EFFECT OF CERIUM OXIDE NANOADDITIVE ON THE WORKING CHARACTERISTICS OF WATER EMULSIFIED BIODIESEL FUELED DIESEL ENGINE; AN EXPERIMENTAL STUDY

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The present article discusses the effect of cerium oxide nanoadditive inclusion on the working characteristics (combustion, performance, and emission) of water emulsified soybean biodiesel-fueled single cylinder diesel engine. Test fuels with 5% and 10% volume of water in soybean biodiesel along with mass fraction of 100ppm cerium oxide nanoparticle were prepared using mechanical agitator and ultrasonicator, and the experiments were conducted under different loading conditions in a single cylinder diesel engine. The experimental results reveal that the emulsion fuel increases the peak in-cylinder pressure and net heat release values compared to pure soybean biodiesel, and cerium oxide nanoparticle inclusion reduces the peak combustion parameters' value. The performance parameters such as brake specific fuel consumption and brake energy consumption are significantly improved with emulsion fuel, and the nanoparticle inclusion further improve the performance parameters. At low load conditions, the emulsion fuels increase the hydrocarbon and carbon monoxide emissions, whereas these emission magnitudes are reduced at high load conditions. As far as the oxides of nitrogen and smoke emissions are concerned, an increase in water concentration directly reduces the emissions irrespective of load conditions. The cerium oxide nanoparticle inclusion reduces the emissions level from the water emulsified soybean biodiesel-fueled diesel engine.

Keywords*: Diesel engine, soybean biodiesel, cerium oxide nanoparticle, combustion, performance, emissions.*

1. Introduction

Diesel engines are normally dominating in all transportation sectors due to their appreciable characteristics such as high engine torque, better fuel economy and longer reliability compared to gasoline engines [1]. Due to the industrialization, the petroleum-based fuels, especially the diesel fuel consumption is greatly increased day-by-day. As far as the British Petroleum Statistical Review of World Energy, the current diesel fuel availability is estimated to lose in two decades [2]. Apart from that, the exit emissions from the diesel engine, particularly the NO_x and smoke emissions are critically affecting the environmental and human health [3,4]. To meet the above two challenges, continuous research in diesel engines is carried out by the scientific community to derive a sustainable and environmentally friendly alternative fuel for the replacement of existing diesel fuel.

Biodiesel derived from the vegetable oils is widely accepted by the researches as an alternative for diesel fuel since the important physiochemical properties are quite similar to petrodiesel [3,5]. The combustion and performance behaviors of biodiesel-fueled diesel engine also followed the similar trend compared to petrodiesel. As far as the emission characteristics are concerned, the biodiesel promotes a marginal impact on greenhouse gases effect since the carbon dioxide gas is recycled for photosynthesis effect. In addition to that, an absence of aromatic and sulphur, and an enriched oxygen nature promote complete combustion and reduce the tendency of soot and CO emissions [6,7]. Meanwhile, the higher NO_x emission and kinematic viscosity, and lower oxidation stability and volumetric energy capacity are identified as an important drawback of biodiesel-fueled diesel engine and had to be overcome for common use [7,8].

Several types of valuable research have been conducted using various biodiesel feedstock such as palm, jatropha, soybean, punnai oil, mahua and castor oil [9-14]. Out of these, soybean biodiesel has been attracted by many researchers since it not only has the higher potential for renewable but also having a high oil derivation rate and cost-effective [6,7,11]. Apart from that, more abundant of soybean feedstock availability in the developed countries that covers a wide range of biodiesel production makes the SB is a favorable feedstock for the present study. Vellaiyan et al., [7] reported that the ICP and NHR values of SB are reduced by 5.5% and 8.6% respectively compared to petrodiesel. At the same time, they reported the advancement in the CA (4°) for the combustion initiation for the SB. The experimental report of Canakci [15] stated that the SB leads to higher BSFC and lower brake thermal efficiency compared to petrodiesel due to its lower heating value. They also reported that the HC and CO emissions are greatly reduced for SB due to an enriched oxygen and lower carbon content nature. However, the NO_x emission is significantly increased for SB. The other reports in the domain of SB also support the above discussion for the working characteristics of SB fueled diesel engine [5,6,11].

