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Effects of nano metal oxide blended Mahua biodiesel on CRDI diesel engine

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KEYWORDS

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Mahua methyl ester (MME);
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Combustion;
Emissions

Abstract In this paper, aluminium oxide nanoparticles (ANPs) were added to Mahua biodiesel blend (MME20) in different proportions to investigate the effects on a four stroke, single cylinder, common rail direct injection (CRDI) diesel engine. The ANPs were doped in different proportions with the Mahua biodiesel blend (MME20) using an ultrasonicator and a homogenizer with cetyl trimethyl ammonium bromide (CTAB) as the cationic surfactant. The experiments were conducted in a CRDI diesel engine at a constant speed of 1500 rpm using different ANP-blended biodiesel fuel (MME20 + ANP50 and MME20 + ANP100) and the results were compared with those of neat diesel and Mahua biodiesel blend (MME20). The experimental results exposed a substantial enhancement in the brake thermal efficiency and a marginal reduction in the harmful pollutants (such as CO, HC and smoke) for the nanoparticles blended biodiesel.

1. Introduction

Owing to the depletion of the fossil fuels day by day, there is a necessity to find out an alternative resolution to fulfil the energy requirement of the world. Petroleum fuels play an vital role in the fields of transportation, industrial development and agriculture [1,2]. Fossil fuels are fast depleting because of increased fuel consumption. Steady with the estimation of the International Energy Agency, by 2025 global energy utilization will increase by about 42% [3]. Many research works are going on to substitute the diesel fuel with an appropriate alternative fuel such as biodiesel. Biodiesel is one of the best available sources to fulfil the energy requirement of the world [4]. Nonedible sources such as cotton seed oil, pongamia oil, Mahua oil, Jatropha oil, and Karanja oil have been investigated for biodiesel fuel production [5]. In the modern years, severe efforts have been made by many researchers to use various sources of energy as feed in existing diesel engines. The make use of straight vegetable oils (SVO) is inadequate due to some unfavorable physical and chemical properties, particularly their viscosity and density. Because of higher viscosity, SVO causes incomplete combustion, poor fuel atomization and carbon deposition on the valve and injector seats ensuing in severe engine problems. When diesel engines are fuelled with straight vegetable oil as fuel, it leads to incomplete combustion. The potential methods to overcome the problem of higher

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Nomenclature

ANP	aluminium oxide nanoparticles
BSFC	brake specific fuel consumption, kg/kW h
BP	brake power, kW
BTE	brake thermal efficiency, %
CO	carbon monoxide, %
HC	hydrocarbon, ppm
NO_x	oxides of nitrogen, ppm
CRDI	common rail direct injection
rpm	revolution per minute
SEM	scanning electron microscopy
MME	Mahua methyl ester
MME20	Mahua methyl ester 20% + Diesel 80%
MME20 + ANP50	(Mahua methyl ester 20% + Diesel 80%) + (50ppm ANP)
MME20 + ANP100	(Mahua methyl ester 20% + Diesel 80%) + (100ppm ANP)

viscosity were blending of vegetable oil with diesel fuel in the proper proportions and transesterification of vegetable oils to produce biodiesel [6–8]. The transesterification process has been established worldwide as a successful means for biodiesel production and viscosity reduction of vegetable oils [9]. Transesterification is the process, by means of an alcohol (e.g. ethanol or methanol) in the presence of a catalyst, to chemically break the triglyceride molecules of the raw vegetable oil into ethyl or methyl esters (fatty acid alkyl esters) of the vegetable oil with glycerol as a by-product [10]. Ethanol is a preferred chemical for transesterification process compared to methanol because it is derived from renewable sources (agricultural waste) and is biologically non-harmful for the environment. Mechanism of transesterification process is shown in Fig. 1.

