Original Research Paper

Experimental Investigation on CRDI System Assisted Diesel Engine Fulled by Diesel with Nanotubes

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Abstract: This paper reports on the use of carbon multiwalled nanotubes as additive to the diesel fuel and the effects of their operational characteristics and performance, emission and combustion characteristics of the CRDI system assisted diesel engine. In this study, the tested fuels were prepared by dispersing carbon multiwalled nanotubes into the diesel fuel at the mass fraction of 25 and 50 ppm with the help of a mechanical homogenizer and an ultrasonicator. Experimental results showed that the flash points and cetane number of the fuels dispersed with carbon multiwalled nanotubes have increased with higher concentration of carbon multiwalled nanotubes. Based on the experimental results, NO_x emissions and smoke noticeably decrease, while CO emissions dramatically increase with increasing the dosing level of carbon multiwalled nanotubes. At the full load, the magnitude of NO_x and smoke emission for the neat diesel was 1282 ppm and 69HSU, whereas it was 910 ppm and 49HSU for the CMNT50 fuel, respectively. The results also showed a significant enhancement in brake thermal efficiency and heat release rate due to the influence of the carbon multiwalled nanotubes addition in diesel blend.

Keywords: Nanotubes, CRDI Diesel Engine, Combustion, Emissions

Introduction

The increase in energy demand has focussed researchers to find the best way of using conventional energy. Therefore, improvement of fuels is an important issue. The increasing usage of this fossil fuel has a degrading effect on the environment through its polluting combustion product. The recent advances in nano science and nanotechnology proved that the nano energetic materials have great advantages over micro sized materials. Ignition delay and ignition temperatures are the significant parameters to characterize the performance of a diesel engine. Tyagi *et al*. (2008) made an attempt to improve the ignition properties of diesel fuel by addition of aluminium and aluminium oxide nanoparticles to diesel. It was observed that in all the cases the ignition probability for the diesel-nanoparticles mixture was higher than that of pure diesel. Tajudeen and Velraj (2014) conducted experiments on cerium oxide nanoparticles with diesel, the results showed reduction in ignition delay, higher cylinder peak pressure and higher heat release at higher loads in the case of cerium oxide fuel blend compared to neat diesel. Kumar and Sharma (2014) studied the effect of addition of nanoparticles with neat diesel. From the results, nanomaterials can act as a burning rate catalyst because when dispersed into liquids they accelerate the burning rate and promote clean burning, also particulate matters and carbon monoxide are reduced. Arul Mozhi *et al*. (2009) investigated the performance and emission characteristics of a diesel engine using cerium oxide nanoparticles as an additive in diesel and diesel biodiesel-ethanol blends. They concluded that cerium oxide nanoparticle additive acts as an oxygen-donating catalyst and their results revealed that the cerium oxide additive improved the complete combustion of the fuel and exhibited high catalytic activity due to their high surface area per unit volume, which leads to improved fuel efficiency. Karthikeyan *et al*. (2014) found that the combustion characteristics improved by the lighter surface to volume ratio of nanoparticles, which allowed most amount of fuel to react with the air. It leads to enhance the brake thermal efficiency. By and large, it is observed that the minimum CO and HC were measured with the use of ZnO blend. Fangsuwannarak and Triratanasirichai (2013) conducted experiments on the addition of TiO_2 nanoparticles with biodiesel in diesel engine. The addition of TiO_2 enhances higher carbon combustion activation and hence promoting complete combustion. Due to complete

combustion of fuel, emissions like CO, CO_2 and NO_x are appreciably reduced. Basha and Anand (2014) experimentally investigated the performance and the emission characteristics of a diesel engine using Carbon Nanoparticles (CNT) blended diesel. They observed a substantial enhancement in the brake thermal efficiency and reduced harmful pollutants compared to that of neat diesel. This is assumed to be due to better combustion. The same team has critically reviewed the applications of nanoparticles in diesel engines and concluded that adding a suitable proportion of nanoparticles to the conventional fuels such as diesel will reduce the evaporation time, which in turn favors shorter ignition delay.

