Influence of nanoparticles in polanga (calophyllum inophyllum) biodiesel operated in an unmodified diesel engine

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Influence of nanoparticles in polanga (calophyllum inophyllum) biodiesel operated in an unmodified diesel engine

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Abstract

The current research work emphases on analysing the characteristics of combustion, performance, and emissions of Polanga Biodiesel (PBD) fuelled single cylinder diesel engine with Al2O3 nano-additives added at concentration of 25ppm and 50ppm. The results were compared with the baseline diesel fuel at varying engine loads (25%, 50%, 75% and 100%) in a agriculture based single cylinder diesel engine of 17.5 Compression ratio at constant engine speed of 1500rpm. Al2O3 nano-additives were blended with PBD using magnetic stirrer and ultrasonicator. Experimentation results revealed that, the nanoparticles addition in PBD improved the combustion and emission characteristics of base fuel due to higher surface area to volume ratio of nano-additives. Moreover, Al2O3 nanoparticles addition enhanced the brake thermal efficiency (BTE) and lowered the brake specific fuel consumption (BSFC) by 6.58% and 7.38% respectively. Subsequently, the emissions of HC, CO, NOx and smoke opacity were improved with the addition of fuel borne additives in PBD owing to improved combustion efficiency.

Keywords: Nano additives; Polanga biodiesel; Surface area; Performance; Emission; Diesel engine

1. Introduction

Increasing dependency on diesel fuel over transportation sector and surge in air pollution levels, has thrived search for a potential alternative feedstock which is environmentally benign as well as bio-based for existing unmodified DI diesel engine. The

rapid increase in automobiles has resulted in higher dependency on fossil fuels and also higher fuel exhaust from internal combustion engines. Compression ignition (CI) engines emit higher oxides of nitrogen (NOx) and carbon dioxide (CO_2) emissions which are the major greenhouse gases responsible for global warming. Other gases include regulated emissions such as hydrocarbon (HC), Carbon monoxide (CO), smoke opacity and unregulated emissions like acetaldehyde, formaldehyde, acetone and toluene. From the 1970s till 2010, the rate of increase in Green House Gases (GHGs) is estimated at 1.8% every year, which is subsequently responsible for increasing earth temperature by 2°C. Another usage of fossil fuels includes agricultural sector, power/transportation and mining sectors. Hence, Many researchers were performed on diesel engines for its capability with alternative fuels in the mere future as there is random fossil fuel depletion. Reduction of harmful gases in any of the above sector, even on a minimal scale can add to environmental sustainability and can replace tonnes of harmful gases plunged into the atmosphere.

Usage of alternative fuels paves the way for sustainable development, the dependency of renewable resources and environmental energy and conservation process. Among various alternative energy sources, biodiesel plays a vital role in reducing the high flash point range and improved lubricity. Added with, biodiesel is of non-toxic in nature and is of renewable and biodegradable in nature. However, certain drawbacks associated with biodiesel utilization are poorer fuel atomization and higher viscous nature which eventually results in improved NOx emissions and lowered BTE. Several research articles with biodiesel application have shown substantial lowering in HC, CO and unregulated emissions with higher NOx spectrum. Several research investigations have proved that appending metal oxide based additives in base fuel facilitates the oxidation process and increases the combustion efficiency of diesel engine along with minimized emissions.

Nanoparticles (10^{-9}m scale) addition in base fuel is found to exhibit improved engine combustion and performance characteristics. Venu Harish and Venkataramanan Madhavan [1] examined the influence of Al_2O_3 nanoparticles in ternary fuels (biodiesel/diesel/ethanol) blends with various injection timings. They perceived that the nanoparticle combustion was better in retarded injection timing in lowering the harmful tailpipe emissions such as CO, HC, NOx and smoke emissions. Venu Harish and Venkataramanan Madhavan [2] also established that the metal oxide nanoparticles inclusion in ternary fuel component is better to that of appending oxygenated additives such as DEE (diethyl ether) in the consent of developed combustion and performance phenomenon. Several investigations were done using Polanga

biodiesel as a probable alternative fuel replacing the mineral diesel fuel. Bari and Hossain [3] investigated in a diesel engine with biodiesel comparing the performance with the baseline diesel fuel. They found that the specific fuel consumption of biodiesel is higher by 10% than the mineral diesel owing to the lowered calorific value of biodiesel even though the thermal efficiency is slightly closer to diesel. Moreover, CO and HC emissions of biodiesel run engine were approximately 50% lesser than that of conventional diesel fuel though NOx emissions were higher by 33%, respectively. Yuvarajan et al. [4] experimented in a single cylinder diesel engine and found, plain biodiesel of 100% v/v could be a potential alternate fuel in an unmodified diesel engine.

Even though various literature were done on Polanga biodiesel and alumina nano additives at individual capacities, there were no reported literatures on analyzing the effect of Al_2O_3 nano-additives at various concentrations (25ppm and 50ppm) in Polanga biodiesel (PBD) on the effect of characteristics of performance, combustion and emissions on an unmodified diesel engine. With this strategic conception, the following experimental work is performed with diesel, Polanga biodiesel and Polanga biodiesel appended with Al_2O_3 nano-additives.

2. Experimental Material & Methods

2.1 Nanoparticle synthesis

Al_2O_3 nano-sized particles were synthesized using sol-gel combustion method where the 0.5M aluminium nitrate solution is blended in 50 ml H_2O at 22^{o}C and stirred using magnetic stirrer. Then 0.05M urea is mixed with aluminium nitrate and treated for 30 minutes until pH 2 solution is attained. Further titration with 25 ml of H_2O and 0.1 M sodium hydroxide was done till pH 6 solution is attained. After the formation of clady gel (pH=8) with sodium hydroxide addition, the sample is dried at 150^{o}C for 12 hours and Al_2O_3 nanoparticles were procured in a container and were allowed to dry at 300^{o}C and 2 hours in the furnace. The flowchart illustrating the synthesis procedure of alumina nanoparticles were shown in Figure 1. The physical properties of synthesized Al_2O_3 nanoparticles were detailed in Table 1. Figure 2 depicts the flowchart for the preparation of Al_2O_3 nanoparticles. Figure 3 shows the SEM and TEM spectroscopy of synthesized Al_2O_3 nanoparticles.

2.2 Polanga Biodiesel preparation and test fuel preparation

Polanga oil biodiesel is synthesized using conventional transesterification method of treating raw Polanga oil with methanol with a catalyst in a batch reactor. Initially, the

Polanga oil is subjected to 80ºC preheating for removing the available moisture in the blend. Since the FFA of raw Polanga oil is higher, the acid pretreatment process is done by reacting it with sulphuric acid (H_2SO_4). Hence, 1.5 Molar ratio of raw oil to methanol and 0.6% v/v H_2SO_4 were heated in the batch reactor for 65ºC for 2 hours at 450 rpm speed. Blending the nanoparticle is done using ultrasonicator operated with 60 kHz operating frequency and 440 kW power operated for 20 min. It is found that the nanoparticles in PBD remained stable for about 96 hrs. PBD+25 ppm $Al_2O_3$is prepared by blending 25ppm Al_2O_3 nanoparticles with 100% Polanga biodiesel while PBD+50ppm Al_2O_3 is prepared by blending 50ppm Al_2O_3 nanoparticles with 100% Polanga biodiesel. The fuel properties were calculated as per American Society for Testing and Materials (ASTM) standards as shown in Table 2.

2.3 Experimental setup

For the current experimentation, Kirloskar-TAF1 diesel engine was used which is agriculturally based, single cylinder, naturally aspirated, four-stroke DI diesel engine with a rated power output of 4.2kW at 1500 rpm. The specifications of used test engine were given in Table 3. The test engine unit comprises a fuel delivery unit, electrical dynamometer for load adjustment, Data Acquisition Systems (DAS), smoke opacimeter (AVL 437 C) and AVL five gas analyzer (measuring CO, O, HC, CO_2 and NOx). Experimentations were done on 5 load intervals of 0%, 25%, 50%, 75% and 100% respectively and in between two test fuels, the engine is allowed to be run with neat diesel fuel for 20 min for attaining standard operating rhythm. Figure 4 shows a schematic of the test engine setup.

