



Studies on Effect of Injection Timing of Graphene Nanoparticles Blended Simarouba Biodiesel Blend on Compression-ignition Engine

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ABSTRACT

Graphene is a monolayer carbon atoms discovered in the recent past which has inspired researchers in a wide range of applications. It has a surface area as high as 2630 m²/g and thermal conductivity value of 3000 W/mK⁻¹ at room temperature. It is chemically the most reactive form of carbon with one carbon atom exposed to reaction from each side. Stable dispersion of graphene was achieved using sodium dodecyl sulfate surfactant. Graphene nanofuel was prepared by dispersing of graphene in simarouba methyl ester blend with diesel. The dispersion was characterized using the ultra violet visible spectrometry. The performance, combustion and emission characteristics were studied on a single cylinder, water cooled, direct injection, four stroke computerized diesel engine test rig. The characteristics were studied for three different dosing levels of graphene nanoparticle and three different fuel injection timings. It resulted in improved brake thermal efficiency, reduced unburnt hydrocarbon and carbon monoxide emission. The addition of graphene nanoparticles and advancing the injection timing has resulted in a significant reduction in the combustion duration and a marginal increase in the peak cylinder pressure at all operational loads.

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NOMENCLATURE

aTDC	After top dead centre	bTDC	Before top dead centre
BTE	Brake Thermal Efficiency	C	Carbon
CD	Combustion Duration	CO	Carbon monoxide
CO ₂	Carbon Dioxide	H	Hydrogen
ID	Ignition Delay	N	Nitrogen
NHRR	Net Heat Release Rate	nm	Nanometer
NO	N ₂	NOx	Oxides of Nitrogen
R1, R2, R3	Hydrocarbon chain of fatty acid	SDS	Sodium Dodecyl Sulphate
SME	Simarouba Methyl Ester	UAS	University of Agricultural Science
UBHC	Unburnt Hydrocarbon	UV-Vis	Ultra violet Visible

1. INTRODUCTION

Nano-fluids are the fluids that are prepared by dispersing the nano particles of sizes 1-100 nm in any conventional base fluids. The fluids with fuel as the base fluid into which the nanoparticles are dispersed are termed as nanofuels. Such nanofuels offer reduced

ignition delay [1]. This advantage can be explored in the field of internal combustion engines in improving the engine performance and reducing the harmful emissions like nitrogen oxides, carbon monoxide, unburnt hydrocarbons [2]. Another advantage of nanoparticle application in internal combustion engines is their size. Chance of fuel injector and filter clogging are less compared to the micron sized particles additives [3]. Recent studies have revealed that the nanoparticles added to the IC engines fuels can approach molecular

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dimensions and modify the physical properties such as flash point, fire point viscosity, etc. [3, 4]. Addition of nanoparticles with liquid fuels modifies the ignition mechanism. Figure 1 shows the micro explosion of fuel droplets and pyrolysis of surfactant molecules. SDS surfactant is having a self-ignition temperature of 248 °C. Once the fuel droplet reaches this temperature, the surfactant inside the fuel droplet absorbs heat, gets pyrolyzed and pressurized and finally explodes. This is termed as primary explosion or as the primary atomization. After this explosion, these pyrolysis products starts diffusing and react with oxygen which lasts only for a short period, till the surfactant in the fuel mixture burns completely.

After primary atomization, the fuel droplets undergo secondary explosion or secondary atomization [5]. The graphene nanoparticles now get exposed to air and undergo combustion and consume oxygen. This reaction takes away the oxygen and reduces the NO_x formation to some extent. The nanoparticles with the highest value of thermal conductivity enhance the convective heat transfer coefficient of fluid inside the combustion chamber. This accelerates the thermal exchange process between fuel droplets and the surrounding air, allowing quick heat transfer and reduced ignition delay, thus promoting a quick, better and more complete combustion. Majority of work to date is carried with nano additives of metals or metal oxides. The solid metal/metal oxide nanoparticles do not undergo combustion and come out as particulates in the exhaust products of combustion [6]. The present study aims at studying the performance, combustion and emission characteristics of nanofuel with varied injection timing.

2. MATERIALS AND METHOD

2.1. Graphene Graphene is the thinnest material available on earth with carbon-carbon bond length of 0.142 nm and interplanar distance of 0.335 nm. It is one atom-thick allotropic form of carbon, consisting of a conjugated sp² carbon honeycomb structure. It has a large specific surface area of 1168 m²/g and thermal conductivity value of upto 5x10³ W/mK at room temperature. It is chemically the most reactive form of carbon with a single carbon atom exposed to reaction