It is observed from the literature that the combustion behavior of diesel with the addition of nanoscale energetic materials as fuel additives enhance the combustion and engine performance in a diesel engine. In addition, due to the small scale of nanoparticles, the stability of the fuel suspensions should be markedly improved. The changes in diesel fuel properties like viscosity, flash point and fire point, due to the introduction of carbon multiwalled nanotubes additive were observed. The diesel fuel with carbon multiwalled nanotubes additive presented a marginal increase in performance. In the present work, the combustion and engine performance characteristics of a single cylinder diesel engine fuelled with the modified fuel blends, diesel with 25 and 50 ppm CMNT, were tested and the results are compared with the neat diesel.

Carbon Multiwalled Nanotubes

CNTs can be divided into two types: Single-Walled Carbon Nanotubes (SWNTs) and Multiwalled Carbon Nanotubes (MWNTs). SWNTs consist of a seamless graphene sheet rolled up into a cylinder of a few nanometers in diameter and several microns in length. Most of them are aligned and packed together to form ropes of 10-100 parallel tubes. A MWNT is an arrangement of several, up to tens and hundreds of concentric tubes of graphite sheet with adjacent shells separation of 0.34 nm on each tube, the carbon atoms are arranged in a helical fashion along the tube axis. The outer diameter of these MWNT is about several tens of nanometers and they have a length of 10-100 nm (Orinakova and Orinak, 2011; Popov, 2004; Hirscher *et al.*, 2002). CNTs can be synthesized by various methods such as arc discharge, laser vaporization and chemical vapor deposition. The first two methods can produce high quality nanotubes. However, the disadvantage is the high temperature or complicated device required, which limits scaling up of their applications. In contrast, chemical vapor deposition is one of the most promising methods for large scale production of graphite fibers and Multiwalled Carbon Nanotubes (MWCNTs). Chemical vapor deposition method has the advantage to produce

high purity CNTs with fewer by products and have a low synthesis temperature (Bahgat *et al.*, 2011; Paradise and Goswami, 2007). Carbon nanotubes are unique nanostructures which are known to have remarkable mechanical properties. These characteristics have sparked great interest in their possible uses for nano mechanical devices. Properties of carbon nanotubes can also be expanded to thermal and optical properties as well. Carbon nanotubes are predicted to have high stiffness and axial strength as a result of the carbon-carbon sp^2 bonding (Ruoff and Lorents, 1995).

Preparation of Fuel Blend

For the blending of carbon multiwalled nanotubes in diesel, first we take a sample of diesel say 1 litre and then 0.025 g of carbon multiwalled nanotubes is added to make the dosing level of 25 ppm. Subsequently, to increase the dosing level of 50 ppm, we have to increase to 0.05 g L^{-1}. After the addition of carbon multiwalled nanotubes, it is shaken well. And then it is poured into signification apparatus where it is agitated for about 45 min in an ultrasonic shaker making uniform suspension. It is of colloidal type. It should be shaken well before use, as excess of nanoparticles settle down on solution.The important physical and chemical properties of diesel and CMNT-blended diesel were determined by standard methods (Table 1).

Properties of Carbon Multiwalled Nanotubes

Scanning electron microscopy provides direct examination of nanotube alignment and size (Cao *et al.*, 2001). The morphology of nanoparticles was investigated by Scanning Electron Microscopy (SEM). The SEM images showed that most of the nanoparticles obtained from all the ablated laser energies have spherical shape with a particle size of less than 100nm. Furthermore, it was observed that the particle size increased with increasing the laser energy (Piriyawong *et al.*, 2012). SEM of carbon multiwalled nanotubes is shown in Fig. 1. Surface and morphological characterization of carbon multiwalled nanotubes were carried out using scanning electron microscopy. Nanosized spherical shaped carbon multiwalled nanotubes obtained were confirmed. The diameter distribution of the particles varies from 2 to 50 nm.

