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RESEARCH

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Effect of fuel injection pressure on the performances of a CI engine using water-emulsified diesel (WED) as a fuel

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Abstract

Background The choice of energy sources is essential for sustainable development to combat different environmental issues caused by the consumption of fossil fuels. Though diesel engines are considered more efficient and reliable than other internal combustion engines, they emit different harmful pollutants which are detrimental to human health and the environment. Researchers are trying to find suitable alternative fuels for diesel engines with lower pollutant emissions and without much compromise in the efficiency of the engine. In this regard, water-emulsified diesel (WED) may be considered to be one of the most suitable alternative fuels. It is expected that the entire world will use electric vehicles in the long term. However, the complete replacement of IC engines in the near future is not feasible. In fact, different European countries have targeted to ban the use of diesel engine cars before the middle of the twenty-first century. Prior to that date, hybrid vehicles will be more popular and diesel engines will continue to play an important role. Hence, research involving improvements in diesel-operated IC engines is still relevant.

Methods An experimental investigation was carried out using WED containing 10% water by volume as a fuel in a diesel engine at four different fuel injection pressures. The WED was prepared using an ultrasonicator.

Results With the increase of injection pressure, peak net heat release rate and in-cylinder pressure are found to have increased. Brake thermal efficiency is also found to have improved at higher injection pressure. The maximum efficiency was recorded when a WED at 210 bar of injection pressure is used, and it is about 3.3% higher than the maximum efficiency achieved when using normal diesel at the same pressure of fuel injection. At a higher load, neat brake-specific fuel consumption is found to be less compared to neat diesel, when only the amount of diesel contained in the emulsion as a fuel is considered. Maximum reduction in both NO_x and smoke emission by using WED is recorded at 210 bar, and the average reductions are determined to be 32.6% and 51.9%, respectively.

Conclusions WED can be used as an alternative fuel for existing diesel engines without any retrofitting and with significant reduction in the emissions of pollutants compared to normal diesel fuel. It can also be concluded that at higher injection pressure, the combustion, performance and emission characteristics of compression ignition engines are improved when using emulsified diesel.

Keywords Ultrasonication, Emulsified diesel, Performance, Combustion, Emission

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Background

Since the invention of the diesel engine, it is considered to be the best internal combustion engine in the fields of transportation, industrial applications and cultivation due to its superior fuel economy, coherent power generation, heavy-duty applications and energetic permanence

[1]. For the last few decades, fossil fuels have played the role of one of the principal energy sources and diesel engines consume a major part of fossil petroleum fuel [2].

Although diesel engines are superior, they emit different gaseous as well as non-gaseous pollutants such as oxides of nitrogen (NO_x), oxides of sulphur (SO_x), carbon monoxide (CO), carbon dioxide (CO_2), unburned hydrocarbon (HC), smoke and particulate matter (PM). These emitted pollutants form noxious substances in the atmosphere undergoing chemical, physical, and biological reactions. These poisonous substance*s* are a real threat to ecological systems and human health [3–6]. The concerns for energy shortage and different environmental issues arising from the consumption of fossil fuels have motivated researchers to explore alternative fuels for diesel engines which will reduce pollutant emissions without sacrificing much in the efficiency of the engine [7–11].

Researchers have experimented with various alternative fuels and, in most cases, blends of diesel with biodiesel and other supplementary fuels have been tested. WED is considered one of the most suitable alternative fuels since it reduces pollutant emissions and improves engine performance. The micro-explosion phenomena [12], longer ignition delay [13] and higher momentum [14] of fuel spray in the case of emulsified diesel result in improved combustion of the fuel.

The combustion, performance and emission characteristics of a diesel engine depend on various factors such as fuel injection timing, the quantity of fuel injected, the shape of the combustion chamber, the size of the nozzle hole and fuel injection pressure. The function of the fuel injection system in a diesel engine is to atomize the injected fuel to a high degree for better penetration and evaporation in a very short time for achieving higher combustion efficiency. At higher injection pressure, the spray penetration distance becomes longer [1] which results in the maximum utilization of the air injected into the cylinder. Also, the fuel particle diameter becomes smaller which also results in better air–fuel mixing [6]. The combined effect of the aforementioned factors improves the combustion efficiency of the injected fuel.

On the other hand, at lower fuel injection pressure, larger diameter fuel particles are formed and the ignition delay becomes longer [1]. A too high of injection pressure is also not desirable because in that case the ignition delay period becomes shorter and thus the possibility of the formation of a homogeneous mixture decreases, which adversely affects the combustion efficiency [15, 16]. The momentum of fuel droplets increases with the increase in fuel injection pressure, and the fuel spray tip penetration length also becomes higher. Thus, at a higher injection pressure, the fuel droplets collide with the cylinder wall and form a fuel oil film on it [6, 17]. This fuel oil film may not be evaporated and combusted completely and may create deposits on the combustion chamber wall [17]. One can conclude from the aforementioned information that the fuel injection pressure has a significant effect on the combustion, performance and emission characteristics of a compression ignition engine. In this work, the effect of variation in fuel injection pressure on engine performance was investigated to analyze and compare the use of both normal diesel and water emulsified diesel as fuels.