Inclusion of water in the base fuel is recommended by many researchers for the simultaneous removal of NO_x and particulate matter emissions with improved engine performance [16-19]. An occurrence of micro-explosion usually non-existent in the normal diesel fuel combustion, which makes the combustion more efficient [16]. The high latent heat evaporation of water particles during the combustion process and heat sink effect of water particles reduce the lower peak flame temperature and restrict the NO_x formation [20]. Numerous studies have been conducted in the domain of water in the diesel engine. The experimental investigation leads to some contradictory results in terms of brake power, BSFC, engine torque and emissions level [21]. However, all the reports conclude that the NO_x and particulate matter emissions are significantly reduced for water-emulsified diesel and biodiesel-fueled diesel engines [17,18]. Hence, the water emulsified SB is preferred in the present work to mitigate the NO_x emission issue from the SB fueled diesel engine. The water concentration is limited to 10% in this study since the water concentration above 10% leads to a much longer IDP and rough engine operation [7].

In order to improve the overall working characteristics of the diesel engine and to reduce the IDP, a nanoparticle is recommended by the many researchers and report the significant improvement. Several nanoadditives such as alumina, CeO_2, zinc oxide, and carbon nanotube are used as a nanoadditive for diesel and biodiesel-fueled diesel engine, and the working characteristics show significant improvement in terms of combustion, performance and emissions level [7,19,22,23]. Gumus et al. [24] pointed out that inclusion of alumina nanoparticle in diesel improves the engine torque and BSFC by 3% and 12% respectively compared to petrodiesel. In addition to that, the emission parameters such as HC, CO, and smoke emissions are reduced by 11%, 13%, and 6% respectively. Similar results are obtained by Vellaiyan et al. [7], Mehta et al. [25], Selvan et al. [19], and Basha and Anand [23] when using different nanoparticles along with diesel/biodiesel blends. Out of different nanoadditives, CeO_2 nanoadditive is preferred for the present study due to its positive thermal characteristics, environmentally friendly and cost-effectiveness [19].

The above discussions based on the previous literature show that the use of SB has the potential for the replacement of existing petrodiesel, and inclusion of water and nanoadditive could lead a positive responses on the working characteristics of the diesel engine. Though several attempts have been made in the domain of SB, water emulsion, and nanoadditive individually, the combined effects of SB, water emulsion and CeO_2 nanoparticle inclusion on the overall diesel engine's working characteristics are not focused by any researchers. Hence, the present study aims to provide detailed insights to understand clearly the effects of combining SB, water emulsion and CeO_2 nanoparticle on the working characteristics of diesel engine.

2. Test fuels preparation, properties measurement, and experimental procedure

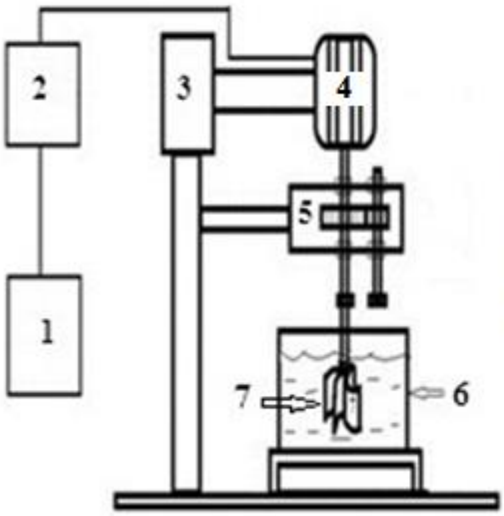

Fig.1. Schematic layout of the emulsion preparation setup

The SB was prepared from crude soybean oil by a traditional transesterification process, where potassium hydroxide was used as a catalyst. During the process, the crude soybean oil was heated along with catalyst and methanol, and constantly stirred about an hour to separate the methyl ester of SB and glycerol. The separated methyl ester was continuously washed and dried using warm water, and the pure methyl ester of SB was derived. Along with pure SB, double-distilled water (5% and 10% of total volume) and sorbitan monolaurate surfactant (1% of total volume) were mixed using the mechanical agitator and named as SB5W and SB10W emulsion fuel. The schematic layout of the emulsion preparation setup is shown in Fig.1. The prepared sample fuels were mixed with a mass fraction of 100ppm CeO_2 nanoparticle using an ultrasonicator (R-4C model; Remi Laboratory instruments, India) and the fuels were named as SB5W100CeO2 and SB10W100CeO_2 respectively.