2.4 Uncertainty analysis

Miscalculations and uncertainties can appear from several influences alike choosing and calibration of devices, varying atmospheric circumstances, trials and interpretations, etc. Uncertainty can be classified into two factors such as fixed and random errors. Fixed error deals with repeatability while random error deals mainly with critical quantities. ΔX , which is defined as measured variable associated uncertainties is assessed by Gaussian distribution as shown in eqn. 1 with ±2σ limit of confidence. The mean value upon which the measured value depends were indicated by 2σ. Xi denotes the reading numbers, and σ indicates standard deviation. Equation 2 indicates uncertainties in parameters calculated in which the functions such as X_1 and X_2 till Xn of the R range represents taken readings (in numbers). Equation 3 represents the uncertainties associated with measuring instruments in which ΔR is the range of uncertainties and is calculated by RMS value of observed error values and is

indicated in Table 4 while Table 5 shows the uncertainties associated with measured parameters.

$$\Delta X_i = \frac{2\sigma_i}{\overline{X_i}} * 100 \tag{1}$$

$$R = f(X1, X2, X3, \ldots\ldots\ldots\ldots Xn) \tag{2}$$

$$\Delta R = \sqrt{\left[\left(\frac{\partial R}{\partial X_1}\Delta X_1\right)^2 + \left(\frac{\partial R}{\partial X_2}\Delta X_2\right)^2 + \left(\frac{\partial R}{\partial X_3}\Delta X_3\right)^2 + \ldots\ldots\ldots\ldots\ldots\left(\frac{\partial R}{\partial X_n}\Delta X_n\right)^2\right]} \tag{3}$$

Where, R in eqn.2 represents the function of X1, X2,……..Xn and X1, X2,…….Xn represents number of readings taken. Hence ΔR is computed by RMS (root mean square) of errors associated with measured parameters. The uncertainties of various measuring instruments were illustrated in Table 4. By using eqn.3, the uncertainties in various measured parameters were evaluated and tabulated in Table 5.

3. Results and discussion

3.1 Combustion characteristics

Figure 5 shows the variation of in-cylinder pressure for all the test fuels at 100% engine load condition. It is observed that at all the test fuel blends exhibits almost similar cylinder pressure style. PBD and DIESEL fuel exhibits in-cylinder pressure range of about 81.23bar and 79.56 bar respectively. The reason for lowered cylinder pressure for DIESEL is shortened delay period which results in combustion getting more uniform followed by lessened peak pressure [5, 6]. Moreover, from Table 2, we can observe that DIESEL fuel has improved calorific value which is responsible for consuming lowered fuel at combustion and high combustion efficiency of DIESEL is also a factor for shortened peak pressure [7, 8]. Addition of Al_2O_3 nano-additives at 25ppm and 50ppm fraction to PBD resulted in improved peak pressure which could be perhaps attributed to the improved thermal conductivity of the resulting nano-fuel mixture [9, 4]. The higher thermal conductivity of nano-fuel causes the fuel combustion to begin earlier thus resulting in higher in-cylinder peak pressure. From the figure, we can infer that with increasing concentration of Al_2O_3 nano Al_2O_3 nano-additive concentration in PBD to 50ppm, the combustion begins earlier, which may be attributed to increment in ignition quality and improved coefficient of thermal conductivity of Al_2O_3 nano-additives. Similar results with observed pressure pattern were reported in several literatures with different nanoparticles in base fuel.

The HRR at every crank angle on behalf of various fuel blends were calculated using the correlation derived from the 1st law of thermodynamics by equation 4:

$$\frac{dQ_n}{d\theta}=\left(\frac{\gamma}{\gamma-1}P\frac{dV}{d\theta}\right)+\left(\frac{1}{\gamma-1}V\frac{dP}{d\theta}\right)+\dot{Q}_{lw} \quad (4)$$

Where, Qn represents the net heat release rate (HRR) (J/degCA), P represents instantaneous in-cylinder pressure (N/m^2), V showcases the instantaneous in-cylinder volume (m^3), θ is crank angle (degree) and γ is defined as the ratio of specific heats Cp/Cv (kJ/kgK) depending mainly on the temperature factor and influences the intensity of $\frac{dQ_n}{d\theta}$ and $\dot{Q}_{lw}$. $\dot{Q}_{lw}$ is defined as the blow by losses which are defined by Rakopoulas [10]. The gross HRR can be calculated by equation 5:

$$\frac{dQ_g}{d\theta}=\frac{dQ_n}{d\theta}+\frac{dQ_{lw}}{d\theta} \quad (5)$$

Where $\frac{dQ_{lw}}{d\theta}$ defines the gross HRR to the combustion chamber walls [10].

Figure 6 illustrates the variation of HRR for all the test fuels at 100% engine load condition. It is observed that DIESEL and PBD exhibit maximum HRR of about 92.37J/degCA and 81.43 J/degCA. Higher HRR for DIESEL fuel can be attributed to a higher calorific value which results in higher heat generation during combustion. With the increase in the concentration of Al_2O_3 nano-additives, the HRR increases further owing to increase in ignition quality and coefficient of thermal conductivity of Al_2O_3 nano additives. This improved thermal conductivity of resulting fuel mixture accelerates the rate of combustion of fuel precursors and thereby liberating the maximum heat release rate. These research findings are in good accordance with the previous research findings, where the HRR is improved with appending of nano materials in the base fuel.

3.2 Performance Characteristics

Figure 7 represents the variation of BTE of DIESEL, PBD, PBD+25ppmAl_2O_3 and PBD+50ppmAl_2O_3 all over the engine load condition. At 100% engine load, DIESEL fuel exhibits highest BTE of 32.19%, followed by PBD+50ppmAl_2O_3 (30.63%), PBD+25ppmAl_2O_3 (29.94%) and PBD (28.74%) respectively. The higher BTE of mineral DIESEL in comparison with oxygenated blends were owing to lowered fuel viscosity and improved calorific value of the blend [11]. At 100% load, the BTE of PBD+25ppmAl_2O_3 and PBD+50ppmAl_2O_3 were 4.21% and 6.58% higher than PBD blend. This is because, with

Al_2O_3 nano additive, the atomization of fuel droplets were increased, thus promoting the combustion efficiency followed by higher BTE [12, 13, 14]. Moreover, it is interesting that BTE of PBD+50ppmAl_2O_3 blend exhibits higher BTE than PBD+25ppmAl_2O_3 blend throughout the engine load condition. The Al_2O_3 nano-additive acts as an oxygen buffer as well as a potential catalyst with increasing concentration (20 ppm to 50ppm). These results are in good accordance with previous research works with biodiesel and nano-additives [15, 16, 17].

Figure 8 shows the variation of BSFC of all the test fuels at varying engine load condition. It is observed that, with an increase in engine load, the BSFC reduces which can be attributed to the engine utilizing higher fuel quantum for maintaining a constant speed (1500 rpm) at higher engine loads. At 100% load, the BSFC of PBD is highest (12.72g/kWh), followed by PBD+25ppmAl_2O_3 (11.82g/kWh) and PBD+50ppmAl_2O_3 (11.783 g/kWh) and DIESEL (10.347 g/kWh) respectively. All the biodiesel blends resulted in higher BSFC than DIESEL fuel which is attributed to the lowered calorific value of blends. In comparison with DIESEL fuel, the viscosity of PBD, PBD+25ppmAl_2O_3 and PBD+50ppmAl_2O_3 is lower than PBD by about 7.08% and 7.38% respectively. The presence of Al_2O_3 nano-additive in PBD improves the oxidation process and subsequently lowers the fuel consumed [18]. BSFC of PBD+25ppmAl_2O_3 is lower than PBD+50ppmAl_2O_3 all over the engine load condition. The presence of in-built oxygen content in Al_2O_3 nano-additive accelerates the combustion process and improves the combustion efficiency and thus lowers the BSFC subsequently. Lowered BSFC with nanoparticle addition were also reported in several research articles [17, 19].

3.3 Emission Characteristics

Figure 9 illustrates the variation of NOx emissions for all the test fuels throughout the engine load condition. It can be observed that NOx emissions keep on increasing with the increase in engine load for all the test fuels owing to improve in-cylinder gas temperatures at higher load spectrums. Among the test fuels, DIESEL fuel exhibits lowered NOx emissions in comparison with PBD, PBD+25ppmAl_2O_3 and PBD+50ppmAl_2O_3 blends owing to the presence of oxygenates in the blend. At full engine load condition, the NOx emissions of PBD+25ppmAl_2O_3 and PBD+50ppmAl_2O_3 were lower than PBD by about 8.75% and 11.73% respectively. This could be attributed to the improvement in cetane number characteristics with increasing Al_2O_3 concentration [20, 21].

$$Al_2O_3 + NO \rightarrow 2AlO + \frac{1}{2}N_2 \quad (5)$$

At improved in-cylinder temperatures, Al_2O_3 molecule reacts with NO to release the molecules, 2AlO and ½ N2, lessening the NOx formation tendency as represented in equ.5. These results are in coherence with several research studies [15, 16, 17] which also reported lowered NOx with biodiesel and nanoparticle addition. At full load condition (100% load), the NOx emissions of DIESEL, PBD, PBD+25ppmAl_2O_3 and PBD+50ppmAl_2O_3 were about 13.06g/kWh, 16.17g/kWh, 14.75g/kWh and 14.27g/kWh respectively.