Some of the European countries have planned to ban diesel engines in the automotive sector due to environmental concerns.. Furthermore, France and the United Kingdom have planned to phase out conventional cars in 2040 and 2050, respectively [18]. However, it is important to consider that batteries and electric motors are not hassle-free [19]. The incorporation of the present global energy mix and the enormous electrification of road transport suggest a maximum benefit of the relocation of the emitted CO_2 [19]. Nonetheless, the generation of CO_2 should be measured not only in the emissions during its use but also during its production as well as disposal. In this regard, the current standard of production and disposal of electric vehicles is less environmentally friendly compared to cars running using IC engines [20]. Moreover, the variations in emission levels associated with electric vehicles depend on the method of electricity production [20], an important factor when considering that renewable energy sources are barely 10% of the total global energy mix [21] and mainly fossil fuels are used for electricity production where around 60% and 20% of energy is lost during electric energy production and transportation, respectively. The Joint Research Centre-EUCAR-CONCAWE (JEC) elaborately analyzed [22] and showed that shifting to electric vehicles will reduce but not eliminate CO_2 emissions.

Briefing in European Union Legislation in Progress February 2022 [23] pointed out that the vehicle cost, availability of infrastructure and driving range should be considered as analytical factors in the market absorption of zero- and low-emission vehicles. Furthermore, battery development should deal with different challenges for use in electric vehicles [18].

Apart from the transport sector, diesel engines are also used in agriculture, power and other industries as prime movers. Advanced injection systems, turbochargers, multi-fuel solutions, advanced combustion and alternative fuel concepts have become a part of emission reduction strategies from the internal combustion engine [19]. Hence, instead of banning the use of diesel engines, the running of improved diesel engines using alternative fuels to minimize environmental issues should be encouraged.

The use of WED can reduce the emission of NO_x and smoke simultaneously [24, 25]. Different researchers conducted experimental investigations using WED as a fuel for CI engines [26, 27]. However, conflicting results have been reported by them. Study findings available in the literature related to the effect of variation of fuel injection pressure using WED as fuel in CI engines are also very limited. Keeping this in mind, an endeavor was made to experimentally investigate the effect of variation of injection pressure on combustion, performance and emission characteristics of a four-stroke diesel engine using both neat diesel and WED10 as a fuel. The investigation was carried out for four injection pressures of 160 bar, 190 bar, 210 bar and 250 bar at a constant engine speed of 1500 rpm and a compression ratio of 17.5:1. Net heat release rate, in-cylinder pressure and rate of pressure rise were considered for analyzing combustion characteristics, whereas the performance characteristics were analyzed based on brake thermal efficiency, brake specific fuel consumption and exhaust gas temperature of the engine operated at different injection pressures using both the tested fuels. The emissions of important pollutants such as NO_x, CO and smoke were also recorded using both emulsified diesel and normal diesel at different fuel injection pressures to investigate the emission characteristics.

Methods

Preparation of WED

An emulsion is formed when two or more immiscible liquids are mixed [28, 29]. These immiscible liquids are mixed using surface-active agents called surfactants [24, 30]. These surfactants reduce the interfacial tension among the immiscible liquids and thus help in emulsion stabilization [28]. In this work, an ultrasonic machine (Model—VCX 750, Sonics & Materials, Inc., USA) was used to prepare the WED containing 10% water by volume and 2% surfactant by volume. The schematic diagram of the ultrasonicator is shown in Fig. 1 and the technical specifications of the same are given in Table 1. The surfactant used in this work was a mixture of Tween 80 (HLB value 15) and Span 80 (HLB value 4.3). They were mixed in the appropriate proportion of 7:13 to get a resultant HLB value of the emulsifier as 8.

Stability analysis

The prepared emulsion was kept in a graduated centrifuge tube under undisturbed condition for a period of two months to observe its stability behavior.

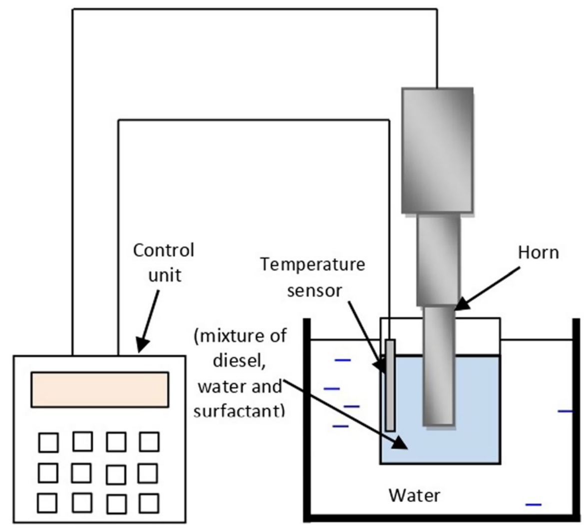

Fig.1 Schematic diagram of the Ultrasonicator

Table 1 Specifications of SONICS vibra cell ultrasonicator

Manufacturer	SONICS & MATERIALS, INC., USA
Model No	VCX 750
Power	750 Watts
Frequency	20 kHz
System Capacity	250 µl to 1L
Sealed converter: Model No	CV33
Temp. probe for monitoring temp	Up to100 °C
Electrical Requirement	220 Volts, 50/60 Hz, Single Phase, 15Amp

Measurement of physicochemical properties

Two important physical properties, namely density and viscosity were measured. The density was measured using a Pycnometer, whereas the Oswald viscometer was used to determine the kinematic viscosity of the tested fuels. The quality of a fuel is primarily determined by its heating value and it was measured using a Bomb calorimeter separately for normal diesel and WED.