The nanotube samples usually consist of nanotubes of different radius and chirality. The Raman spectrum contains information about the nanotubes diameters and chirality. This determines the role of the resonant Raman spectroscopy as an important tool for the structural characterization of the nanotubes (Popov, 2004). Figure 2 gives the Radial Breathing Mode (RBM) of CMNTs, which shows the groups of vibration modes among which 126.3, 182.5 and 209.1 cm^{-1} might be considered from outer layer vibration. The G band in the 1500-

$1605cm^{-1}$ range can be used to analyze CMNTs, according to a recent report (Li *et al.*, 2005) and it characteristically shows two dominant features, the lower frequency component associated with vibration along the circumferential direction (G^-) and the higher frequency component (G^+) attributed to vibration along the direction of the nanotube axis. After curve fitting, it was found that the G band observed in our CMNTs includes three peaks, which correspond to G^-inner, G^- outer and G^+ (Fig. 2). Splitting of the G band in MWNTs is both small in intensity and smeared out due to the effect of the diameter distribution within the individual MWNTs and because of the variation between different tubes in an ensemble of MWNTs in typical experimental samples. Therefore, the G^-band feature predominantly exhibits a weakly asymmetric characteristic lineshape (Dresselhaus *et al.*, 2005).

Experimental Setup and Test Procedure

Experiments were conducted on Kirloskar AV1, four stroke, single cylinder and air cooled diesel engine assisted by common rail direct injection system. The rated power of the engine was 5.2 kW. The engine was operated at a constant speed of 1500 rpm and a standard injection pressure of 220 bar. The engine was initially fuelled with diesel fuel to provide the baseline data and then, it was fuelled with diesel and carbon multiwalled nanoparticles blended fuel in two different proportions. Details of the engine specification are given in Table 2.
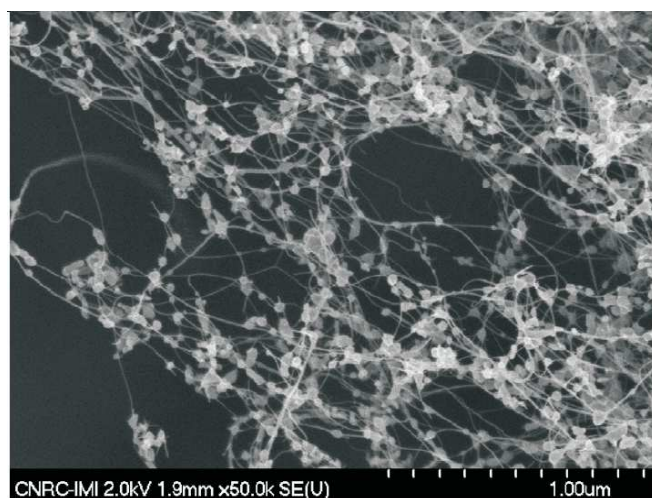

