decreased by 31.5% during the RME combustion in comparison with neat RME and diesel under various engine speeds. It was also obtained that the number of emitted particles (n_{po}) reduced by 23.5% with adding nanoparticles to the RME in comparison with diesel, while the diameter of soot nanoparticles (d_{po}) increased by 8.6% in comparison with diesel. Furthermore, the addition CuO_2 to the RME decreased the size and number of particles more than to the diesel fuel.

Keywords: Engine speed, Renewable fuels, Particulate matter, Soot particles, BSFC, BTE

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1. Introduction

Recently, the biggest challenge of the twenty-first century is global warming due to increase the temperature of the Earth in the past 10 decades (Al-Ghezi, 2022; Chaichan *et al*, 2018). The world faces many challenges to manage the energy resources and develop logical energy policies. Also, the last fall in oil prices, economic and political fluctuations in the world, the spread of the Coronavirus disease (COVID-19) and the expected impairment in the energy sources for 2020 increases the difficulty task of repair the deficiency of power supply since time ago. The crisis is exacerbated with the growth of energy consumption in the world annually, and the increase in energy consumption is attributed to an increase in population, higher temperatures and pollutant emissions. Therefore, most of countries focused on using the renewable energy sources to be a good alternative to the conventional energy sources. In contrast, the central generation capacity was increased in last years. The current deficit in supply and demand will increase in 2022, while total energy demand in 2030 increase with an increase in energy consumption growth in the next five years (Prol, 2020; Zhang *et al*, 2021). The availability of renewable energies, the extent of the territory, and diversity of the climate in the world helps to study these energies in seriously. The problems and current costs of renewable energy storage and transmission can be solved by exchanges with neighbouring countries and expanding trade with countries in border areas.The global population will expand to 30% by the year of 2040 according to the World Energy Outlook. Therefore, the renewable energies will significantly growing in different sectors to supply the 30% of power demands. Over the world, the largest renewable source to provide the power is hydropower in 2023, followed wind, solar PV, and bioenergy by 16%, 6%, 4%, and 3%, respectively (Loseva, 2019). The growing of world's population is increasing at a fast pace. Thus, the conventional energy sources cannot completely meet world energy needs in the future. Different benefits can be obtained from the use of renewable energies such as economic diversification, more sustainable trade balances, creating high quality jobs, achieving energy security, and

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reducing the demand of fossil fuel energy (Mirza, 2009; Verbruggen, 2010).

The combustion process of diesel engine is the main cause of greenhouse effect gases and air pollutants. In particular interest, the reduction of particulate matter (PM) and nitrogen oxide (NO_X) emissions is constitutes a big challenge to meet the slandered emissions regulations. In addition, the pollution emissions emitted from the engines such as carbon dioxide (CO_2), NO_X, sulphur dioxide (SO_2), soot emissions, and Hydrocarbons (HCs) contributors to the negative environment effects (Chaichan, 2018; Ekaab, 2019). Further research is needed to find and improve the environmental friendly fuel and sustainable fuel alternatives for regular diesel that used in diesel engines, which in turn decreases the pollutant emissions and fuel consumption of diesel engine (Bueno, 2017). Over the last years, the use of biodiesel plays a key role in the transport sector and internal combustion process due to the interrelation of politics with climate change and the depletion of fossil fuels. According to that, more research has been focused on study the impact of thermophysical properties and the molecular structure of biodiesel on exhaust emissions and thermal efficiency of diesel engine (Azeez, 2020). Renewable energies including biofuel (n-butanol) and oxygenated fuels were interesting topics for researchers to control or reduce the emission of engine and decrease the fossil fuels consumption.

Biodiesel can be produced from renewable sources to produce clean fuel as a renewable fuel and good replace to conventional fuel. In the past decades, the latest researches of using oxygenated fuels in the sectors of power generation and transportation have shown improvement in both engine performance and emissions (Fayad, 2021; Jiaqiang, 2019). An excellent reputation of using oxygenated fuels in diesel engine due to the high durability, high reliability, and high thermal efficiency (Rahiman, 2022; Singh, 2021). Fang *et al.* (Fang, 2013) reported that a hygroscopic mixture can be occurred when ethanol blended into the diesel fuel which affects the fuel injector. To solve this issue, biodiesel was mixed with ethanol-diesel blend. An interesting potential of biodiesel can contributing in decreasing the chemical emissions emitted from the combustion process. This is depending on the engine speed, type of engine, the ambient conditions, load conditions, quality and origin of biodiesel. Numerous studies (Huang, 2021; Teoh, 2022) reported that the engine performance and emissions characteristics improved during ethanol-biodiesel-diesel blend combustion. The combustion of ethanol-diesel blend produce lower soot and NO_X emissions compared to the diesel fuel as presented in in work by Zulkurnai *et al.* (Zulkurnai, 2021) which contributing in better environmental future and superior engine performance.

