Effects of hexagonal boron nitride based nanofluid on the tribological and performance, emission characteristics of a diesel engine: An experimental study

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Abstract
In recent years, nanoparticles have attracted researchers attention due to its wear and friction reduction characteristics in lubricating oil. Hence, it is of utmost importance to consider nanoparticles additive in the lube oil and study its impact on the tribological and performance characteristics of mechanical systems. Therefore, this paper intends to explore the impact of conventional and hexagonal boron nitride (hBN) nanoparticles-based lubricant on the wear of engine components, performance, and emission characteristics of a diesel engine. The different concentration namely, 0.5 wt.%, 0.75 wt.%, and 1 wt.% BN-based nanofluids were formulated. The formulated nanofluids were characterized by UV-spectroscopy and differential scanning calorimetry (DSC) for dispersion and heat capacity analyses respectively. From the characterization results, 1wt.% BN nanofluid was found stable and well dispersed and therefore, considered for further experimental analysis. The outcomes of the present study revealed that 1 wt.% BN-based nanofluid shown better anti-wear properties and improvement in performance, emission characteristics of the diesel engine. The obtained results will be useful for the lubricant industry to think toward formulating nanoparticles-based lubricating oil.

KEYWORDS
diesel engine, hexagonal boron nitride nanoparticle, UV-spectroscopy, differential scanning calorimetry, wear

1 INTRODUCTION

Reliability, higher fuel efficiency and durability properties of the diesel engine are making it more versatile in the automotive and agricultural industries. However, the endeavors are still going on to reform the performance and emission standards of diesel engine. A diesel engine comprises of an enormous number of moving components. Poor lubrication between these components may lead to frictional losses and wear of the moving surfaces. Further, during the combustion process, higher pressure and temperature have been experienced by the components of a diesel engine. This results in additives depletion in the lubricating oil present at the interface thereby causing the wear of engine...
components particularly piston rings and liner which influences the overall performance of the engine. Hence, it is necessary to understand the role of nanoparticles in lube oil and analyze its impact on the tribological, performance, and emission characteristics of a diesel engine.

Lubricating oil also plays a significant role in reducing the emission standards of a diesel engine as it takes part in the combustion process by three different ways such as keeping the thin film of lubrication between cylinder liner and piston rings, lubrication in the crankshaft and the valve guides of the engine. Gligorijevic et al. examined the effect of lubricating oil on the exhaust emissions of a diesel engine. Authors have considered mineral oil SAE 15W40 and synthetic oil (PAO) 5W40 to monitor the emission levels of a diesel engine. The results revealed that the mineral oil produced higher emissions of particulate matters (19%-24%) and NOx (8%) as compared to synthetic oil. Zara et al. conducted experimental studies to investigate the impact of diesel and waste lubricating oil on the performance and emission parameters during hot and cold starts of a diesel engine. The diesel fuel was mixed with waste lubricating oil in the concentration of 1% and 5%. The results revealed that amid the cold start of the engine with 5% waste lube oil, a significant reduction in the particle number and size, an increment in the rate of pressure rise and indicated mean effective pressure was observed. On the other hand, during the hot start of the engine, an increment in the particle number, size and friction mean effective pressure was observed. Wei et al. investigated the impact of nano-copper additives based lubricant on the exhaust emission of a diesel engine. The results revealed that the nano-additives showed a good catalytic effect on the combustion process due to which the combustion temperature reduced to 520°C from 580°C. Further, the reduction in the exhaust emission parameters such as particulate matter, HC and CO by 99.9%, 33.33%, and 81.30% was observed due to nano-additives based lubricant. Musthafa investigated the effect of synthetic oil lubricant and conventional lubricant SAE 40 on the performance and emission characteristics of the diesel engine. Authors have considered two different types of the engine such as coated and uncoated. The coated type of engine was operated with synthetic lubricant whereas the uncoated type of engine was operated with conventional engine oil SAE 40. Authors have concluded that the decrement in engine efficiency (5%-9%) and specific fuel consumption (8%-17%) and improvement in exhaust emission parameters except NOx was observed in coated type engine with synthetic lubricant. Mohammad et al. examined the rheological characteristics of synthetic lubricant 5W50 by blending multiwalled carbon nanotube (MWCNT) and zinc oxide (ZnO) nanoparticles in the ratio of 30% to 70%. Authors have noticed non-Newtonian nature of lubricating oil by the addition of MWCNT and ZnO nanoparticles which helped to reduce the damage to the cold start engines and thereby results in the improvement of the performance and emission characteristics of the engine. Further, the authors stated that the low concentration of nanoparticles (0.75% volume fraction or less) provides better lubrication at a higher temperature. Xu et al. studied the effects of lubricants additives on the characteristics of diesel exhaust particulate matter (DEPM). The additives such as antioxidant, foam inhibitor and detergent were blended with diesel fuel. The results showed an increment in the chemical heterogeneity of DEPM when combustion takes place with antioxidant-diesel fuel whereas, with foam inhibitor-diesel fuel, an increase in average crystallite size of primary carbon particles (PCP) was observed. Further, the increase in interlayer spacing of PCP was observed in case of detergent-diesel fuel. Kim et al. compared the impacts of lube oil with and without additives on the exhaust emission of a diesel engine. The additives-based lubricant indicated a decrease in total hydrocarbon and CO emissions while an increment in NOx emission due to the variation in lubricant composition and viscosity levels. An increment in particle numbers and reduction in particulate matter size were also noticed due to additive-based lubricant as compared to base lubricant. Guangju et al. studied the impact of pure diesel and diesel/oil mixed fuel on the micropysical properties of exhaust particulate matter. A reduction in particle concentration by 46.5% in nuclear mode and an increment by 47.4% in the accumulated mode were observed due to the combustion of diesel/oil mixture. Further, the reduction in oxidation and decomposition of particulate matter was observed because of the coagulation and collision of ash content in the oil after combustion. In the past few years, many researchers worked on the use of nanoparticles in the diesel fuel on account of its inclination to improve combustion efficiency and reduce the exhaust emission. Nanoparticles are responsible for increasing the thermal conductivity of base fluid because of its size which is generally in the extent of 1 to 100 nm. The nanoparticles dispersion in the base oil is termed as Nanofluid. Most of the literature was focused on the use of oxide-based nanoparticles such as aluminium oxide (Al2O3), copper oxide (CuO), and titanium oxide (TiO2) due to their increasing combustion efficiency characteristics. The performance and wear analyses of a diesel engine using nanofluid were investigated by Kotia et al. SiO2 and Al2O3 nanoparticles-based nanofluids were used to assess the wear and performance characteristics of a diesel engine. Authors have considered SAE 15W40 lubricating oil to formulate nanoparticles-based nano lubricants and carried out tribological tests using pin-on-disc apparatus. The study revealed that 0.3 vol% Al2O3 nanofluid showed better tribological and performance characteristics. Further, the authors stated that the surface polishing and ball bearing effects of nanoparticles in the lubricating oil were responsible for reducing the wear of pin and disc material. Further, Kotia et al. examined the performance of diesel engine using
Al₂O₃ nanoparticles-based nanolubricants. Authors have concluded that 0.3 vol% Al₂O₃ nanofluid helped to reduce the frictional losses and thereby increased the brake thermal efficiency of a diesel engine.