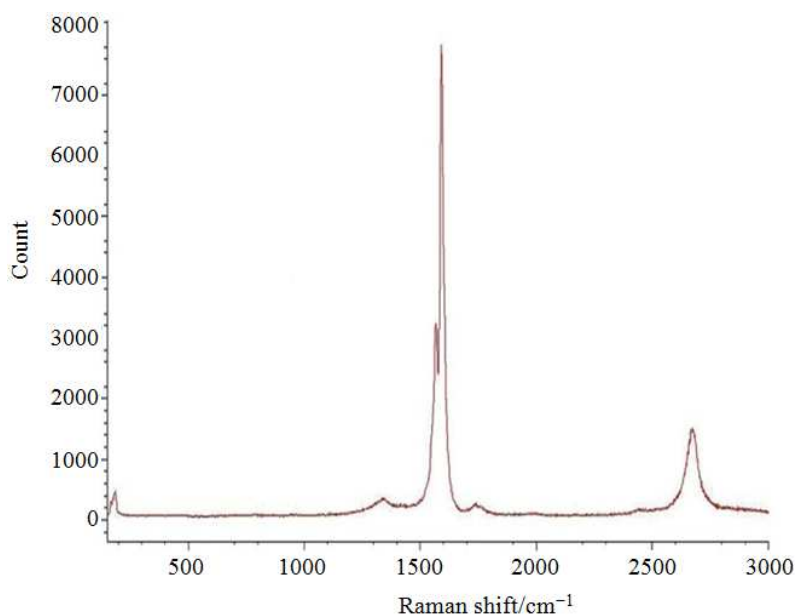Fig. 1. SEM of carbon multiwalled nanotubes
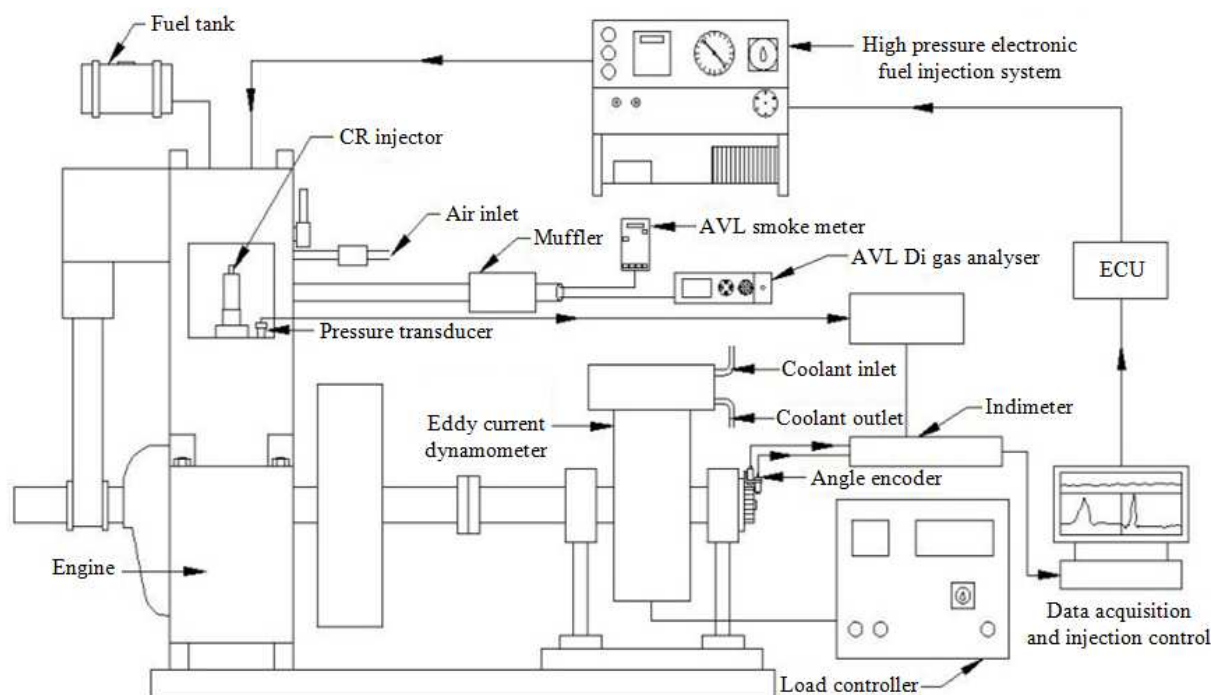

Fig. 2. Raman spectroscopy ($\lambda = 514$ nm)

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Fig. 3. Experimental setup

Table 1. Properties of diesel - CMNT blend samples

Description	Density @ 15°C (kg/m3)	Flash Point (°C)	Calorific value, (kJ/kg)	Cetane number
Diesel fuel	815	58	42,000	47.0
Diesel fuel with 25 ppm CMNT	819	61	42426	48.4
Diesel fuel with 50 ppm CMNT	823	65	42731	49.6

Table 2. Engine specification

Type	:	Vertical, water cooled, four stroke
Number of cylinders	:	One
Bore	:	80 mm
Stroke	:	110 mm
Compression ratio	:	17.5:1
Maximum power	:	5.2 kW
Speed	:	1500 rev/min
Dynamometer	:	Eddy current
Injection timing	:	23 (before TDC)
Injection pressure	:	220 kgf/cm^2

The fuel flow rate is obtained on the gravimetric basis and the airflow rate is obtained on the volumetric basis. Eddy current dynamometer was used for loading the engine. The AVL smoke meter is used to measure the smoke density. AVL five-gas analyzer is used to measure HC, CO and NO$_x$ emissions. A burette is used to measure the fuel consumption for a specified time interval. During this interval of time, how much fuel the engine consumes is measured, with the help of a stopwatch. The experimental setup is indicated in Fig. 3.

Results and Discussion

The operation of the engine was found to be very smooth throughout the rated load, without any operational problems for the carbon multiwalled nanotubes blended diesel fuel. In the present section, based on the combustion data, cylinder pressure and heat release rate are plotted against crank angle. The performance attributes such as brake thermal efficiency, specific fuel consumption and the emission characteristics such as NO$_x$, CO, HC and smoke density are plotted against brake power.