In the last years, many tests on biodiesel have been done to clarify the effects of biodiesel properties on diesel emissions. From all engine emissions, the NO_X emissions and PM are considered the critical factors that limited diesel engines development. In case of regulated emissions, it was reported that further development needs in fuels and injection strategies to meet the emission regulations in diesel engines (Fayad, 2019). The effect of biodiesel produced from cotton seed oil on PM and engine performance was investigated by Nabi *et al.* (Nabi, 2009). They found that the NO_X emissions slightly increase while the engine performance significantly improved. Rakopoulos *et al* (Rakopoulos, 2008) stated that the soot emissions reduced by 73–83% during the burning of methyl-laurate, methyl-oleate, and methyl-palmitate compared to those produced from combustion of diesel fuel. They reported that the absence aromatic compounds in biodiesel were the main reason for this reduction in comparison with diesel fuel. In low temperature combustion, the influence of biodiesel on emissions and engine performance was examined by Zheng *et al.* (Zheng, 2008). The results showed that the soot emissions and NO_X emissions decreased in common-rail diesel engine fed with biodiesel. Ranjan *et al.* (Ranjan, 2018) studied the effect of waste cooking oil on the combustion characteristics and compared with diesel fuel. They found that the combustion of waste cooking oil decreases the NO_X emissions and improves the thermal efficiency in comparison with conventional diesel fuel. Dagaut *et al.* (Dagaut, 2007) studied the effect of oxidation kinetics of biodiesel on exhaust emissions. A significant reduction was found in hydrocarbon (HC), carbon monoxide (CO) and smoke emissions by the work of Dhahad *et al.* (Dhahad *et al*, 2020). It is stated that the combustion duration is lower from the combustion of methyl ester of vegetable oil in comparison with vegetable oil.

More environmentally friendly and cleaner fuel has been proved with adding nano additives to the diesel fuel than to the neat diesel fuel. Previous study (Shaafi, 2015) reported that a great potential to improve combustion characteristics and engine performance with addition of nanoparticles into diesel fuel. Biodiesel is receiving much attention when mixed with fuel additives to enhance the oxidation characteristics of biodiesel (Trana *et al* 2021). The fuel additives such as nanofluid into the blending of diesel-biodiesel can effectively improve engine performance and decrease pollutant emissions (Raju *et al*, 2020). It was documented that the engine performance has the potential increase with adding nanoparticles to the fuel due to their high reactive nature and high surface area of nanoparticles (Sarangi, 2011). Javed *et al.* (Javed, 2016) found lesser emissions and better combustion efficiency from adding nanoparticles to the biodiesel blends. They found that these parameters depend on the quantity and sizes of nano additives mixed into the biodiesel. A marginal change in the properties of fuel was obtained with adding metal additives into the biodiesel blend, which in turn increases the engine performance and thermal efficiency (Dhahad *et al* 2013). The properties of biodiesel (sulfur content, volatility and density) can be modified through adding nano additives. It was found that the combustion characteristics improved with adding these nano additves to the biodiesel, the researchers have worked on these modified fuels in internal combustion engines.

Two-phase colloidal mixture is represent the nanofluid which consisting of nanoparticles dispersing in the liquid fuel. The size of nanoparticles is approximately between 1 nm and 100 nm. The dispersion of nanoparticles into the base fluid is significantly effect on the thermophysical properties of the base fluid (Ağbulut, 2019; Saraee, 2017). It is reported that a considerable enhancement in the calorifc value and a great reduction in the emissions of CO, HC and PM from the blend of Zinc oxide into the biodiesel (Karthikeyan, 2014). These results also concluded that using nano additives into the biodiesel can give an extra push to enhance engine performance. The size and amount of the nanoparticles into the biodiesel blends can influence on the performance and engine emissions. The utilizing of nanoparticles into the fuel plays the huge role in providing the required positive outcome of diesel engine (Sangeetha, 2021). A perceptible improvement in the fuel properties was found with using metallic nanoparticles into the fuel blend. More uniform burning process, shorter ignition delay and higher heat release rate from the more contact of fuel with oxidizer (Galfetti, 2007). In recently, aluminum nanoparticles were used into the ethanol blend which leads to shorter ignition delay and increasing ignition probability (Gan, 2011a). The same trend was observed with adding metallic additives by increasing the heat transfer and ignition probability. Thus, the emissions of CO and HC decrease and increasing the cetane number (Gürü, 2002). It is stated that better fuel penetration into the combustion chamber, improving brake thermal efficiency, more complete combustion and lower emissions level regarding to the nano additives with fuels (EL-Seesy, 2019).