Setup and procedure for the experimental study

A Kirloskar, Indian-made, single-cylinder, four-stroke, water-cooled diesel engine fitted with an eddy current dynamometer was used for this experimental work. The setup for the experimental work is shown in Fig. 2 and the details of the engine are presented in Table 2. The

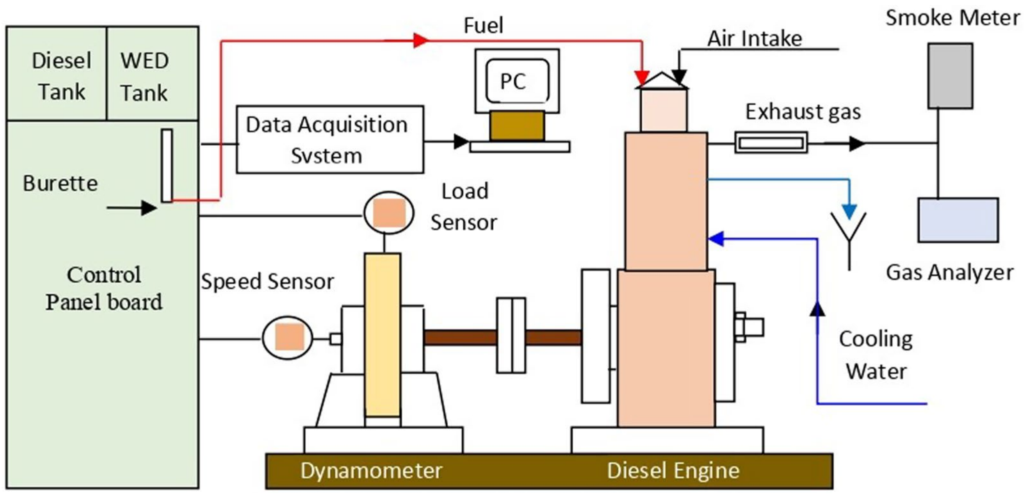

Fig. 2 Schematic View of the Experimental Setup

Table 2 Specification of diesel engine

Make	Kirloskar Oil Engines Ltd., India
Model	TV1
Type	Four-stroke, Single-cylinder
Bore and stroke	87.5 mm and 110 mm
Rated Power	3.5 KW
Compression ratio	17.5:1
Injection timing	23° before TDC
Injection nozzle	3 holes, hole diameter 0.3 mm
Cooling media	Water
Engine loading	Eddy current dynamometer

Table 3 Specification of Testo 350 flue gas analyzer

Parameters	Resolution	Accuracy	Range
CO	0.001 vol%	±0.3 vol%	0–15 vol%
CO2	0.01 vol%	±0.3% < 25 vol%	0–50 vol%
NO	1 ppm	±5% reading < 2000 ppm	0–3000 ppm
NO2	0.1 ppm	±5% < 100 ppm	0– 500 ppm
O2	0.01 vol%	±0.2 vol%	0–25 vol%
HC	1 ppm	±10% of reading	0–40,000 ppm

Table 4 Smoke meter specification (Indus OMS 103 smoke meter)

Parameters	Resolution	Accuracy	Range
HSU	0.1%	–	0–99.9
K	0.01 m^{-1}	±0.1 m^{-1}	0–∞

engine used in this work was fitted with a direct injection (DI) type fuel injection system. The fuel injection nozzle was fitted inside the nozzle holder in the cylinder head and was connected via a high-pressure pipe to the fuel pump. The fuel injection pressure was changed by adjusting the tension of the injector spring. The spring tension can be increased or decreased by tightening or loosening the screw provided at the top of the injector. The fuel injection pressure was measured using a fuel injector pressure tester available in the IC engine laboratory of the Indian Institute of Engineering Science and Technology, Shibpur.

Performance and emission characteristics were investigated and analyzed at different engine loads and injection pressures. All the data associated with the engine's performance characteristics were collected using a laptop connected to the electronic data acquisition system (EDAS). The LabVIEW-based software 'EnginesoftLV' was installed on the laptop and used for this purpose. A flue gas analyzer, namely the Testo 350, was used to measure NO_x and a smoke meter (Indus OMS 103) was employed to measure the smoke level in the exhaust gas. The specifications of the flue gas analyzer and smoke meter are given in Tables 3 and 4 respectively.

Results

Stability behavior

The shelf life of WED is low, and hence the stability of the emulsion may be an issue for its use as a fuel in diesel engines. Keeping this in mind, stability analysis of the WED prepared by an ultrasonicator was studied before its use in the engine. It was observed that no separation took place in the first 40 h, i.e., the stability of the fuel was 100%. After four days, the WED showed about 98% stability and after 15 days and one month, the stabilities went down to 96% and 92% respectively. This indicates that it is desirable to use WED within a short period after its preparation.

Physicochemical properties

The values of the measured density and kinematic viscosity at 30^{0}C of normal diesel and WED prepared by ultrasonication are shown in Table 5. The density of base diesel and WED were noted to be 823.1 kg/m^3 and 840.7 kg/m^3, respectively. The viscosity of the WED was also found to be higher than that of base diesel. The kinematic viscosity of base diesel and WED were measured to be 2.979 cSt and 3.322 cSt, respectively. The measured data of density, viscosity, and the calorific value of both tested fuels are presented in Table 5. The calorific value of WED is found to be lower than that of normal diesel.

Uncertainty analysis

Uncertainty analysis is carried out to estimate the maximum error that may incur in any experimental work. The adequacy of the experimental results becomes dubious if the estimated error is above the tolerable limits. Based on repeated experiments and the errors associated with all the equipment and instruments used in this study, the uncertainties in measuring different parameters were estimated and presented in Table 6. It is also important to evaluate the uncertainty of important parameters, such as BSFC and brake thermal efficiency (BTE) of the engine, which are computed from the experimentally measured data using standard, well-established relations. The uncertainty in BSFC depends on the uncertainties in measuring engine speed, load, and fuel flow rate. Hence, the percentage of uncertainty for BSFC was calculated following Holman [31] as uBSFC = [(speed)^2 + (load)^2 + (fuel flow rate)^2]$^{1/2}$ = ± 1.02%. Similarly, for BTE, the percentage of uncertainty, uBTE = [(liquid fuel flow rate)^2 + (LHV of the fuel)^2 + (height of the liquid column)^2 + (Load cell)^2 + (Speed sensor)^2]$^{1/2}$ = ± 1.51%. Each term on the right hand of the above relation denotes the error associated with that particular parameter. It may be noted that the uncertainty values of BTE and BSFC lie within acceptable limits.

