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The Impact of Incorporating EGR Rates and Coconut Biodiesel on Morphological Characteristics of Particulate Matter in a Compression Ignition Diesel Engine

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ABSTRACT

In recent research, further studies on the measurement and analysis of particulate morphology have become necessary to decrease the negative effect of particulate (PM) characteristics. The influence of Coconut biodiesel (CB100) and rates of EGR technique on morphological characteristics of PM was studied using CI diesel engine. The results showed that the PM size distribution decreased by 36.27% from CB100 combustion in comparison with diesel for different EGR rates. Furthermore, introduce high rate of EGR contribute in increasing the PM formation by 26.48% from the CB100 combustion compared with absence EGR technique. It is indicated that the number of particulates significantly decreased by 42.35% when the engine fed with CB100 compared to the diesel. The presence EGR technique leads to decrease the radius of gyration (R_g) and diameter of soot particles by 31.75% and 27.38%, respectively, for both fuels; this trend is more clearly with CB100 combustion. The fractal dimension (D_f) declined as the EGR rate increasing during the burning of CB100 by 44.93% in comparison with neat diesel. For both fuels, the presence 40% of EGR increased the fractal dimension by 1.76 and 1.97 from CB100 and diesel, respectively, compared to the absence EGR.

1. Introduction

The quality of global air started to deteriorate from the combustion of many applications of diesel engines through increasing the particulate matter (PM) and nitrogen oxides (NO_X) emissions. The nano size of the PM may induce cardiovascular and respiratory diseases as well as it become a major concern on the environment issues [1]. Many stringent standards have been carried out to control the adverse effect of these emissions that emitted from diesel engines over the world. Generally, the difficulties in control PM and NO_X emissions lead to concluding that the improvement degree still not

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very satisfactory. To keep environment safe, the researchers has focused on alternative fuels, solar energy and nanofluid to reduce the impact of pollutants emission [2,3]. The use of first-generation biofuels is considered one of the good strategies in road transport to reduce the harmful emissions [4]. Also, it was reported that biodiesel is eco-friendly alternative and a good alternative fuel to fossil fuels in diesel vehicles. The variations of viscosity and density of diesel biodiesel blend was studied by Maksom *et al.,* [5] for different blending ratio using Computational Fluid Dynamic (CFD). Honeycomb structure monolith of diesel particulate filter (DPF) is usually used in diesel engine to control the PM, which including the soot, ash, and sulfates. It is reported that the combination of oxygenated fuels and DPF eliminated the PM at low exhaust temperatures [6]. Biodiesel production selecting depends on cost, availability, stability, and manufacturing techniques. It is pointed out that EGR technique extensively used in compression ignition (CI) engines to decrease emissions of NO_X for different EGR rates, while it leading to high Brake specific fuel consumption (BSFC) and PM [7]. The area of alternative fuels is expanded and receiving attention over the past years to use in diesel engines, especially biodiesel represents a very favourable fuel. Prior works showed that the oxygen-born in the biodiesel decrease the PM, CO, and HC, volatile organic compounds (VOCs), and sulfur oxides (SO_X), with increased the NO_X emissions [8,9]. Besides, the using of different biodiesel fuels in diesel engine appeared increase brake thermal efficiency and BSFC compared than diesel fuel [10]. Mono-alkyl esters of long chain fatty acids are the components of biodiesel, which derived from animal fats and vegetable oils. It well known that biodiesel has attractive properties such as oxygenated, biodegradable, renewable fuel, nontoxic, and sulfur-free. Veza *et al.,* [11] discussed the development of microalgae biodiesel and the greater potential of biodiesel to be used in internal combustion engines. The much oxygen and comparable energy density in biodiesel provides better horsepower and high fuel efficiency than to the regular diesel fuel.