Many researchers examined the tribological characteristics of nanoparticles-based lube oil using emulator tribotesting machines. Srinivas et al. ¹⁷ contemplated the physio-chemical and tribological characteristics of surface-modified MWCNT using four balls tester. Authors have considered cetrimonium bromide and sorbitan monooleate surfactants to surface modify the MWCNT. Further, they suggested that the friction and wear characteristics of lubricant with modified MWCNT showed better tribological behavior due to their enhanced stability. Gayatri et al. ¹⁸ studied the tribological behavior of dodecylamine functionalized graphene nanosheets-based lubricating oil using UMT-2 tribotester. Authors have concluded that SAE 5W30-based nanolubricant was helpful to reduce the coefficient of friction (COF) by 40% in comparison to the base engine oil. Further, the authors concluded that the formation of protective film on the worn surfaces was the plausible mechanism for reducing the COF whereas the variation in sliding velocity, load, and concentration have a considerable impact on COF. The tribological analysis of low-density polyethylene nanocomposites (LDPE) was investigated by Hassan et al. ¹⁹ using graphene nanoplatelets (GNP) and paraffin oil (PO) as a base additive using pin-on-disc tribotester. Authors stated that LDPE/GNP nanocomposites showed better tribological characteristics as compared to pure LDPE because of the development of transfer film amid sliding. Further, the addition of PO in LDPE augmented the friction and wear rates. Furthermore, authors studied the mechanical properties of LDPE/GNP nanocomposites and stated that the microhardness and elastic modulus of LDPE were increased due to the increase in the concentration of GNP as it shows strengthening behavior. The anti-friction and anti-wear behavior of CuO nanoparticles-based coconut oil were examined by Thottackkad et al. ²⁰ by utilizing a pin-on-disc tribometer. The results showed that the wear and friction properties of CuO based coconut oil increased as compared with the neat coconut oil. Moreover, friction and wear were increased when the concentration of nanoparticles increased beyond a certain limit. Further, the authors stated that the reduction in the COF value and wear was because of the sliding to rolling behavior of nanoparticles. Tribological behavior of Zn and Cu oxides-based vegetable oil lubricant were studied by Alves et al. ²¹ using high-frequency reciprocating test rig. Authors noticed a significant improvement in the tribological properties of oxides-based vegetable oil lubricant. Further, they concluded that the formation of smoother and compact tribofilm on the worn surfaces minimized the wear and friction. Mohan et al. ²² examined the tribological characteristics of SAE 20W40 lube oil with and without Al₂O₃ nanoparticles by using the pin-on-disc tribotesting machine. Authors have formulated three different concentration, namely, 0.25, 0.5, and 0.75 wt.% nanolubricants and tested with pure oil. The results revealed that 0.5 wt.% Al₂O₃ nanolubricant showed better tribological properties due to its rolling effect under flooded condition. Srinivas et al. ²³ investigated the anti-frictional properties by dispersing WS₂ and MoS₂ nanoparticles in the concentration of 0.05 and 0.1 wt.% in SAE 20W40 motor oil by using pin-on-disc apparatus. Authors have concluded that, at lower loads, MoS₂ and higher loads, WS₂ dispersed nanolubricants showed lower friction coefficient values. Further, Srinivas et al. ²⁴ studied the antifriction, antiwear, and extreme pressure (EP) properties of SAE 20W40 engine oil by dispersing MoS₂ nanoparticles in the concentration of 0.25, 0.5, 0.75 and 1 wt.% using four-ball tester. The results showed that 0.25 and 0.5 wt.% MoS₂-based nanolubricants shown a decrease in friction coefficient, wear scar diameter, load wear index, and weld load because of the nanoparticles deposition on the worn surfaces. Sajith et al. ²⁵ analyzed the lubricating oil properties namely, viscosity, kinematic viscosity and flash point under different temperatures ranging from 30 to 65°C by dispersing CuO and Al₂O₃ nanoparticles in the volume fraction varying from 0.02 to 0.2% in the SAE 20W40 engine oil. Authors have observed that in the case of CuO nanoparticles, the viscosity and the flashpoint of the oil was decreased with the increasing concentration. Further, in the case of Al₂O₃ nanoparticles, the kinematic viscosity and the flashpoint were observed to be increased up to the concentration of 0.02% and then decreased.