Table 5 Physicochemical properties of normal diesel and WED

Type of fuel	Density (kg/m^3)	Viscosity (cSt)	Calorific value (kJ/kg)
Normal Diesel	823.1	2.979	43,300
WED	840.7	3.322	39,700

Table 6 Errors in measuring different parameters

Parameter	Unit	Measuring range	Errors (%)
LHV of the fuel	MJ/kg	–	± 1
Liquid fuel flow rate	kPa	1–100 kPa	± 1
Height of liquid column	ml	0–100 ml	± 0.5
NOx	ppm	0–5000 ppm	± 0.5
CO	vol%	0–15%	± 0.3
HC	ppm	0–30,000 ppm	± 0.1
Smoke opacity	HSU	0–99.9	± 1
Temperature indicator	°C	0–600 °C	± 0.15
Crank angle encoder	°CA	–	± 0.2
Pressure transducer	V	–	± 1
Load cell	kg	–	± 0.15
Speed sensor	rpm	–	± 0.1

Cumulative heat release

Figure 3 shows the variations of cumulative heat release with a crank angle using both normal diesel and emulsified diesel at an injection pressure of 210 bar. The cumulative heat release reached its maximum value at 60 °CA after TDC in the case of neat diesel. The corresponding value for WED is noted to be 64 °CA after TDC. The maximum values for cumulative heat release using base diesel and emulsified diesel were found to be 0.93 kJ and 0.95 kJ, respectively.

Net heat release rate

The variations of neat heat release rate with a crank angle for both base diesel and emulsified diesel at injection pressures of 160 bar and 190 bar are presented in Fig. 4a.

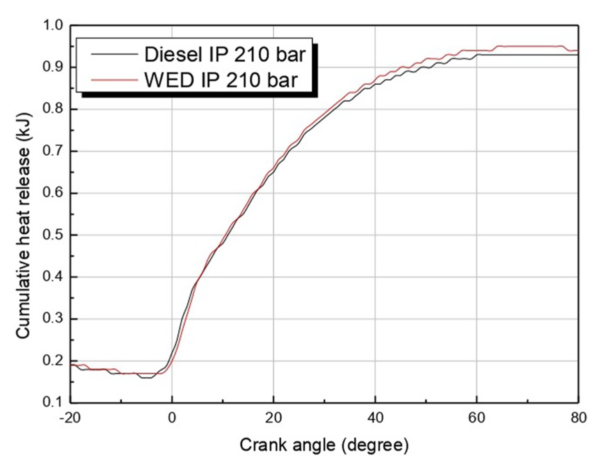

Fig. 3 Variations of cumulative heat release with crank angle at injection pressure of 210 bar for base diesel and WED

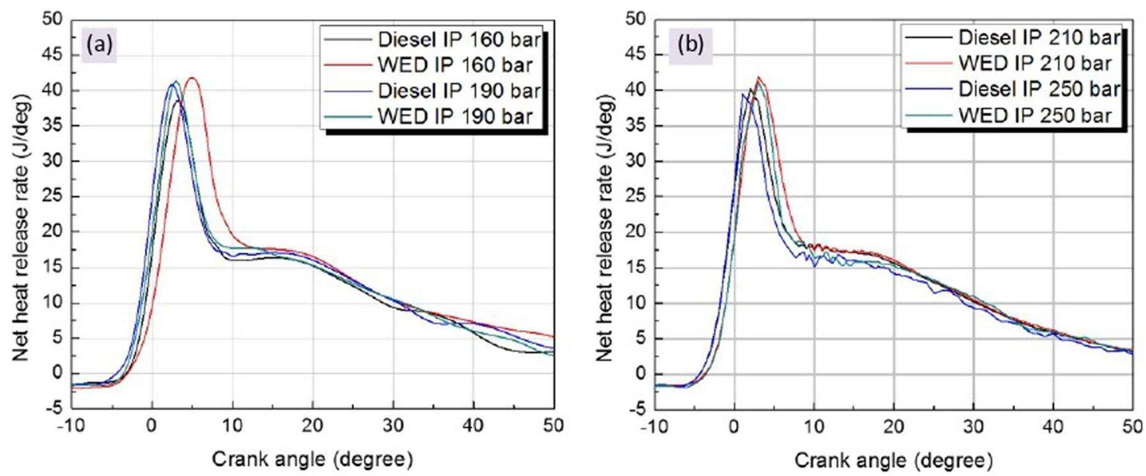

Fig. 4 Variations of net heat release rate with crank angle at injection pressures of **a** 160 bar and 190 bar and **b** 210 bar and 250 bar for base diesel and WED

Table 7 Ignition delay periods at different fuel injection pressures

Type of fuel	Injection pressure (bar)	Ignition delay (ms)
Diesel	160	1.33
WED	160	1.55
Diesel	190	1.22
WED	190	1.44
Diesel	210	1.22
WED	210	1.44
Diesel	250	1.11
WED	250	1.33

The same variations for injection pressures of 210 bar and 250 bar are shown in Fig. 4b. These two figures indicate longer ignition delay for WED compared to normal diesel. The ignition delay periods using normal diesel and WED at different injection pressures are also presented in Table 7. Likewise, Fig. 4a and b show that the ignition delay is higher at lower injection pressure for both normal diesel and WED. It can also be observed from these figures that the peak net heat release rates using both base diesel and emulsified diesel fuels were found to be higher for an injection pressure of 210 bar. The peak net heat release rates using normal diesel at injection pressures of 160 bar, 190 bar, 210 bar, and 250 bar were recorded as 38.46 J/deg, 40.12 J/deg, 40.25 J/deg, and 39.57 J/deg, respectively. The corresponding values using emulsified diesel were observed to be 41.82 J/deg, 41.39 J/deg, 41.96 J/deg, and 41.25 J/deg, respectively.