The test fuels' properties were measured based on EN standards. The density and viscosity of test fuels were measured based on EN ISO 3675 and EN ISO 3104 methods with an accuracy of

±0.0002 and ±0.001 respectively. The flash point, calorific value, and cetane index were measured based on EN ISO 2719, DIN 51900-1, and EN ISO 4264 methods with an accuracy of ±0.02, ±1, and ±0.03 respectively. The measured fuel properties are represented in Table 1. From the representation, it is observed that the modified test fuels' properties are at par with standard limits that indicates the direct usage in the existing diesel engine.

Table 1. Physicochemical properties of test fuels

Fuels	Density at 15^0 C (kg/m^3)	Viscosity at 40˚C (mm^2/s)	Calorific value (MJ/kg)	Flash point ˚C	Cetane index
SB	871.2	3.92	38.1	129	55.8
SB5W	877.6	4.46	36.4	134	54.5
$SB5W100CeO_2$	878.2	4.51	36.7	139	56.6
SB10W	884.4	4.88	34.8	140	53.4
$SB10W100CeO_2$	885.2	4.92	35.2	145	55.4
EN14214 limits	800-900	3.5-5	-	min 120	min 51

The experimental studies were carried out in a single-cylinder, four-stroke, and naturally aspirated diesel engine connected with an eddy current dynamometer. The performance and emission parameters were recorded using ICENGINESOFT_9 software which was integrated with the engine test setup. The emission parameters were measured using AVL-Di gas analyzer and AVL smoke meter. The engine was warm-up with each test fuels about 10mins to attain a steady state condition, and then the measurements were recorded. An average value of five consecutive experiments was considered to avoid the error in the measurements. The schematic layout of the test engine setup is shown in Fig.2, and the specification of test engine and emission analyzer are represented in Table 2.

Table 2. Specifications of the engine and emission analyzer

(a) Engine specifications			
Parameter	Specification		
Engine type	Computerized, 4-S, Single cylinder, VCR diesel engine		
Bore × Stroke (cm)	8.75 × 11		
Displacement volume (cc)	661.45		
Max. power	3.5 kW at 1500 rpm		
Dynamometer	Eddy current dynamometer (max. load of 7.5 kW)		
(b) Gas analyzer specifications			
Measured quality	Measuring range	Resolution	Uncertainty percentage
NO_x	0 to 5000 ppm vol	1 ppm vol	±0.02
HC	0 to 20000 ppm vol	≤ 2000: 1 ppm vol, > 2000: 10 ppm vol	±0.05
CO	0 to 10% vol	0.01% vol	±0.1