The stability aspects of nanoparticles are the main concern for selecting nanoparticles as additives to the fuels in compression ignition (CI) diesel engines. In some cases, due to the surface activity and large surface area, nanoparticles, the nanoparticles tend to aggregate in the fuel mixture. However, a few articles in the literatures are focused on the emission characteristics, engine performance and stability of both fuels diesel and biodiesel blended with nanoparticles. The nano additives used in the blend of diesel-biodiesel are iron oxide (Fe_2O_3), aluminium oxide (Al_2O_3), cerium oxide (CeO_2), copper oxide (CuO), silver oxide (Ag_2O), nonmetal oxides like carbon nanotubes (CNTs), titanium oxide (TiO_2), and zinc oxide (ZnO). The stable and homogeneous nanofluid for both scientific and practical applications is considered a crucial phenomenon. The properties of nanofluid such as stability play a vital role on performance effect as a thermophysical properties and heat carrier. The influence of nano-additives such as CeO_2 nanoparticles on thermal efficiency was investigated by Sajith *et al.* (Sajith, 2010) in diesel engine. They found that the thermal efficiency improved with these additives due to high catalytic activity of these nanoparticles, which in turn tends to decrease fuel consumption and emissions. The effect of adding CeO_2 nanoparticles to the biodiesel on the combustion behavior, performance and emission characteristics was reviewed by Hoang (Hoang, 2021). The physicochemical properties and preparing methods of nano blend (biodiesel containing CeO_2 nanoparticles) were introduced in the review paper. It was found that addition of CeO_2 nanoparticles to the biodiesel has benfical effect on decreasing the NO_X, CO, HC, smoke opacity and soot emissionas well as improving the fuel consumption, brake power and thermal effciency. It is appeared that the biodiesel containing 100 ppm of CeO2 nanoparticles has shown high stability and increasing the oxygen content, reducing exhaust emissions and improving the engine performance.

Many methods (surface modification, ultrasonication, and the addition of surfactants) have been reported in the literature to enhance the nanoparticles stability in the fuel bend (Fayad *et al*, 2021; Raju *et al*, 2021). There are near common consensus of group of researchers that adding nano additives into the liquid fuels enhance the combustion characteristics and decrease emissions of diesel engine (Gan, 2011b). Prior works investigated effect of nanoparticle laden fuel on engine performance and concentration level of NO_X emissions (Mehta, 2014). The combustion characteristics of Karanja biodiesel improved with adding 5%, 10%, 15% and 20% by volume of nano additives (Iranmanesh, 2008). In addition, improves the physicochemical properties of Karanja biodiesel blend like viscosity, calorifc value and gravity when adding nano additives. Sajith *et al.* (Sajith, 2010) studied the potentials effects of adding nanoparticle (CeO_2) into the biodiesel on combustion characteristics with actual working diesel engines. They found that the fire point and the flash point increased with adding these particles to the biodiesel.

Previous studies discussed adding different types of nanoparticles into the biodiesel blends on BTE, BSFC, engine torque, NO_X, PM, and CO. Different dosages (10-50 mg/l) of Al2O3 nanoparticles was mixed into the blends of 20% Jojoba methyl ester and 80% neat diesel which result in decrease brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC) by 15% and 12%, respectively. Ağbulut *et al.* (Ağbulut, 2019) and Fayad *et al.* (Fayad and Dhahad 2021) reported that lower level of particulate emissions and high thermal efficiency can be reached when nanoparticles added to the diesel fuel. They found that the high thermal properties and nanoparticles catalytic activity during burning are the main reason to justify the PM reduction and enhances in the thermal efficiency. The lower aromatic compounds and oxygen-born in the oxygenated fuels have the vital role in improve the combustion process and emissions during nanoparticles addition to the biodiesel.