The variations of heat release rate with crank angle using separately base diesel and emulsified diesel at 210 bar of injection pressure have been presented in Fig. 5 to show different phases of combustion. The figure indicates a higher ignition delay for emulsified diesel and the ignition delay using base diesel and WED were shown to be 1.22 ms and 1.44 ms, respectively.

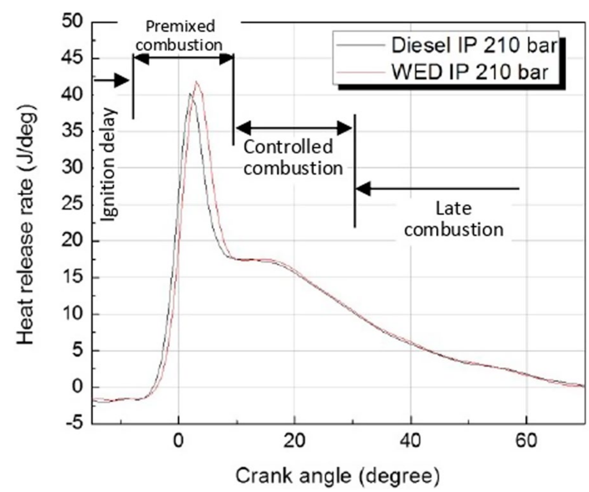

Fig. 5 Comparison of the net heat release rate with crank angle using base diesel and WED

In-cylinder pressure

Figure 6a shows the variations of in-cylinder pressure with crank angle for both normal diesel and WED for injection pressures of 160 bar and 190 bar and the same variations for injection pressures of 210 bar and 250 bar are shown in Fig. 6b.

The figures show that the peak in-cylinder pressure increases with the increase of fuel injection pressure up to 210 bar for both tested fuels. The peak in-cylinder

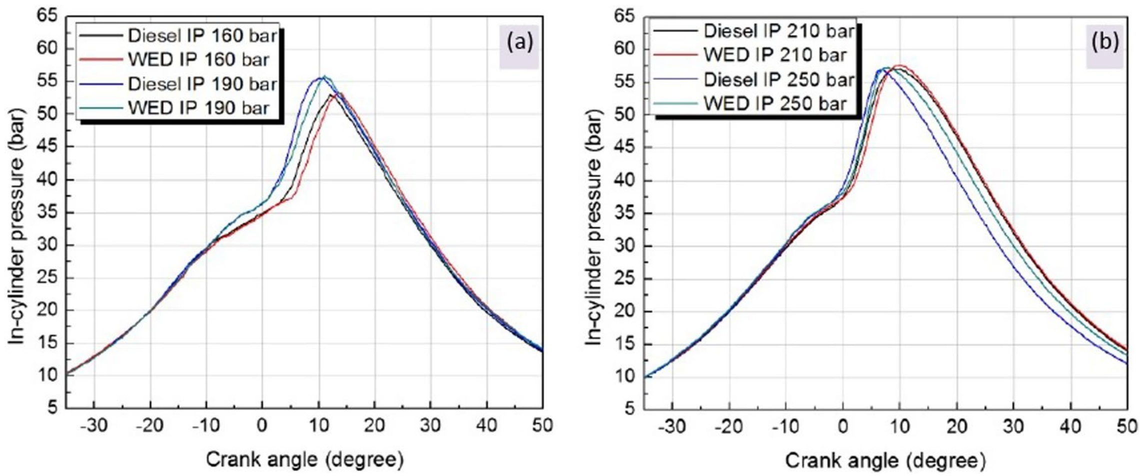

Fig. 6 Variations of in-cylinder pressure with crank angle at injection pressures of **a** 160 bar and 190 bar and **b** 210 bar and 250 bar for neat diesel and WED

pressures using neat diesel as fuel were found to be 53.33 bar, 55.57 bar, 57.11 bar, and 57.02 bar when the injection pressures were set to 160 bar, 190 bar, 210 bar, and 250 bar respectively. The corresponding values were shown to be 54.37 bar, 55.94 bar, 57.68 bar, and 57.22 bar, respectively when WED was used instead of normal diesel. It can also be observed from the above figures that pressure rises due to fuel combustion starting earlier at higher injection pressure. This indicates a shorter ignition delay at higher injection pressure.

Brake thermal efficiency

The variations of brake thermal efficiency with load at different injection pressures using normal diesel and emulsified diesel are shown in Fig. 7a and b, respectively. The figures demonstrate that the maximum brake thermal efficiency is achieved at an injection pressure of 210 bar for both fuels. In previous sections, it is mentioned that the in-cylinder pressure is found to be maximum at an injection pressure of 210 bar. The brake thermal efficiencies were noted to be 26.25%, 27.52%, 27.64%, and 27.55% at the injection pressures of 160 bar, 190 bar, 210 bar, and 250 bar, respectively using neat diesel. The corresponding values using WED were found to be 27.05%, 28.5%, 28.54%, and 28.26%, respectively.