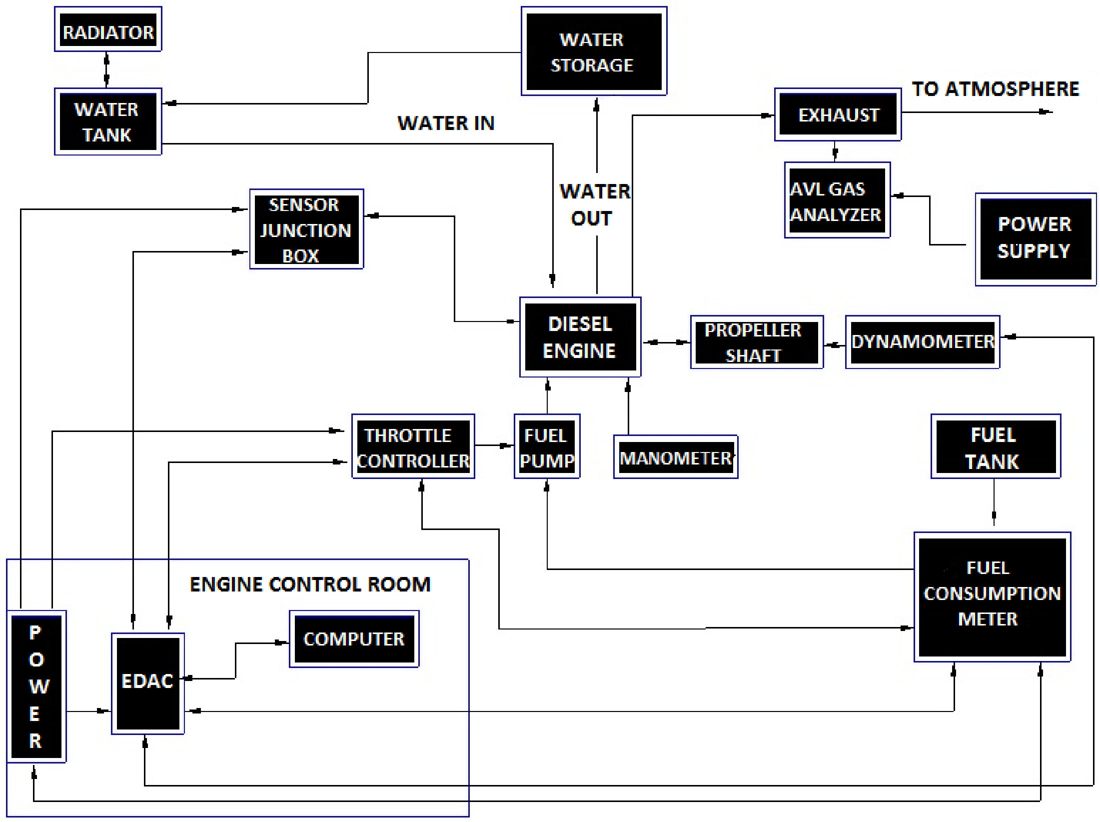

Fig.2. Schematic layout of the test engine setup

3. Results and discussion

3.1. Combustion characteristics

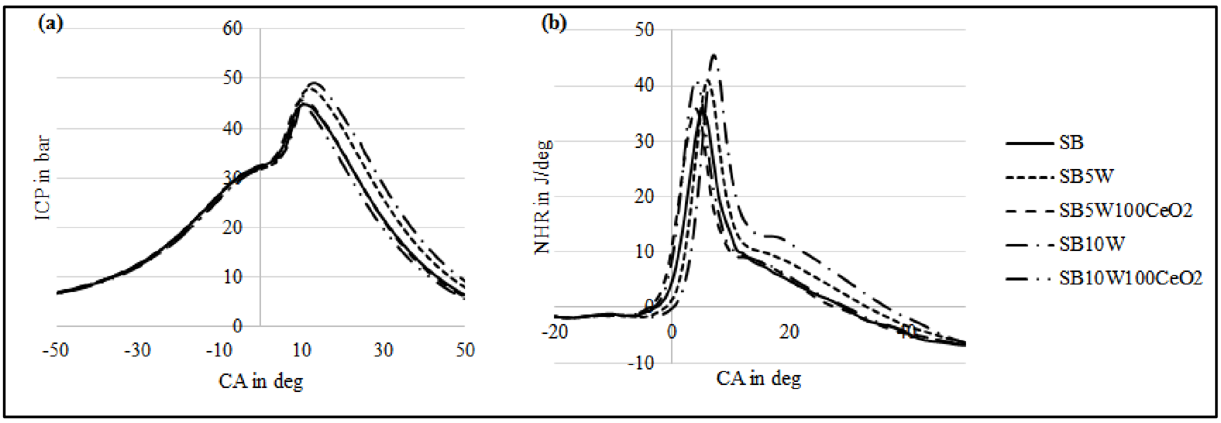

Fig.3. Combustion characteristics of test fuels: (a) ICP variation, and (b) NHR variation

The ICP variation of test fuels with respect to CA under peak BMEP (4.14bar) is represented in Fig.3(a). The pure SB exhibits the peak ICP of 44.79bar at the CA of 11° ATDC. The water inclusion in the base fuel increases the peak ICP value and the corresponding CA. The emulsion fuel with 5% water in SB exhibits the peak ICP of 48.11bar at the CA of 12° ATDC, whereas the 10% water in SB exhibits 49.21bar at the CA of 13° ATDC. At high water concentration, the intensity of micro-explosion is stronger and the explosion duration is extended. The strong micro-explosion promotes a more combustible air-fuel mixture that results in high peak cylinder pressure. The endothermic reaction of water particles present in the fuel leads to extended IDP. Due to the longer IDP, the occurrence of peak cylinder pressure for emulsion fuels is later degree of CA compared to plain fuel [21,26]. The CeO_2 nanoparticle inclusion with emulsion fuels significantly reduces the peak ICP value and the corresponding CA. The nanoparticle presents in the fuel enhances the thermal properties of fuel and initiates the earlier combustion compared to plain emulsion fuels. Due to the earlier combustion, the fuel accumulation during the pre-mixed combustion phase is reduced for emulsion fuels that results in low peak cylinder pressure compared to SB [2,7]. SB5W100CeO_2 emulsion fuel reduces the peak ICP value and the corresponding CA by 6.5% and 2° respectively compared to SB5W emulsion fuel, whereas SB10W100CeO_2 emulsion fuel reduces the peak ICP value and the corresponding CA by 7.5% and 3° respectively compared to SB10W emulsion fuel.