In general, methyl esters of vegetable oil propose the reduction of harmful exhaust emissions from the diesel engine such as CO, HC and smoke but it increased the NO_x emissions [11–17]. The NO_x emission is the most dangerous parameter that has an effect on the environment through acid rain, human diseases, etc. Furthermore, CO and NO are primary pollutants in the formation of atmospheric ozone, which is an important greenhouse gas [18,19]. The common rail direct injection (CRDI) system has been observed to significantly reduce the fuel consumption and soot emissions as compared to conventional injection. When the diesel engines are designed for passenger cars, there is a demand for a maximum power output, less noise and reduced emissions. To fulfil these demands, the CRDI system, which enables high pressure injection and precise control of injection timing, is attracting a great deal of attention [20,21]. Many researchers have found that the B20 biodiesel blend gives greater thermal efficiency and emission parameters compared with other biodiesel blends [22,23]. Among the different techniques accessible to reduce exhaust emissions from the diesel engine while using biodiesel, the use of fuel-borne metal catalyst is presently focused because of the advantage of an enhancement in fuel efficiency while reducing harmful exhaust emissions and health-threatening chemicals [24,25]. Aluminium oxide nanoparticles at high temperatures dissociate into Al_2O and oxygen:

$$Al_2O_3 \rightarrow Al_2O + 2O$$

Al_2O_3 is unstable at high temperatures during combustion in the combustion chamber, so it also decomposes as follows:

$$Al_2O \rightarrow 2Al + O$$

Many researchers found that the combustion behaviour of methyl esters with the addition of nanosize energetic materials as an additive improves the combustion and engine performance of diesel engines. In addition, due to the small size of nanoparticles, the stability of fuel suspensions should be noticeably improved [26–30]. In this investigation, aluminium oxide nanoparticles were added in different proportions (50 and 100 ppm) to a biodiesel blend (MME20) to investigate the performance, emission and combustion of the CRDI system assisted diesel engine.

2. Biodiesel production

Mahua oil is heated to a temperature of 100–120 °C to remove water contents present in vegetable oil followed by filtration. The oil is processed under base-catalysed transesterification method where it is mixed with 200 ml of methanol and 7 g of potassium hydroxide (KOH) pellets per litre of vegetable oil and placed on a hot plate magnetic with stirring arrangement for 1–1.5 h up to 60 °C and then it is allowed to settle down for about 6–8 h to obtain biodiesel and glycerol. The biodiesel obtained is further washed with distilled water two to three times for the removal of acids and heated above 100 °C to remove the moisture present in the biodiesel. Schematic diagram of biodiesel plant is shown in Fig. 2.

3. Nanofluid preparation

The morphological characterization of ANPs was carried out using scanning electron microscopy (SEM). Spherical-shaped ANPs obtained were confirmed. SEM image of aluminium oxide nanoparticles is shown in Fig. 3. The mean size of the nanoparticles varies from 32 to 48 nm. The nanoparticles were diffused in the solvent with the help of a homogenizer. Nanoparticles usually have a high surface contact area and therefore surface energy will be high. Nanoparticles clustered together to form a micro molecule and start to sediment. To make nanoparticles be steady in a base fluid, it should need to surface modification. Cetyl trimethyl ammonium bromide (CTAB) is a cationic surfactant and it creates an envelope on the surface of the nanoparticles and makes the surface as a negative charge. Hence the particle sedimentation was controlled. In order to disperse the nanoparticle to the base, the magnetic stirrer procedure was followed. A known quantity of aluminium oxide nanoparticles (50 and 100 ppm) and

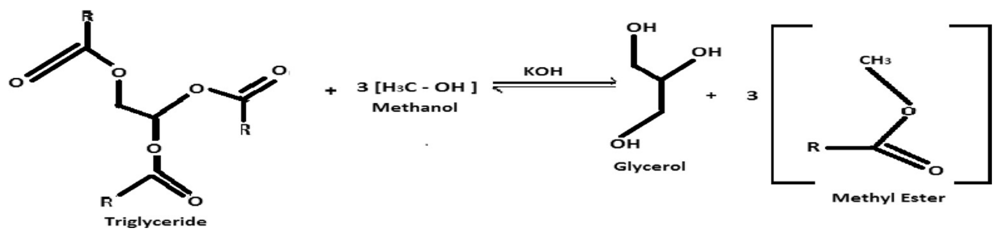

Figure 1 Mechanism of transesterification process.