Debbarma *et al.* (Debbarma, 2018) studied the effect of adding metal oxide of Fe and Cu to the biodiesel under various engine conditions. Previous work indicated that the adding nano-additives of metal oxide to the biodiesel decreased the PM concentration in diesel engine (Basha and Anand 2011). The addition nanoparticles of CeO_2 leading to improve fuel efficiency and decreased particulate emissions because of high nanoparticles catalytic activity (Skillas, 2000). Metals have been used as nano additives such as alumina, (Attia, 2014; Shaafi, 2015), cerium oxide, cerium (Selvan, 2014; Zhang and Balasubramanian 2017), manganese (D'Silva, 2015) and carbon nanotube (Chen, 2018) that result in enhancement of engine performance and reduced PM. Very few studies in the literatures are discussed the effect of adding nano additives to the biodiesel on number and size of soot nanoparticles, while most of these studies focused on the emissions (CO, HC, NO_X) and combustion characteristics. Therefore, this study focused on fill the gap in the literature by study how the effect of adding CuO_2 nanoparticles into the renewable fuels (RME) on thermal efficiency, fuel economy, and soot nanoparticles emissions. Furthermore, the number and size of soot nanoparticles characteristics from the combination effect of CuO_2 nanoparticles and RME in CI diesel engine was also analysed.

2. Experiments and materials

2.1 Engine setup and equipment

The details and technical specifications of the research engine are presented in Table 1. The schematic representation of the equipment, tools and diesel engine is shown in Figure 1. To evaluate exhaust, vibration effect and noise emission characteristics of the fuel blends, an eddy current dynamometer were used in this experimental study. All tests were carried out at various conditions of engine speeds (1000-2500 rpm). To reach the stable operating conditions, the research engine was run for 15 min before the real experiments. Three times of tests were repeated for each fuel and the average of measurements was recorded.

Table 1
Specifications of diesel engine

Properties	Diesel	Biodiesel (RME)
Chemical formula	$C_{16}H_{34}$	$C_{19}H_{36}O_2$
Derived cetane number	51.8	62
Latent heat of vaporization (kJ/kg)	242	216
Bulk modulus (MPa)	1410	1554
Density at 15 °C (kg/m^3)	844.3	886.1
Calorific value (MJ/kg)	45.80	38.90
Flash & Fire point (°C)	65-80	157-1620
Water content by coulometric KF (mg/kg)	40	170
Kinematic Viscosity at 40 °C (cSt)	2.77	5.0
Stoichiometric air fuel ratio	14.4	-
Lubricity at 60 °C (μm)	312	205

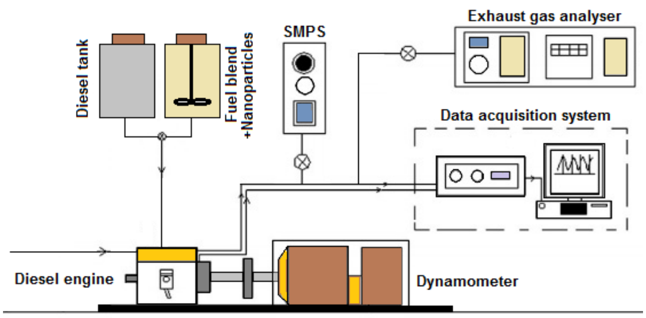

Fig. 1 Schematic view of the engine test and tools

The gas analyzer was calibrated to ensure the accuracy of the measured values before the each measurement. An overall uncertainty of 2.2% was applied to collect the experimental results. All tests were carried out under various conditions of engine speeds between 1000 to 2500 rpm.

2.2 Fuels and nanoparticles preparation

In this investigation, the fuels used were regular diesel fuel and pure biodiesel of rapeseed methyl ester (RME). Table 2 listed the main properties of fuels tested in this experiment. In this work, the copper oxide (CuO_2) nanoparticles were produced through a method of chemical precipitation. The nanofluid was prepared according to the Lee *et al.* (Lee, 2008) by dissolving a measured amount of nanoparticles deionized sodium lauryl sulfate and water. These nanoparticles were dispersant in an ultrasonic vibrator. It is reported that the nanoparticles agglomeration occurred due to poor dispersion with the base fluids (Das, 2007). The blend of nanofluid was stirred for 2 h to enhance the mixture and to avoid the agglomeration that could be occurred. In addition, a magnetic stirrer rotating was used to stir the emulsion with the suspension at high speed. After these processes, the sample was stable without settling nanoparticles for more than 2 weeks.