Boron nitride (BN) nanoparticles exhibit good tribological properties. They are effectively used for lubricating the surfaces operating at higher temperature and pressure. They have a high thermal conductivity which makes them applicable where the application involves rapid heat removal rate. The nanoparticles in powder form are well-known solid lubricant due to their friction reduction and tribofilm formation behavior. They are environmentally friendly and inert to most of the chemicals which make them appealing for most of the tribological applications. ²⁶ Effect of dispersant with and without BN nanoparticles was studied by Gupta et al. ²⁷ using four-ball testing machine. The results showed that in the presence of a dispersant, BN nanoparticles did not play an effective role in the lubricating oil; however, it is proven as a good anti-wear additive by enhancing weld load properties of lubricating oil. Further, the authors stated that the enhancement in anti-wear and EP properties was due to the tribofilm formation on the worn surfaces. Mursel et al. ²⁸ examined the wear and friction characteristics of epoxy resin by the addition of BN nanoparticles using ball-on-disc tribometer. Authors have formulated four different concentration, namely, 0.3, 0.5, 0.7, and 1 wt.% BN/epoxy mixture. The results indicated that 0.5 wt.% BN/epoxy mixture showed a lower COF and wear due to the lamellar structure of BN.
nanoparticles. Furthermore, it was noticed that the conduction property of epoxy resin was enhanced due to the addition of BN nanoparticles. The EP properties of hBN as an engine oil additive in SAE 15W-40 was investigated by Muhammad et al\textsuperscript{29} using a four-ball tribotesting machine. The outcomes indicated that hBN-based lube oil has the potential to minimize the wear of the mating surfaces due to the development of tribofilm on worn out surfaces. Further, the authors stated that the improvement in load-carrying and EP ability of lube oil was enhanced due to the dispersion of hBN nanoparticles. The tribological characteristics of epoxy resin were studied by Hayrettin et al\textsuperscript{30} using MWCNT and hBN as nanoparticles additive in epoxy resin by using a ball-on-disc test. The results revealed that modified epoxy resin has shown improved wear resistance and friction reduction behavior at higher working temperature. Further, the authors suggested that thermal softening showed a pivotal role in minimizing friction and wear of polymeric material. Jaime et al\textsuperscript{31} formulated and studied the high thermal conductivity Newtonian nanofluids by incorporating the exfoliated layers of two-dimensional hBN in the standard transformer mineral oil. The results demonstrated that the hBN-based mineral oil indicated higher electrical and thermal conductivity in comparison to the graphene-based conventional mineral oil. Further, Jaime et al\textsuperscript{32} developed multifunctional nanofluids by using two-dimensional hBN and graphene nanofillers reinforced in conventional mineral oil for studying thermal and tribological characteristics. Authors have considered two tribological tests namely ITEePib polish and ASTM D5183 methods to monitor the wear and friction coefficient. The results revealed that the minimum concentration of nanofillers/nano-additives minimized the COF and wear scar to a more prominent extent with higher thermal performance. Furthermore, Jaime et al\textsuperscript{33} carried out molecular dynamic simulation and experimental analysis to investigate the thermal conductivity of two-dimensional hBN nanosheets dispersed in conventional mineral oil. Authors have proposed that the predicted thermal conductivity by using Green-Kubo autocorrelation function and transient hot-wire method were found in a good agreement. Charoo and Hanief\textsuperscript{34} studied the lubrication characteristics by incorporating three distinct nanoparticles namely hBN, tungsten disulphide (WS\textsubscript{2}) and graphite by using the ball-on-disc tribotesting machine. Authors have concluded that among the studied nano-additives-based lubricants, hBN-based nanolubricant showed a better reduction in COF and wear. Zhao et al\textsuperscript{35} studied the tribological performance of polydopamine modified hBN and cubic boron nitride (CBN) epoxy resin by using a reciprocating type ball-on-plan tribotesting machine. The outcomes indicated that the COF value was diminished under dry and seawater condition because of the self-lubricating effect of hBN nanoparticles and high hardness of CBN particles. Further, the authors concluded that the CBN-based epoxy resin showed lower wear rates as compared to hBN-based epoxy resins. Cagri et al\textsuperscript{36} analyzed the effects of hBN-based minimum quantity lubrication (MQL) on the turning of Ni-based Inconel 625 by considering tool wear, tool life, tool-chip interface temperature, and surface roughness. Authors have carried out analysis with four different lubricating conditions namely, dry, pure MQL, 0.5 vol.% and 1 vol.% nano-fluid MQL. The outcomes demonstrated that 0.5 vol.% nano-fluid MQL indicated low tool wear, high tool life, and low surface roughness. Wang et al\textsuperscript{37} carried out experimental studies to analyze the impact of covalent functionalized hexagonal boron nitride nanosheets (h-BNNSs) as an additive on the tribological behavior of lubricating oil by using a four-ball tribotesting machine. Authors have functionalized h-BNNSs with 3-aminopropyltriethoxysilane and 4-carboxyphenylboronic acid (CPBA). The outcomes indicated that CPBA-BNNSs showed the reduction in friction coefficient, wear scar diameter and mean wear volume by 32.3%, 42.9% and 88.4% respectively due to the formation of protective film on the worn-out surfaces. Ma et al\textsuperscript{38} examined the impact of exfoliated BNNSs as an additive on the tribological properties of base oil by using ball-on-ball configuration. The results showed the reduction in the COF and wear scar diameter by 35.7% and 35.2% respectively because of the formation of tribolayer on the counterpart surfaces. He et al\textsuperscript{39} examined the tribological performance of hBN nanofluids by utilizing four-ball and pin-on-disc tribotesting machines. The reduction in friction coefficient and wear scar diameter was observed by as much 29% and 15%, respectively, using hBN based nanofluid. Further, the authors stated that the decrease in friction and wear rates was because of the sliding, rolling, polishing and mending effect of nanoparticles causing tribofilm on the worn surfaces.