Figure 10 displays the distinction of HC emissions for all the test fuels throughout the engine load condition. It can be seen that HC emissions improves with increasing loads owing to more fuel entering into the combustion chamber thus resulting in several rich mixture zones, poor combustion, thus emitting higher unburnt fuel fractions, i.e. higher HC emissions. The presence of inbuilt O_2 in biodiesel blend helps in sustaining the combustion thus resulting in lowered HC emissions for PBD, PBD+25ppmAl_2O_3 and PBD+50ppmAl_2O_3 respectively. This is because; the presence of Al_2O_3 nano-additive with higher thermal conductivity improves the combustion process and lowers the possibility of rich mixture zone formation, thus lowering the HC emissions. HC emissions of PBD+50ppmAl_2O_3 are lower than PBD+25ppmAl_2O_3 throughout the engine load condition. This could be attributed to the presence of sufficient nanoparticles which enhances the rate of combustion thus generating O_2 assisted combustion followed by lowered HC emissions. The obtained results were in good accordance with the previous research findings [22, 23, 24] that have reported lowered HC emissions with nanoparticle addition in base fuel. At 100% load, the HC emissions of DIESEL, PBD, PBD+25ppmAl_2O_3 and PBD+50ppmAl_2O_3 were about 0.533g/kWh, 0.468 g/kWh, 0.35/kWh and 0.32g/kWh respectively.

Figure 11 shows the variation of smoke emissions for all the test fuels throughout the engine load condition. It is observed that smoke emissions increases with increasing engine load condition for all the test fuels, owing to the presence of excess fuel quantity which subsequently causes rich mixture zone, incomplete/poor combustion followed by improved smoke spectrum. In contrast with DIESEL, the smoke emissions of PBD, PBD+25ppmAl_2O_3 and PBD+50ppmAl_2O_3 were lower by about 7.39%, 30.62% and 41.97% respectively. This is due to the occurrence of in-built O_2 content in biodiesel that promotes the rate of combustion

followed by lowered smoke opacity. At 100% engine load, in comparison with PBD, the smoke emitted by PBD+25ppmAl_2O_3 and PBD+50ppmAl_2O_3 were lowered by about 25.09% and 37.34% respectively. This can be possible because of the presence of Al_2O_3 nano-additive which improves the evaporation rate of the fuel. With increasing nanoparticle concentration to 50ppm, the smoke is further reduced which can be attributed to the presence of sufficient quantum of nanoparticles providing O_2 assisted combustion thus lowering the formation of soot precursors and suppressing the NOx formation. These observations are in good agreement with findings of several researchers [14, 15, 16] where nanoparticle addition lowered the smoke emission formation. At 100% engine load condition, the smoke emitted by DIESEL, PBD, PBD+25ppmAl_2O_3 and PBD+50ppmAl_2O_3 were about 1.67%, 1.54%, 1.15% and 0.96% respectively.

Figure 12 displays the variation of CO emissions with respect to varying engine load condition. From the figure, it can be found that CO emissions increase with increase in engine load condition owing to the higher quantum of fuel taking part in combustion with the unchanged air quantity inside the cylinder which eventually causes a rich mixture thus liberating higher CO emissions. At 100% engine load, in comparison with DIESEL, the CO emissions of PBD, PBD+25ppmAl_2O_3 and PBD+50ppmAl_2O_3 were lowered by about 7.24%, 30.71% and 36.45% respectively. Perhaps, this can be attributed to lowered O_2 availability in DIESEL which hinders the conversion of CO to CO_2. Addition of nanoparticle in PBD at a concentration of 25ppm and 50ppm lowers the CO emission by about 25.3% and 31.49% respectively, which could be attributed to the presence of Al_2O_3 nano-additives providing excess O_2 during combustion thereby facilitating the faster CO_2 conversion followed by lessened CO emissions.

At higher in-cylinder temperatures, Al_2O_3 nanoparticle further breaks up to Al_2O and O. "Al_2O" molecule is remarked as a highly unstable compound at higher in-cylinder temperatures within the combustion chamber which can further dissociate to 2Al and $\frac{1}{2}O_2$. The available excess oxygen molecule further rejoins with CO to get transformed to a CO_2 molecule as illustrated in the following Equation (6-8):

$$Al_2O_3 \rightarrow Al_2O+2O \quad (6)$$

$$Al_2O \rightarrow 2Al+\frac{1}{2}O_2 \quad (7)$$

$$O+CO \rightarrow CO_2 \quad (8)$$

With increasing nanoparticle concentration to 50ppm, CO emissions further reduce by 8.28% to 2.6g/kWh which could be attributed to improved fuel properties of PBD+50ppmAl_2O_3 as well as the presence of sufficient concentration of nano-additives boosting the rate of combustion efficiency. These experimental results were in good agreement with previous research findings [15, 21, 25] where the nanoparticle assisted in lowering the CO emissions subsequently.

4. Conclusion

The current experimental study deals with analyzing the diesel engine's characteristics of performance, combustion and emissions in a single cylinder engine run with PBD blended with Al_2O_3 nano-additives at 25ppm and 50ppm concentration. Nano-additives were blended with PBD using magnetic stirrer and ultrasonication process. Tests were performed only after the dispersion of nanoparticles is checked for non-settling for about 96 hrs. Experimentation was done using DIESEL as a baseline, PBD, PBD+25ppmAl_2O_3 and PBD+50ppmAl_2O_3. Based on experimentation, the following conclusions can subsequently be drawn:

- Addition of Al_2O_3 nano-additives at a concentration of 25ppm and 50ppm in PBD improves the combustion characteristics (HRR, Cylinder pressure) owing to the improved surface area to volume ratio of nanoparticles improving the thermal conductivity of fuel mixture which subsequently improves the combustion efficiency.
- The obtained BTE of PBD blend is lower than DIESEL fuel at all the engine load conditions. However, with Al_2O_3 nanoparticle addition, the BTE is increased by 4.21% and 6.58% with 25ppm and 50ppm concentration. Similarly, the BSFC is lowered by 7.38% with nanoparticle addition. These are attributed to the improved calorific value of the blends which increases the energy density of fuel mixture and thus utilizing lesser quantum of fuel to maintain the engine speed constant (1500 rpm)
- Emission wise, PBD blends emits higher NOx emissions with respect to DIESEL fuel owing to in-built O_2 content in the blend which favours the NOx formation chemistry. However, the addition of Al_2O_3 nano-additive acts as a potential reduction catalyst and

breaks the chain of nitrogen and oxygen molecules and thereby subduing the NOx formation process. With Al_2O_3 nanoparticle addition, other emissions such as hydrocarbon (HC), carbon monoxide (CO) and smoke opacity were reduced by 30.32%, 31.49% and 37.34% respectively which could possibly be attributed to the presence of nano-additives acting as oxygen buffer and supplies O_2 during combustion thus lowering the possibility of formation of fuel-rich zones and lowered exhaust emissions.

Nomenclature

Al_2O_3	Aluminium oxide nanoparticle
BSEC	Brake Specific Energy Consumption
BTE	Brake Thermal Efficiency
CO	Carbon monoxide
CO_2	Carbon dioxide
CI	Compression Ignition
DI	Direct Injection
HRR	Heat Release Rate
HC	Hydrocarbon
NOx	Oxides of Nitrogen
TEM	Transmission Electron Microscope
SEM	Scanning Electron Microscope