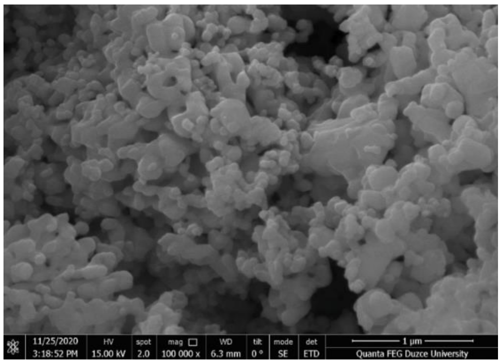

Fig. 2 SEM image of CuO_2 nanoparticles (Gumus, 2016)

Table 2
Properties of diesel fuel and oxygenated fuel

Engine parameters	Specifications
Engine type	Diesel 4- cylinder, water cooled, 4-stroke
Number of cylinders	4
Cylinder bore x stroke (mm)	104 x 118
Connecting rod length (mm)	160
Compression ratio	17.9:1
Displacement (cc)	4009
Maximum engine speed range (rpm)	3000
Fuel pressure range (bar)	500 – 1000

Table 3
Specifications of copper oxide nanoparticles

Properties	Values measured
Purity	≥ 99.5 %
Chemical name	Copper oxide (CuO_2)
Colour	Black powder
CAS No.	1344-28-1
Molecular weight	104.62
Size	77 nm
Density	6.0 g/cm3
Specific heat	551 J/kg.K
Thermal conductivity	33 W/m.K

The size of nanoparticle (CuO_2) used in this experiment is smaller than 77 nm with approximately spherical shape. The spectroscopy of Energy-dispersive X-ray (EDX) showed that the CuO_2 nanoparticles includes copper and oxygen of 88.37% (by weight) and 11.63% (by weight), respectively. The scanning electron microscope (SEM) image of CuO_2 nanoparticles is shown in Figure 2. The details and main properties of CuO_2 nanoparticles are listed in Table 3.

3. Results and discussion

3.1 Brake thermal efficiency

The effects of various conditions of engine speeds and adding CuO_2 nanoparticles to the diesel and rapeseed methyl ester (RME) on brake thermal efficiency (BTE) are shown in Figure 3. According to the results, the chemical oxidation speed of the fuel by air increased because of the nanoparticles acted as catalysts for sintering to provide a wide interactive surface.