In a previous work,\textsuperscript{40} we have carried out tribological analyses of engine components using hBN-based nanofluid by employing a realistic diesel engine. The results showed that the friction and wear of engine components were minimized due to the mending/patching effects of nanoparticles in the base oil which resulted in the formation of tribolayer. However, the effects of base oil and nanofluid on the overall performance of the engine were not investigated. Further, several studies have been carried out to analyze the tribological properties of lubricating oil using nano-additives to minimize the friction and wear of mating surfaces but their effects on the overall performance of the mechanical system have been found limited. Therefore, in this work, we have investigated the effects of conventional and hBN-based nanofluid on the tribological and performance, emission characteristics of a diesel engine.
BACKGROUND OF EXPERIMENTAL ANALYSIS

2.1 Tribological application of hBN nanoparticles

At higher service temperature, hBN nanoparticles are used effectively due to its ability to retain at higher temperature and pressure makes it appropriate for lubrication purpose. The structure comprises of boron and nitrogen associated as hexagonal rings to form platelet or lattice structure as appeared in Figure 1. The shorter bonds between the boron and nitrogen atoms make the covalent bond stronger which provides highest load-carrying capacity thereby avoiding metal to metal contacts. The number of lattice planes is held together by weaker Van der Waals forces. These forces are normally found weaker due to the longest $d$-spacing between the atoms which permits easy shearing due to the forces developed along the shear planes. This causes effective lubrication which results in the reduction of friction and wear of the mating surfaces.

The polar and nonpolar end of the nanoparticles is appended to the metal surfaces and hydrocarbon molecules respectively. The polar nature of hBN nanoparticles in the lube oil results in the formation of tribofilm on the contacting surfaces due to the adsorption mechanism as shown in Figure 2 which results in the reduction of friction and wear of the mating surfaces.

2.2 Lubricant degradation analysis by oxidation reaction

The lubricating oil in the engine mainly subjected to the high-temperature thermal stresses arising from the combustion chamber. Most of the gasses from the combustion chamber react with the lubricating oil while entering to the crankcase through the clearance between piston-cylinder assembly. This results in the oxidation of the lubricating oil which initiates a series of chain radical reactions. These chain radical reactions produce several oil degradation products namely alcohol, aldehydes, ketones, and carboxylic acids. The free-radical chain reaction of the lubricating oil under oxidized environment is given by Equations (1-7).42,43

2.2.1 Induction of the radical chain reaction

The wear particles in the lube oil increases the formation of alkyl radicals under the influence of heat and oxygen.