In road vehicles, the formation of particulates emitted from process of combustion chamber due to the reactions of polycyclic aromatic hydrocarbon (PAH) in the oxygen-deficient regions of the chamber after injected fuel is heated. The liquid-like young soot formed from the fuel molecules through hydrogen abstraction to become solid soot particles. During the combustion process, the soot particles agglomerate together in irregularly superimposed to form the different shapes of PM, with nearly spherical shapes in mostly. Rohani and Bae [12] and Stanmore *et al.,* [13] reported that the morphological characteristics of PM is affecting on the soot reactivity of nanostructure of graphen layers. Many studies in the literatures documented that high-resolution transmission electron microscopy (HRTEM) [x] and Scanning Electron Microscopy (SEM) have been successfully used to analyse the nanoparticles morphology characteristics [14]. The soot morphology was analysed using HRTEM under different engine parameters such as fuel injection strategies, engine load, and fuel type [15-17]. In most of studies, the morphological characteristics of soot particles were investigated from biodiesels combustion in heavy-duty diesel engines [18-20]. Several researchers have found that the oxygen-born in the oxygenated fuels properties has active effect on PM reduction. The nanostructure of soot particles has shorter graphitic layers and disordered configuration during the oxygenated fuels burning [21,22].

Recently, exhaust gas recirculation (EGR) and the injection strategies have been suggested as a technique to reduce the NO_X emissions. Previous works studied the influence of EGR and biodiesel on PM and NO_X emissions under different engine conditions [23,24]. They found that the combination between biodiesel and EGR was reduces the emitted emissions of NO_X and PM than those emitted during diesel combustion. It is reported that the different EGR level and biodiesel leading to high level of smoke under low engine load, while less level of smoke at higher load in single cylinder diesel engine [25]. In Another work by Agarwal *et al.,* [26] stated that the combining between 20% of biodiesel blend and 15% of EGR rate equipped with two-cylinder engine was optimum effect on engine emissions. Further, the combination between medium rate of EGR and alcohol-diesel blends reduced soot emission and NO_X with slight effect on engine performance [27]. On the other hand, it is documented that the 30% level of EGR increased the formation of PM [27,28]. The use of alternative fuels with EGR become essential to reduce the penalty effect of oxygen deficiency inside combustion chamber occurred from EGR [29]. Limited works were carried out about the impact of EGR rates on the PM characteristics. Also, it was found that not much works is performed on the PM characteristics from the combination of the using Coconut biodiesel and EGR. Therefore, this work is focused towards exploring the PM characteristics from different EGR rates for diesel and biodiesel. Also, it was focused on the determination of the effect of combining of EGR rates (15%, 30% and 40%) and CB100 on the morphological parameters.

2. Experimental Setup

2.1 Engine and Fuels

This study was conducted on a single-cylinder diesel engine equipped with Exhaust gas recirculation (EGR) system as shown in Figure 1. This engine had 5 indicated mean effective pressures (IMEP) at 2000 rpm. The rated power was 8.6 kW at 2500 rpm, with 15.1 of compression ratio. Brake dynamometer was fixed with engine to control the speed and torque of the engine. The cylinder bore and stroke were 98.4 mm and 101.6 mm, respectively, with 165 mm of connecting rod length. The range of fuel injection pressure was from 500 to 1000 bar. In this study, the injection pressure of the fuel is 650 bar for all fuels tested. The rates of EGR (0%, 15%, 30%, and 40%) were controlled through the valve which fixed at the right corner of the engine. K-type of thermocouples was fixed in different positions of engine parts to record the variation in temperatures of exhaust, oil, and air. The diesel fuel was used in this study as reference fuel. The biodiesel was used as a renewable fuel and derived from Coconut biodiesel. The main properties of diesel and Coconut biodiesel are listed in Table 1. Most of these properties were found from calculations, suppliers, and publications.