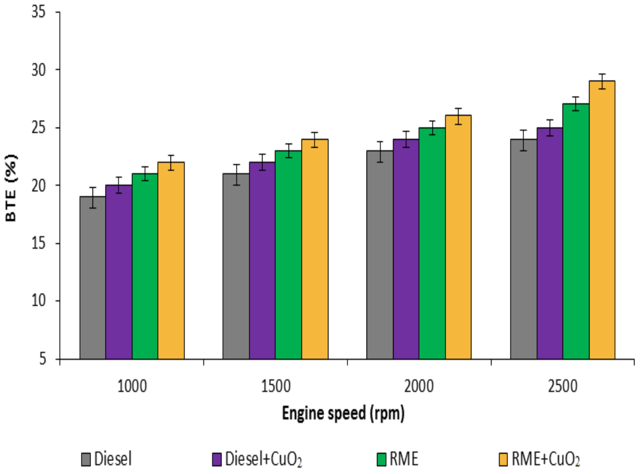

Fig. 3 The impact of adding CuO_2 to the RME on BTE for the tested fuels

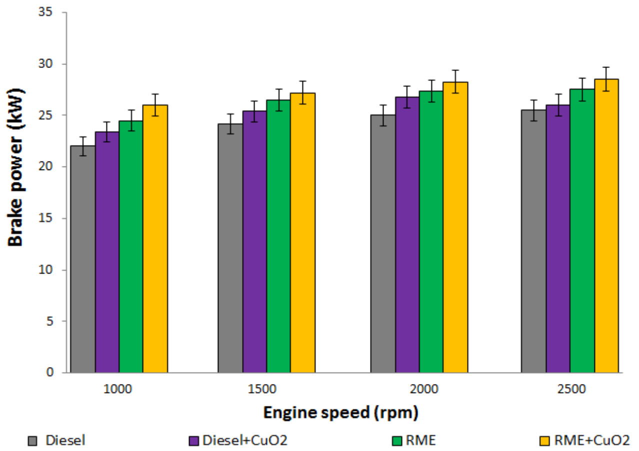

Fig. 4 The impact of adding CuO_2 to the RME on brake power for the tested fuels

Thus, adding nanoparticles to the fuel tends to enhance the combustion efficiency and radiative heat transfer for both fuels in comparison with the fuels without nano additives. Furthermore, these nanoparticles additives enhanced thermal conductivity of the biodiesel which ensuring heat transfer of the fuel blends. In comparison of fuels, the oxygen-bond in the RME improve the combustion efficiency which in turn increase the BTE during RME combustion compared to the diesel fuel for with and without nano additives (Figure 3). Furthermore, the highest BTE was obtained from the combustion of RME + CuO_2 compared to the neat RME and diesel fuel. Higher activity, larger surface area of nanoparticles and additional oxygen from the copper oxide as well as oxygen content of RME improves the combustion process which result in higher BTE. Previous works (Chen, 2018; Fayad and Dhahad, 2021) reported that the fuel combustion and efficiency improved when adding nanoparticles to the diesel fuel and biodiesel. Figure 3 shows that the BTE significantly increase with adding CuO_2 into the RME and regular diesel by 23.6% and 9.3%, respectively, in comparison with neat RME and diesel fuel without nano additives for various engine speeds. The enhancement in BTE with adding CuO_2 nanoparticles to the RME are compatible with previous study by Murugesan *et al.* (Murugesan, 2021). They found that the addition of different concentrations of Graphite oxide to the biodiesel blends enhance the BTE at HCCI mode of operation. They indicated that this could be due to the triple effect of inherent O_2 in the nano blend, the heating value of H_2 and the catalytic reaction of Graphite oxide.

3.2 Brake power (BP) of engine

The influence of adding CuO_2 to the RME and engine speeds on brake power is shown in Figure 4. The double effect of oxygen-bond in RME and CuO_2 nanoparticles improves the engine efficiency and results in an increase the BP for various engine speeds in comparison with diesel fuel. Previous study reported that the high cetane number and use of co-solvent contributing in lower emissions and better engine performance (Basha and Anand, 2010). It can be seen that the BP increased by 12.6% and 20.4% when adding CuO_2 to the RME compared to the neat RME and diesel, respectively, as depicted in Figure 4.

Furthermore, the BP increased by 9.7% and 12.6% with addition of CuO_2 to the RME and diesel, respectively. The renewable fuel (RME) and nano blend (RME+CuO_2) significantly enhance the BP more than to the conventional diesel fuel. This could be due to the better air/fuel mixture and high oxygen concentration from RME and CuO_2 which result in improving the BP for various engine speeds (Nireeksha, 2017).

3.3 Brake specific fuel consumption

The variation in the brake specific fuel consumption (BSFC) from the addition of CuO_2 nanoparticles to RME and diesel is shown in Figure 5 for different engine speeds. RME has the highest BSFC value in comparison other fuels tested. Prior works reported that more amounts of fuel injected into the cylinder to reach the same engine output with lower heating value. The high increase of SBFC can be referred to the high calorific value of the RME which result in an increase the BSFC (Hoang, 2021). After adding nanoparticles of CuO_2 to the RME and diesel a significant reduction was found in BSFC compared to the neat fuel as illustrated in Figure 4 at all engine speed. Previous studies reported similar trend of BSFC (Dhahad *et al*, 2021; Fayad, 2021).

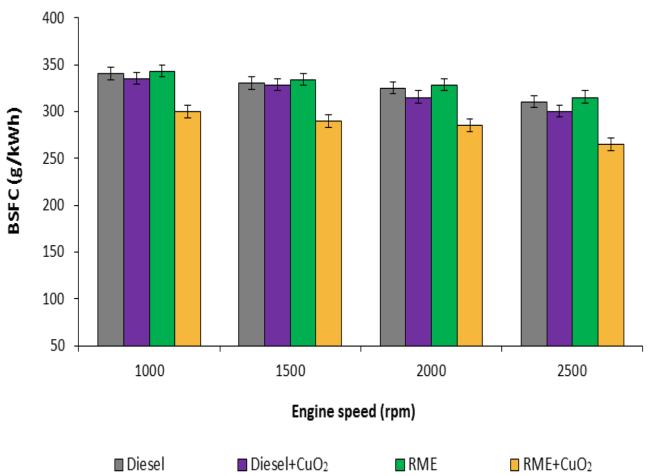

Fig. 5 The impact of adding CuO_2 to the RME on BSFC for the tested fuels

The addition of CuO_2 nanoparticles into the fuel increases the heating value of fuel. Accordingly, the BSFC decreased more with adding CuO_2 nanoparticles to the RME by 7.6% in comparison with neat RME and diesel fuel under various engine speeds. The drop in BSFC with adding CuO_2 nanoparticles to the biodiesel is in agreement with previous study by Murugesan *et al.* (Murugesan, 2021) which reported that BSFC decreased by 2.9% with adding 80 ppm of Graphite oxide to the biodiesel blend.