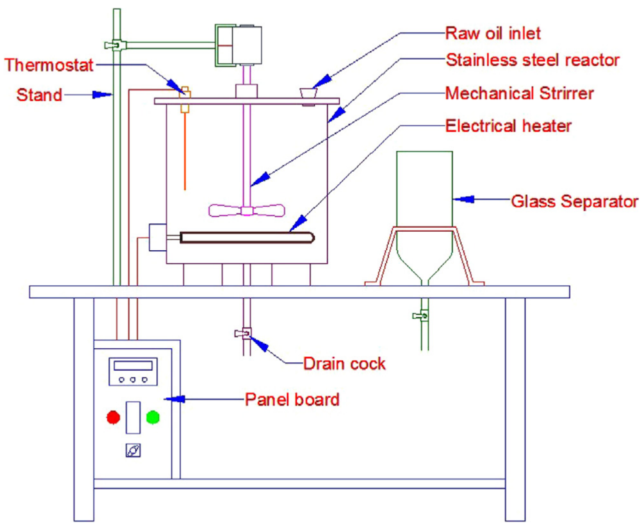

Figure 2 Schematic diagram of biodiesel plant.

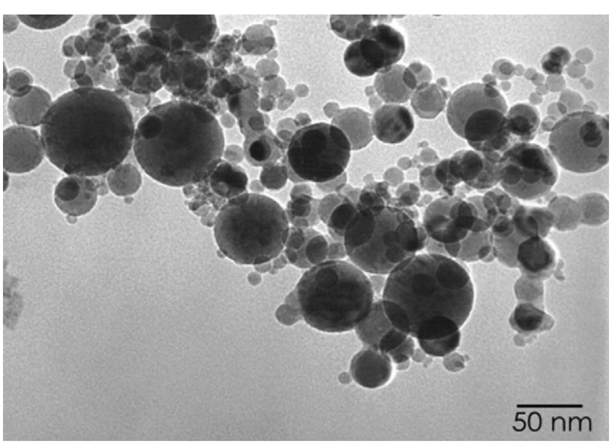

Figure 3 SEM of aluminium oxide nanoparticles.

CTAB was weighed and poured in the ethanol solvent and magnetically stirred for 2 h. Then it forms an even nanofluid.

3.1. Mahua methyl ester-nanofluid blend preparation

The aluminium oxide nanofluid was added to the Mahua methyl ester blend (MME20) in two different proportions (50 and 100 ppm). After the addition of aluminium oxide nanofluid, it is shaken well. And then it is poured into signification apparatus where it is agitated for about 30–45 min in an ultrasonic shaker, making a uniform MME20-ANP blend. The properties of Mahua methyl ester (MME) and ANPs blended Mahua methyl ester blend are given in Table 1.

Table 1 Properties of biodiesel-nanoparticles blended samples.

Description	Viscosity @ 40 °C (cSt)	Density @ 15 °C (kg/m^3)	Flash point (°C)	Calorific value, (kJ/kg)	Cetane number
Diesel fuel	3	815	56	42,000	47
Mahua methyl ester (MME)	4.9	869	136	39,950	56
MME20	3.4	826	76	41,620	49
MME20 + ANP50	3.37	827.5	71	41,665	49.5
MME20 + ANP100	3.33	829	65	41,690	51

4. Experimental set-up and test procedure

The experiments were conducted on Kirloskar AV1, four stroke, single cylinder diesel engine assisted by common rail direct injection (CRDI) system. The rated power of the diesel engine was 3.7 kW. The engine was operated at a constant speed of 1500 rpm by maintaining the injection pressure from 250 to 500 kgf/cm^2 at various load conditions. The engine was at the start fuelled with neat diesel to provide the baseline data, and then it was fuelled with MME20, MME20 + ANP50 and MME20 + ANP100. Details of the engine specification are given in Table 2. Eddy current dynamometer was used for loading the engine. The AVL smoke meter was used to measure the smoke density present in the exhaust. AVL five-gas analyzer was used to measure HC, CO and NO_x emissions. In-cylinder pressure and heat release rate were measured by using data acquisition system interfaced with dual core processor. The experimental set-up is indicated in Fig. 4.