Fig.3(b) represents the NHR variation of test fuels under peak BMEP condition. The maximum NHR value for SB is noted as 35.39J/deg at the CA of 5° ATDC. The NHR value becomes negative during the IDP due to the occurrence of endothermic reaction during the pre-mixed combustion phase. Similar to the ICP variation, NHR value and the corresponding CA also increased for emulsion fuels, and SB10W emulsion fuel exhibits a higher NHR value compared to other test fuels. An enhancement in the strength and onset of the micro-explosion associated with emulsion fuel promotes better atomization and forms more combustible air-fuel mixture. Apart from that, the longer IDP due to the latent heat absorption of water particles allows more fuel to prepare physically and chemically for the combustion during the pre-mixed combustion phase. Hence, the peak NHR value is increased with increases in water concentration [18,20]. SB5W emulsion fuel increases the NHR value by 15.9% compared to pure SB, whereas SB10W emulsion fuel increases the NHR by 28.6%. The enhancement in physicochemical properties due to the presence of CeO_2 nanoparticle leads to lower IDP for emulsion fuels. Due to the lower IDP, the peak NHR value is reduced and CA is advanced for CeO_2 nanoparticle included emulsion fuels compared to plain emulsion fuels [19]. SB5W100CeO_2 emulsion fuel reduces the NHR value and the corresponding CA by 12.5% and 2° respectively compared to SB5W emulsion fuel, whereas SB10W100CeO_2 emulsion fuel reduces the peak ICP value and the corresponding CA by 9.8% and 3° respectively compared to SB10W emulsion fuel.

3.2. Performance characteristics

In the present investigation, the exact amount of SB alone is considered as a total fuel instead of SB+water as a total fuel. The BSFC of test fuels under varying BMEP conditions is represented in Fig.4(a). From the graphical representation, it is observed that an increase in engine load significantly reduces the BSFC due to the efficient combustion at higher engine loads, and the SB consumes higher BSFC compared to other test fuels. The water inclusion in SB significantly reduces the BSFC at all engine loads, and 10% water in SB shows lesser BSFC compared to pure SB and SB5W emulsion fuels. This may be due to the micro-explosion phenomena, improved air-entraining in the spray, higher pre-mixed combustion, drop in the cooling loss and suppression of thermal dissociation associated with emulsion fuel [7,17,21]. At full load condition, SB10W emulsion fuel promotes 2.8% and 5.4% lower BSFC compared to SB5W emulsion fuel and pure SB respectively. The catalytic activity and an enhanced fuel properties due to the presence of CeO_2 nanoparticle further improve the BSFC of the engine. The nanoparticle encapsulated in the water droplet explodes along with the fuel and reacts with the air effectively. These phenomena promote catalytic combustion that results in improvement in engine performance [23,25]. SB5W100CeO$_2$ emulsion fuel reduces the BSFC by 2.2% compared to SB5W emulsion fuel, whereas SB10W100CeO$_2$ emulsion fuel reduces the BSFC by 2.4% compared to SB10W emulsion fuel.

The BSEC of test fuels under different BMEP conditions is represented in Fig.4(b). Similar to BSFC, BSEC also reduces with an increase in engine load due to efficient combustion. Among the test fuels, the SB shows higher BSEC though the heating value of SB is higher than other test fuels. This could be the attribute of micro-explosion associated with emulsion fuels. Due to the micro-explosion phenomenon, the additional force is acting on the piston surface that will reduces the fuel energy consumption compared to SB for the same power development [20,26]. At peak engine load condition, SB5W emulsion fuel reduces the BSEC by 7% compared to pure SB, whereas SB10W emulsion fuel exhibits 13.6%. The enhanced air-fuel mixing and lower IDP associated with CeO$_2$ nanoparticle included emulsion fuels further marginally reduces the BSEC irrespective of load conditions. SB10W100CeO$_2$ emulsion fuel shows lower BSEC when compared to other test fuels.