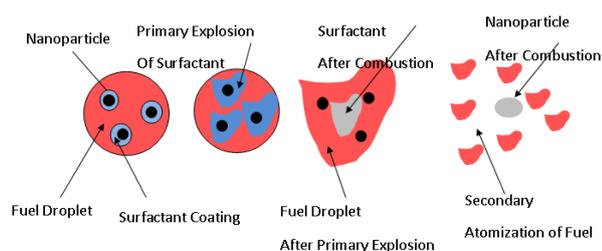


Figure 1. Micro Explosions of Fuel Droplets

from two sides. Graphene burns at low temperature of 350 °C [7, 8]. Graphene can be synthesized by various methods like mechanical exfoliation of graphite, chemical vapor deposition method. Chemical methods are most promising methods for graphene production. The most common method of graphite exfoliation is oxidation of graphite to graphite oxide by strong oxidizing agent and further reducing to graphene. Methods like thermal expansion, ball mixing, liquid phase exfoliation were tried, but oxidation-reduction method is the most widely used method for large scale production of graphene [6, 9]. Commercially available graphene used for the present work was purchased. Table 1 shows the properties of graphene used in the study².

Among of the advantages of using graphene as additive are that it is fully consumed in combustion, contributes to the fuel energy density and no exhaust particulate matter emission unlike metals and metal oxides.

2.2. Biodiesel Simarouba biodiesel was used in this work. Simarouba belongs to the family of the Simarouba ceae Quasia, also called the Acetuno or Laxmi taru locally in southern part of India; it grows well under a wide range of ecological conditions. Simarouba can adapt easily to the diverse soil and climatic conditions; it is also drought tolerant. An important factor in selection of oil for the biodiesel production is the fatty acid profile. Vegetable oils with certain fatty acids yield a biodiesel with characteristics close to conventional diesel. The unsaturated to saturated fatty acid ratio is an important factor in deciding the properties of biodiesel obtained after transesterification.

If the oil has more saturated fatty acids, the biodiesel obtained will have more viscosity. Whereas, the oils with higher unsaturated fatty acids yield biodiesel that are less viscous and have higher cloud and pour points. Biodiesel produced from feedstock with higher unsaturated fatty acids have a strong effect on the long term oxidative stability of biodiesel. The simarouba oil was then converted into biodiesel by a simple transesterification in which triglycerides were converted into methyl ester using alcohols and alkaline catalyst.

TABLE 1. Properties of graphene

Sl.No	Parameter	Property
1	Average X and Y dimensions	5 – 10 microns
2	Thickness average Z dimension	5 – 10 nm
3	Surface area	492 m ² /gm
4	Carbon purity	>99 %
5	Thermal conductivity	3,000 W/m K

² <https://www.unitednanotech.com/img/cms/TDS%20UGRAY%20Graphene.pdf>

Methyl alcohol was used as alcohol and potassium hydroxide as the alkaline catalyst. Trans-esterification process happens in three stages as shown in Figure 2. First, one fatty acid chain is broken off the triglyceride molecule and bonds with methanol to form a methyl ester molecule, leaving a diglyceride molecule (two chains of fatty acids bound by glycerin). Then, a fatty acid chain is broken off the diglyceride molecule and bonded with methanol to form another methyl ester molecule, leaving a mono-glyceride molecule. Finally, the mono-glycerides are converted to methyl esters. The esterification was carried out at atmospheric pressure in a closed vessel at 60 °C

The contents were stirred using a mechanical stirrer continuously for 1-1.25 hour followed by settling, separation of glycerin and washing of biodiesel with hot water acidified with organic acids. Biodiesel was heated to a temperature of 120 °C to remove the moisture at the end. The properties of biodiesel thus obtained were within the accepted ranges of ASTM standards. Cetane number was measured as per ASTM D613 standards [10] using AFIDA cetane analyser-9b847c16-2. Further, for the experimentation, already established optimum biodiesel blend of 80% diesel fuel and 20% biodiesel was prepared. Table 2 shows the measured fuel properties of diesel, simarouba biodiesel and its blend SME20.

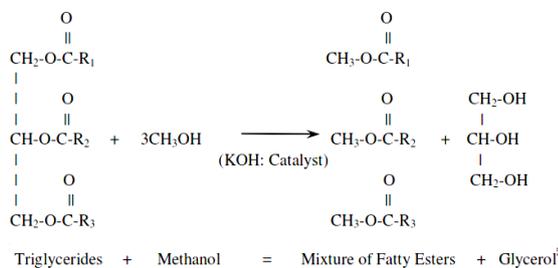


Figure 2. Transesterification reaction process

TABLE 2. Fuel properties of Diesel, SME and its blend SME20

Properties	Unit	ASTM standards (0-20 blends)	SME Biodiesel	D100	SME20
Kinematic Viscosity	Cst	1.9-4.1 D445	4.68	2.54	3.104
Calorific value	kJ/kg	--	37,933	42500	42270
Specific Gravity	gm/cc	0.87-0.90	0.875	0.82	0.838
Flash Point	°C	52° min D93	165	54	79
Cetane Number	D613	40(minimum) D613	52.8	44.5 5	45.1

2. 3. Surfactants

The stability of nanoparticle suspension under practical conditions is a crucial issue for practical applications. The stability of nanofuels depends upon homogeneous dispersion of nanoparticles in the base fluid which in turn depends on the success of preparation method adopted in dispersion and on the maximizing the absolute value of the surface charges present on the nanoparticles. If the surface charges are larger on each nanoparticle, the electrostatic repulsive forces will be larger, and aggregation will be less. Among the surfactants, ionic surfactants show a higher thermal conductivity than non-ionic surfactants in the stable region [11]. Among the ionic surfactants themselves, the anionic surfactant gives higher thermal conductivity values than the cationic surfactant [9]. Therefore, in this work, an anionic surfactant, namely sodium dodecyl sulfate was used. Commercially available analytical grade SDS was used in the experimentation. Figure 3, shows the structure of the SDS surfactant.