Authors' contributions

Both authors equally contributed to this work

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Figures

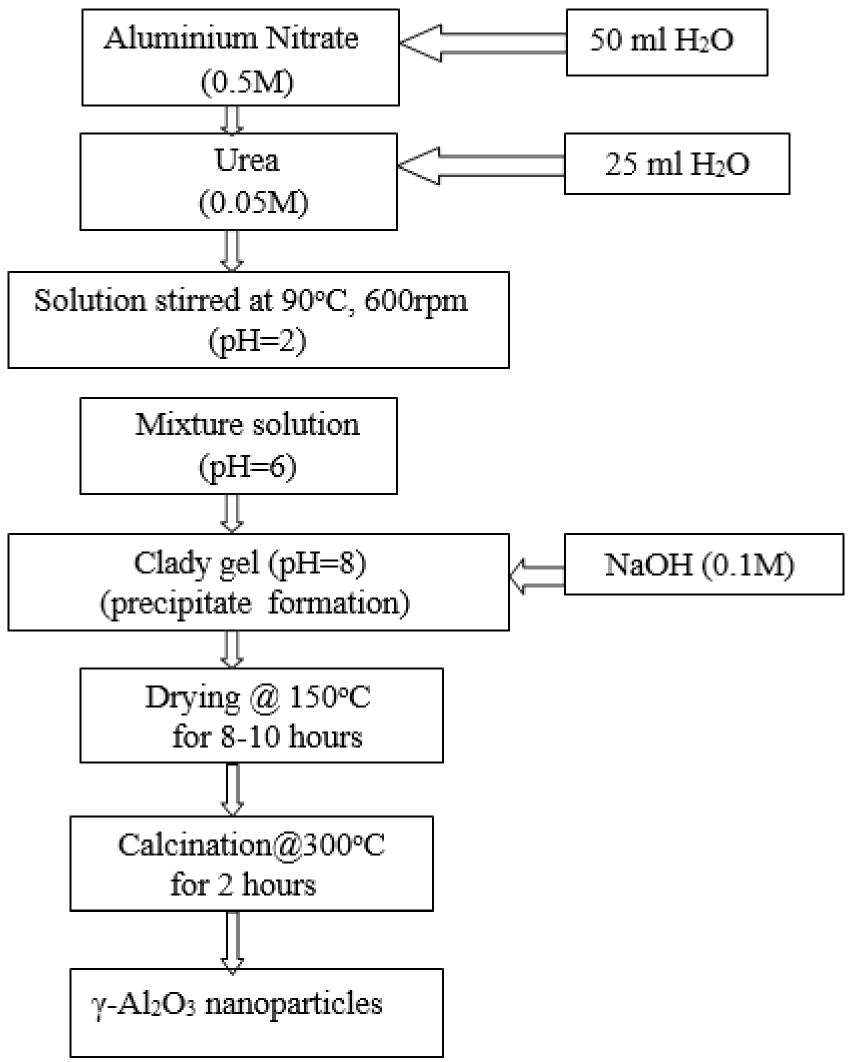

Figure 1

Flowchart illustrating synthesis of alumina nanoparticles

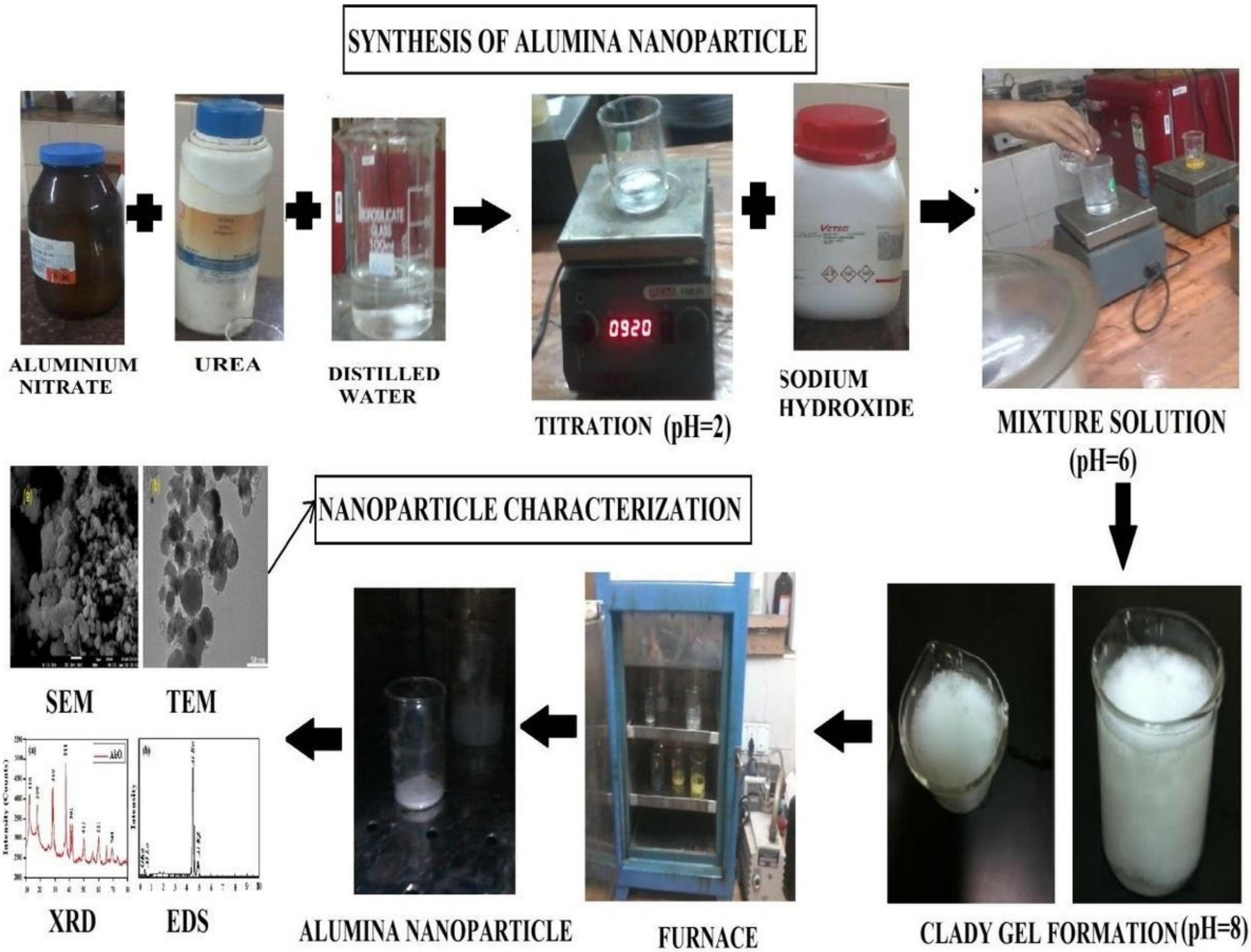

Figure 2