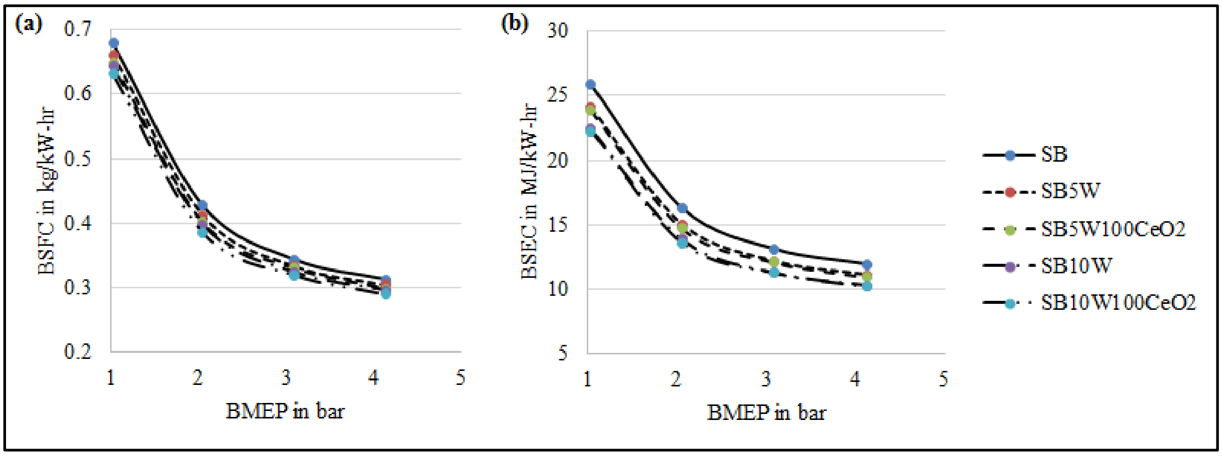

Fig.4. Performance characteristics of test fuels: (a) BSFC, and (b) BSEC

3.3. Emission characteristics

The NO$_x$ emission characteristics of test fuels under varying BMEP conditions is depicted in Fig.5(a). Among the test fuels, the pure SB exhibits the higher NO$_x$ emission due to the enriched oxygen concentration [5,6]. The water inclusion in SB significantly reduces the NO$_x$ formation, and increases in water concentration is directly proportional to drop in the NO$_x$ emission. This may be due to the lower peak flame temperature associated with emulsion fuel during the combustion process. The high latent heat absorption during the water evaporation and heat sink effect are the major contributors to reduce the peak flame temperature of emulsion fuel [17,18]. At peak BMEP condition, SB5W emulsion fuel exhibits 10.3% drop in NO$_x$ emission compared to pure SB, whereas SB10W emulsion fuel exhibits 21.3% drop. The CeO$_2$ nanoparticle inclusion with emulsion fuels further reduces the NO$_x$ formation. The presence of nanoparticle in the fuel enhances the heat transfer rate and reduces the IDP that results in lower peak flame temperature [24,27]. A drop of 6.6% and 26.5% in NO$_x$ formation is recorded with SB10W100CeO$_2$ emulsion fuel when compared with SB10W emulsion fuel and pure SB respectively at full load condition.

