PERFORMANCE EVALUATION OF DIRECT INJECTION DIESEL ENGINE FUELED WITH DIESEL-ZNO NANOPARTICLES BLENDS

Sanaur REHMAN**[1], Aijazul HAQ,[2] Taliv HUSSAIN[3] and Mohammad ASIF[4]

[1,2,3,4] Department of Mechanical Engineering, Zakir Hussain College of Engineering and Technology AMU, Aligarh-202002, UP, India

*Corresponding author; E-mail: sanaur.rehman@zhcet.ac.in

Present experimental study focused on investigating the effects of diesel-zinc oxide nanoparticles blends on the performance evaluation of a four stroke two-cylinder direct injection diesel engine. Two blends were employed to analyze engine combustion and performance parameters at various engine loads and constant speed (1500 rpm) conditions. Blends were prepared by dispersing zinc oxide nanoparticles with diesel fuel in different dosing levels through the ultrasonication process. One blend has 30 ppm zinc oxide nanoparticles per liter of diesel (D100ZnO30) and another has 60 ppm zinc oxide nanoparticles per liter of diesel (D100ZnO60). It was found that combustion and performance characteristics improved at higher engine loads for all blends. Present experimental results revealed that blending of zinc oxide nanoparticles in diesel fuel enhance engine performance due to better in-cylinder combustion. Combustion characteristics like maximum cumulative heat release, maximum net heat release rate and peak rate of pressure rise of diesel engine were promoted due to nanoparticles additive. Percentage increase of 9.09 and 10.09 in duration of combustion of D100ZnO30 and D100ZnO60 blends respectively than diesel was recorded at full load. At full load conditions, brake thermal efficiency was improved by 2.63 % and 0.36 % for D100ZnO30 and D100ZnO60 blends respectively as compared to diesel. Moreover, brake specific fuel consumption of D100ZnO30 and D100ZnO60 blends also improved significantly than diesel. Hence, it can be stated that zinc oxide nanoparticles in lower concentration would be an effective approach to significantly improve diesel engine combustion and performance parameters.

Keywords: zinc oxide nanoparticles; concentrations; diesel engine; performance; combustion, blending

1. Introduction

The escalating global energy demand, concerns over detrimental engine emissions and the depletion of fossil fuels have propelled the exploration of alternative fuels and fuel additives [1]. Among these alternatives, nano-fuel additives have gained attention as potential solutions to address the energy and environmental challenges [2-4]. Nano-oxide additives such as ZnO, TiO_2, CeO_2, CO_3O_4, and Fe_2O_3, etc., have been utilized to curtail fuel consumption and exhaust emissions [2]. These nanoparticles (NPs) have enhanced combustion kinetics and subsequently improved the overall combustion process. The incorporation of NPs like ZnO, TiO_2, and carbon nanotubes (CNT) have demonstrated enhanced heat transfer properties in vehicle cooling water and lubrication oil, aiding heat dissipation [5]. Nano-additives exert a positive influence on heat transfer and chemical reactivity, contributing to improved engine performance and emissions reduction [6]. Nano-additives reduce ignition delay, enhance oxidation rates, and mitigate exhaust emissions [6,7]. NPs, including metals (Fe, Al, Mg, Mn, Ag, Au, Cu, B, Si), metallic oxides (Al_2O_3, Co_3O_4, CeO_2, TiO_2, ZnO, CuO), and metallic combinations (Mg-Al, Carbon Nanotubes), serve as valuable additives in biofuel production, enhancing fuel properties and engine performance [7-9].

Many studies have been done on NPs addition in diesel fuel or diesel-biodiesel blends in diesel engines to investigate its performance [9-20]. Sukumar et al. [6] highlighted notable changes in CO and NOx emissions for biodiesel blends due to the incorporation of ZnO and Ag-ZnO NPs in diesel engines. Selvaganaapthy et al. [7] compared diverse NPs with diesel to enhance CI engine performance. Aalam and Saravanan [10] found that NPs additives could be an effective approach for improving combustion and performance characteristics of a CRDI diesel engine. Vali et al. [13] analyzed 30.75% brake thermal efficiency (BTE), 13.92 MJ/kWhr specific energy consumption, reduced emissions and enhanced in-cylinder pressure and heat release rate due to NPs addition in diesel fuel. Kumar et al. [14] investigated that addition of ZnO NPs improves heat transfer rates, flash point and fire point while enhancing energy storage capacity. Nanthagopal et al. [15] studied the addition of ZnO and TiO_2 in diesel blends and found that BTE improved by 5–17%. Moreover, addition of NPs led to reduced CO and HC, lower NOx, decreased smoke emissions across all engine loads, increased cylinder gas pressure and heat release rate [15]. Suhel et al. [16] found that ZnO NPs can be used as a suitable additive in waste plastic oil (WPO) to improve the overall engine characteristics. Venkatesan et al. [5] investigated that aqueous ZnO nanofluid with diesel improved engine combustion and emissions characteristics significantly. Singh et al. [17] found that blends of biobutanol and biodiesel doped with ZnO NPs improved diesel engine performance significantly. Youseef and Ibrahim [18] done performance evaluation on diesel engine using Zinc-Aluminate nanoparticles as additives and observed that nanoparticles slightly improved performance for certain engine operating conditions. Rajak et al. [19] used ZnO NPs in various concentrations in diesel fuel in CI engine and found better combustion characteristics and improved engine performance parameters for diesel-ZnO NPs blends than pure diesel. Chelliah et al. [20] studied influence of ZnO and TiO_2 nanoparticles doped diesel-biodiesel blends on the performance of diesel engine and results indicate relatively improved engine combustion, performance and reduced emissions.