5. Results and discussion

The operation of the CRDI system assisted diesel engine using Mahua methyl ester blend (MME20) and ANPs added Mahua methyl ester fuel blends was found to be very smooth

Table 2 Engine specifications.

Type	Vertical, water cooled, four stroke
Number of cylinders	One
Bore	80 mm
Stroke	110 mm
Compression ratio	17.5:1
Maximum power	3.7 kW
Speed	1500 rev/min
Dynamometer	Eddy current
Injection timing	23° (before TDC)
Injection pressure	250–500 kgf/cm^2

throughout the rated load, without any operational trouble. The performance characteristics such as specific fuel consumption (SFC), brake thermal efficiency (BTE) and the emission characteristics such as NO_x, HC, CO and smoke density are plotted against the brake power. Based on the combustion data, cylinder pressure and heat release rate are plotted against crank angle.

5.1. Engine performance

5.1.1. Specific fuel consumption (SFC)

The variation of specific fuel consumption for the Mahua biodiesel blend (MME20), Mahua biodiesel with aluminium oxide nano additive and neat diesel with brake power is shown in Fig. 5. Mahua biodiesel blend has a lower calorific value compared to the diesel fuel; hence, to retain the same power output, excess of fuel was consumed during MME20 operation. This leads to an increased fuel consumption of MME20 compared to diesel fuel. To increase the engine performance, nanoaluminium oxide additive (ANP) was mixed with the biodiesel blend (MME20). The addition of ANP (ANP100) resulted in 7.66% reduction in SFC at maximum load.

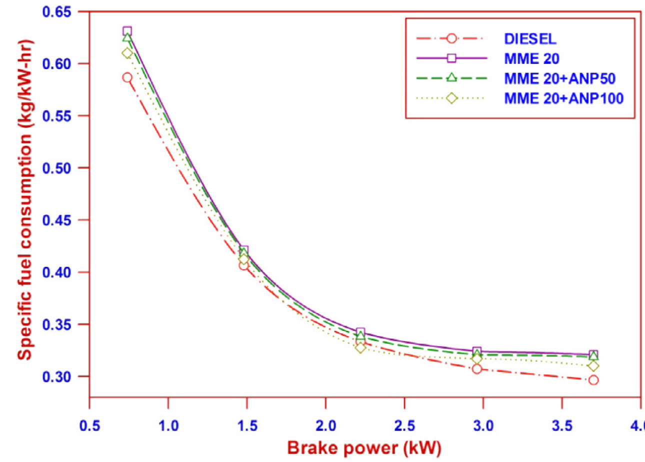

Figure 5 Specific fuel consumption against brake power.

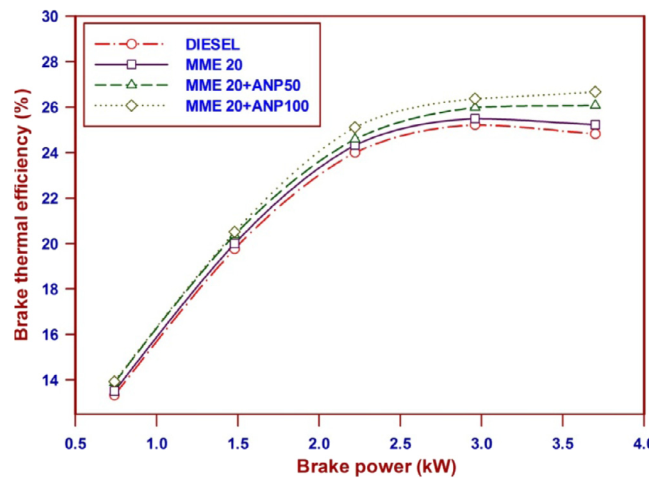

Figure 6 Brake thermal efficiency against brake power.