Brake-specific fuel consumption

The variations of the BSFC with load at different injection pressures using neat diesel and WED are presented in Fig. 8a and b, respectively. The BSFC is found to increase

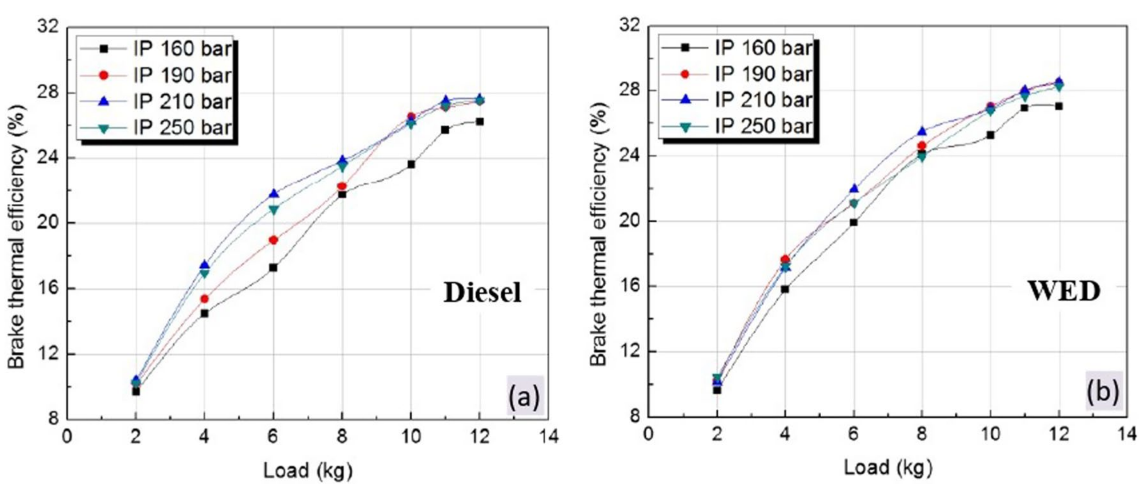

Fig. 7 Variation of the brake thermal efficiency with load at different injection pressures using **a** normal diesel and **b** WED

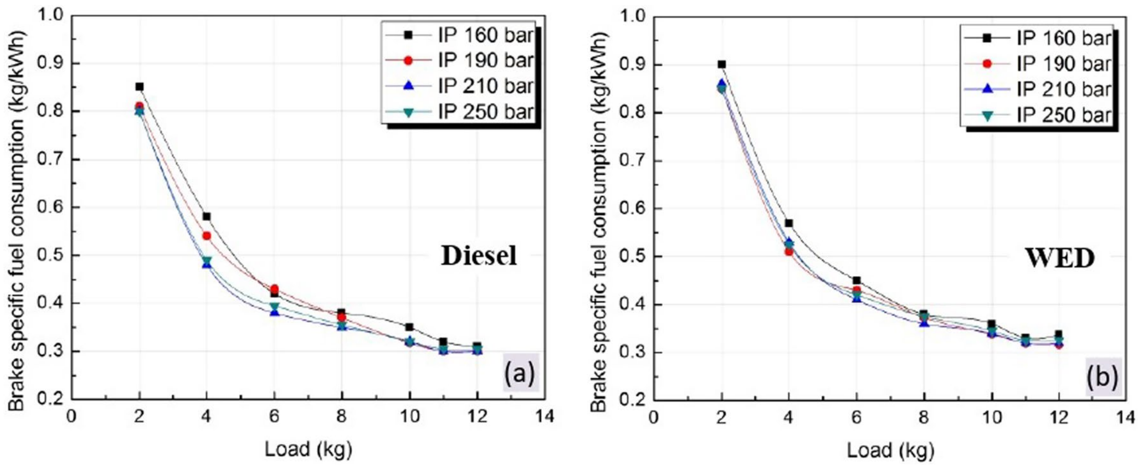

Fig. 8 Variation of the BSFC with load at different injection pressures using **a** normal diesel and **b** WED

at all fuel injection pressures using WED as a fuel instead of neat diesel. The figures indicate that with an increase in injection pressure, the BSFC decreases for both fuels up to certain injection pressure. But, with a further increase in injection pressure, the BSFC increases. At full load, the BSFC using neat diesel at injection pressures of 160 bar, 190 bar, 210 bar, and 250 bar were noted to be 0.31 kg/kWh, 0.30 kg/kWh, 0.30 kg/kWh, and 0.31 kg/kWh, respectively. The corresponding values using WED were found to be 0.33 kg/kWh, 0.32 kg/kWh, 0.32 kg/kWh, and 0.33 kg/kWh, respectively.

Exhaust gas temperature

The variations of exhaust gas temperature with load using both WED and base diesel for injection pressures of 160 bar and 190 bar are presented in Fig. 9a. The corresponding variations of exhaust gas temperature for injection pressures of 210 bar and 250 bar are shown in Fig. 9b. It can be observed from the two figures that the exhaust gas temperature increases with the increase in load for both normal diesel and emulsified diesel. At full load, the exhaust gas temperatures using normal diesel were noted to be 285 °C, 290 °C, 293 °C, and 292 °C at injection pressures of 160 bar, 190 bar, 210 bar, and 250 bar, respectively. The corresponding values with emulsified diesel as a fuel were shown to be 271 °C, 280 °C, 278 °C, and 277 °C, respectively.