3.4 Soot nanoparticles characteristics

Figure 6 shows the effect of adding CuO_2 to the RME and diesel on the level concentration of soot nanoparticles of particulate matter (PM) via variable conditions of engine speeds. It can be seen that soot nanoparticles decreased with adding CuO_2 nanoparticles to the diesel and RME. The high heating value of fuel and combustion quality improved with adding CuO_2 nanoparticles which result in an increase the combustion temperature (Fayad *et al*, 2018; Zhang and Balasubramanian, 2016). These reasons are significantly reduce the particle formed during the combustion as well as decrease the soot particles concentration along the exhaust pipe. The decreases in soot nanoparticles were observed with adding CuO_2 nanoparticles to the RME and diesel by 33% and 17%, respectively, in comparison with neat RME and diesel fuel (Figure 6). Furthermore, the blend of RME + CuO_2 has the best decline in the concentration and number of soot nanoparticles than to the diesel + CuO_2 blend, RME and diesel. The additional oxygen from CuO_2 nanoparticle and oxygen born in RME fuel leads to improve the combustion process which result in inhibition of soot formation (Fayad *et al* 2021). Previous study has shown that oxygen-born in the RME boost the oxidation rate of emitted particles during the combustion process (Dhahad *et al*, 2021; Fayad *et al* 2021). The oxidation of carbon promoted due to the oxygen availability and enough combustion temperature which results in significantly decreases the concentration and number of soot nanoparticles that already formed.

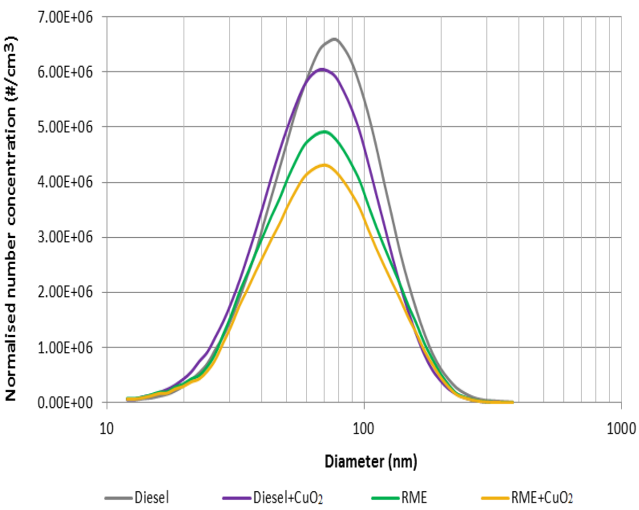

Fig. 6 The impact of adding CuO_2 to the RME on soot nanoparticles size distribution for the tested fuels

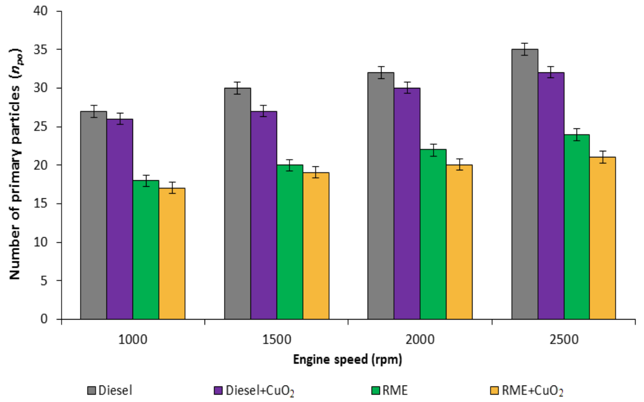

Fig. 7 The impact of adding CuO_2 to the RME on number of soot primary particle for the tested fuels

Impact of adding CuO_2 into the RME and diesel fuel on the number of primary particles (n_{po}) is presented in Figure 7. For all fuels tested, lower number of soot nanoparticles produced from the burning of RME compared to the diesel fuel under all conditions of engine speed. The lower number of soot particles emitted from biodiesel was stated in the introduction through the literature studies. Under various engine speeds, the burning of RME with CuO_2 additives enhances the reduction in the total particles number compared to the RME without nano additives. The adding CuO_2 particles to the diesel fuel also decreased the n_{po} in comparison with neat diesel fuel. The aggregation of soot particles decreased and particle oxidation increased during RME+CuO_2 combustion which result in inhibition soot formation and increase the n_{po} (Crookes, 2003). In addition, this can be justified due to the high rate oxidation of RME and disappearance of the primary particles fraction which resulted from adding CuO_2 nanoparticles and oxygen-born in RME (Zhang and Balasubramanian, 2015).