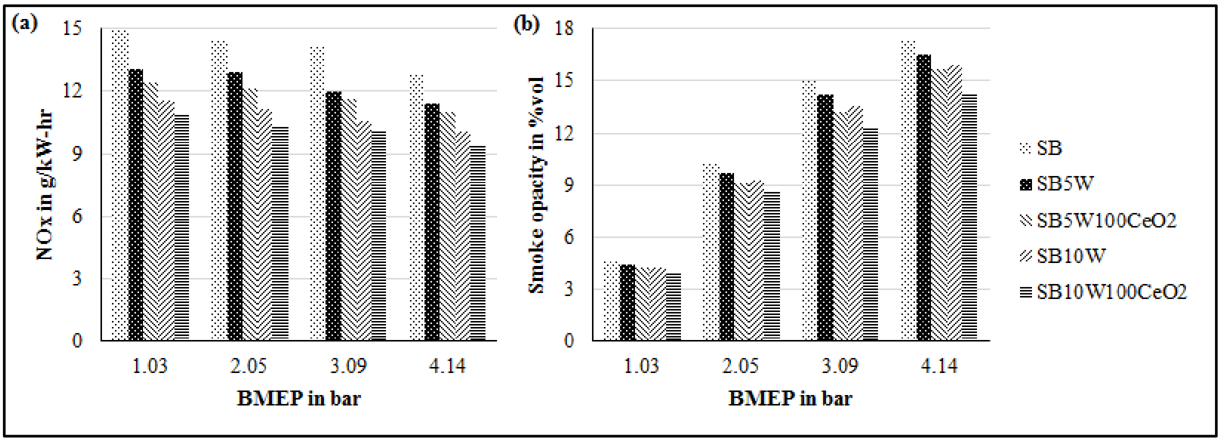

Fig.5. Emission characteristics of test fuels: (a) NO_x, and (b) Smoke emission

The partial and/or incomplete reaction of carbon and hydrogen particles present in the fuel leads to smoke formation [28,29]. The smoke emission of test fuels under varying BMEP conditions is represented in Fig.5(b). From the figure, it is noted that an increase in engine load increases the smoke emission due to an increase in fuel consumption. The pure SB exhibits higher smoke formation among the test fuels irrespective of load conditions. The water inclusion in base fuel significantly reduces the smoke formation, and an increase in water concentration is directly proportional to drop in smoke formation [6,17,18]. An improved air entrainment in the emulsion spray volume and an increase in concentration of OH radicals reduce the smoke formation for emulsion fuel [23]. At full load condition, SB5W emulsion fuel exhibits 4.6% drop in smoke emission compared to pure SB, whereas SB10W emulsion fuel exhibits 8.1% drop. The enhanced combustion reaction and drop in the IDP due to the presence of CeO_2 nanoparticle further reduce the smoke formation [19,23]. A drop of 10.7% and 17.9% in smoke emission is recorded with SB10W100CeO_2 emulsion fuel when compared with SB10W emulsion fuel and pure SB respectively at full load condition.

The graphical representation of test fuels' HC emission under varying BMEP conditions is shown in Fig.6(a). The low in-cylinder temperature at low engine load conditions leads to incomplete combustion and results in the high magnitude of HC emission. An increase in engine load increases the in-cylinder and cylinder wall temperature, and promotes better combustion that results in the low magnitude of HC emission [5,11]. The water inclusion in base fuels significantly reduces the HC emission at high engine load conditions due to the enhanced micro-explosion phenomenon associated with emulsion fuels. At low engine load conditions, the HC formation is marginally increased for emulsion fuels compared to pure SB. The increases in HC emission at low engine load conditions is due to the latent heat absorption of water particles, which will further reduces the in-cylinder temperature [6,21]. SB5W emulsion fuel exhibits 11.2% drop in HC emission at peak BMEP condition compared to pure SB, whereas SB10W emulsion fuel exhibits 16.8%. An enhancement in the surface-area-to-volume ratio for emulsion fuels due to the inclusion of CeO_2 nanoparticle reduces the HC emission irrespective of load conditions. The occurrence of secondary atomization and catalytic activity of CeO_2 nanoparticle also promote complete combustion and results in low HC formation [23,24]. At full load condition, SB10W100CeO_2 emulsion fuel promotes 20.1% and 33.5% drop in HC emission compared to SB10W emulsion fuel and pure SB respectively.