Nitrogen oxide emission

The variations of NO_x emission with load at different injection pressures using normal diesel and emulsified diesel are presented in Fig. 10a and b, respectively. It can be observed from the figures that at all loads and injection pressures result in NO_x emissions that are lower

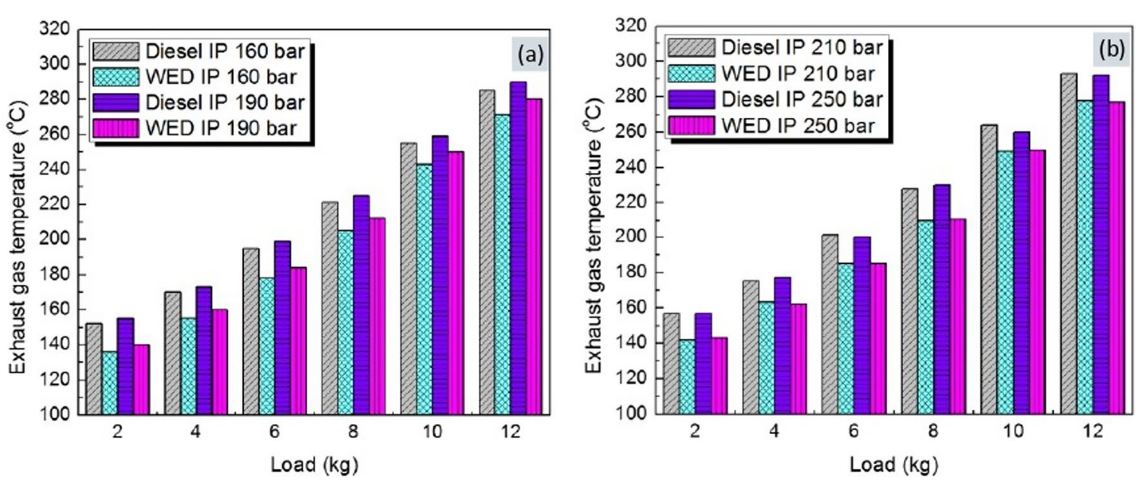

Fig. 9 Variation of exhaust gas temperature with load at injection pressures of **a** 160 bar and 190 bar and **b** 210 bar and 250 bar for base diesel and WED

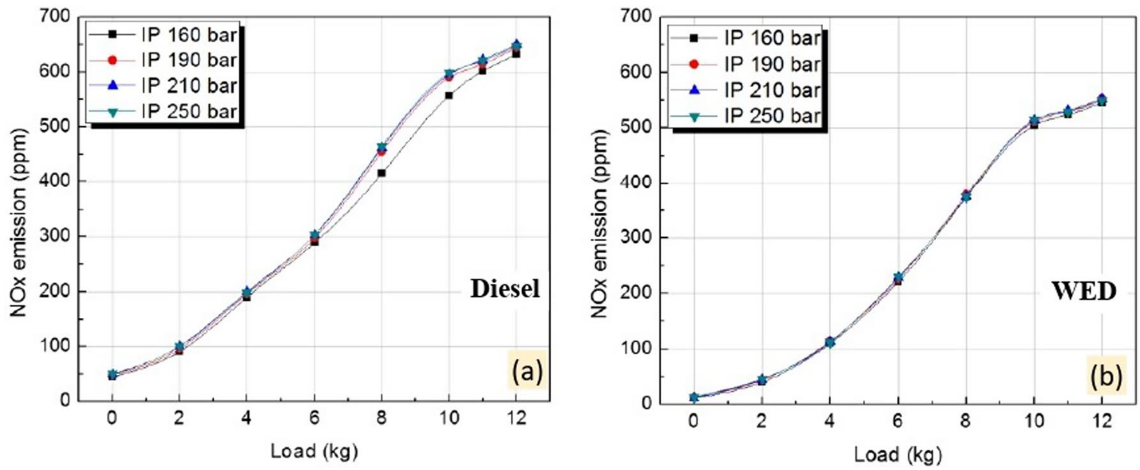

Fig. 10 Variation of NO_x emission with load at different injection pressures using **a** normal diesel and **b** WED

when using WED rather than neat diesel. At full load, the NO_x emissions using neat diesel at injection pressures of 160 bar, 190 bar, 210 bar, and 250 bar were observed to be 632 ppm, 645 ppm, 650 ppm, and 647 ppm, respectively. The corresponding values using WED as a fuel were noted to be 546 ppm, 553 ppm, 553 ppm, and 550 ppm, respectively. At no load, the NO_x emissions using diesel fuel at the injection pressures of 160 bar, 190 bar, 210 bar, and 250 bar were found to be 45 ppm, 48 ppm, 49 ppm, and 50 ppm, respectively and the corresponding values using WED were recorded as 11 ppm, 12 ppm, 12 ppm and 13 ppm, respectively.

Carbon monoxide emission

The variations of CO emission with load using both normal diesel and WED at injection pressures of 160 bar and 190 bar are shown in Fig. 11a and the same variations at injection pressures of 210 bar and 250 bar are presented in Fig. 11b. The figures indicate that at any load the CO emission is lower for higher fuel injection pressure. Comparing the two figures, it can be concluded that the CO emission is higher for emulsified diesel than that using base diesel. At full load, the CO emissions using base diesel as a fuel at the injection pressures of 160 bar, 190 bar, 210 bar, and 250 bar were recorded as 0.042%, 0.040%, 0.039%, and 0.038%, respectively. The corresponding values in CO emission using WED as a fuel were found to be 0.055%, 0.051%, 0.052%, and 0.048%, respectively.