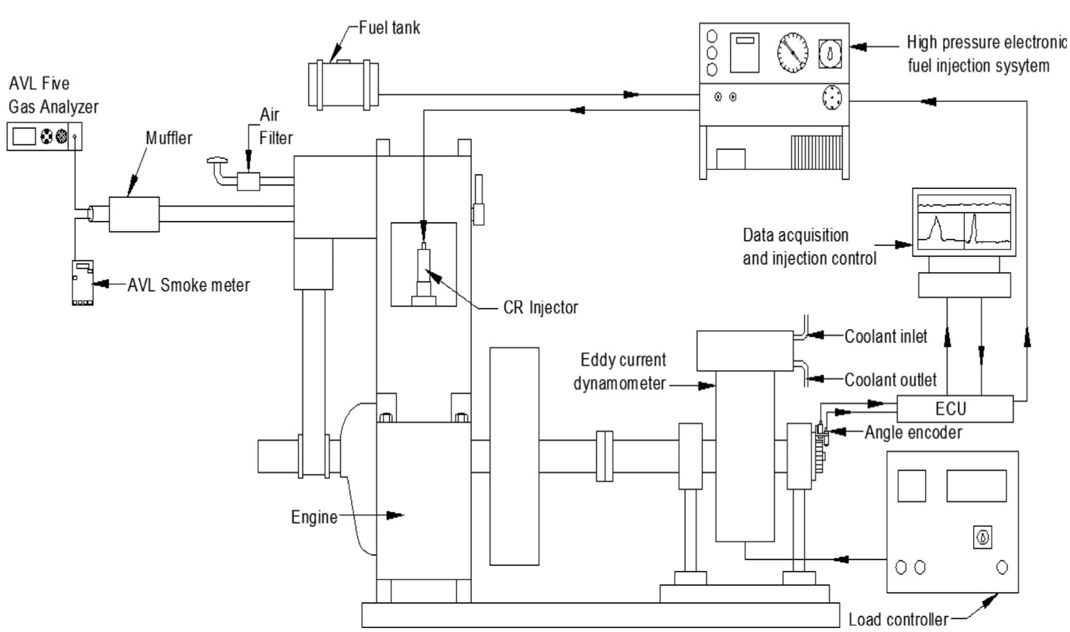

Figure 4 Experimental set-up.

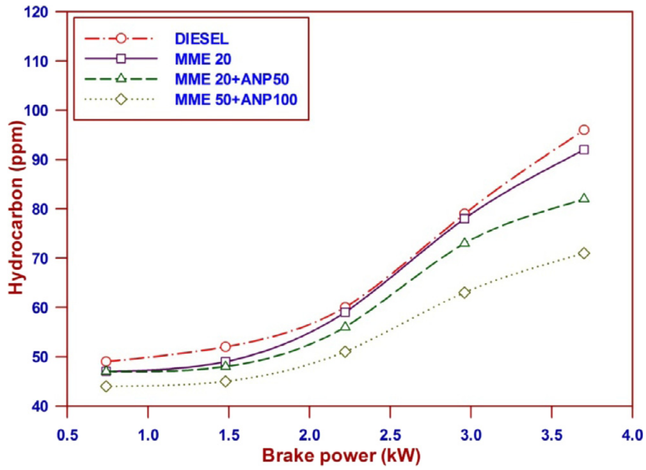

Figure 7 HC against brake power.