On the basis of the previous studies [1-20] it can be stated that NPs improved combustion, performance as well as emission characteristics of pure diesel and diesel-biodiesel blends in diesel engines. Moreover, previous studies showed performance improvement of the diesel engine when operated on diesel-ZnO NPs and diesel-biodiesel-ZnO NPs blends. Few studies used ZnO NPs in varying concentrations in pure diesel fuel and most of the studies have been done on diesel-biodiesel-ZnO NPs blends. Therefore, current study aims to examine the effects of different dosing levels of ZnO NPs in pure diesel fuel on the combustion, ignition and performance parameters of direct injection diesel engine operating at varying loads and constant speed (1500 rpm) conditions. Moreover, it has been found in the literature that no previous study has been conducted on the diesel engine utilizing typical concentrations i.e., 30 ppm and 60 ppm of ZnO NPs per liter of pure diesel. The novelty of the present work is the doping of ZnO NPs in 30 ppm and 60 ppm concentrations in pure diesel fuel. The addition of ZnO NPs would compensate the poor combustion characteristics of pure diesel fuel in diesel engines and as a result shall improve engine performance significantly without any major engine modification. The objective of present study was to investigate and analyze various combustion and performance parameters of diesel engine fueled with ZnO NPs blends and their comparison with pure diesel fuel.

2. Experimental Set-up

In present experimental study, a two-cylinder, four-stroke, water-cooled, constant-speed, direct injection (DI) diesel engine was utilized and coupled with a hydraulic dynamometer as shown in Fig. 1. The experimental setup includes components such as Kirloskar diesel engine test bed, orifice meter, air box, pressure transducer, manometers, hydraulic dynamometer, thermocouples,

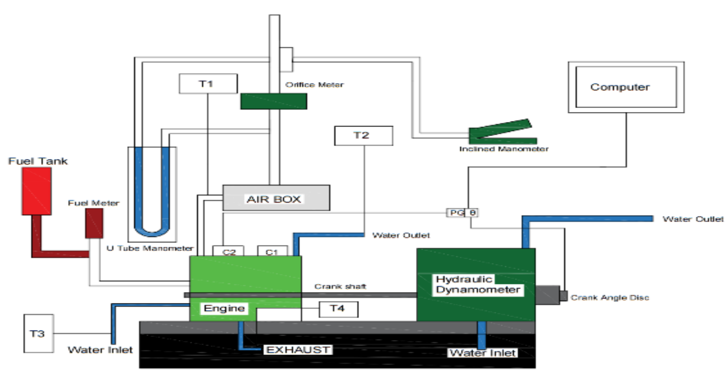


Figure 1: Block diagram of experimental setup

crank angle encoder, piezo powering unit, and a desktop computer. Engine test bed details are given in table 1. Accuracies of the instruments used in the setup are given in table 2.

During combustion, pressure within the cylinder was measured using a pressure transducer and a crank angle encoder at various engine crankshaft crank angles. K-type thermocouples were employed to measure inlet air and exhaust gas temperatures. The engine's load was measured through a hydraulic dynamometer. All combustion parameters were measured at each crank angle (CA) of a cycle. At each operating condition, average of five cycles were taken to ensure reliability in data and to minimize errors in obtained combustion parameters.

Table 1: Engine Test Bed Details [21]

Engine Type	**Kirloskar, TV2, 2-Cylinder, 4-Stroke, Water Cooled, Diesel Engine**
Power	10 kW @ 1500 rpm
Cylinder Bore	87.50 mm
Stroke Length	110.00 mm
Compression Ratio	17.50
Swept Volume	661.45 cc
Injection Timing	27^{o} bTDC
Orifice Diameter	25 mm
Fuel Pipe diameter	34.50 mm
Ambient Temperature	27 ^{o}C
Fuel Injection Pressure	200 bar

Table 2: Accuracy of Instruments Used [21]

Instrument	**Accuracy**
Pressure Sensor (Model S111A22)	± 0.1 mV/psi
K-type thermocouple	± 2.2 %
Hydraulic dynamometer	± 0.1 Kg
CA sensor	1 degree (resolution)

2.1 Experimental methodology

The experimental investigation was done on pure diesel fuel and ZnO NPs blends. The properties of diesel fuel used are given in table 3. Some properties of ZnO nanoparticles are given in table 4.