An optimum Graphene-to-surfactant ratio is an important parameter that significantly affects the quality and stability of dispersion. Surfactant concentrations above or below this ratio deteriorate the stability and quality of a dispersion [12]. Thus, the surfactants concentration should be just sufficient to coat the nanoparticle surface, avoiding any excess amount of surfactant that decreases the dispersion stability. It was found that an optimum graphene to surfactant ratio of 1:4 gives a homogenous, uniform and stable dispersion.

2. 4. Fuel Preparation and Characterization

When inorganic nanoparticle is used for dispersion, dispersion is indispensable because of its tendency to agglomerate. The ultrasonication technique is most suited method for preparing any nanofluid, as it facilitates possible agglomerate nanoparticle back to nanometer range. The nanofuels are prepared for the required dosage level of nanoparticle by the process of sonication on probe type ultrasonicator. Ultra violet - visible spectral analysis was employed as a simple and reliable method for monitoring the stability of nanoparticle solutions. There is a linear relationship between the suspended nanoparticles and absorbance of the suspended nanoparticles [9]. Prepared nanofluid samples are periodically analyzed by the UV-vis spectroscopy measurement. For the UV-Vis spectral analysis, initially baseline is fixed considering the SME20 as the reference sample as well as the specimen sample.

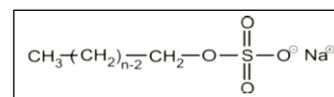


Figure 3. Structure of SDS

After fixing the baseline, the SME20 is taken as the reference sample and the graphene nanofluids as the specimen samples. To characterize the dispersion, the absorbance values were recorded within a range of 250 to 750 nm [13]. The UV-Vis spectrum of graphene shows two absorption peaks; the first one at 240 nm and the other at 300 nm [13, 14]. Therefore, the absorbance spectra were recorded in the 250 to 750-nm wavelength range in a spectrometer. Data are obtained for a regular time interval of one week and plotted as shown in Figure 4. It was observed that the UV absorption was highest immediately after dispersion for graphene to surfactant ratio of 1:4 [8]. The nanoparticles began to agglomerate and settle as the time elapsed. Absorbance was measured at the end of each week, when kept in static condition is as shown in Figure 4.

The stability of the nanoparticles suspended in a solution is decided by the Van Der Waals attractive and repulsive forces of electrical double layer as particles approach each other during the Brownian movement within the solution. The thickness of the diffuse electrical layer plays an important role in the stable suspension of the nanoparticle [8, 13]. An increase in thickness of the electrical diffuse layer, increases electrostatic repulsion between dispersed particles and hence the suspension become stable [8, 13, 14]. Conversely, the thickness of the electrical double layer decreases with increase in ionic strength of the electrolyte, making the suspension unstable and the nanoparticles agglomerate [13, 14]. In a liquid medium, the ionic groups of surfactant disassociate in the solution and adhere onto the nanoparticle surface imparting an effective charge on it [13], as shown in Figure 5. The surfactant tail group adsorbs onto the nanoparticles by Van der Waals interactions.

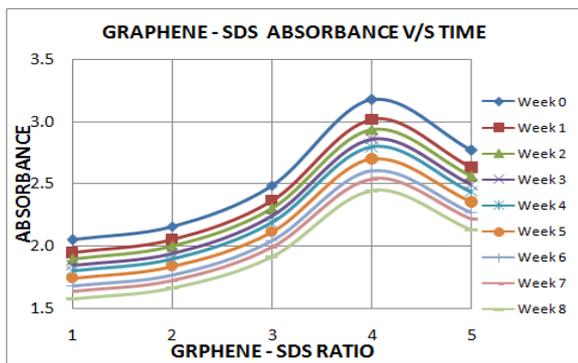


Figure 4. UV-Vis absorption over time of 8 weeks



Figure 5. Ionic groups of surfactant adhered on graphene sheet

Figure 6 shows the formation of a simple monolayer of surfactant coated graphene nanoparticles. However, if favorable interactions occur between the surfactant tails groups, a bilayer shown in Figure 7 is formed.