Flowchart indicating the nanoparticle preparation

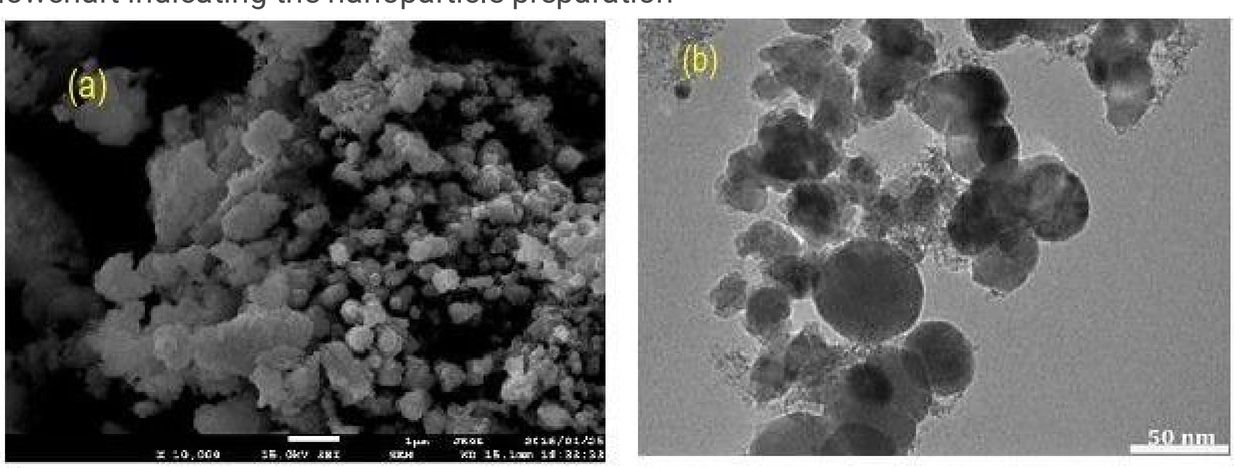

Figure 3

Characterization of Al2O3 nanoparticles a) SEM b) TEM

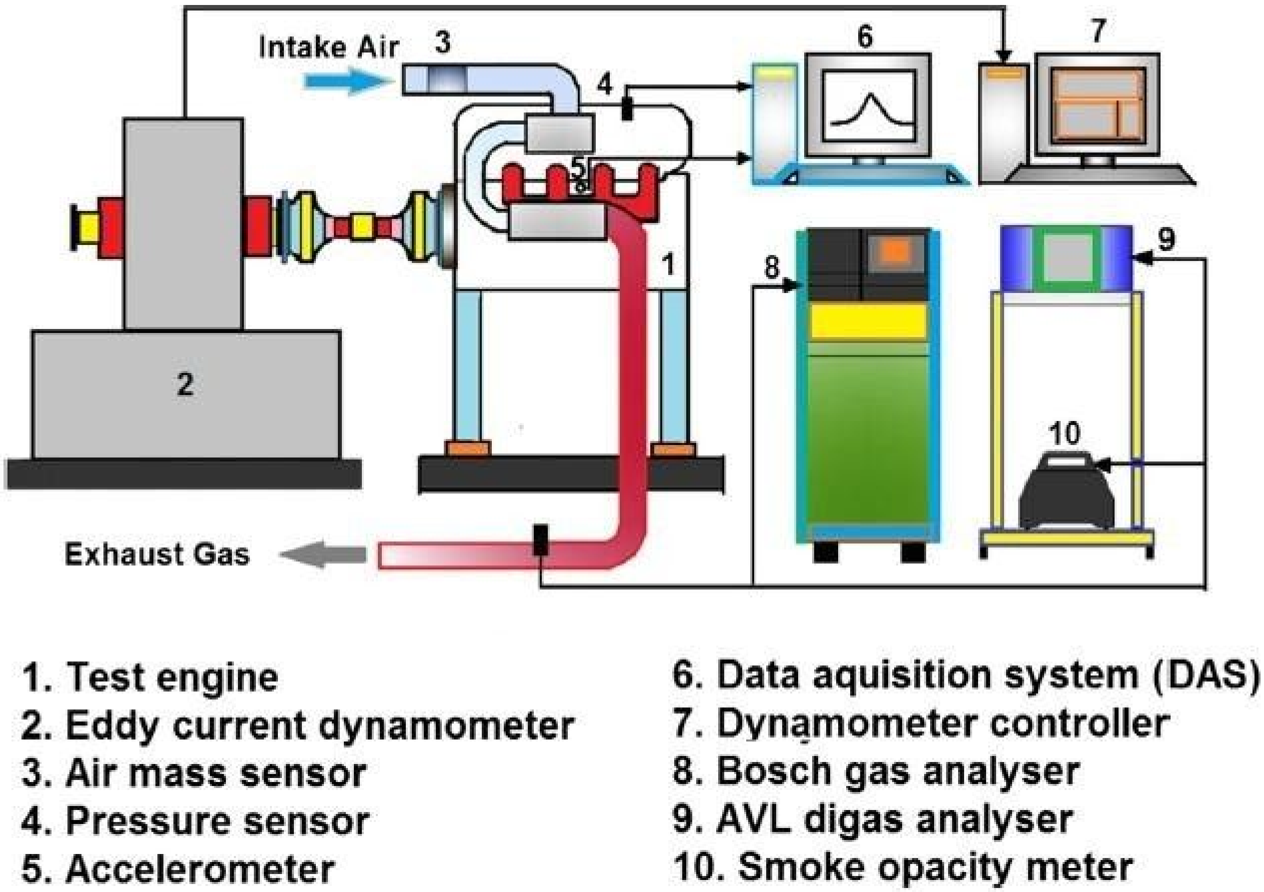

Figure 4

Layout of experimental setup

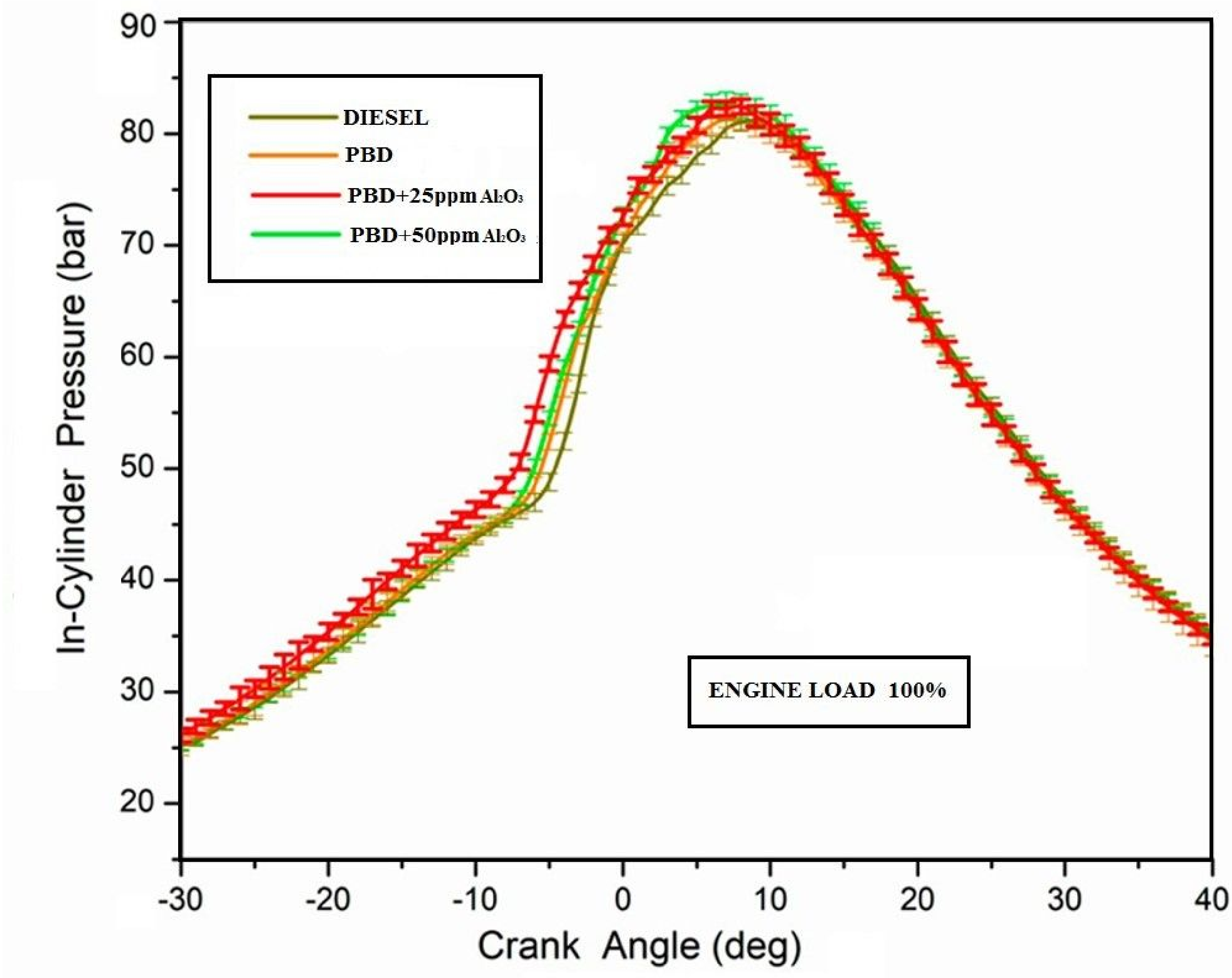

Figure 5

Variation of in-cylinder pressure with crank angle at 100% engine load