$$RH \rightarrow_{O_2+\text{heat}}^{M^{xx}} \dot{R} + \dot{H},$$

where $M^{xx}$ defines the transition metals namely Cr, Co, V, Cu, Fe, Mn, and $R$ denotes the alkyl radical.
2.2.2 | Advancement of the radical chain reaction

The formation of peroxide radicals occurs in this stage due to the reaction of free radicals with the oxygen.

\[ R + O_2 \rightarrow ROO^\cdot. \] (2)

Further, absorption of hydrogen from hydrocarbon occurs by peroxide radicals which results in hydro-peroxide and an alkyl radical.

\[ ROO^\cdot + RH \rightarrow ROOH + ^\cdot R. \] (3)

2.2.3 | Chain branching

At the beginning of the oxidation reaction, the formation of alkoxy and a hydroxy radical occurs due to the separation of hydro-peroxide at low concentration.

\[ ROOH \rightarrow R^\cdot O + HO^\cdot. \] (4)

\[ R^\cdot O + RH \rightarrow ROH + ^\cdot R. \] (5)

\[ HO^\cdot + RH \rightarrow ^\cdot R + H_2O. \] (6)

2.2.4 | Completion of the radical chain reaction

The oxidation reaction results in the production of alcohol, aldehydes, ketones caused due to carboxylic acids obtained during the combustion process.

\[ 2RR^1CHO^\cdot \leftrightarrow [R(R^1)CHOOOCH(R^1)R] \rightarrow R(R^1)C = O + O_2 + HO - CH(R^1)R, \] (7)

where \(R^1\) defines a terminal alkyl group.

3 | EXPERIMENTAL DETAILS

3.1 | Selection and formulation of nanofluids

In the present study, BN nanoparticles are purchased from the Nanolabs, India whereas base oil 20W40 is purchased from a local supplier. The nanoparticle morphology is hexagonal as shown in Figure 3 and the mean particle size is in the range of 30 to 50 nm. The physical characteristics of BN nanoparticles and base oil 20W40 are given in Tables 1 and 2, respectively.

The different concentration namely 0.5 wt.%, 0.75 wt.%, and 1 wt.% BN nanoparticles-based nanofluids were formulated by the two-step technique. In the first step, the different wt.% of nano-additives were blended with the conventional base oil 20W40 with the help of magnetic stirrer at 750 RPM for 12 hours. Further, the adequate amount of surfactant, that is, oleic acid in the concentration of 1, 1.5, and 2 mL were added to the 0.5 wt.%, 0.75 wt.% and 1 wt.% BN nanofluids, respectively, for effective dispersion and preventing the nanoparticles from sedimentation and agglomeration. In the second step, the different concentration of nanofluids was allowed to keep in an ultrasonication bath for 1 hour at a 20 kHz frequency so that all the nanoparticles get legitimately dispersed in the base oil. The nanofluids were found stable for more than a week. The stable and homogeneous mixture of different concentration of nanofluids is shown in Figure 4. The steps taken for the preparation of nanofluids is shown in Figure 5.
**FIGURE 3** The nanostructure of hexagonal boron nitride nanoparticles

**TABLE 1** Physical characteristics of hexagonal boron nitride nanoparticles

| Parameters          | Characteristics |
|---------------------|-----------------|
| Purity              | 99.50%          |
| Average particle size | 30-50 nm      |
| True density        | 2.5 gm/cm³      |
| Melting point       | 2527 °C         |
| Appearance          | White           |
| Morphology          | Hexagonal       |

**TABLE 2** Physical characteristics of base oil 20W40

| Parameters          | Value           |
|---------------------|-----------------|
| Viscosity @ 40°C    | 121 cSt         |
| Viscosity @ 100°C   | 12 cSt          |
| Viscosity Index     | 86              |
| Flash point         | 200°C           |
| Pour point          | -21°C           |

**FIGURE 4** Stable concentration of boron nitride-based nanofluid
3.2 Characterization of nanofluids

3.2.1 Dispersion stability analysis by UV-spectroscopy

The dispersion stability of nanofluids and conventional base oil 20W40 was analyzed by using UV-spectrometer. The make model of the spectrometer was Shimadzu UV-1800 having a specific wavelength range from 190 to 1100 nm. This range was utilized for measuring the absorbance value of base oil and different concentration of nanofluids. The result of UV-spectroscopy analysis is shown in Figure 6. It was noticed that the nanofluids and base oil 20W40 showed a higher absorbance value of 4 (a.u). However, the absorbance trend of base oil 20W40 started decreasing from the wavelength of 540 nm and reached up to 0.15 (a.u). Further, it was observed that the absorbance values for all the nanofluids were stable up to the wavelength of 590 nm and started decreasing up to the 1.9 (a.u). This shift in wavelength was conceivable because of the dispersion of nanoparticles in the base oil which indicated that the absorbance ability of base oil was improved because of hBN nanoparticles. Moreover, the researchers said that the absorbance value of any fluid is directly associated with the dispersion stability of nanoparticles in the particular fluid, hence, 1 wt.% BN-based nanofluid showed stronger dispersion stability and observed to be well-dispersed and hence, considered for the further analysis.
3.2.2 | Heat capacity analysis of 1 wt.% BN nanofluid by DSC