The repulsive forces between the same charge particles stabilize the SDS-adsorbed graphene suspensions. Electrostatic forces strongly depend on ionic strength. The tendency of the particles to aggregate more quickly at higher ionic strengths is obvious [11]. The sizes of the electrical double layer of particles formed reduces as ionic strength increases over a certain level [12]. This reduces the repulsive forces that prevent the aggregation of the particles. Large ionic strengths therefore allow the attractive Vander Waals forces to dominate, and the dispersion tends to become instable. Also, addition of nanoparticles increases viscosity of fuel that adversely affects the atomization leading poor combustion. Viscosity is reduced after the nanoparticle is dispersed with surfactant [2]. The nanofuels with different graphene nanoparticle mass fraction of 20, 40 and 60ppm are prepared with SME20 biodiesel blend. For this set, standard ratio of 1:4 was taken as standard for preparation of fuel blends. The composition of fuel samples prepared for the experimentation is as given in Table 3.

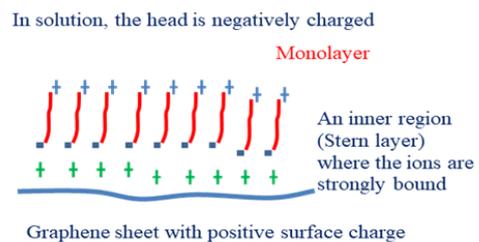


Figure 6. Formation of Simple inner thin monolayer

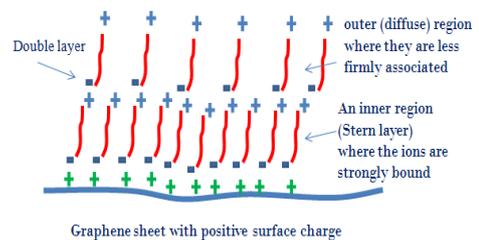


Figure 7. Formation of electrical double layer charges

TABLE 3. Composition of fuel samples prepared

Sl.No	Sample	Diesel (%)	SME	Graphene (ppm)
1	SME20	80	20	--
2	SME2020	80	20	20
3	SME2040	80	20	40
4	SME2060	80	20	60

2. 5. Engine Specifications and Test Procedures

The engine tests were carried out on a single cylinder 4 stroke water-cooled diesel engine. Figure 8 shows the schematic diagram of computerized diesel engine test rig used for the experimental work. Table 4 shows the part list of the test rig used for experimentation. During the experiments, the injection pressure was kept constant at 180 bar. Initially, experiments were carried out for the manufacturer standard injection timing of 23° bTDC, using diesel fuel. Extensive engine tests were conducted using different fuels D100, SME20, SME2020, SME2040 and SME2060 to optimize the mass fraction of graphene nanoparticle in the nanofuels. The nanofuel SME2040 was found to be optimum for the manufacturer standards of 180 bar injection pressure and injection timing of 23° bTDC of the engine test rig. The nanofuel SME2040 was selected for the study for present work.

It was observed that the NO_x emission was high with increase in the advancement of injection timing. Therefore, the advancement of injection was restricted to 25bTDC and further studies beyond 25bTDC were not carried out. Similarly, the performance was reduced drastically with high bsfc and reduced BTE for a retarded injection timing of 21bTDC. Hence, further retardation in injection timing was not attempted.

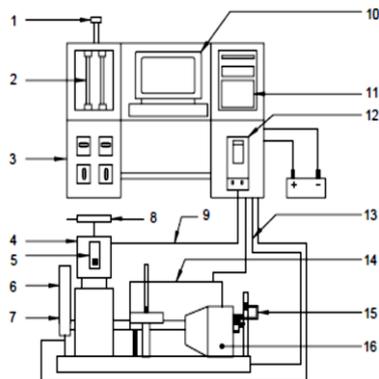


Figure 8. Computerized CI Engine Test rig

TABLE 4. Parts list of computerized CI engine test rig

Sl. No.	Name of the Part	Sl. No.	Name of the Part
1	Fuel tank inlet	9	Exhaust gas line
2	Fuel flow sensor	10	Computer
3	Control Panel	11	Data capture card
4	CI Engine	12	Gas analyzer
5	Pressure sensor	13	Fuel line
6	Crank Angle encoder	14	Gas Calorimeter
7	Speed sensor	15	Load sensor
8	Air flow sensor	16	Dynamometer

The experiments were carried out with SME2040 nanofuel for 3 different injection timings. First, by retarding the injection to 21° bTDC and then by advancing the injection timing to 25° bTDC. The injection timings were altered by adding or removing the shims fitted under the plunger in the pump. The results were compared with diesel fuel D100 for standard injection timing of 23° bTDC.