Engine Performance

Specific Fuel Consumption (SFC)

Figure 4 shows the variation of specific fuel consumption with brake power. It was observed that the SFC of the CMNT-blended diesel is lower than that of neat diesel for all loads because of improved atomization and better mixing process at higher injection pressure. The decrease in SFC can be due to the positive effects of nanoparticles on physical

properties of the fuel and reduction of ignition delay time (Karthikeyan *et al.*, 2014). Corresponding to brake power, the specific fuel consumption decreases with an increase in the dosing level of CMNT. The average decrease in SFC compared to diesel is found as 0.25% for CMNT25 and 0.46% for CMNT50.

Brake Thermal Efficiency (BTE)

Figure 5 illustrates the variation of the brake thermal efficiency with brake power. The results show that the brake thermal efficiency of the diesel engine is improved by the addition of CMNT in diesel fuel. In general, the nanosized particles possess a high surface area and reactive surfaces that contribute to higher chemical reactivity to act as a potential catalyst (Tyagi *et al.*, 2008; Aalam *et al.*, 2015). It has been observed that the improvement in the brake thermal efficiency increases with the dosing level of carbon multiwalled nanotubes. A maximum increase of 2.5% in the brake thermal efficiency was obtained when the dosing level of CMNT is 50 ppm.

Emission Parameters

Oxides of Nitrogen (NO_x) Emission

Observation has been made on the level of the NO_x emissions from diesel, in the purest form and in the modified form. The NO_x emissions were found to be generally decreased with the addition of carbon multiwalled nanotubes to diesel, as shown in Fig. 6. NO_x emissions of diesel without the addition of carbon multiwalled nanotubes were 870 ppm and after addition of carbon multiwalled nanotubes it has been decreased.

At the dosage of 25 ppm carbon multiwalled nanotubes, NO_x emissions will be 740 ppm and for dosage of 50 ppm carbon multiwalled nanotubes, NO_x emissions will be 630 ppm. It is observed that the presence of the carbon multiwalled nanotubes in the diesel blend decreases the nitrogen oxide emissions.

Carbon Monoxide (CO) Emission

Figure 7 shows the influence of the carbon multiwalled nanotubes addition with biodiesel on carbon monoxide emissions. If the combustion is incomplete due to shortage of oxygen or low gas temperature, CO will be formed. Carbon multiwalled nanotubes act as an oxygen reduction catalyst. Hence, there was a slight rise in carbon monoxide (CO) emissions for carbon multiwalled nanotubes blended diesel. At the full load, the CO emissions for diesel were 0.49% (by volume) and 0.67 and 0.75% (by volume) for CMNT25 and CMNT50, respectively.

Hydrocarbon (HC) Emission

The variation of hydrocarbon emission with brake power is shown in Fig. 8. The addition of carbon multiwalled nanotubes slightly increases the HC emission when compared with neat diesel. Carbon multiwalled nanotubes are an oxygen reduction catalyst that increases the carbon combustion activation temperature and thus decrease hydrocarbon oxidation. From this figure, it is seen that the HC emission increased with the increase of CMNT dosing level with diesel. HC emission for CMNT25 was 120 and 135 ppm for CMNT50 blend, respectively.
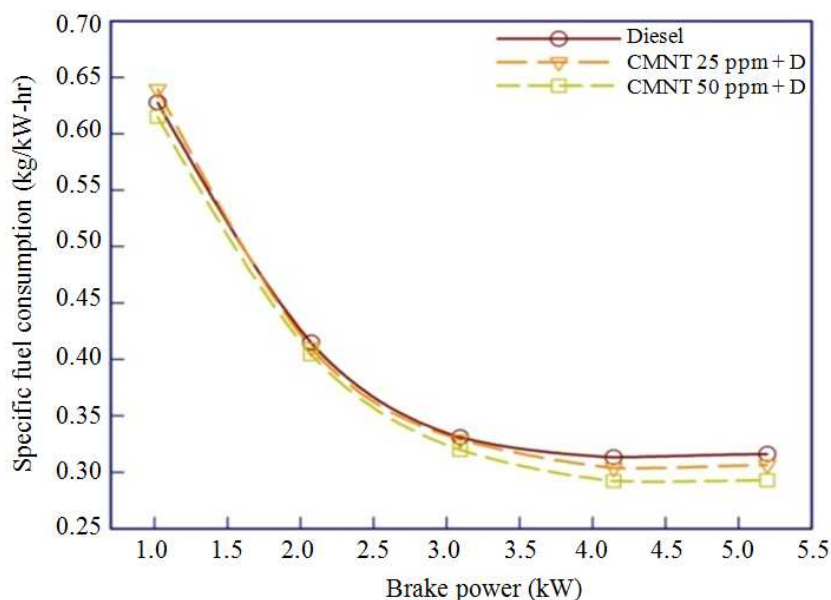