Initially, to ensure accurate measurements and reliable results, engine was first operated at no load for few minutes to achieve a steady state condition and then observations were taken. The load was applied in the order of 2, 4, 6, 8 and 10 kgf (full load) at a nearly constant engine speed of 1500 rpm. At a particular operating condition, pressure transducer installed in one of the engine cylinder and crank angle encoder at engine crankshaft gave signals to the computer to obtain various combustion characteristics graphs with the help of "IC Engine Soft' software as shown in Figs 3-6.

Table 3: Properties of Diesel Fuel [21]

Properties	**API gravity (degree)**	**Density (kg/m^3)**	**Aniline Point (°C)**	**Diesel Index**	**Flash Point (°C)**	**Cloud Point (°C)**	**Molecular mass (kg/kmol)**	**Boiling Point (K)**
Diesel Fuel	38.98	830	74	64.39	55	6	198	536.4

Table 4: Properties of ZnO Nano particles [22]

S. No	**Parameters**	**ZnO**
1	Chemical name	Zinc oxide
2	Form color	Powder white
3	Particle size	30–50 nm
4	Specific surface area	120 m^2/g
5	Purity	99.9%

2.2. ZnO NPs blends preparation and its stability analysis

The fuel blends were pure diesel (100% diesel), D100ZnO30 (100% diesel & 30 ppm ZnO NPs) and D100ZnO60 (100% diesel & 60 ppm ZnO NPs). Ideal nanofluid is the one with proper NPs suspension and its distribution as well as good stability. Nanoparticles can freely agglomerate and precipitate in the base liquid because of high surface to volume ratio and high surface charge [4]. Moreover, dispersion effectiveness and stability of a nanofluid are heavily dependent on the preparatory procedure [4]. Therefore, in the present study proper procedure of making nanoparticle blends is followed. Initially, ZnO NPs were weighted in the amount of 30 ppm with help of a precise weighing machine. Then, ZnO NPs were dispersed with diesel fuel using a probe sonication bath as shown in Fig. 2(a) for a duration of 30 minutes. A probe sonicator (equipped with a 12 mm probe diameter and a frequency of 40 Hz) was employed to blend the solution and ensuring prevention of sedimentation and agglomeration. Thereafter, ultrasonic waves were applied to blend for a duration of 30 minutes in the ultrasonicator called as ultrasonication (Fig. 2b). Finally, stable D100ZnO30 blend is prepared as shown in Fig. (c). Since nanoparticle blends remain stable for few days after their preparation as reported by Basha et al. [23], therefore these blends must be utilized as soon as possible. The prepared stable blend subsequently used in the engine to minimize the possibility of sedimentation and agglomeration. Same procedure is used for preparation of D100ZnO60 blend. Selvaganapthy et al. [24] followed the same method for the synthesis of diesel-ZnO NPs blends and used the blend immediately after its preparation. Also, Karthikeyan et al. [25, 26] followed the similar procedure (probe sonification and ultrasonication) for preparing diesel-ZnO NPs and diesel-biodiesel-ZnO NPs blends and hence developed stable NPs blends.

(a) Probe sonicator **(b) Ultrasonicator** **(c) ZnO NPs blend**

Figure 2. Procedure of making nanoparticle blends

2.3 Uncertainty analysis

The uncertainty of measured parameters was evaluated utilizing the Gaussian distribution method, with a confidence interval of ±2σ (indicating that 95% of measured values fall within the 2σ range of the mean). The maximum percentage deviations in parameters such as BTE, BSFC, BP, ID, and DOC are estimated to be 0.84%, 3.46%, 0.9%, 0.80%, 0.15% respectively.

3. Results and Discussion

3.1 Combustion and ignition characteristics

Combustion and ignition characteristics of pure diesel and diesel-ZnO NPs blends (D100ZnO30 and D100ZnO60) are analyzed at various engine operating conditions i.e., constant engine speed of 1500 rpm and full load (100% load).

3.1.1. Effect of ZnO NPs on cylinder pressure

The variation of in-cylinder pressure with crank angle (CA) is often analyzed to gain insights into the in-cylinder engine combustion process as shown in Fig. 3. The in-cylinder pressure versus CA was recorded for five cycles for all test cases in the present study. At 100% load, the peak in-cylinder pressure for diesel fuel is measured to be 64.03 MPa, occurring at a crank angle of 371^0. While using D100ZnO30 blend, the in-cylinder's peak pressure decreases to 63.44 MPa. Similarly, for the blend D100ZnO30, in-cylinder's peak pressure is recorded to be 63.15 MPa at the crank angle of 370^0. The peak in-cylinder pressure slightly decreases by the addition of NPs in various concentrations in pure diesel fuel. The percentage decrease in peak in-cylinder pressure of D100ZnO30 and D100ZnO60 with respect to pure diesel are found to be 0.92 and 1.3 respectively at full load condition. The percentage decrease of in-cylinder pressure is very nominal or insignificant when ZnO nanoparticles are added in pure diesel fuel. Thus, we can say that in-cylinder pressure almost remains same with the addition of ZnO NPs in diesel fuel. However, it is found that in several studies [4] that in-cylinder pressure rises when nanoparticles are doped in diesel fuel at full load. The improved in-cylinder peak pressure is due to high surface to volume ratio, high catalytic activity, micro-explosion phenomenon and increased burning velocity that results better fuel combustion [4]. Similar effects of ZnO nanoparticles on cylinder pressure is reported by Rajak et al. [19].