3. RESULTS AND DISCUSSION

3. 1. Combustion Characteristics

3. 1. 1. Cylinder Pressure and Net Heat Release Rate

The heat release rate during combustion causes a variation in the gas pressure and temperature inside the engine cylinder which in turn strongly affects the fuel economy, power output and exhaust emissions. It also provides a good insight of the combustion in the engine. Therefore, finding an optimum heat release rate is important in any engine research study. Addition of chemically highly reactive exothermic, energetic nanoparticles (10-100 nm range) to the liquid fuel is characterized by a high rate of energy release. Graphene nanoparticles having a higher volumetric heat of oxidation, enable transportation of more energy per given fuel volume. When dispersed in a fuel, they generally exhibit faster ignition due to the dramatic increase in the surface-to volume ratio and increased combustion efficiencies [15]. The mechanism in which nanoparticles reduce the ignition delay is a result of an increased thermal conductivity of liquids droplets seeded with nanoparticles [15]. Addition of nanoparticles of higher thermal conductivity to liquid fuel leads to more rapid internal heating and vaporization of fuel droplets and earlier fuel vapor ignition. Once the nanoparticle-carrying fuel droplets evaporate, the nanoparticles are exposed to hot oxidizing environment [15]. The nanoparticles which ignite in advance of the fuel provide another route to a shorter ignition delay. The nanofuel dispersed with graphene nanoparticle, having the highest value of thermal conductivity of 3000 W/mK, increases the overall convective heat transfer coefficient of the mixture and thus increases the flame propagation and hence leads to a quick combustion and reduced combustion duration. The involvement of nanoparticle increases the mixing of fuel and air. Nanoparticle promotes fuel spray properties like droplet size, momentum, mixing, penetration and evaporation [16]. In addition to this, the localization of radiation near the fuel droplet surface with nanoparticle creates regions of local hot spots. This promotes localized fuel boiling. This localized boiling near the surface of the fuel droplet promotes faster evaporation of fuel causing an increase in the burning rate [17, 18]. Presence of nanoparticles in the base fuel decreases the

homogeneity of fuel composition. This accelerates the fuel droplet breakup during injection that leads to a better air fuel mixture [17]. The nanoparticles spilt the fuel droplets into smaller droplets when they enters the combustion chamber resulting in the higher spray angles and hence reduced ignition delay and earlier ignition [14]. Advanced fuel injection leads to higher combustion temperatures, reduced premixed combustion period and shorter ignition delay [16]. This leads to the quick release of heat and hence also to the increased rate of pressure rise and maximum power output of the engine [16]. Figure 9 shows the variation of cylinder pressure with crank angle for 180 bar injection pressure and 3 different injection timings of 21°, 23° & 25° bTDC. As shown in Figure 9, the cylinder pressure reached its highest value of 70.36 bar for crank angle of 373° for diesel fuel at 23°, whereas for the nanofuel SME2040 it was 43.96 bar at crank angle of 381°, 70.72bar at 370° crank angle and 75.38 bar at 368° crank angle for 21°, 23° and 25° bTDC injection timings, respectively. Figure 9 shows that with the advancement in injection, the highest cylinder pressure was obtained, whereas the cylinder pressure was minimum for a retarded injection of 21° bTDC.

Figure 10 depicts that the net heat release rates obtained were maximum for advancing the injection timing, whereas it is minimum for retarded injection timing of 21° bTDC.