A thermoanalytical technique in which the differences in the heat flow capabilities of fluid samples have been analyzed against the time or temperature is known as differential scanning calorimetry (DSC). The DSC analysis was carried out on Mettler Toledo TGA/DSC1 star system in the temperature range from 25°C to 800°C and a constant heating rate of 10°C/min. The result of the DSC analysis is shown in Figure 7. The fluids experienced endothermic reaction where all the heat supplied was absorbed by the fluids. The decrements in peak indicated that the fluid experienced thermal transition and resulted in melting. When compared both the fluids, 1 wt.% BN nanofluid showed better thermal resistance and prohibited the melting of fluid at a speedier rate due to the presence of nanoparticles. This indicates its suitability for the application where higher temperature between the engine components affects the lubrication mechanism and degrades the performance of the engines.

3.3 | Engine performance test and procedure

In this work, experiments were conducted on a Kirloskar single-cylinder four-stroke diesel engine. The technical specification of the engine is shown in Table 3 and its schematic is shown in Figure 8. The setup has a provision to measure the in-cylinder combustion pressure by using a piezoelectric pressure sensor placed on the engine head. An eddy current dynamometer is provided for providing distinct loading conditions. The lubricating oil samples are analyzed by using Shimadzu IRAffinity-1S Fourier transform infrared spectroscopy (FTIR) method. The engine performance namely brake power (BP), brake thermal efficiency (BTh), brake-specific fuel consumption (BSFC) and in-cylinder combustion pressure is monitored by using LabView-based “EnginesoftLV” software. The emission analysis of the engine is carried out using AVL DIGAS 444 exhaust gas analyzer.

In the first phase of the experiment, the morphology of healthy liner and piston rings was assessed using SEM analysis which is appeared in Figure 9A to C. Further, the surface roughness of the healthy liner and weight analysis of rings

**Table 3** Specification of diesel engine

| Engine       | Kirloskar water cooled |
|--------------|------------------------|
| Compression ratio | 12 to 18:1            |
| Rated Power  | 3.5 kW @ 1500 RPM     |
| Fuel         | H.S Diesel            |
| Cylinder diameter | 85 mm                 |
| Number of cylinder | 1                    |
| Number of strokes | 4                    |
| Stroke length | 110 mm                |
were estimated. Afterwards, the healthy liner and rings with fresh oil were utilized in the engine and permitted to run for 12 hours. During the in-service condition, performance and exhaust emission analyses were carried out. Further, these components were disassembled and analyzed for morphological, surface roughness and weight loss estimation. The aged base oil 20W40 sample was also collected and analyzed by using FTIR method. In the case of 1 wt.% BN nanofluid, a similar procedure was employed.
4 | RESULTS AND DISCUSSIONS

The proceeding section presents the results of tribological and performance, emission analyses carried out using base oil 20W40 and 1 wt.% BN nanofluid.

4.1 | Tribological analysis of engine components

4.1.1 | Morphological analysis of liner and rings

Figure 10A to D shows the morphology of engine components surfaces obtained under the influence of base oil 20W40. It was noticed that the surfaces showed severe wears which incorporates fretting, micro-pitting, fatigue, and abrasive wear. The fretting wear occurred due to the cyclic sliding of the two surface across each other (in this case rings on the liner). The micro-pitting wear occurred due to the asperities contact of rings and liner surfaces. Further, there might be a poor film of lubrication between these asperity contacts. The fatigue cracks occurred on the top compression ring was due to the weakening of rings material due to thermal loads as top compression ring was always subjected to the higher pressure and temperature of the combustion zone. All the rings showed three-body wear mechanism due to the hard solid wear particles that arise due to the friction between rings and liner. These particles get trapped between rings liner assembly forming a deep groove on the rings and liner surfaces. Further, in the case of 1 wt.% BN nanofluid, a tribofilm has been formed on the surfaces of rings and liner which is shown in Figure 11A to D. The surface wears observed in case of base oil 20W40 were filled up or trapped with BN nanoparticles due to adsorption mechanism and resulted in the formation of tribofilm. The tribofilm formation helped to minimize the frictional losses between the rings and liner assembly and thereby increased the overall engine performance. The confirmation test of tribofilm formation was carried out by using energy dispersive spectroscopy analysis (EDAX) analysis and the results of which are shown in Tables 4 and 5, respectively. The results showed that the boron and nitride elements on the surface of rings and liner confirmed the formation of tribofilm. This indicates nanofluids proficiency to reduce the frictional losses occurring in a diesel engine. These results are found in a good agreement with 27,28,32 who confirmed the formation of protective films on the tribological surfaces which helps to minimize the friction and wear to a greater extent.