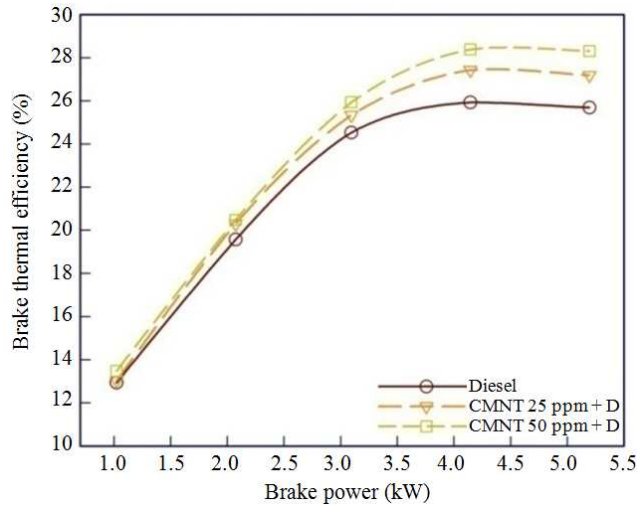Fig. 4. Specific fuel consumption against brake power

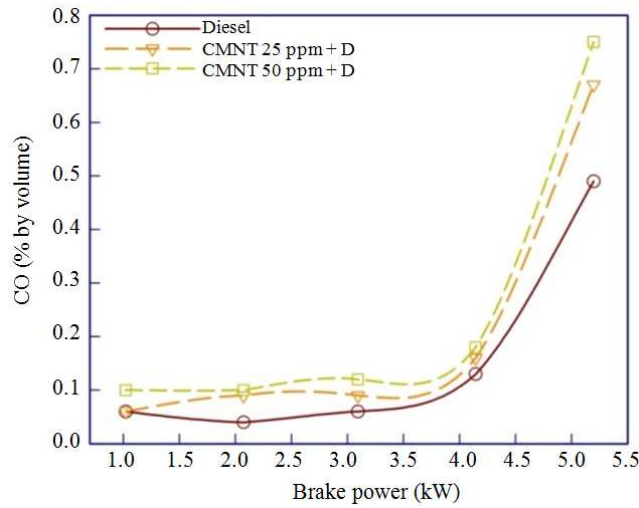Fig. 5. Brake thermal efficiency against brake power

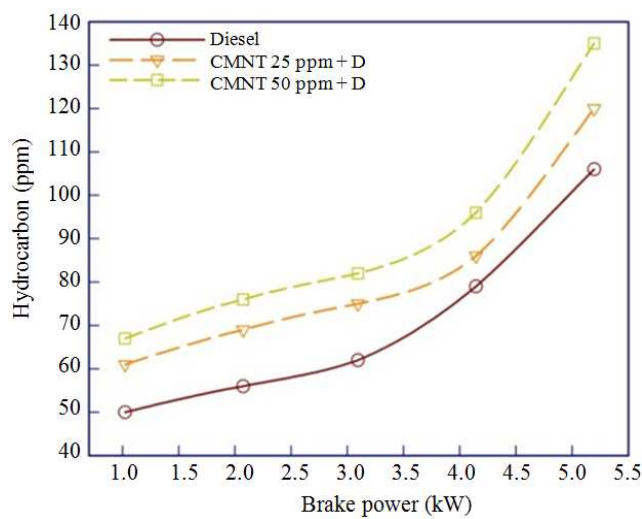Fig. 6. Oxides of nitrogen against brake power