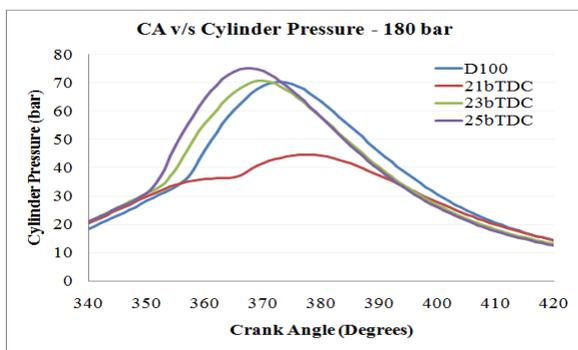


Figure 9. Variation of Cylinder Pressure with CA

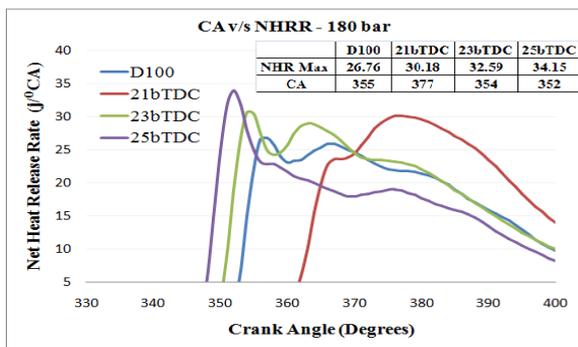


Figure 10. Variation of NHRR with CA

In addition to this, the peak pressure and NHRR are found earlier for advanced injection compared to the standard and retarded injection. This is due to early start of the combustion initiated and promoted by the nanoparticles present in the fuel. It is observed that the net heat release rate increases with an increase in the injection advancement due to the release of more heat during the premixed phase. The NHRR was 30.18, 32.59 and 34.15 J/°CA at crank angles of 355°, 377° and 352° for injections timings of 21°, 23° and 25° bTDC respectively, compared to 26.76 J/°CA at 355° CA for diesel fuel. The presence of nanoparticles dynamically boosts the process of combustion by increasing the air fuel mixing; increased momentum density that can improve the fuel injection velocity into the combustion chamber, thereby reducing the ignition delay and the combustion duration [15, 17, 19]. The advancement of injection timing reduces the delay period, whereas retarding the injection decreases the rate of pressure rise with a slight shift away from the TDC; however, the ignition delay increases. Similar effects are observed on the rate of heat release. Figure 11 shows the variation of rate of pressure rise with the crank angle. It is observed that the rate of pressure rise increases with an increase in the injection advancement, due to more heat release during the premixed phase. The rate of pressure rise was 1.2, 3.54 and 4.23 dp/dθ at crank angles of 366°, 354° and 352° for injections timings of 21°, 23° and 25° bTDC, respectively compared to 3.41 dp/dθ at 354° crank angle in case of diesel fuel.

Figure 12 depicts the combustion duration and the mass fraction burnt during the combustion. For nanofuel SME2040 for standard injection timing of 23, the combustion starts at -10.31° bTDC and ends at 27.18° aTDC with total combustion duration of 37.49 degree crank rotation. For advanced injection of 25° bTDC, the combustion starts at -14.03° bTDC and ends at 19.14° aTDC with total combustion duration of 33.17° crank rotation. Whereas the combustion starts at -9.33° bTDC and ends at 27.16° aTDC crank angle with the total combustion duration of 36.49 degree crank rotation for injection timing of 21° bTDC.

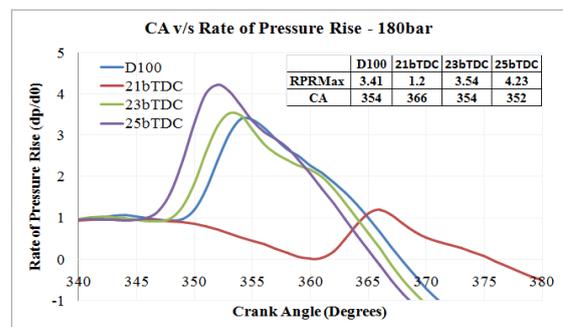


Figure 11. Variation of Rate of Release Rate with CA

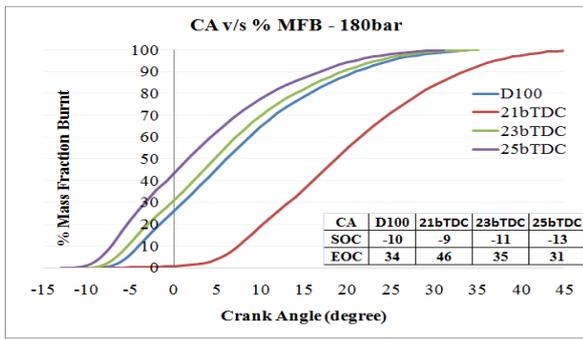


Figure 12. Variation of Mass Fraction Burnt with CA

The combustion starts at -13.21° bTDC, and ends at 21.05° aTDC with a total of 34.26° crank rotation for standard injection timing of 23° bTDC.

3. 2. Brake Thermal Efficiency Figure 13 shows the variations of the measured Brake Thermal Efficiency with Break Power for 3 different fuel injection timings of 21° , 23° and 25° bTDC for diesel and optimum nanoparticles added to the fuel SME2040. It was observed that for 80% of full load, the BTE increases to 25.5%, 27.32% and 28.35% for injection timing of 21° , 23° and 25° bTDC, respectively for nanofuel as compared to pure diesel fuel which is 24.01%. The increase of BTE for the nanofuel obtained were 6.2%, 12.11% and 15.3% for 21° , 23° & 25° bTDC, respectively. With advanced injection timing, the combustion duration reduced and for the retarded injection timing the combustion duration increased causing a higher fuel consumption and reduced BTE.

3. 3. Carbon Monoxide Emission Figure 14 shows the variations of percentage in volume of carbon monoxide at different loads for diesel and nanofuel SME2040. It is observed that there is an increase in the CO emission with the increase in the load. This is because the fuel becomes richer as the air fuel ratio decreases with the increase in load [17].