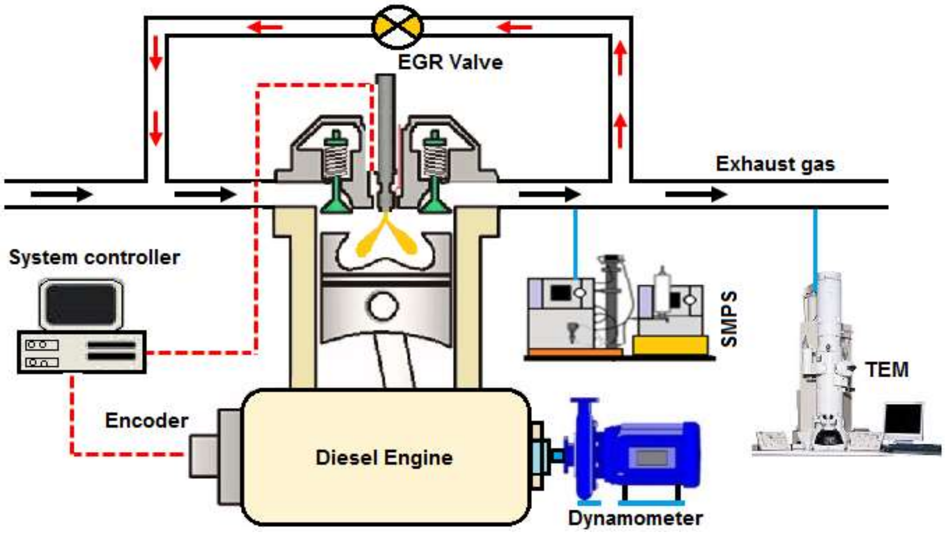

Fig. 1. Engine test bed, tools, equipment and sampling system

Table 1
Properties of fuels used

Properties	Diesel	Biodiesel
Chemical formula	$C_{16}H_{34}$	$C_{19}H_{36}O_2$
Derived cetane number	51.8	62
Heat of vaporization (kJ/kg)	242	216
bulk modulus (MPa)	1410	1554
At 15 °C, fuel density (kg/m^3)	844.3	896.1
Fuel calorific value (MJ/kg)	45.80	38.90
Lower heat value (MJ/kg)	42.50	40.41
Falsh & Fire point (°C)	65-70	157-162
Water content by coulometric KF (mg/kg)	40	170
At 40 °C, kinematic viscosity (cSt)	2.77	5.0
Stoichiometric air fuel ratio	14.4	-
lubricity at 60 °C(µm)	312	205

2.2 Equipment and Testing Conditions

Model TSI/3080 of scanning mobility particle sizer (SMPS) was employed to calculate the number and PM concentration emanated from fuels combustion. The dilution ratio and temperature of air dilution were set at 150 C and 1:200, respectively, in order to avoid the nucleation of HC. The range of particle diameter was ranged from 10.4 to 340 nm. The PM morphological parameters of number of primary particles (n_{po}), radius of gyration (R_g), size of primary particles (d_{po}), and fractal dimension (D_f) were examined using high-resolution transmission electron microscopy (HR-TEM). These parameters of PM were obtained using software of a homemade Matlab (digital image process) [30,31]. For all tests, the engine load and speed were fixed at 4 bar indicated mean effected pressure (IMEP) and 1800 rpm, respectively. Different rates of EGR were carried out at 0%, 15%, 30%, and 40% for diesel and biodiesel. The uncertainty of experimental measurements could have been occurring due to a variety of factors during the tests. Table 2 shows the accuracy measurement of the experimental equipment and tools used in this work.

Table 2
Measurement accuracy of the equipment and tools

Equipment measurements	Accuracy %
Engine speed tachometer	± 1.72%
Flow meter of diesel fuel	± 0.56%
Thermocouples	± 1.20%
Level of sound pressure	± 0.66%
Meter of air flow	± 1.10%
Engine dynamometer	± 0.91%
PM emission analyser	± 0.80%

3. Results and Discussion
3.1 PM Characteristics

From Figure 2, the size distribution of PM from the effect of Coconut biodiesel (CB100) and EGR rates was measured using statistical analysis in a unit area. The results showed that the normal distribution of particle size is over the range of 20–60 nm for both fuels studied. With use of biodiesel, the mean diameter of the PM reduced higher by 36.27% when compared with diesel under EGR rates technique as depicted in Figure 2. This can be justified due to the high oxygen-born into the oxygenated fuel compared to the regular diesel which result in improve the PM oxidation [32,33].

Higher cetane number and oxygen content into the Coconut biodiesel properties enhance the efficiency of fuel combustion. For both fuels, it is clear that the increase the rate of EGR (40%) leading to increase the probability of particulate formation by 26.48% in comparison with absence EGR technique. Reduce the oxygen concentration inside cylinder could be the main reason for that as well as increasing the rate of EGR help in produce high particulates [34,35]. In addition, the deterioration of the combustion can be occurred with apply the technique which results in enhance the formation possibility of PM. The PM size distribution was lower from the burning of CB100 especially with 20% of EGR rate compared to the other rate of EGR. The particulate formation increased with increasing the rate of EGR due to the lower combustion temperature from the high rate of EGR which result in decreasing the PM oxidation [36]. Furthermore, the PM was smaller from the burning CB100 in comparison with diesel for different rate of EGR technique. The lower impacts between individual particles and agglomerate of particles from the CB100 combustion leading to generate smaller size of PM [37]. The trend of PM size distribution is tending to be smaller diameter for without EGR technique and using CB100 combustion (Figure 2).