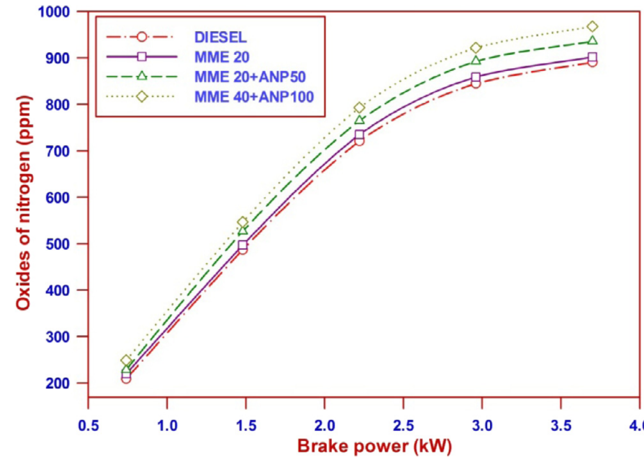

Figure 9 Oxides of nitrogen against brake power.

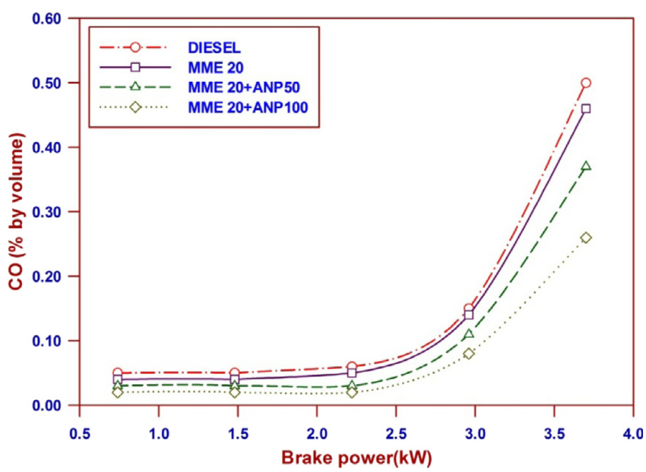

Figure 8 CO against brake power.

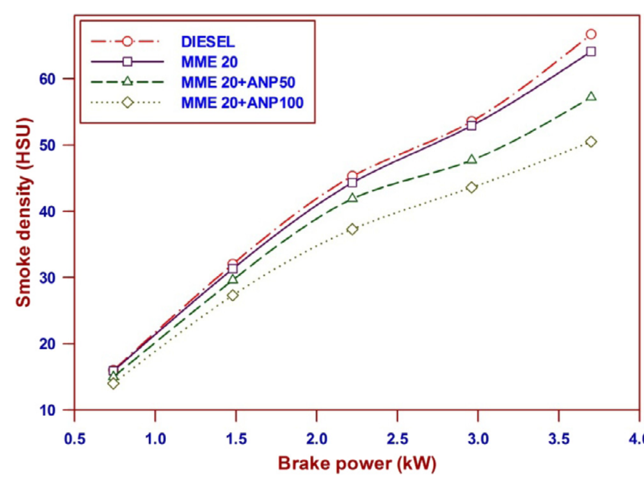

Figure 10 Smoke density against brake power.

5.1.2. Brake thermal efficiency

From Fig. 6, it can be observed that the brake thermal efficiency (BTE) increases with the load for both Mahua biodiesel blend (MME20) and ANP-blended MME20. The BTE of the MME20 + ANP100 was better than that of other fuel blends and neat diesel. A gain of 1.58% and 7.34% in BTE was recorded when ANP was added with the MME20 in different concentrations of 50 ppm and 100 ppm. This could be attributed to the better combustion characteristics of ANP. The catalytic activity of ANP might have improved because of the existence of high active surfaces. In addition, for MME20 + ANP100 fuel, the catalytic activity may be improved due to the high dosage of ANP compared to that of MME20 + ANP50.

5.2. Emission parameters

5.2.1. Hydrocarbon (HC)

It is observed from Fig. 7 that as the load increases the HC emissions steadily increases for all cases. Many authors' results show a significant reduction in HC emissions when replacing diesel fuel with biodiesel [17,31]. The higher cetane number of biodiesel blend (MME20) reduces the combustion delay period and the reduction has been connected to decreases in the HC emissions. Further addition of aluminium oxide nanoparticles reduces the hydrocarbon emissions, because ANP supplies the oxygen for the oxidation of hydrocarbon and CO during combustion [29]. From the figure, it is shown that the diesel fuel had the highest HC emission at full load. There was a reduction of 26.04% hydrocarbon emission for the MME20 + ANP100 case.