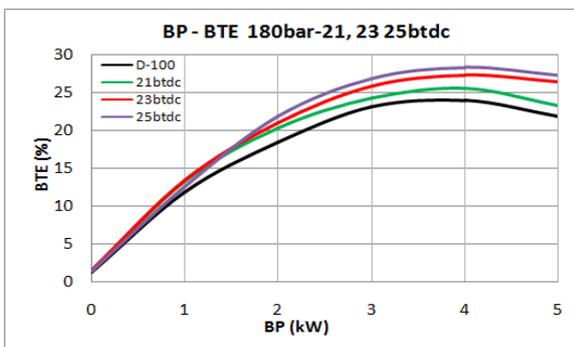


Figure13. Variation of BTE with BP

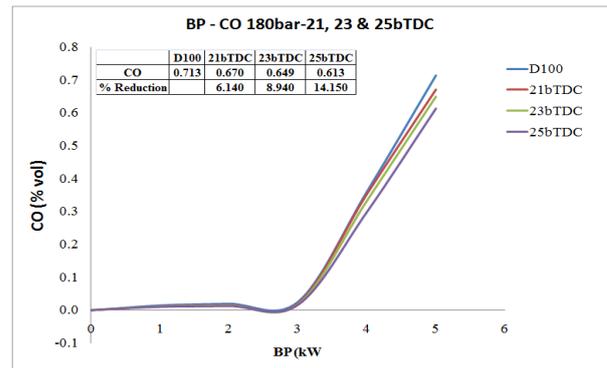


Figure14. Variation of CO with Brake Power

A reduction in Carbon monoxide emission of 6.14%, 8.94% and 14.15% is observed for injection timings of 21° , 23° and 25° bTDC, respectively as compared to emission in case of diesel fuel.

3. 4. Carbon Dioxide Figure 15 depicts the increase of CO_2 emission level for advanced injection with the nanoparticle added fuel. Added nanoparticles promote the fuel spray droplet interaction and propagation, reduce the fuel cohesion and promote easier fuel droplet breakup [17]. Moreover graphene with its atoms exposed from both sides for reaction, is chemically the most reactive form of carbon. It undergoes combustion in the combustion chamber and adds to the fuel efficiency. The biodiesel with inbuilt oxygen content when dispersed with chemically highly reactive graphene undergoes a better and complete combustion with the increased emission of carbon dioxide. The increase of carbon dioxide emission of 1.09%, 4.69% and 13.01% is observed for injection timing of 21° , 23° and 25° bTDC, respectively as compared to diesel fuel.

3. 5. Unburnt Hydrocarbon Emission The unburnt hydrocarbons are generated due to the non-availability of sufficient accessible air during the combustion. Figure 16 shows the variation of the UBHC with brake power. The emission of the UBHC is higher for the SME due to its higher viscosity, poor atomization and combustion.

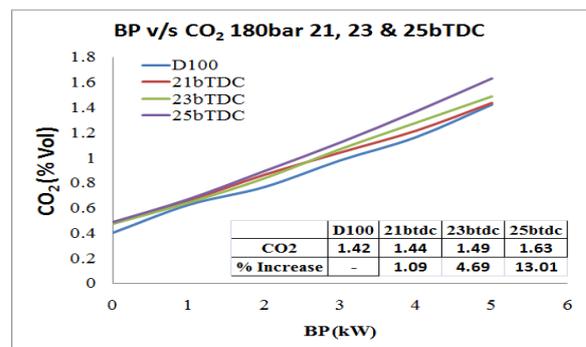


Figure 15. Variation of Carbon Dioxide with BP

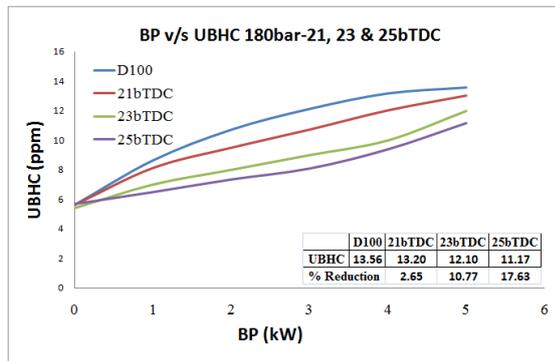


Figure 16. Variation of UBHC with BP

However, the UBHC emission is comparatively lower for nanoparticle-added nanofuels. It is observed that at all loads, the UBHC emission marginally decreases with an increase in the dosage level of the graphene nanoparticles. A reduction of 2.65%, 10.77% and 17.63% UBHC emission is observed for injection timings of 21°, 23° and 25° bTDC for nanofuel compared to diesel fuel.

3. 5. Nitrogen Oxides Emission

It is imperative to add additives that improve the properties of biodiesel fuels and their blends and obtain better engine performance and control emission. According to Zeldovich kinetics the NO_x formation in any combustion system depends on oxygen concentration, temperature and resident time [15]. In CI engines, thermal NO_x formation takes place during premixed combustion. The third phase of combustion is called the period of controlled combustion. In this period, the fuel droplets injected during the second stage burn faster with reduced ignition delay due to high temperature and pressure [17]. Thermal NO_x refers to nitrogen oxides formed at high temperature oxidation of nitrogen found in air during premixed combustion. The rate of thermal NO_x is basically a function of temperature and residence time of nitrogen at higher temperatures of combustion chambers wherein the nitrogen and oxygen disassociates to participate in a series of reactions given by Zeldovich mechanism [16]. The reactions are: N₂+O→NO+N; and N+O₂→NO+O; N+OH→NO+H.

Use of antioxidant additives with biodiesel can be effective in controlling the NO_x emission [15]. Graphene is a uni-atmoic layer thick sheet; with the carbon atoms exposed from both sides, it is chemically the most reactive allotrope of carbon. Graphene is a highly oxidizing agent; at higher temperature of combustion chamber, it undergoes combustion minimizing the oxygen availability for nitrogen to undergo oxidation. Furthermore, the nitrogen oxides are reduced as per the reduction reaction, C + 2NO→CO₂ + N₂.