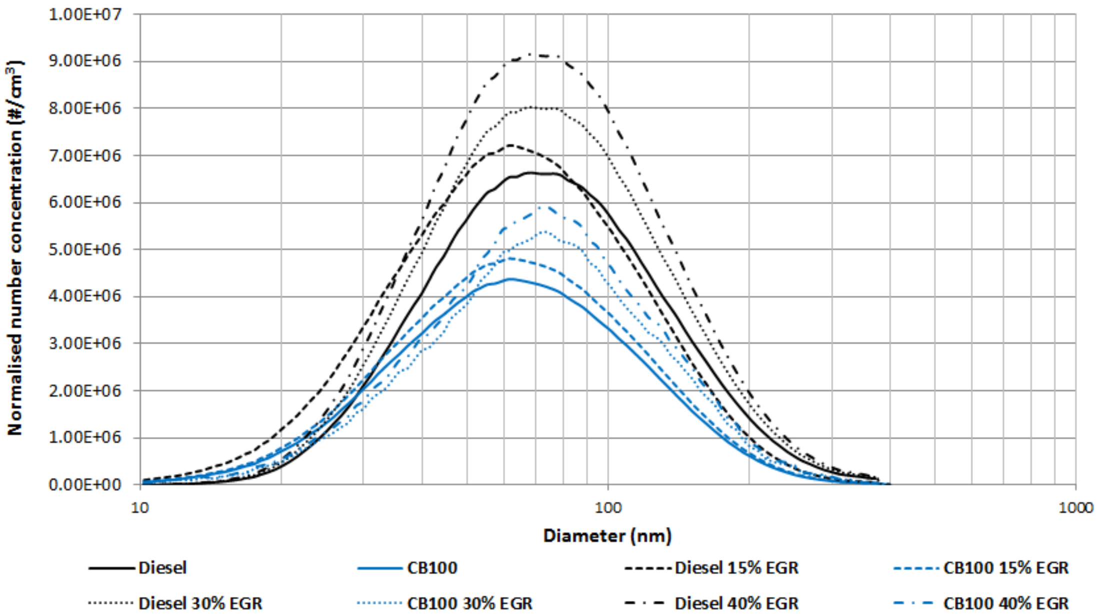

Fig. 2. Effect of EGR rates on size distribution of particulate for diesel and CB100

The histograms of diesel and Coconut biodiesel are shown in Figure 3 for with EGR and without EGR technique. From the results, it can be noticed that the high rate of EGR and diesel fuel produces high rate of particle number compared to the lower EGR rate. This is clear in Figure 4 when the particles agglomerate together to form big soot agglomerate. The results confirm that large soot agglomerate is produce from the 40% of EGR rate and diesel fuel in comparison with CB100. This can be attributed to highly randomly impacts between soot particles within cylinder and during the pipe line of exhaust. Figure 5 shows that the number of particulates is significantly lower from CB100 combustion by 42.35% than to the diesel fuel over 20%, 30% and 40% of EGR rate. The particle formation decreased with from twofold effect of high oxygen content during combustion and better mixing between fuel and air [38]. It is reported that the oxygenated fuels have high ability in oxidise the PM formation [39]. Number of primary particles decreased more with absence EGR technique and presence coconut biodiesel fuel compared to the presence EGR and diesel as shown in Figure 5. Through soot oxidation, most formation of soot occurred at the beginning of combustion are disappears depending on soot precursors, availability of oxidants and reaction kinetics between different size of primary particles.

Figure 6 displays the influence of coconut biodiesel and EGR rates on the radius of gyration (R_g) to form final shape of PM. The soot agglomerates from CB100 more pronounced and tends to form spherical particles shape of soot in comparison with the diesel under low and high rates of EGR. The increasing EGR rate leading to decrease the R_g by 31.75% for both fuels tested (Figure 6). The lower temperature within combustion could be increase the soot formation and randomly collisions of soot particles which result in produce soot agglomerates with less spherical shape like clusters as shown in TEM images of Figure 4. It well known that the R_g determine the size of soot agglomerates [40]. The R_g gradually increased from the combustion of CB100 by agglomerate the soot particles together around the centre of total soot agglomerate to be more spherical shape. The results show that the radius of gyration distributions decreased at high EGR rate (40%) compared to the absence of EGR and low EGR rate. This could be due to the lower density number of particles from increasing the EGR rate which result in decreasing the agglomeration rate [41].