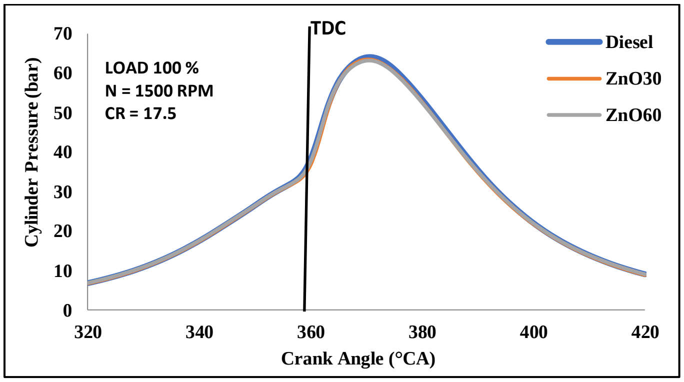


Figure 3: CP versus crank angle for diesel and ZnO NPs blends

3.1.2. Effect of ZnO NPs on cumulative heat release

The cumulative heat release (CHR) is indeed a crucial parameter for assessing the efficiency of combustion process [27]. It represents the total heat released from the fuel during the entire combustion event. The CHR curve has a characteristic S-shape as described [27]. The CHR curve shows the rate at which fuel-air mixture burns inside the combustion chamber over an appropriate crank angle duration. The CHR duration extends from start of fuel injection (SOI) to the end of combustion (EOC) [4]. Fig. 4 shows the CHR for diesel, D100ZnO30 and D100ZnO60 blends at 100% load condition. The maximum CHR values observed for diesel, D100ZnO30 and D100ZnO60 blends are 0.96 kJ, 0.97 kJ and 0.96 kJ at crank angles of 408°, 409° and 410° respectively. It is observed that ZnO nanoparticle blends show maximum CHR at a fixed crank angle. Increment is recorded in maximum CHR values of NPs blends as compared to diesel fuel and this trend is also reported in the study [4]. The reason may be the enhancement in the fuel properties due to the addition of NPs.

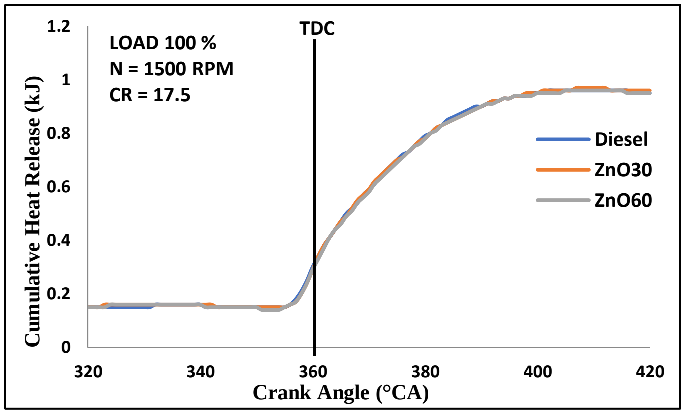


Figure 4: CHR versus crank angle for diesel and ZnO NPs blends

3.1.3. Effect of ZnO NPs on net heat release

The net heat release rate (NHRR) is a measure of the rate at which heat is released during the combustion process. The NHRR is calculated as per the approach adopted by Heywood [27]. NHRR is affected by the fuel viscosity, density and heating value, burning velocity and combustion temperature [4]. Fig. 5 shows the variation of NHRR with crank angle for diesel and NPs blends at full load and 1500 rpm engine condition. The average of NHRR of five engine cycles is calculated to minimize combustion irregularities. Initially, NHRR is having negative values due to fuel atomization and droplet vaporization effects [28]. The heat transferred from the hot compressed air to the high-pressure fuel droplets to initiate fuel autoignition phenomenon. Once fuel is auto-ignited, heat release increases towards the positive values and the peak rises rapidly. In present study, maximum NHRR observed for pure diesel fuel is 46.56J/°CA while for D100ZnO30 and D100ZnO60 blends, maximum NHRR are found to be 50.20J/°CA and 46.67J/°CA respectively at same CA (363°). The percentage increase in NHRR of D100ZnO30 and D100ZnO60 blend with respect to pure diesel are 7.8 and 0.24 respectively. Increase in NHRR of NPs blends than diesel is due to increased oxygen content, improved thermal conductivity, micro-explosion of fuel droplets (rapid atomization and fast evaporation) and high burning velocity [4,5,29]. Similar trend in NHRR is reported in the study [30] for various concentrations of ZnO NPs in diesel fuel. Gavhane et al. [31] also reported similar trend in NHHR due to the addition of ZnO NPs in diesel that causes enhancement of oxygen content in combustion and atomization of fuel particles.