Figure 17 shows the variation of measured Nitrogen oxides emission with brake power for diesel fuel and

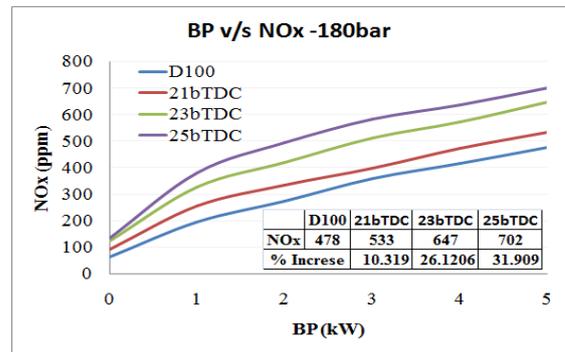


Figure 17. Variation of measured NO_x with BP

nanofuel at full loads. An increase of 10.32%, 26.12% and 31.91% NO_x emission was observed for nanofuel compared to diesel fuel. In nanoparticle added fuel, the combustion duration is minimum and the presence of graphene nanoparticle whose thermal conductivity (k) is as high as 3000 W/mK [17] causes a temperature decline with its high rate of convective heat transfer coefficient. This leads to a quick heat transfer to the cylinder walls of the engine, thereby reducing the combustion chamber temperature and hence reduced NO_x formation [17].

4. CONCLUSION

Based on the results obtained from the tests conducted on the diesel engine, the following conclusions were drawn.

- A stable homogenously dispersed Simarouba Biodiesel nanofuel can be prepared with the help of SDS surfactant.
- An increase of BTE for the nanofuel was 6.2%, 12.11% and 15.3% was obtained for 21°, 23° and 25° bTDC, respectively. Advancing the fuel injection to 25° bTDC has resulted in an increase of BTE by 15.3% and 12.11% for 23°bTDC against D100.
- A reduction in CO emission of 6.14%, 8.94% and 14.15% is observed for injection timings of 21°, 23° and 25° bTDC. Advancement of fuel injection to 25° bTDC has resulted in reduction of CO by 14.15% and 8.94% for 23 bTDC against D100.
- The advancement of injection timing and addition of graphene nanoparticles reduced harmful emissions of CO and UBHC.
- An increase in CO₂ emission level for advanced injection with nanofuel as graphene nano particles undergo combustion, indicating a higher percentage of CO₂.
- Advancing the injection timing proved to be advantageous with reduced combustion duration and increased rate of heat release by using nanofuel.
- An increase of 10.32%, 26.12% and 31.91% NO_x emission was observed for nanofuel compared to

diesel fuel. Advancement of fuel injection to 25° bTDC has resulted in an increase of NO_x by 31.91% and 26.12% for 23° bTDC against D100.

- Even though performance was improved with advanced injection 25° bTDC, NO_x emission was increased; therefore, standard timing of 23° bTDC was found to be optimum and hence recommended as a conclusion.

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Studies on Effect of Injection Timing of Graphene Nanoparticles Blended Simarouba Biodiesel Blend on Compression-ignition Engine

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گرافن یک اتم کربن تک‌لایه‌ای است که اخیراً پیدا شده است و محققان را در طیف وسیعی از کاربردهای الهام داده است. سطح ویژه‌ی این ماده تا ۲۶۳۰ مترمربع بر گرم و مقدار رسانایی حرارتی آن $3000/mK^{-1}$ وات در دمای اتاق است. از لحاظ شیمیایی، واکنش‌پذیرترین شکل کربن با یک اتم کربن در معرض واکنش از هر طرف است. پراکندگی پایدار گرافن با استفاده از سورفکتانت سدیم داودسیل سولفات به دست آمد. گرافن به وسیله‌ی پراکندگی گرافن در مخلوط مایع متیل استر سیماروبا با دیزل تهیه شد. پراکندگی با استفاده از اسپکترومتری فرابنفش مرئی مشخص شد. عملکرد، احتراق و ویژگی‌های انتشار بر روی موتور دیزل کامپیوتری آزمایشگاهی تک سیلندر تزریق مستقیم چهار مرحله‌ای سردشده با آب مورد مطالعه قرار گرفت. خصوصیات برای سه سطح مختلف مقادیر نانوذرات گرافن و سه زمان تزریق سوخت بررسی شد. این باعث بهبود بازده حرارتی و کاهش هیدروکربن‌های نسوخته و انتشار گاز مونوکسید کربن می‌شود. اضافه شدن نانو ذرات گرافنی و پیش‌گیری از زمان تزریق موجب کاهش قابل توجهی در مدت احتراق و افزایش حاشیه‌ای در فشار کلی سیلندر در تمام بارهای عملیاتی شده است.

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