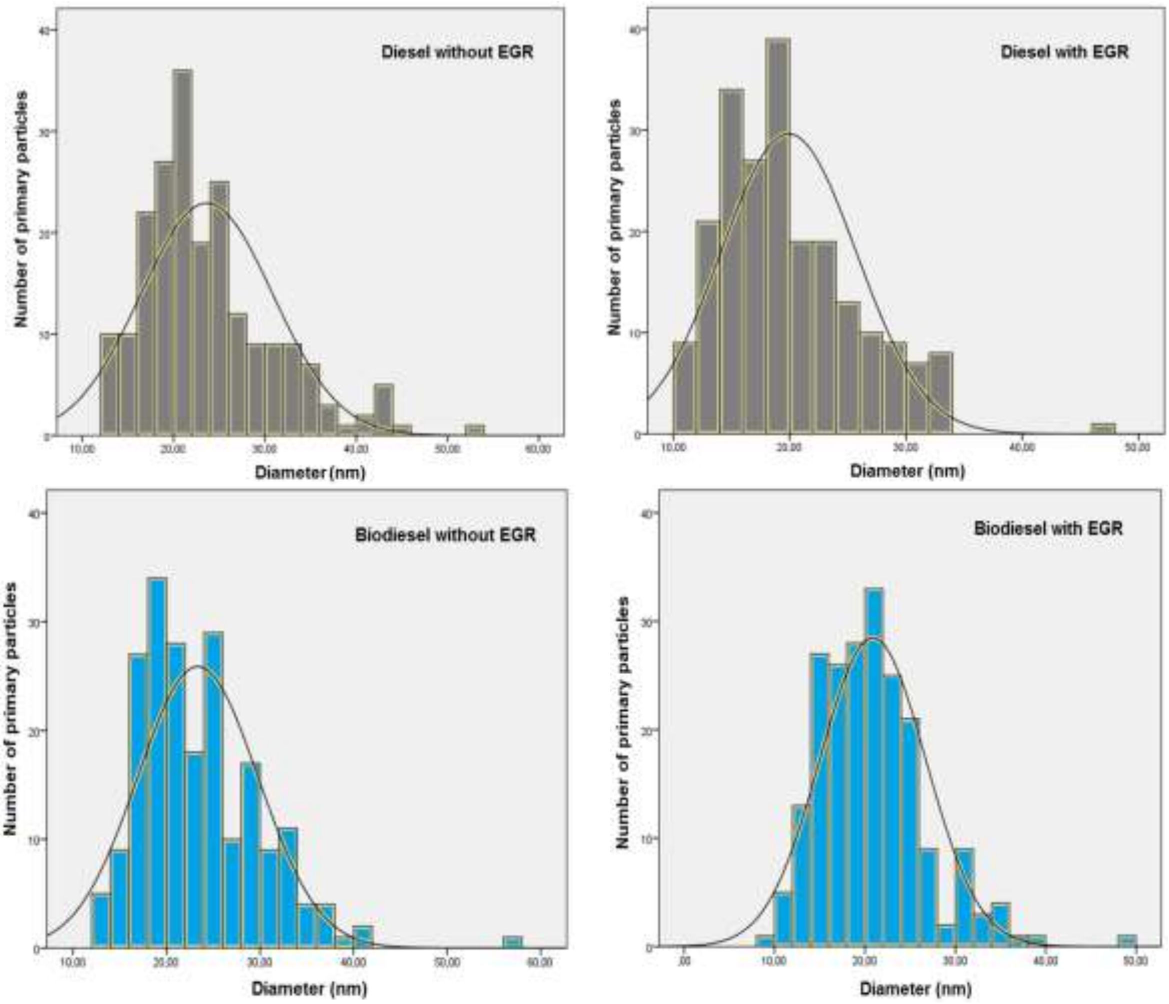

Fig. 3. Size distribution of primary particles (n_{po}) for Coconut biodiesel and diesel fuel under different EGR rates