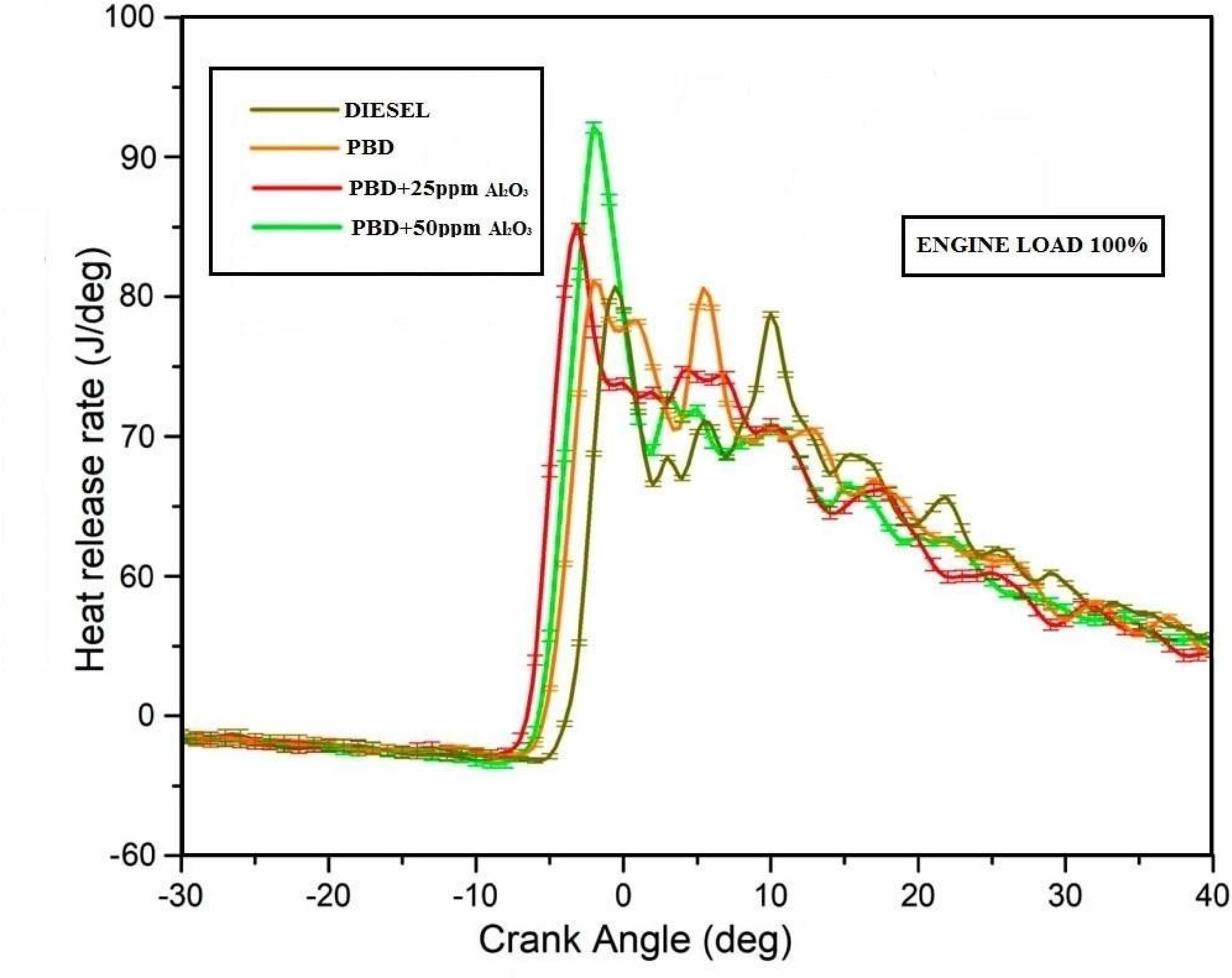

Figure 6

Variation of heat release rate with crank angle at 100% engine load

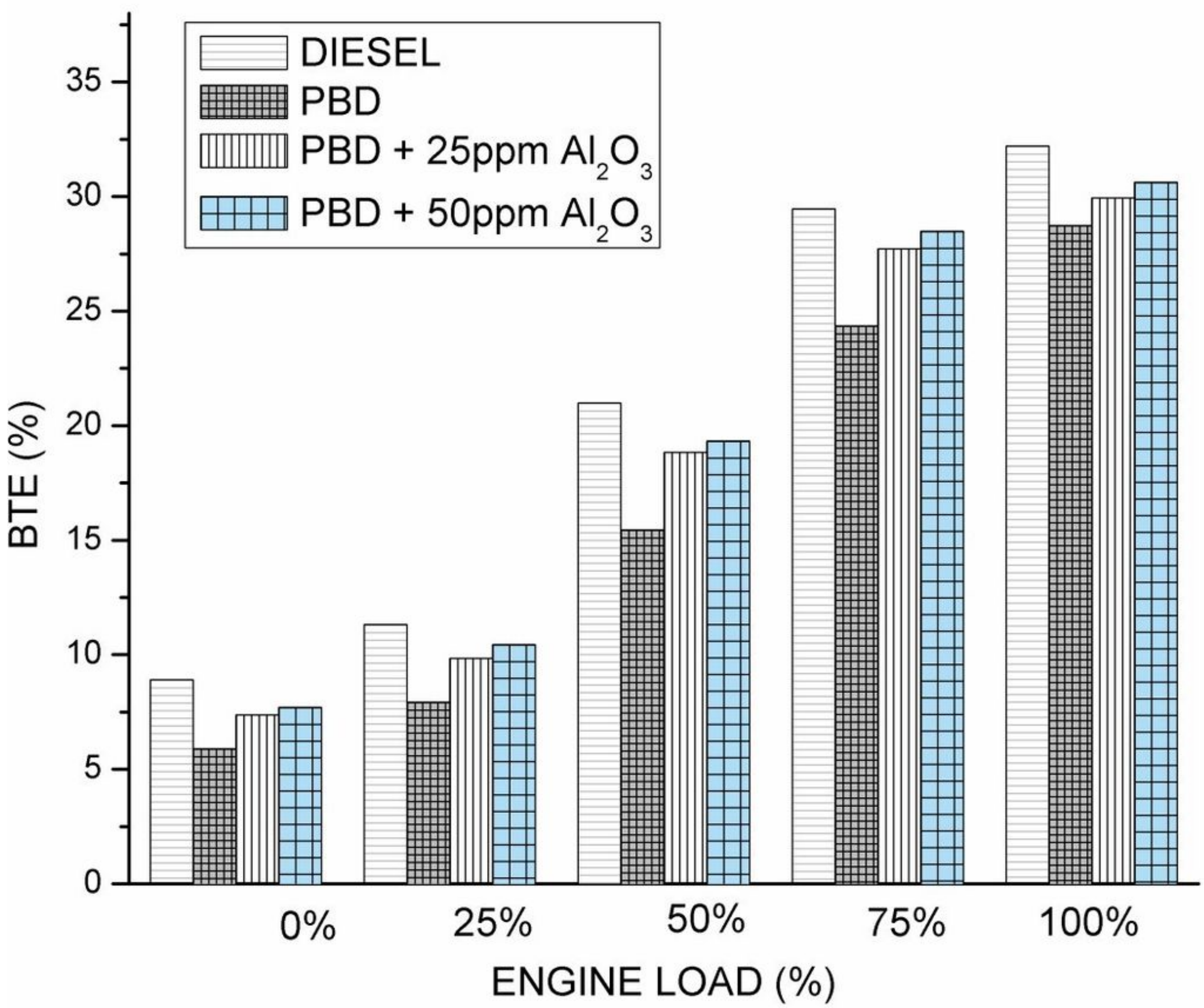

Figure 7

Variation of brake thermal efficiency (BTE) with respect to engine load

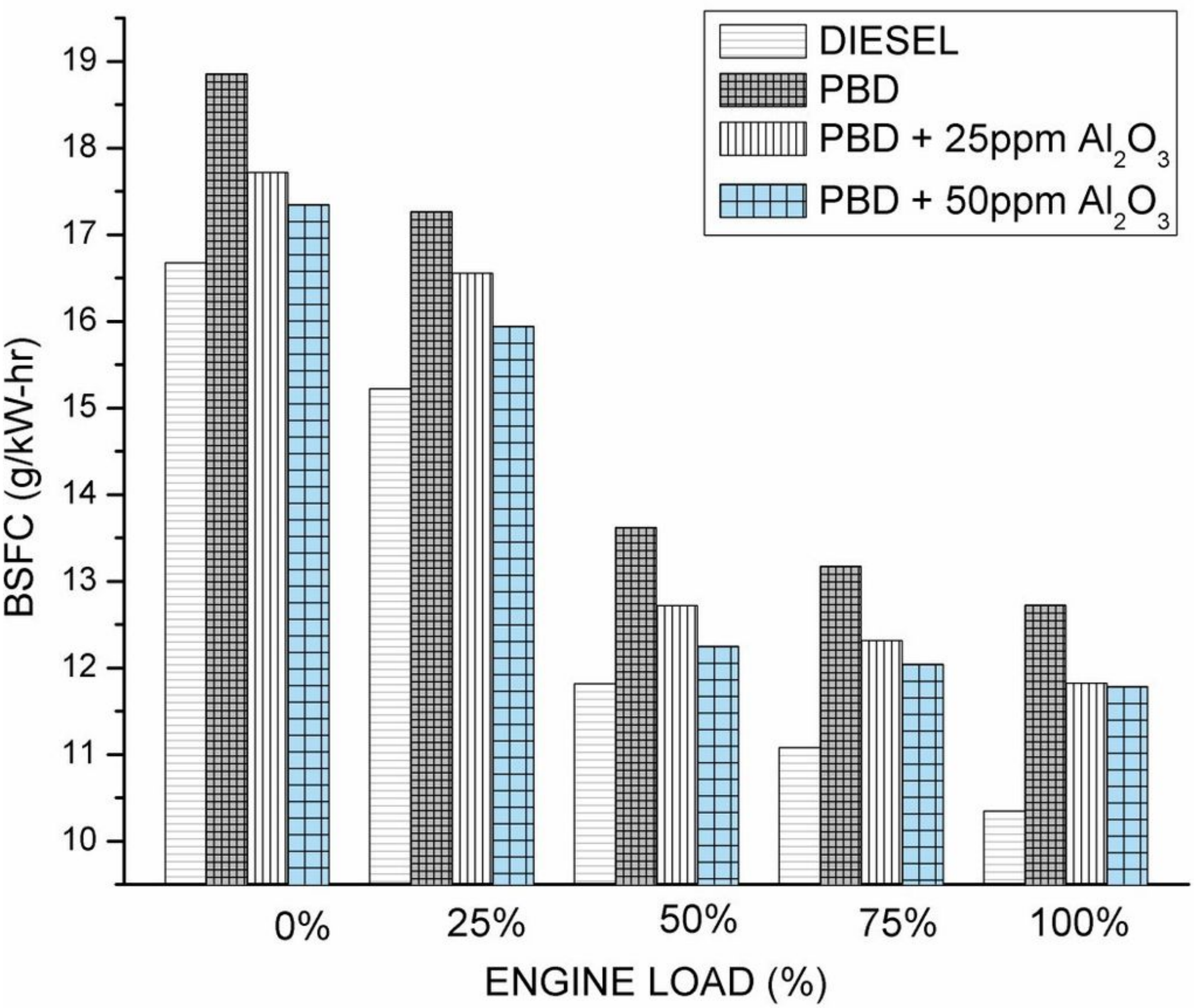