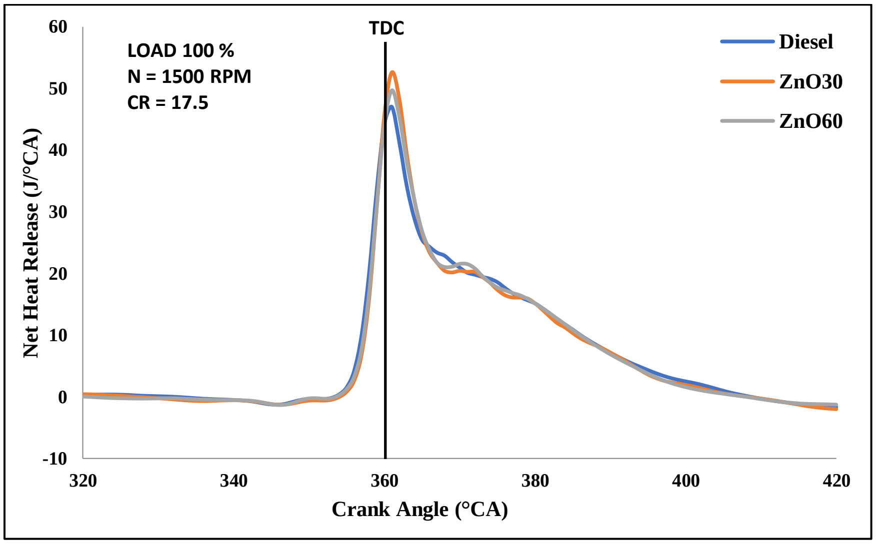


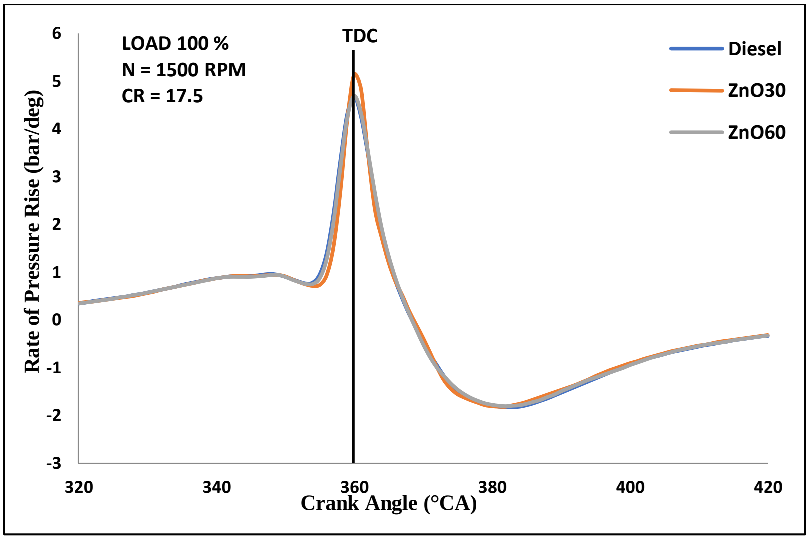
Figure 5: NHRR versus crank angle for diesel and ZnO NPs blends

3.1.4. Effect of ZnO NPs on rate of pressure rise

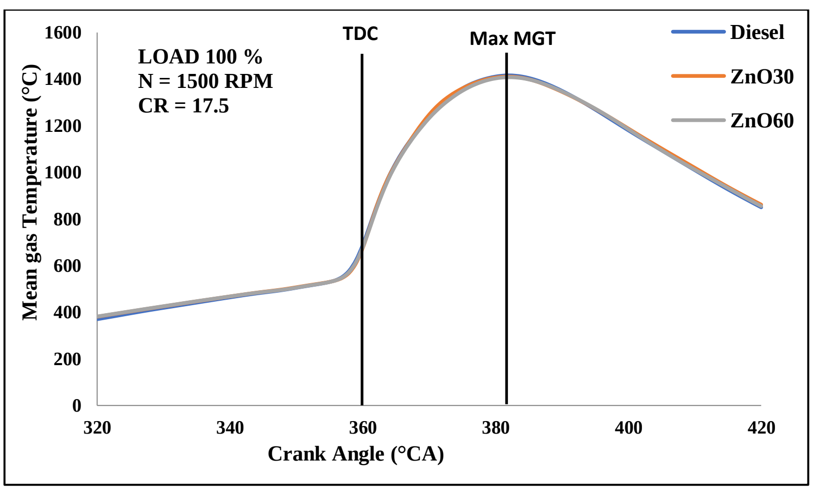
The rate at which the pressure within the engine cylinder increases during the combustion process is known as rate of pressure rise (ROPR). ROPR in engine cylinder during combustion is significantly dependent on the NHRR [27]. It can be seen in Fig. 6(A) that maximum rate of pressure rise recorded for D100ZnO30, D100ZnO60 and diesel fuel are 5.05 bar/deg, 4.69 bar/deg and 4.68 bar/deg respectively at full load condition. Maximum pressure rise rate is found for the NPs doped diesel-biodiesel blend than pure diesel fuel in the diesel engine at maximum load condition in the study [32], which is a similar finding as in present study. A greater rate of pressure rise was actually noticed for the D100ZnO30 NPs blend because of its improved NHRR.