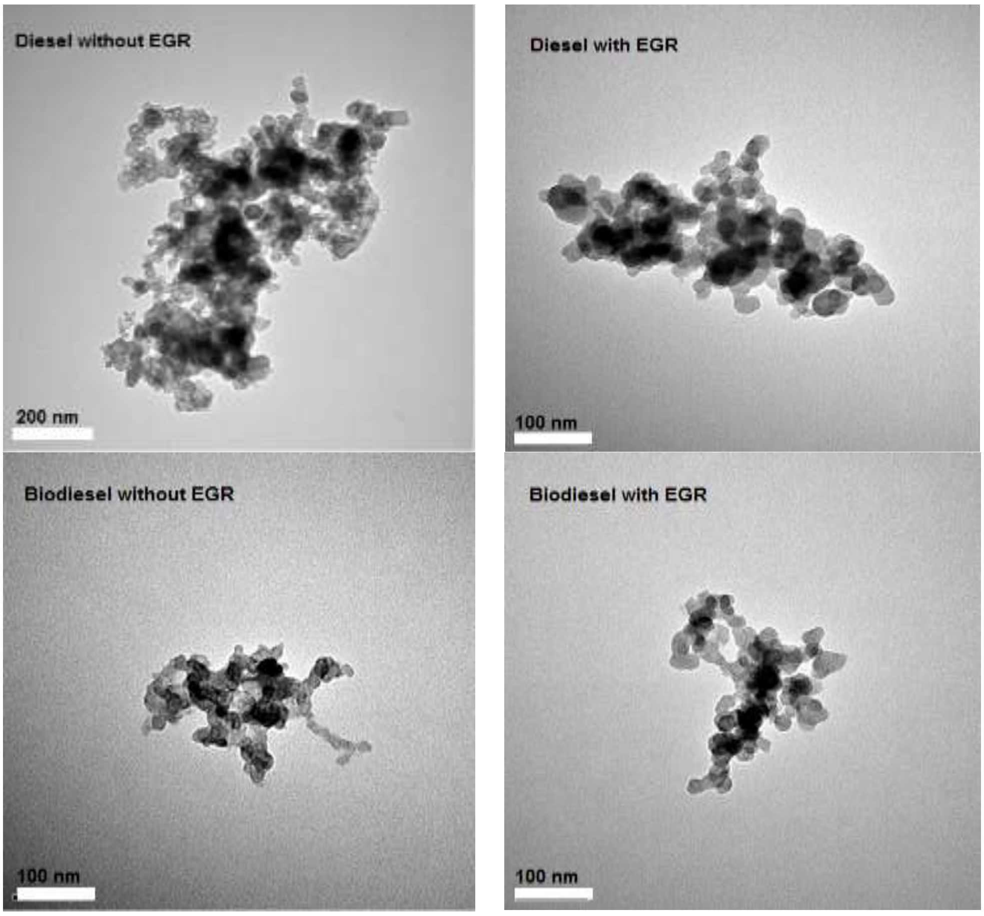

Fig. 4. TEM micrographs for diesel fuel and Coconut biodiesel for with and without EGR technique

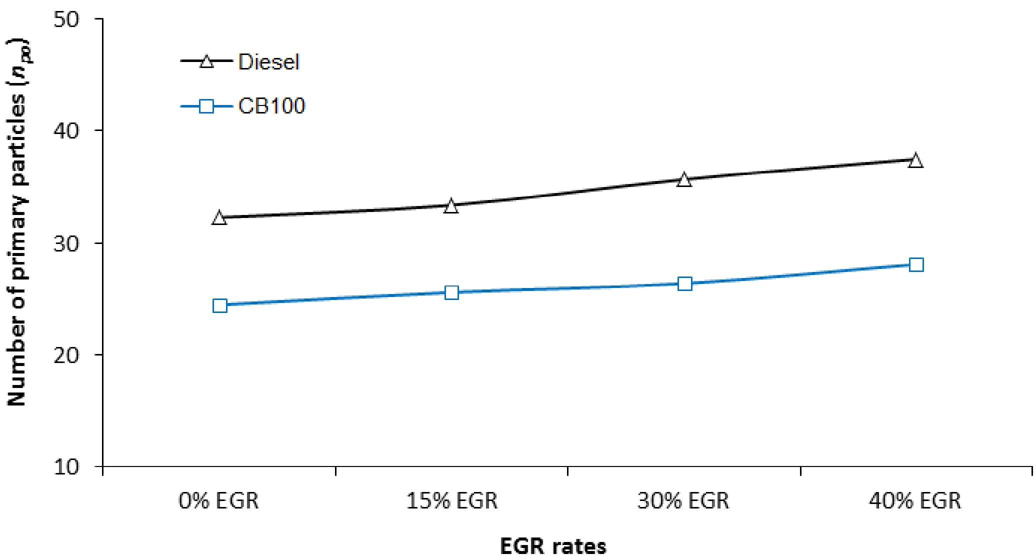

Fig. 5. Effect of EGR rates on number of primary particles (n_{po}) for diesel fuel and CB100