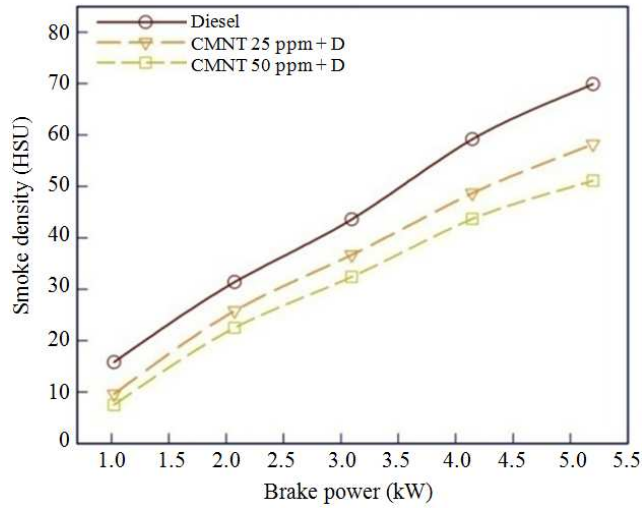Fig. 7. CO against brake power
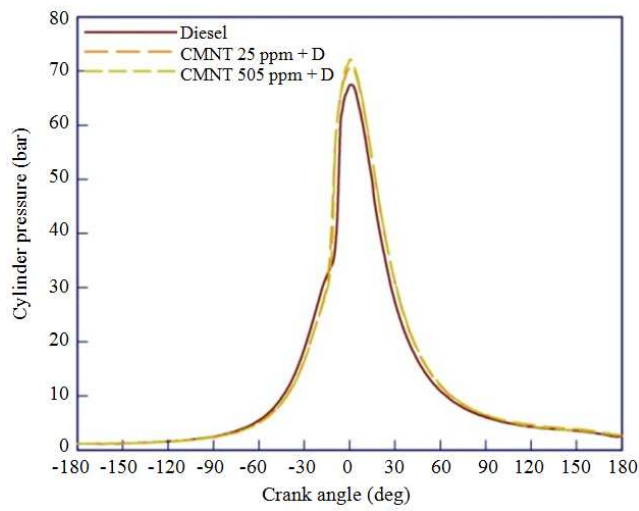
Fig. 8. Hydrocarbon against brake power
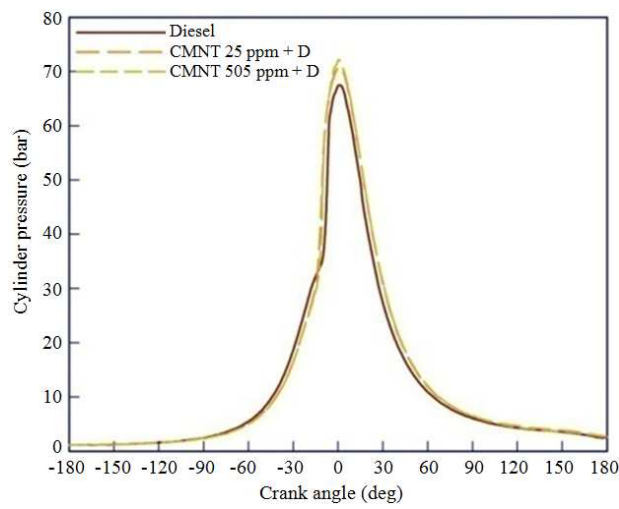

Fig. 9. Smoke density against brake power

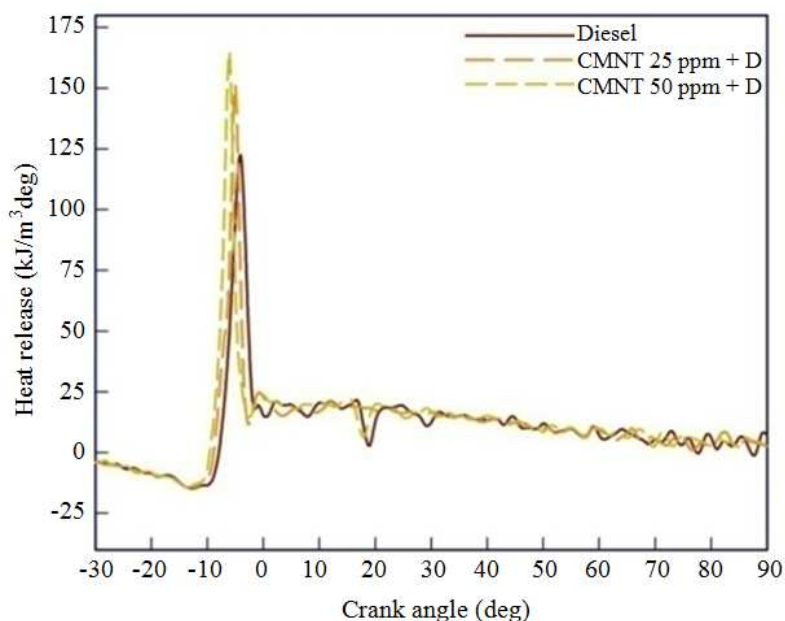Fig. 10. Cylinder pressure against crank angle