3.1.5. Effect of ZnO NPs on mean gas temperature

Figure 6(B) illustrates the effect of NPs blends on the mean gas temperature (MGT) with respect to diesel fuel. Mean value of cylinder temperature of the burned and unburned gases present in the engine cylinder during a cycle is called as mean gas temperature (MGT). MGT of the fuel depends on rate of chemical reaction and ideal value should be near to the adiabatic flame temperature. Adiabatic flame temperature is reached when there is no loss of heat during combustion process to the cylinder walls i.e., combustion process is adiabatic. At full engine load condition, all nano-additives blends in the present work exhibited higher MGTs as compared to pure diesel fuel. The maximum MGT of pure diesel fuel, D100ZnO30 and D100ZnO60 blends were measured to be 1408.92°C, 1413.64°C and 1410.05°C respectively at a crank angle of 382°. Lower MGT for NPs blends as compared to pure diesel is reported in the study by Gavhane et al. [31]. Moreover, Gavhane et al. [31] also found peak MGT at nearly 379-380° CA for ZnO nanoparticles blends. The reason behind present observation of MGTs can be attributed to the improvement in thermophysical properties of NPs blends that results in high CHR. The presence of these NPs in the fuel mixture enhances combustion efficiency and promotes better homogenization of the NPs in the diesel fuel [4,15].



(A)



(B)

Figure 6: (A) ROPR versus crank angle for diesel and ZnO NPs blends, (B) MGT versus crank angle for diesel and ZnO NPs blends

3.1.6. Effect of ZnO NPs on ignition delay

Ignition delay (ID) in diesel engines is the time span between fuel injection commencement and the start of ignition [21,27]. Fig. 7(A) highlights the ID variations for the NPs blends along with pure diesel at various loads. Fig. 7(A) shows increment in the ID periods with the addition of ZnO NPs. It can be noticed in Fig. 7(A) that ID reduces at higher loads due to increased cylinder temperature and pressure [27]. The ID values for pure diesel, D100ZnO30, and D100ZnO60 are 7, 15 and 15 CA respectively at full load condition. The change in ID values of blends due to addition of ZnO NPs is attributed to the significant change in fuel properties of blends [4]. With increase in concentrations of ZnO nanoparticle from 30 ppm to 60 ppm, ID increases at all loads. This effect is due to the fact that viscosity of blend increases slightly with high concentration of NPs. Similar effect on ID by the NPs concentration is also reported in the study conducted by Gavhane et al. [31].

3.1.7 Effect of ZnO NPs on duration of combustion

Duration of combustion (DOC) or combustion duration can be defined as the time difference in milliseconds between start of combustion and the end of combustion [33]. DOC can also be defined as the crank angle interval between crank angle corresponding to 5% (CA5) and 95% (CA95) mass burnt [34]. Fig. 7(B) shows the variation of DOC of pure diesel and ZnO NPs blends at various load conditions. It can be noticed in Fig. 7(B) that DOC reduces with the addition of doses of ZnO NPs in the diesel fuel i.e., ZnO NPs blends have significantly lower DOC than pure diesel. This may be due to the fact that doping of ZnO NPs in diesel causes micro-explosion of the fuel droplets and rapid fuel evaporation and fuel-air mixing process that resulted in the faster combustion process [4]. Moreover, addition of ZnO NPs increases the oxygen quantity in the air-fuel mixture thereby accelerates the combustion process and therefore DOC reduces El-Adawy [4]. At full load condition, percentage reduction in DOC for D100ZnO30 and D100ZnO60 as compared to diesel were 9.09% and 10.09% respectively. El-Adawy et al. [4] showed reduction in DOC for NPs blends as compared to diesel fuel. While at 20% load condition, percentage reduction in DOC for D100ZnO30 and D100ZnO60 as compared to diesel were 3.70% and 5.55% respectively.