![Figure 10](image_url)
4.1.2 | Surface roughness analysis of tribological surfaces

The surface roughness ($R_a$) profiles were obtained according to ISO 4287 standards by using stylus type profilometer Rugosurf 10G at different locations of TDC and BDC which is shown in Figure 12A,B. In the case base oil 20W40, the surface roughness values increased at liner TDC and BDC when compared with the initial surface roughness values of
FIGURE 12 The variation of surface roughness profiles at (A) Top dead center (B) Bottom dead center under different operating conditions

TABLE 6 The mean values of surface roughness ($R_a$) under different operating conditions

| Parameters          | Fresh liner $R_a$, µm | Base oil 20W40 $R_a$, µm | 1 wt.% boron nitride nanofluid $R_a$, µm |
|---------------------|------------------------|---------------------------|--------------------------------------|
| Top dead center     | 0.273                  | 0.611                     | 0.216                                |
| Bottom dead center  | 0.109                  | 0.198                     | 0.180                                |

the fresh liner. This was because of the failure of a thin lubrication film at TDC and BDC due to higher combustion temperature and pressure which resulted in the direct asperities contact of the surfaces thereby causing severe wear. However, the reduction in surface roughness values at TDC and BDC was observed when the engine operated with 1 wt.% BN nanofluid which is given in Table 6. The development of tribofilm on the liner and ring surfaces reduced the surface irregularities causing a reduction in surface roughness values.

4.1.3 Wear prediction of piston rings through weight loss measurement

A Contech Instruments precision weighing machine was employed to carry out the weight loss measurements having the precision of 0.00001 g to 300 g. It was noticed that the piston rings subjected to severe wear when the engine allowed to operate with conventional base oil whereas the reduction in weight loss was observed when the base oil was replaced with the 1 wt.% BN nanofluid as shown in Figure 13. The total weight loss obtained in each case is given in Tables 7 and 8, respectively. The reduction in weight loss was noticed due to the formation of strong tribofilm between the rings and liner interface and thus avoiding the direct asperities contact between these tribological surfaces.

4.1.4 Lubricating oil analysis using FTIR method

The condition of the engine components mainly depends on the effective lubrication system. The effective lubrication can reduce the wear of mating surfaces and thus helps to improve the performance characteristics of the engines. In this work, fresh, and aged lubricating oil samples obtained under different operating environments were analyzed to assess their conditions during the in-service condition. The outcomes of the FTIR analysis are illustrated in Figures 14-16. The infrared spectra obtained within the wavenumber 400 to 800 cm$^{-1}$ indicate C=C bending vibrations whereas the spectra obtained from the wavenumber 1300 to 1700 cm$^{-1}$ indicate the sulfate (S=O) stretching, methylene and aromatic (C-H) bending vibrations. The infrared spectra obtained from the wavenumber 400 to 800 cm$^{-1}$ indicate the
FIGURE 13 The total weight loss obtained in case of base oil 20W40 and 1 wt.% boron nitride nanofluid.

| Parameters | Before experimentation | After experimentation | Total weight loss |
|------------|------------------------|-----------------------|-------------------|
| Compression rings | g | g | mg |
| Top ring | 14.06543 | 14.01081 | 54.62 |
| Middle ring | 14.11990 | 14.06659 | 53.31 |
| Bottom ring | 14.10701 | 14.05190 | 55.11 |

TABLE 7 Weight of piston rings obtained with base oil 20W40

FIGURE 14 Transmittance spectra of base oil 20W40

| Parameters | Before experimentation | After experimentation | Total weight loss |
|------------|------------------------|-----------------------|-------------------|
| Compression rings | g | g | mg |
| Top ring | 13.90873 | 13.85977 | 48.96 |
| Middle ring | 13.99347 | 13.95843 | 35.04 |
| Bottom ring | 13.95910 | 13.93177 | 27.33 |

TABLE 8 Weight of piston rings obtained with 1 wt.% BN nanofluid.
The efficiency of the diesel engine is enormously affected due to the frictional losses between piston rings/liner assembly, bearing friction, valvetrain friction, and blow-by losses. In the present work, the more focused is on piston rings/liner...
assembly friction as it affects directly to the performance of the engine. The outcomes of the experimental investigations showing the variation of BP, BTh, and brake specific fuel consumption (BSFC) with the varying load under different operating conditions are depicted in Figure 17A to C. An increment in BP and BTh by as much 5.09% and 4.33% and decrement in BSFC by as much 46.20% was observed in the case of 1 wt.% BN nanofluid. This is due to the following reasons,

- Increasing temperature and pressure inside the combustion chamber resulted in the failure of the lubricant film between rings and liner interface. This causes boundary lubrication regime between the contacting surfaces which allowed direct asperity contacts resulting in frictional losses.
- On the other hand, the formation of strong tribofilm on the tribological surfaces due to the nanofluids ability to retain at a higher temperature and pressure resulted in the reduction of frictional losses.