Figure 8

Variation of brake specific fuel consumption (BSFC) with respect to engine load

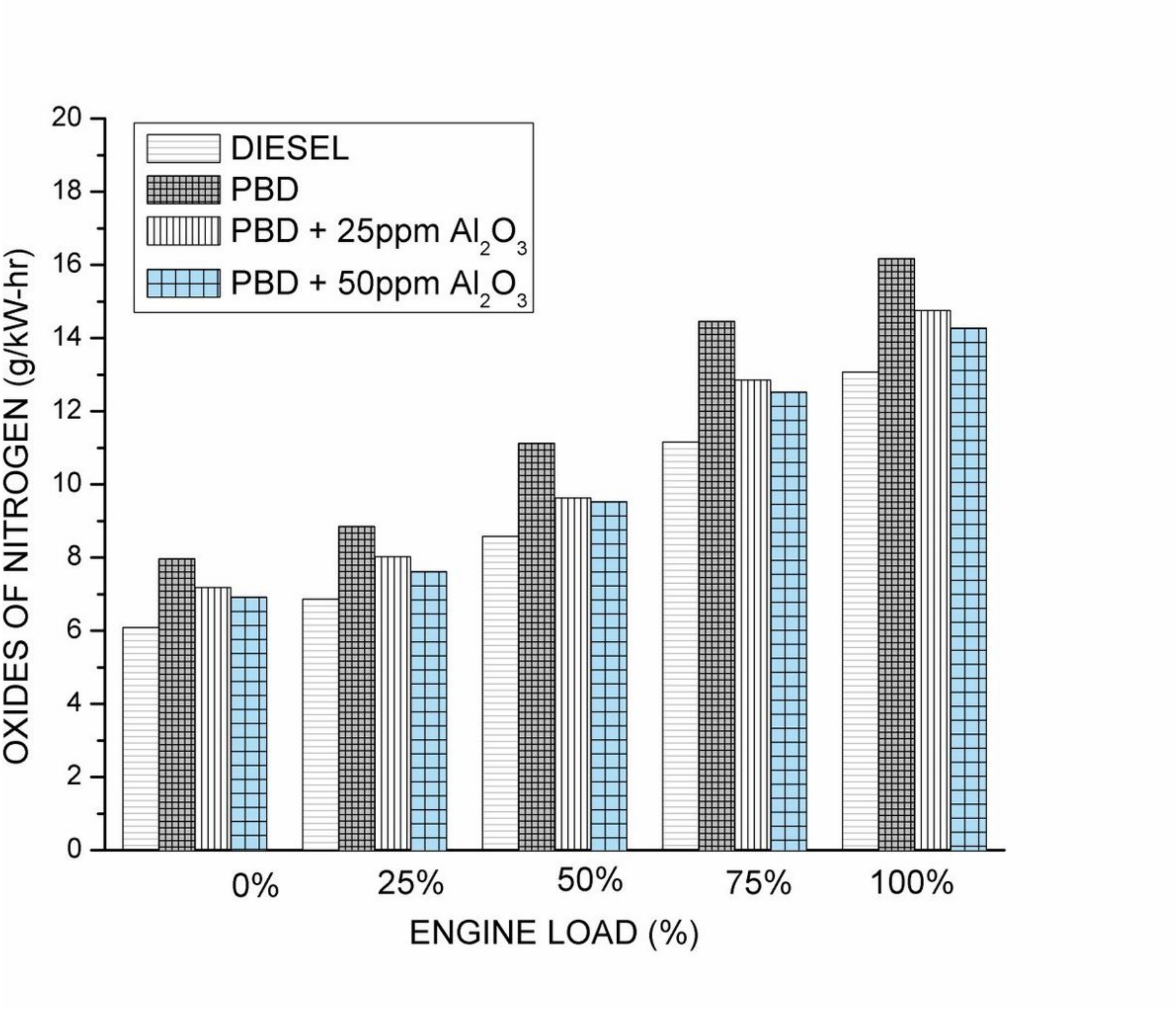

Figure 9

Variation of oxides of nitrogen (NOx) with respect to engine load

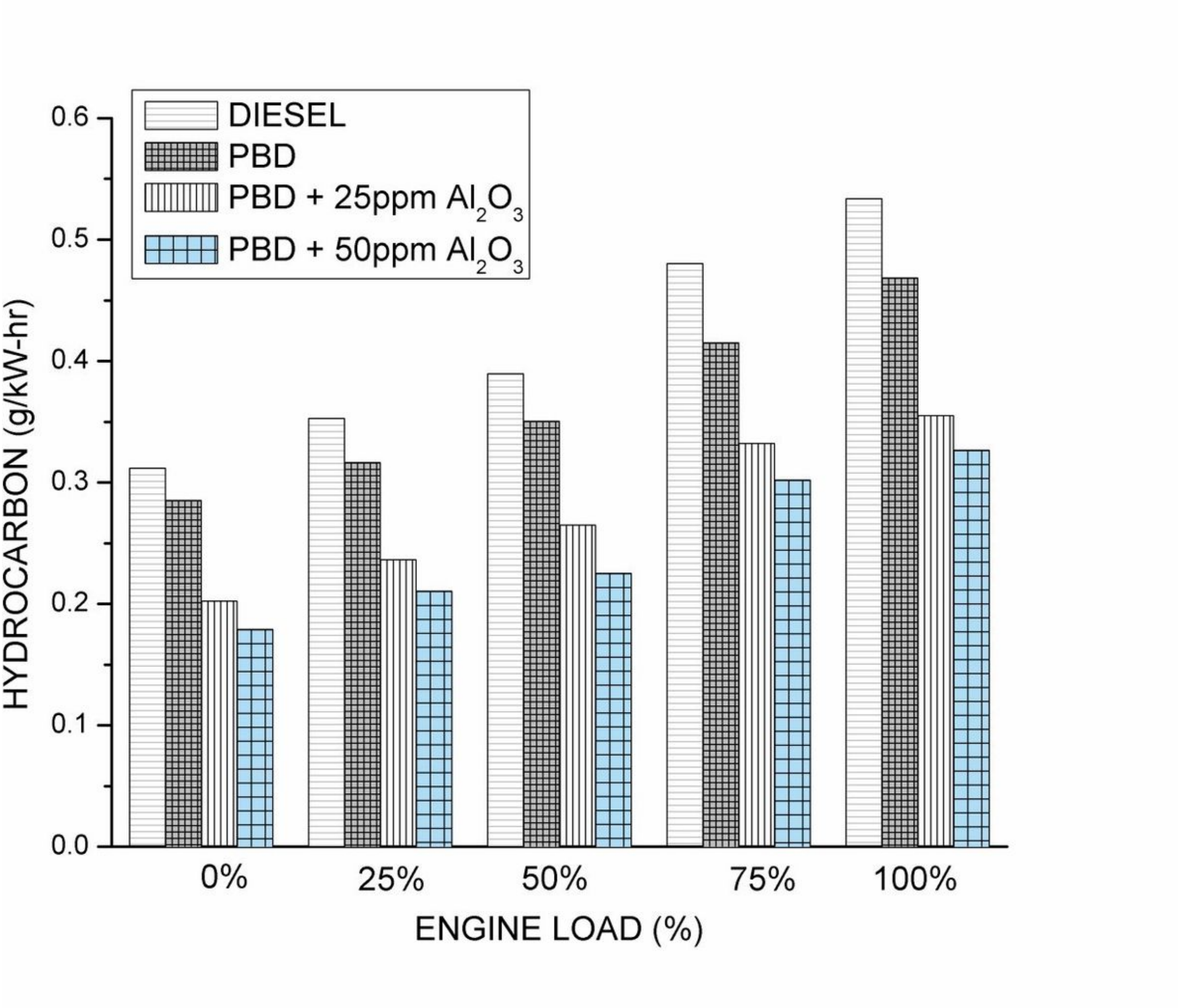

Figure 10

Variation of hydrocarbon (HC) with respect to engine load