Fig. 11. Heat release rate against crank angle

Smoke Density

Figure 9 shows the variation of smoke density with brake power for diesel and modified diesel. However, reduced smoke opacity is observed in the case of CMNT-diesel blended fuels. The smoke density of diesel was decreased with the addition of CMNT by about 10-15%, especially at full load. This could be attributed to shorter ignition delay characteristics of CMNT-diesel-blended fuels. It was also observed that the reduction in the smoke density increases with the increase in the concentration of CMNT.

Combustion Characteristics

Figure 10 shows the variation of cylinder pressure with crank angle for diesel and modified diesel with different dosing levels of the CMNT at different engine operating conditions. Addition of nanoparticles tends to reduce the ignition delay (Sadik Basha and Anand, 2011). From the figure, it is seen that the cylinder pressure for two different dosing levels of CMNT25 and CMNT50 was 66.117 and 69.946 bar, respectively. It is clear that the cylinder pressure slightly decreased with the increase in CMNT in biodiesel.

The variation of heat release rate with crank angle is shown in Fig. 11. The addition of nanoparticles enhances higher carbon combustion activation and hence promotes complete combustion (Sajith *et al*., 2010). The nanoparticle blended fuels showed accelerated combustion due to the shortened ignition delay. Due to

shortened ignition delay, the degree of fuel-air mixing and uniform burning could have improved (Bahgat *et al*., 2011). The results show that the heat release rate was found to be generally decreased with the addition of CMNT to diesel. This is due to premixed and uncontrolled combustion phase. The amount of heat release rate is 124.727, 149.818 and 164.928 kJ/m^{3}deg for diesel, CMNT25 and CMNT50, respectively.

Conclusion

From the experiments carried out on the CRDI system assisted diesel engine fuelled with diesel and carbon multiwalled nanotubes blended diesel, the following conclusions can be drawn:

- Good improvement in brake thermal efficiency was observed with carbon multiwalled nanotubes blended diesel at optimized operating conditions
- With the addition of carbon multiwalled nanotubes to diesel fuel, the level of harmful pollutants in the exhaust gases, such as NO$_x$ and smoke, was significantly reduced when compared to that in neat diesel. At the dosage of 25 ppm CMNT, NO$_x$ emissions will be 740 ppm and for dosage of 50 ppm CMNT, NO$_x$ emissions will be 630 ppm. The smoke density of diesel was decreased on addition of carbon multiwalled nanotubes by about 10-16%, especially at full load

- Carbon multiwalled nanotubes blended diesel fuel showed higher cylinder gas pressure and heat release rate at optimized operating conditions

Hence, CMNT is efficient in improving performance and reducing the exhaust harmful pollutants from the diesel engine.

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Author's Contributions

This research work is carried out by the first author C. Syed Aalam and guided by the second author Dr. C.G. Saravanan. M. Kannan helped in conducting the experimental work.

Ethics

This article is original and contains unpublishedmaterial. The corresponding author confirms that all ofthe other authors have read and approved the manuscriptand no ethical issues involved.

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Nomenclature

bmep	Brake mean effective pressure, MPa
SFC	Specific fuel consumption, kg/kW.h
BP	Brake power
CO	Carbon monoxide, %
HC	Hydrocarbon, ppm
NO	Nitrogen oxide, ppm
CRDI	Common rail direct injection
CMNT25	CMNT of 25ppm blended with diesel
CMNT50	CMNT of 50ppm blended with diesel
rpm	Revolution per minute