During the past few years, the emission standards for the vehicles has been made very stringent. Carbon monoxide (CO), hydrocarbon (HC), and nitrogen oxide (NOx) have been renowned as the most serious pollutants from the diesel and gasoline engines. Therefore, the control of exhaust emissions from these engines is very significant to reduce air pollution. In this work, the exhaust emissions of diesel engine were monitored with the varying load under the different operating conditions. The outcomes of the experiments are shown in Figure 18A to C. A significant reduction in CO and HC emissions by as much 46.15% and 55.95% whereas an increment in the NOx emission by as much 40.03% was observed by using 1 wt.% BN-based nanofluid. The decrements in the CO and HC emission was observed because of an increment in the oxidation stability of nanofluid. Further, the formation of the tight sealing between the rings and liner surfaces reduced the blow-by emission losses. A reduction in the blow-by emission losses helps to maintain the proper air/fuel mixture for the combustion process and supports for complete combustion and thereby minimizes the exhaust emissions. However, an increment in NOx emission was observed as nanofluid contained the nitride molecules which on oxidation caused to increase the NOx emission.

The combustion pressure during the combustion process influences the total power output of the engine and it is completely dependent on the rate of combustion of the air/fuel mixture in the combustion chamber. In this work, an in-cylinder combustion pressure was monitored with respect to crank angle (degree) with the variation of engine load. The results of the experimental outcomes are depicted in Figure 19A,B. The frictional and blow-by losses occurred in case
Variation of (A) carbon monoxide, (B) hydrocarbon, (C) nitrogen oxide with respect to load.

Variation of in-cylinder combustion pressure obtained with (A) base oil 20W40; (B) 1 wt.% boron nitride nanofluid.

Summary and conclusions

In the present study, different concentration namely 0.5 wt.%, 0.75 wt.%, and 1 wt.% BN nanofluids were formulated by the two-step technique and characterized by UV-spectroscopy and DSC methods for dispersion and heat capacity analyses,
respectively. The characterization results showed stable dispersion of 1 wt.% BN nanofluid and hence, considered for wear and performance analyses of the diesel engine. The outcomes of the experimental investigations are summarized below,

1. In the case of 1 wt.% BN nanofluid, the tribological surfaces of liner and rings were improved due to the formation of tribofilm which reduced the surface wears and frictional losses as compared to the base oil 20W40.
2. The formation of tribofilm on the worn surfaces resulted in the reduction of the mean surface roughness values of the liner at TDC and BDC.
3. A reduction in the weight loss of piston rings was noticed in the case of 1 wt.% BN nanofluid by overcoming the frictional losses.
4. A conformity test of aged lubricating oil by using FTIR indicated that the aged 1 wt.% BN nanofluid showed a reduction in the formation of harmful degradation products during the in-service condition.
5. The performance analysis showed an increment in BP, BTh by 5.09% and 4.33% whereas the decrement in BSFC by 46.20% in the case of 1 wt.% BN nanofluid. Moreover, decrement in carbon monoxide, hydrocarbon by 46.15% and 55.95% and an increment in nitrogen oxide emissions by 40.03% were observed by using 1 wt.% BN nanofluid. Further, the combustion pressure in the combustion chamber was increased with the application of nanofluid which helped to increase the total power output of the engine.

It is postulated that the BN nanoparticles-based nanofluids can be used for lubrication at higher service temperature where conventional lubricant fails to provide effective lubrication. Further, it is cooperative in enhancing the service life of the engine components by reducing the frictional losses. The obtained results will also encourage the oil industries to formulate nanoparticles based lubricant.

ACKNOWLEDGMENTS
The authors wish to thank St. Aloysius College, Jabalpur and Indian Institute of Technology, Indore for providing facilities for UV-spectroscopy and DSC analysis, respectively.

PEER REVIEW INFORMATION
Engineering Reports thanks María Jesús García Guimarey, José Jaime Taha-Tijerina, and other anonymous reviewers for their contribution to the peer review of this work.

AUTHOR CONTRIBUTIONS
Sangharatna Ramteke: Conceptualization-Equal, Data curation-Equal, Formal analysis-Equal, Investigation-Equal, Methodology-Equal, Resources-Equal, Software-Equal, Supervision-Equal, Validation-Equal, Visualization-Equal, Writing-original draft-Equal, Writing-review & editing-Equal. H Chelladurai: Conceptualization-Equal, Data curation-Equal, Formal analysis-Equal, Investigation-Equal, Methodology-Equal, Project administration-Equal, Resources-Equal, Supervision-Equal, Validation-Equal, Visualization-Equal, Writing-review & editing-Equal.

CONFLICT OF INTEREST
The authors declare no potential conflict of interest.

NOMENCLATURE
BP Brake power (kW)
BTh Brake thermal efficiency (%)
BSFC Brake specific fuel consumption (kg/kWhr)
BDC Bottom dead center
CO Carbon monoxide (%)
DSC Differential scanning calorimetry
EDAX Energy dispersive spectroscopy
FTIR Fourier transform infrared spectroscopy
hBN Hexagonal boron nitride
HC Hydrocarbon (ppm)
NOx Nitrogen oxide (ppm)
SEM Scanning electron microscope
TDC Top dead center
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How to cite this article: Ramteke SM, Chelladurai H. Effects of hexagonal boron nitride based nanofluid on the tribological and performance, emission characteristics of a diesel engine: An experimental study. Engineering Reports. 2020;2:e12216. https://doi.org/10.1002/eng2.12216