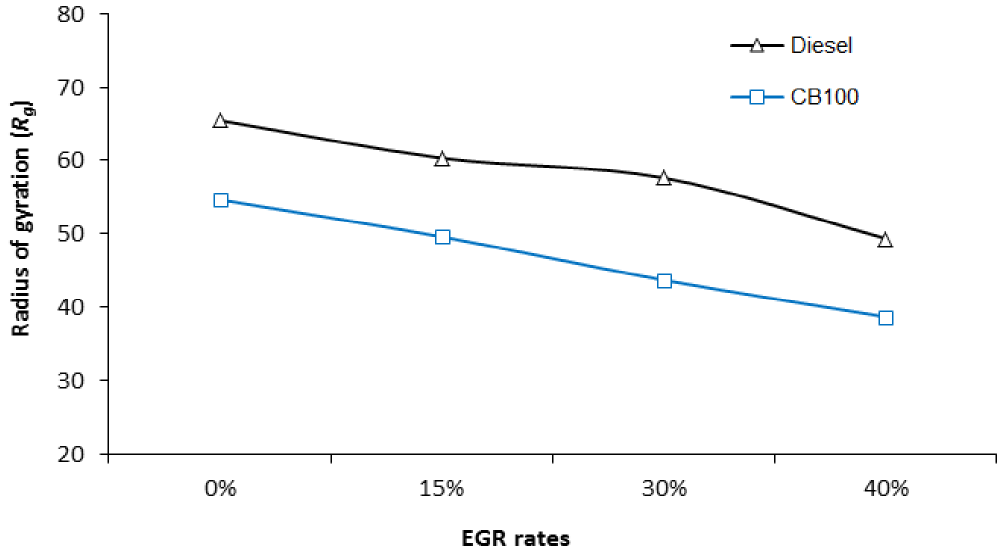

Fig. 6. Effect of EGR rates on radius of gyration (R_g) for diesel fuel and CB100

The values of particles diameter from the effect of EGR rates and coconut biodiesel under various loads are shown in Figure 7. It is clear that the CB100 combustion produce smaller diameter of particle compared to the diesel due to the less collisions between particles which result in smaller diameter [42]. In case of particulate morphology, the particulate quantities and size were affected by different parameters of formation process for soot such as pressure, temperature of flame and residence time. It is mentioned that these parameters could be modify the particle dimension, number of particles, number of agglomerates and size of the radius of gyration, which in turn effect on the changes of particulate size and quantity. High EGR rate leads to notable decreases in diameter of particulate due to increase the impacts between formed soot as well as between soot agglomerate and soot particles [41,43]. It can be observed that the particle diameter decreased by 27.38% with increasing the EGR rate for both fuels studied as presented in Figure 7. In contrast, other authors obtained that no significant changes with increasing the EGR in the size of the soot particle [36]. This can be justified due to the lower oxygen concentration in the flame and unstable between temperature levels inside the cylinder.