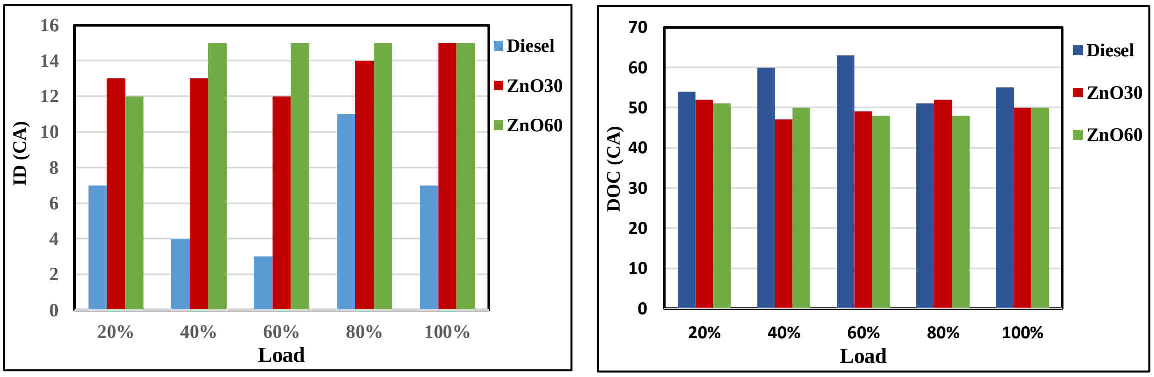


Figure 7. (A) Variation of ID of diesel and ZnO NPs blends at various loads, (B) Variation of DOC of diesel and ZnO NPs blends at various loads

3.2. Engine performance parameters

Effects of ZnO NPs blends on engine performance parameters such as brake power (BP), brake thermal efficiency (BTE), and brake specific fuel consumption (BSFC) are analysed at various engine loads and constant speed (1500 rpm) conditions.

3.2.1. Effect of ZnO NPs blends on brake power

Fig. 8 shows comparison of engine BP of pure diesel and ZnO NPs blends at various loads. Engine power is basically dependent on the heating value or calorific value of the fuel or blend burnt in the cylinder of the engine. Generally, higher the heating value of the fuel more will be the BP or torque developed by the engine [4]. It can be seen in the Fig. 8 that BP of all blends increases with increase in load and this may be due to the fact at higher loads more amount of fuel burnt in the engine cylinder that generates higher BP [27]. Moreover, it can be noticed in Fig. 8 that BP of ZnO NPs blends are slightly lower than pure diesel fuel at all loads. However, slightly higher BP is reported for the NPs blends than pure diesel in the study [4].

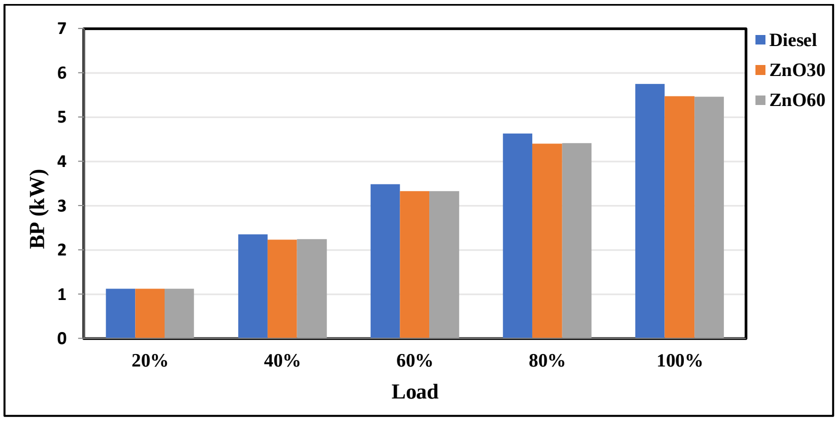


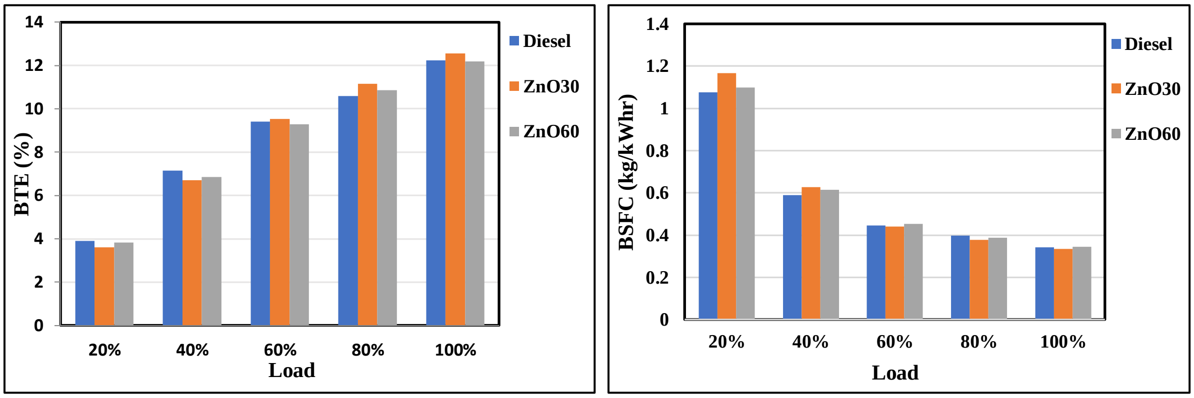
Figure 8: Comparison of BP of diesel and ZnO NPs blends at various loads.