5.2.2. Carbon monoxide (CO)

The effects of ANP with a biodiesel blend (MME20) on the carbon monoxide emission at various engine loads have been shown in Fig. 4. ANPs have high surface contact areas which raise the chemical reactivity which consecutively shortened the ignition delay period. From Fig. 8, it is shown that the nanoparticles blended fuel has no major influence on the CO emission at minimum load condition, but for the full load, the CO emission increases considerably due to the use of ANP additives. These CO decrements are about 26% and 48% of the cases of MME20 + ANP50 and MME20 + ANP100 fuels, respectively, at the full load compared with neat diesel fuel. The above-mentioned results are in accord with several existing investigations on this issue [14,31,32].

5.2.3. Oxides of nitrogen (NO_x)

The reduced ignition delay and combustion timing are obtained when using the biodiesel blend. It is widely accepted that the shorter ignition delay may contribute to slightly increased NO_x emissions with biodiesel blend (MME20). The addition of nano metal oxide particles leads to complete combustion because of the aluminium oxide nanoparticles acting as an oxygen-donating catalyst. NO_x emissions increased for ANP blend due to maximum heat release rate and high peak pressure during the combustion. NO_x emissions of the engine at different nanoparticle concentrations with a biodiesel blend with engine loads are shown in Fig. 9. From the figure, it is clear that the NO_x emission noticeably increases by means of aluminium oxide nanoparticle additives, with the average increment of around 4.8% and 7.95% for the cases of MME20 + ANP50 and MME20 + ANP100 fuels, respectively.

5.2.4. Smoke

Fig. 10 shows the smoke emission for neat diesel, biodiesel blend (MME20) and nanoparticle blended biodiesel (MME20 + ANP50 and MME20 + ANP100) at different brake power. The considerable reduction in smoke may be attributed to the oxygenated biodiesel blend and aluminium oxide nanoparticles present in the fuel. The main reason for the smoke is the incomplete combustion of fuel in the diffusive combustion phase. The ANP and oxygenated biodiesel blend (MME20) make possible an improvement in diffusive combustion for MME20 + ANP100 fuel blend. Reduced smoke opacity is observed in the case of MME20 + ANP100 blended fuel. The smoke opacity for MME20 + ANP50 and MME20 + ANP100 is 57HSU and 50.5HSU, whereas it is 67HSU for neat diesel at full load.

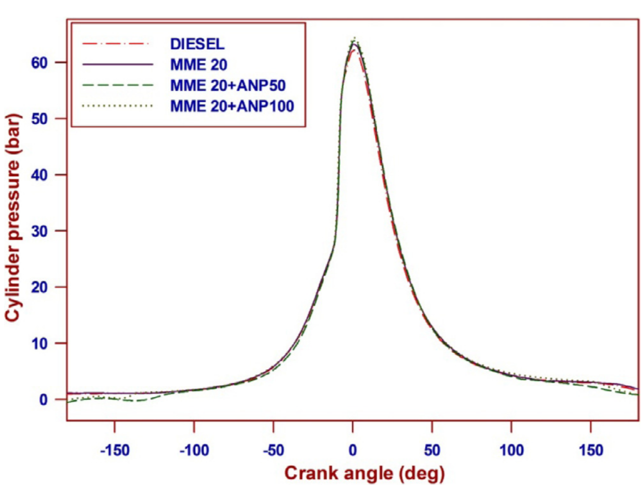

Figure 11 Cylinder pressure against crank angle.