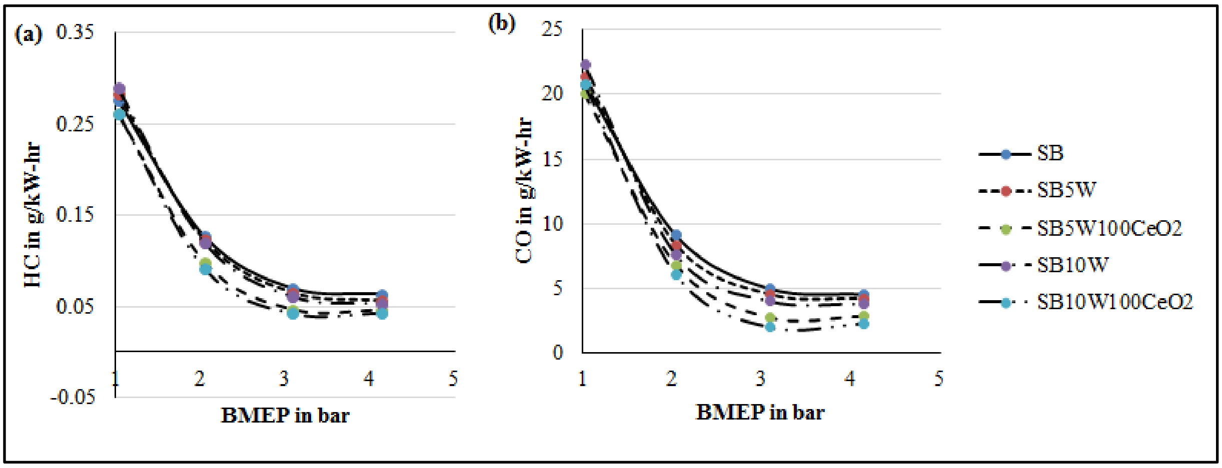

Fig.6. Emission characteristics of test fuels: (a) HC, and (b) CO emission

The incomplete fuel oxidation and slow burning of soot are the major sources for CO exhaust from the diesel engine. Similar to HC emission, the CO emission also increased at low load conditions and reduced at high load conditions due to the better oxidation rate at high engine loads. The CO emission of test fuels under varying load (BMEP) conditions is represented in Fig.6(b). The emulsion fuels exhibit a marginal increases in CO emission at low engine loads compared to pure SB. At high engine loads, the CO emission formation of emulsion fuels is significantly reduced compared to SB due to the efficient combustion [4,18]. At full load condition, a drop of 8.2% and 16.4% in CO emission are recorded for SB5W emulsion fuel and SB10W emulsion fuel compared to pure SB respectively. An inclusion of CeO_2 nanoparticle with emulsion fuel further improves the oxidation rate and enhances the combustion process that results in the low magnitude of CO emission. At full load condition, SB10W100CeO_2 emulsion fuel promotes 40.1% and 50.1% drop in CO emission compared to SB10W emulsion fuel and pure SB respectively.

4. Conclusion

The effect of CeO_2 nanoparticle inclusion on the working characteristics of water emulsified SB fueled diesel engine has been detailed in the present study, and the experimental results are compared with pure SB. Based on the experimental study, the following conclusions can be drawn.

- An increase in water concentration increases the ICP and NHR value. SB10W emulsion fuel increases the ICP and NHR value by 8.9% and 28.6% respectively compared to pure SB. The CA of peak value also delayed to 2° of CA. The CeO_2 nanoparticle inclusion significantly reduces the IDP and the peak value of ICP and NHR.
- The BSFC and BSEC of emulsions fuel significantly improved compared to pure SB. SB10W emulsion fuel reduces the BSFC and BSEC by 5.4% and 21.3% compared to SB at full load condition. The CeO_2 nanoparticle inclusion further marginally improves the performance parameters.
- The NO_x and smoke emissions are reduced with increase in water concentration, and SB10W emulsion fuel reduces the NO_x and smoke emission by 21.3% and 8.1% respectively compared to SB. The nanoparticle included SB10W emulsion fuel further reduces the NO_x and smoke emission by 6.6% and 10.7% respectively compared to plain SB10W emulsion fuel.

- The HC and CO emissions are slightly increased with emulsion fuel at low load conditions compared to pure SB, and these emissions are significantly reduced at high load condition. At full load condition, SB10W emulsion fuel reduces the HC and CO emissions by 16.8% and 16.4% compared to SB. SB10W100CeO_2 emulsion fuel further reduces the HC and CO emissions by 20.1% and 40.1% compared to SB10W emulsion fuel.

Acronyms

ATDC	:	After Top Dead Centre	HC	:	Hydrocarbon
BMEP	:	Brake Mean Effective Pressure	ICP	:	In-cylinder Pressure
BSEC	:	Brake Specific Energy Consumption	IDP	:	Ignition Delay Period
BSFC	:	Brake Specific Fuel Consumption	NHR	:	Net Heat Release Rate
CA	:	Crank Angle	NO_x	:	Oxides of Nitrogen
CeO_2	:	Cerium Oxide	SB	:	Soybean Biodiesel
CO	:	Carbon monoxide			

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