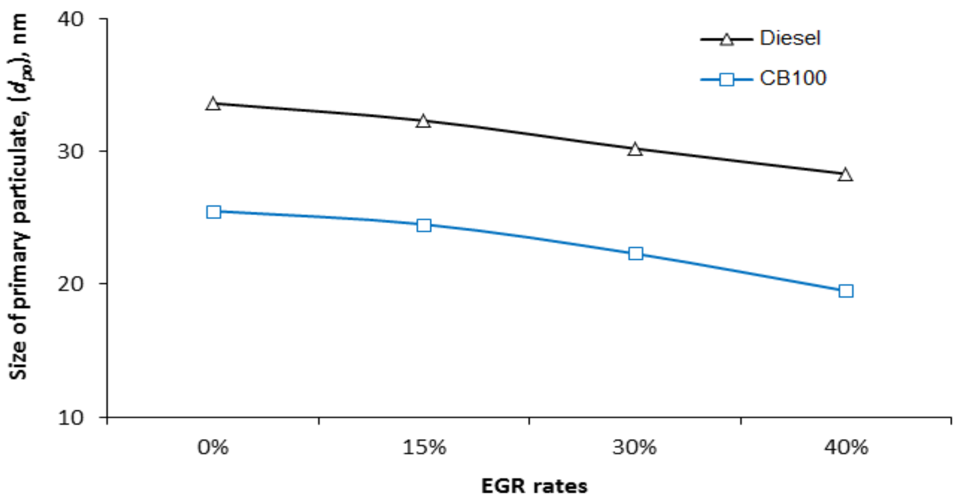

Fig. 7. Effect of EGR rates on radius of primary particulate size (d_{po}) for diesel fuel and CB100

The additional information and the shape (three-dimensional) in the mechanism of agglomerate formation both can determine the fractal dimension. Small variation in the D_f with increasing the EGR rates during the process of combustion. The experimental tests indicated that the fractal dimension significantly higher with 40% of EGR rate by 1.76 and 1.97 from CB100 and diesel, respectively, in comparison to the absence EGR for both fuels as presented in Figure 8. Furthermore, the D_f decreased from the burning of CB100 by 44.93% compared to the diesel under low and high rate of EGR technique. This may be due to the disorder of internal structure of soot particles which result to easier oxidation and change the external shape of the particles [36,44]. Moreover, the oxygen-bond in the properties of CB100 provides high potential of soot oxidation, thereby decrease the total values of fractal dimension [45,46].

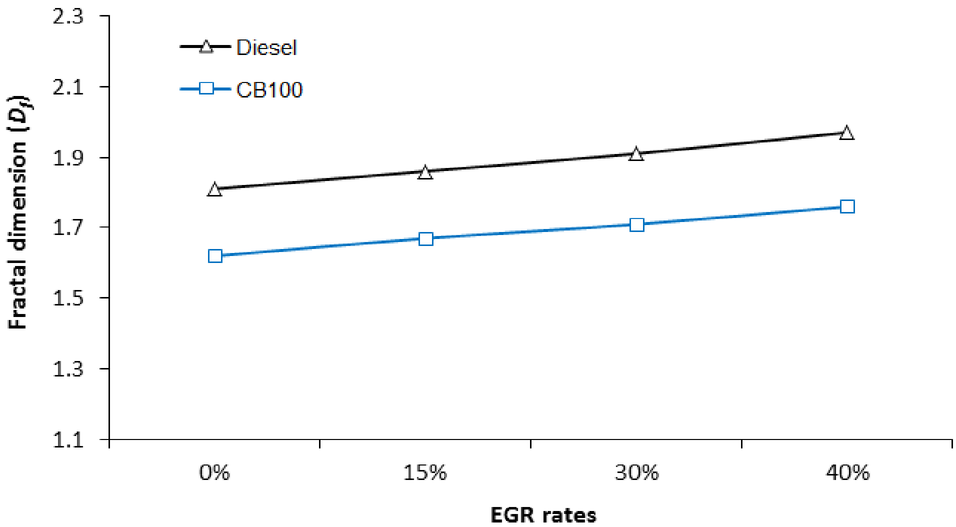

Fig. 8. Effect of EGR rates on fractal dimension (D_f) for diesel fuel and biodiesel

4. Conclusions

An investigation was performed to analyse the EGR rates effect and Coconut biodiesel together on the size and morphological parameters of PM in diesel engine. The PM size distribution decreased from CB100 combustion with EGR rates with respect to PM size from diesel. In addition, introduce of EGR technique leading to increase the PM concentrations and number compared to the absence EGR technique. The results indicated that the soot particles number decreased more than to the diesel, while increased with high rate of EGR. The average particles diameter of soot emissions and radius of gyration both declined through CB100 combustion compared to diesel for both conditions of EGR technique. On the other hand, these results have opposite trend increasing the number of soot particles with increasing the EGR rates, meanwhile these results decreasing with high EGR rate. It can be concluded that the same trend was obtained for the size of soot particles and fractal dimension. It is suggested that the effect of different blends of alcohol blends, EGR and fuel injection strategy on morphology parameters and nanostructure will be interesting point in the next study.

Conflict of Interests
The authors confirm and declare that there is no conflict of interests regarding the publication of this paper.

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