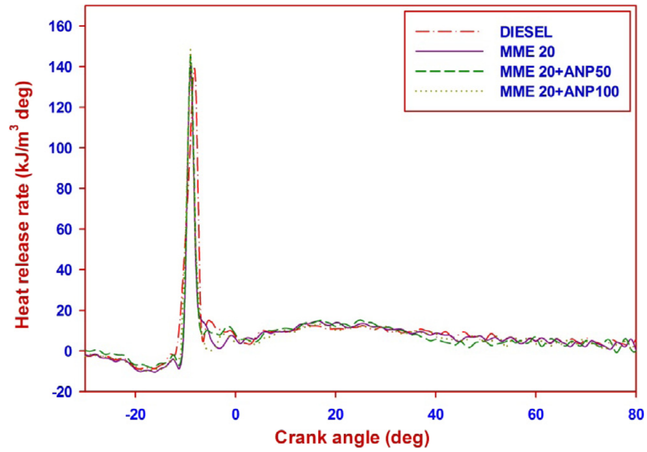

Figure 12 Heat release rate against crank angle.

5.3. Combustion characteristics

5.3.1. Cylinder pressure

Fig. 11 shows the variation of the in-cylinder pressure of the engine with crank angle. From the figure, it is seen that the pressure starts increasing significantly from 9° before top dead center (TDC) for MME20 + ANP100 blend and from 6° for neat diesel. An increase in the in-cylinder pressure is observed up to 7° after TDC in the case of MME20 + ANP100 and diesel. The pressure enhancement observed in the case of MME20 + ANP100 compared to the diesel fuel is due to the high surface contact area of the aluminium oxide nanoparticles and the inbuilt oxygen present in the MME20 that increases the improved rapid combustion [27]. The peak pressure is 63.19 bar in the case of MME20, whereas for MME20 + ANP100 it is 64.35 bar at full load. This is because of the higher viscosity of MME20 in the fuel and further improvement due to the addition of ANP.

5.3.2. Heat release rate

Fig. 12 shows the heat release rate for diesel, Mahua biodiesel blend and nano aluminium oxide added Mahua biodiesel blend fuels at various crank angles from the end of compression to the beginning of the expansion stroke. The heat release rate curves indicate the available heat energy, which can be rehabilitated into useful work. Mahua methyl ester (MME) includes a small amount of diglycerides having high boiling points compared with the diesel fuel. The chemical reactions during the injection of the Mahua methyl ester blend (MME20) at very high temperature resulted in the breaking of the diglycerides. These chemical reactions produce the gases of monoglycerides. Gasification of these monoglycerides in the tassel of the spray spreads out the fuel jet, and the volatile combustion compounds present in the fuel are ignited in advance and reduced the ignition delay period [23]. The heat release rate in the combustion chamber during the starting of combustion is not enough to entirely combust the fatty acids. From the figure, it is seen that nearer to TDC the amount of the heat release rate for MME20 + ANP100 is higher than that of diesel fuel. The addition of ANP considerably increases the heat release rate of MME20.

6. Conclusions

In the present investigation, ANP-mixed Mahua methyl ester blend fuelled CRDI diesel engine performance, emission and combustion characteristics were studied, and based on the experiments the following conclusions were drawn:

- ANP-blended biodiesel (MME20 + ANP50 and MME20 + ANP100) showed an improvement in the calorific value and a reduction in the flash point compared to MME20.
- Biodiesel has higher fuel consumption, because of its inferior heating value. With the addition of aluminium oxide nanoparticles, there is a considerable reduction in fuel consumption compared to biodiesel operation.
- A minor increment in BTE was observed with the addition of ANP to biodiesel blend.
- ANP reduced HC and CO emissions up to 26.04% and 48% compared with a biodiesel blend (MME20), because ANP acts as an oxygen buffer catalyst and donates surface lattice oxygen for the oxidation of HC and CO. NO_x emissions increase with the use of ANP and biodiesel blend compared to the diesel fuel.
- The peak pressure increases with the addition of ANP. The addition of ANP reduces the ignition delay period. The heat release rate also increases with the addition of ANP. The addition of ANP accelerates the hydrocarbon combustion and is the reason for the higher heat release rate when compared with neat diesel and biodiesel blend (MME20).

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