Figure 8 shows the effect of adding CuO_2 nanoparticles to the RME and diesel fuel on the diameter of primary particles (d_{po}) under various engine speeds. For without nano additives, it is clear that RME has smaller size of soot primary particles in comparison with regular diesel. These results were previously stated in the work by Fayad *et al* (2021), the high oxidation rate of particles from biodiesel led to decrease the soot particle size. Besides, the decrease main parameters such as the soot precursors, soot growth, and soot formation also have the vital role in decreasing the soot particles diameter (Hwang, 2014). In general, a slight increase in the d_{po} when adding nanoparticles to the RME and diesel as depicted in Figure 8. The addition of CuO_2 nanoparticles to the tested fuels increase the agglomeration of these particles into the soot particles components which result in an increase the diameter of soot particles in comparison with the without nano additives. Furthermore, increase the collisions of CuO_2 and solid soot particles contribute in a slight increase in the diameter of formed soot particles. Due to the large surface area of CuO_2 nanoparticles, nanofluid has high surface energy result in enhance the soot particles agglomeration to form large size of particles before deposition. It is reported in the literatures that adding nanoparticles to the fuel lead to the increase the total mass concentration of particles (Fayad and Dhahad, 2021).

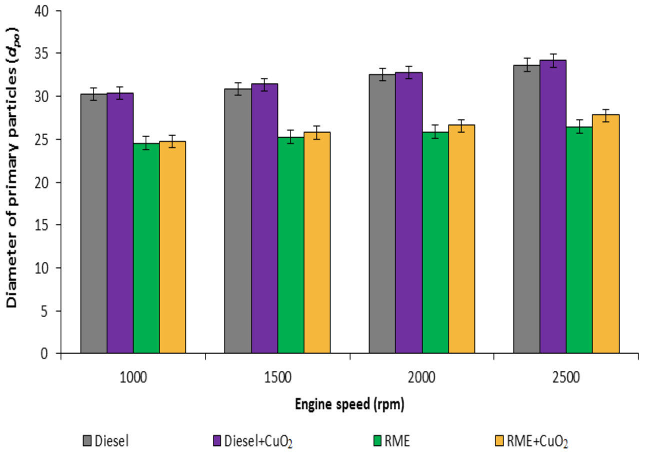

Fig. 8 The impact of adding CuO_2 to the RME on diameter of soot primary particle for the tested fuels

4. Conclusion

The soot nanoparticles characteristics and engine performance were investigated from the adding copper oxide (CuO_2) to the Renewable fuel (RME) and diesel fuel under various conditions of engine speed. It was found that the adding CuO_2 nanoparticles into the RME and diesel fuel improved the BTE and decreased BSFC for both fuels under various engine speeds. Furthermore, the oxygen-born into RME and additional oxygen donated from nanoparticles significantly improve thermal efficiency by 27% and fuel economy by 9.3% in comparison with regular diesel. It was observed that Soot nanoparticles concentration and number of PM reduced with addition CuO_2 to the RME more than to the neat RME and diesel for different engine speeds. It was observed that the number of soot nanoparticles (n_{po}) decreased during the combustion of RME+CuO_2 in comparison with diesel+CuO_2, neat RME and neat diesel fuel. The average diameter of soot nanoparticles was slightly increased with adding nanoparticles of CuO_2 to the tested fuels in comparison with the fuels without nano additives. Furthermore, RME combustion produced smaller d_{po} of soot particles in comparison with other fuels tested. The findings from this study revealed that the adding nanoparticles and RME were an effective way to improve the engine performance and reduced the soot nanoparticles characteristics (number, concentration and size). In the future study, it is recommended that using different concentrations and levels of CuO_2 nanoparticles into the different proportion of RME to evaluate how they effect on PM and NO_X emissions. This suggestion could be interesting topic to study and will be addressed for next work.

Conflicts of Interest: The authors confirm and declare that there is no conflict of interests regarding the publication of this paper.

Abbreviations

Symbols	Definition
BP	Brake power
BSFC	Brake specific fuel consumption
BTE	Brake thermal efficiency
CI	Compression ignition
CO	Carbon monoxide
CO_2	Carbon dioxide
CuO_2	Copper oxide
d_{po}	Diameter of primary particles
HCs	Hydrocarbons
n_{po}	Number of soot primary particles
NO_X	Nitrogen oxide
PM	Particulate matter
RME	Rapeseed methyl ester
SEM	Scanning electron microscope
SO_2	Sulphur dioxide

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