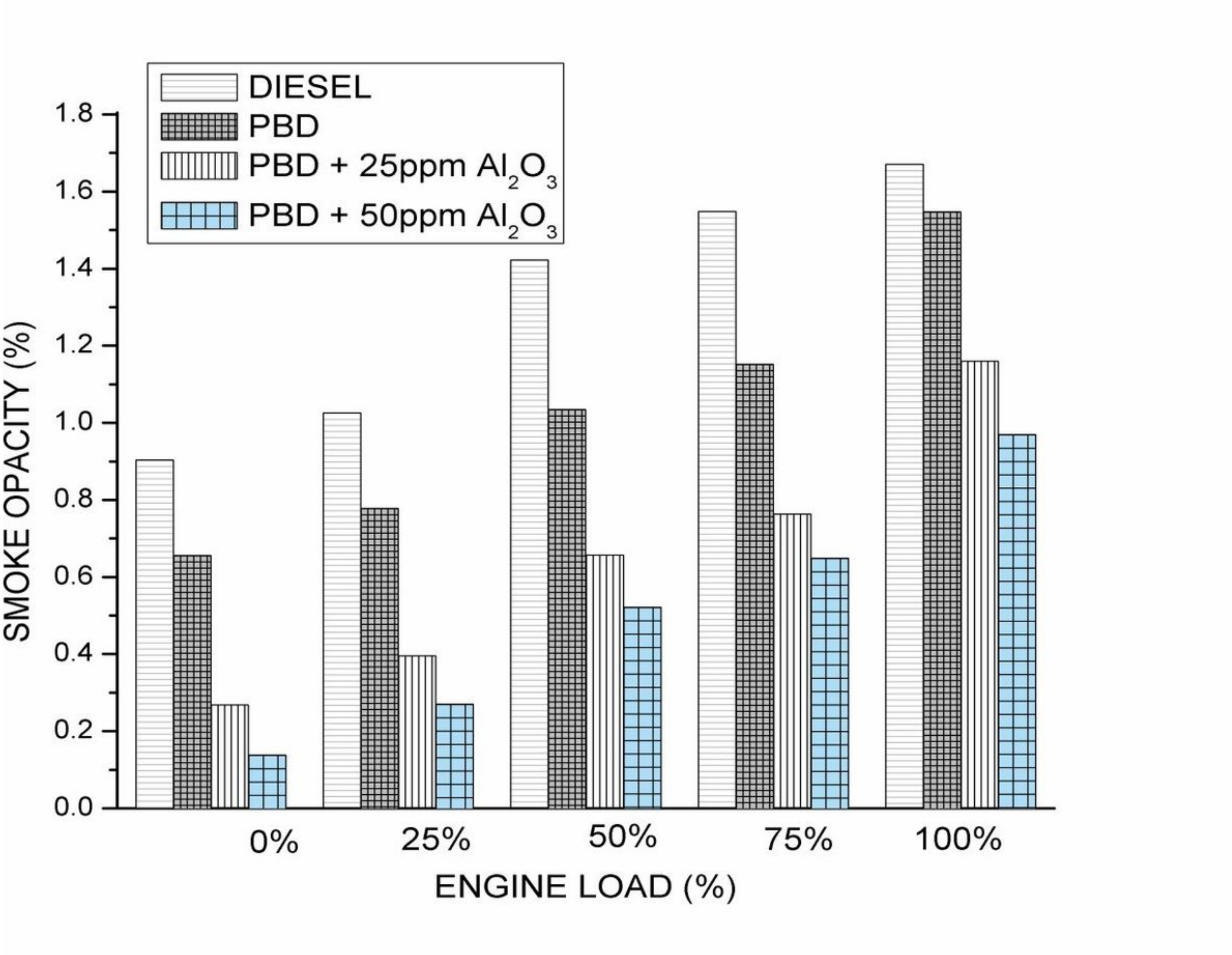

Figure 11

Variation of smoke opacity with respect to brake power

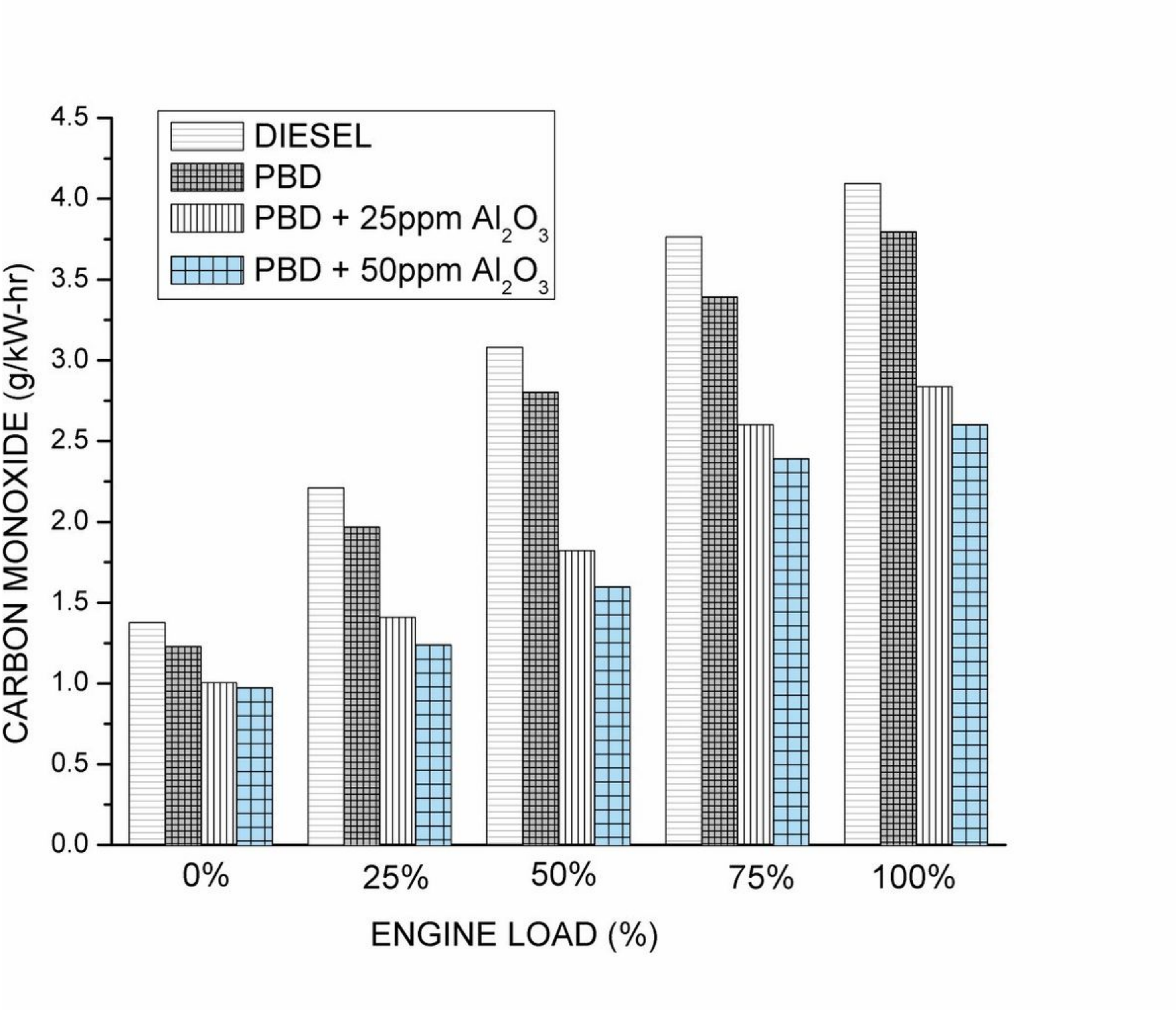

Figure 12

Variation of carbon monoxide (CO) with respect to engine load

Supplementary Files

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- Tables.pdf