3.2.2 Effect of ZnO NPs blends on brake thermal efficiency

Brake thermal efficiency (BTE) of engine can be significantly improved by improving the combustion process [4,27]. Moreover, engine combustion improves when heat losses in the engine cylinder are minimum. Fig. 9(A) shows the variation of BTE of pure diesel and ZnO NPs blends at various loads. It is found in Fig. 9(A) that BTE improves at higher engine loads which is due to the fact that better combustion occurs at higher engine loads [2, 4]. In Fig. 9(A), it is also observed that highest BTE is found for ZnO NPs blends than diesel at all loads. Higher BTE for ZnO NPs blends is due to high surface to volume ratio of ZnO NPs, which results in good atomization and rapid evaporation of the liquid fuel droplets, thereby improving the combustion efficiency [2]. Addition of NPs enhances fuel dispersion inside the combustion chamber due to a wider spray cone angle and faster fuel droplet propagation which cause more fuel oxidation, easy droplets formation, reduced fuel cohesiveness and viscosity [Ansari 2023]. Similar trend of BTE with load is found in the studies [3, 31, 32]. Percentage increase in BTE for D100ZnO30 and D100ZnO60 blends than pure diesel is 2.63% and 0.3 % respectively.

3.2.3. Effect of ZnO NPs blends on brake specific fuel consumption

Brake specific fuel consumption (BSFC) is defined as the rate of fuel consumption per unit brake power generated by the engine. It is found in many studies that addition of NPs in fuel to improve the engine's brake specific fuel consumption is a preferred method [4, 35].



(A) **(B)**

Figure 9: (A) Comparison of BTE of diesel and ZnO NPs blends at various loads, (B) Comparison of BSFC of diesel and ZnO NPs blends at various loads.

BSFC of the fuel with ZnO nano-additives is significantly lower than that of pure diesel as shown in Fig. 9(B). ZnO NPs blends showed lower fuel consumption than pure diesel fuel as illustrated in shown in Fig. 9(B). Addition of ZnO NPs showed a considerable decline in the BSFC due to better combustion inside the combustion chamber [4]. Moreover, ZnO NPs increase the heating value that leads to better combustion [4]. The ZnO NPs dispersed into the diesel were able to enhance atomization and improve the air-fuel mixture homogeneity. In addition, these NPs increase the surface area to volume ratio, which leads to better combustion and lowers fuel consumption. In the studies [3,22,31,32], similar trends of BSFC with load are reported for pure diesel and NPs blends. Improvement in BTE and BSFC of NPs blends than pure diesel or diesel-biodiesel blends is found in many previous studies [4, 16, 20, 22, 29, 30,32].

4. Conclusions

The aim of the present study was to examine the effects of various doses of ZnO NPs in diesel fuel on the ignition, combustion and performance characteristics of diesel engine operating on varying load and constant speed conditions. The main findings of the study are summarized below:

- All combustion and performance parameters improved at higher engine loads for diesel fuel as well as for ZnO NPs blends.
- The combustion characteristics like maximum CHR, maximum NHRR, peak ROPR and maximum MGT were enhanced due to ZnO NPs addition in diesel. Improved and faster combustion is observed due to better fuel properties of NPs blends like micro-explosion phenomenon, higher heating value, high oxygen content, high flame velocity and high surface to volume ratio.

- Percentage increase of 7.8 and 0.24 in peak NHRR of D100ZnO30 and D100ZnO60 blends respectively than diesel was found at full load. Also, percentage decrease of 9.09 and 10.09 in DOC of D100ZnO30 and D100ZnO60 blends respectively than diesel was recorded at full load. Blend D100ZnO30 showed somewhat better combustion and performance characteristics than D100ZnO60 blend.
- At full load condition, BTE was improved by 2.63% and 0.36% for D100ZnO30 and D100ZnO60 blends respectively than diesel. Moreover, BSFC of D100ZnO30 and D100ZnO60 blends also improved than diesel. However, engine emissions are not studied in present work but it is found in previous studies that they are reduced appreciably through the use of ZnO NPs blended fuels.
- It can be concluded that addition of ZnO nano-additives in pure diesel fuel in proper concentration would significantly improves blends properties that enhances in-cylinder combustion thereby producing good engine performance.

Nomenclature			
ID	Ignition delay	CA	Crank angle
MGT	Mean gas temperature	Cu	Copper
NHR	Net heat release	Al	Aluminum
ROPR	Rate of pressure rise	CA	Crank Angle
CHR	Cumulative heat release	TiO_2	Titanium Oxide
TDC	Top dead centre	ICE	Internal Combustion Engine
BDC	Bottom dead centre	CuO	Copper Oxide
CP	Cylinder pressure	Al_2O_3	Aluminum oxide
DI	Direct Injection	ZnO	Zinc oxide
NPs	Nanoparticles	DOC	Duration of combustion

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