Smoke emission

The variations of smoke emissions with load at different injection pressures using neat diesel and emulsified diesel are shown in Fig. 12a and b, respectively. For the fuels, smoke emissions decrease with the increase of injection pressure. At all injection pressures, the smoke emissions using emulsified diesel were found to be significantly

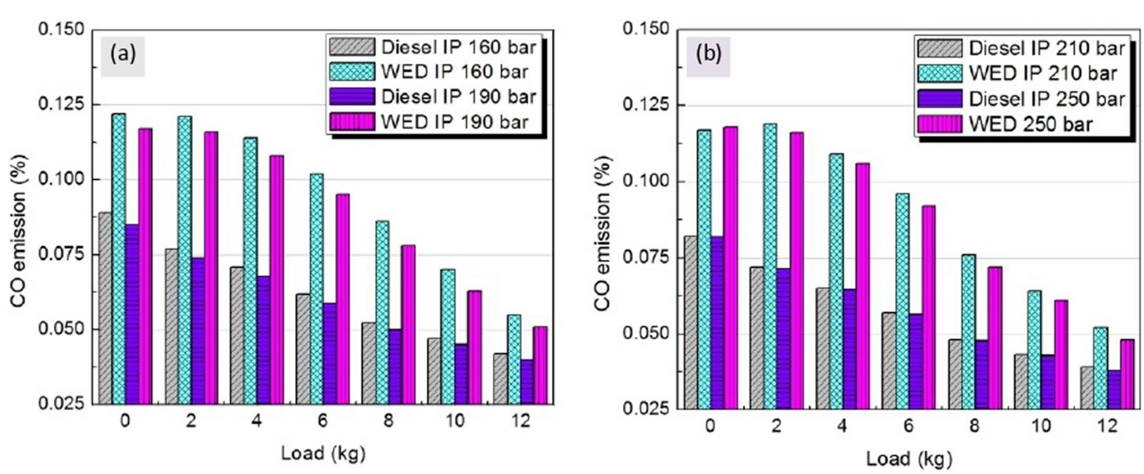

Fig. 11 Variation of CO emission with load at injection pressures of **a** 160 bar and 190 bar and **b** 210 bar and 250 bar for base diesel and WED

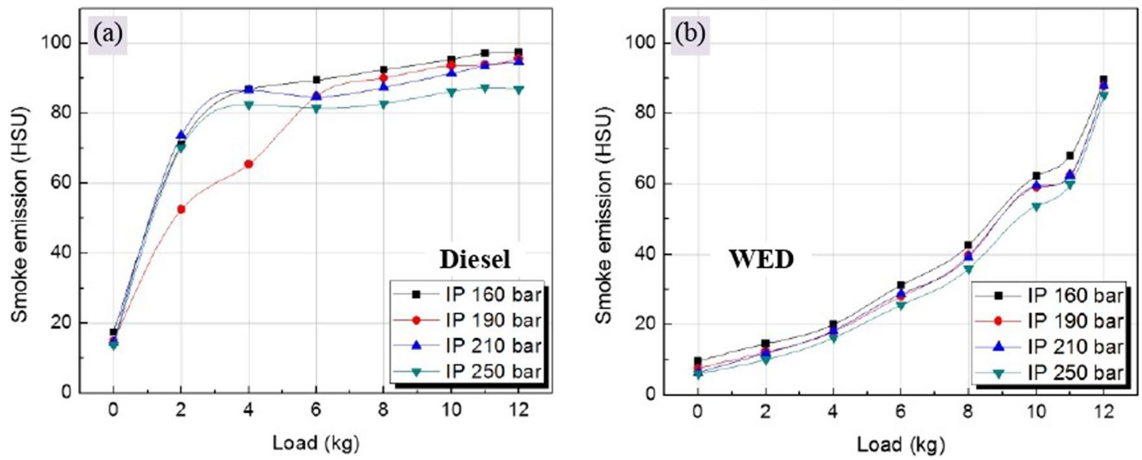

Fig. 12 Variation of smoke emission with load at different injection pressures using **a** normal diesel and **b** WED

lower compared to normal diesel. At an injection pressure of 160 bar, the average reduction in smoke emissions using WED was noted to be 49.2% compared to normal diesel. The corresponding reductions in smoke emissions using emulsified diesel at the injection pressures of 190 bar, 210 bar, and 250 bar were noted to be 50.1%, 51.9%, and 51.8%, respectively. These measurements indicate that the reduction in smoke emissions using WED increases compared to neat diesel with the increase in injection pressure.

Discussions

Physicochemical properties

The density of the WED was noted to be higher than that of base diesel, which is due to the addition of relatively higher-density water to lower-density diesel. In the case of emulsified diesel, the frictional force between dispersed water particles and the continuous diesel phase generates static electricity which increases the viscosity of the WED. The calorific value of the emulsified fuel was found to be lower since some quantity of diesel fuel is replaced by an equal amount of water.

Cumulative heat release

During the ignition delay period, pressure and temperature decrease, and heat release becomes negative. This is due to the evaporation of the injected fuel which absorbs the sensible as well as latent heat [32]. As combustion starts, the heat release becomes positive and increases until all the phases of combustion are over. The heat release characteristics give a clear idea to assess the engine performance and the effects of different operating conditions on the performance of an engine [33]. The maximum value of cumulative heat release using WED reached 4 °CA later than that using neat diesel. This happens due to the longer ignition delay period for the emulsified fuels. In the late combustion phase, the cumulative heat release for WED is higher than base diesel. This indicates that more fractions of WED fuel remained unburned after the controlled combustion phase. A higher amount of cumulative heat release (0.02 kJ) for emulsified diesel than base diesel indicates better combustion of the first one than the later one.

Net heat release rate

The heat release rate curves (Fig. 4) and Table 7 show longer ignition delay for WED compared to normal diesel. The higher ignition delay of emulsified diesel can be explained by the phenomenon of the heat sink effect. The heat sink effect is the lowering of temperature to some extent due to the evaporation of water present in the emulsified fuel. Also, the higher viscosity in the case of WED affects the atomization and evaporation to form the combustible mixture [34, 35]. Longer ignition delay was observed at lower injection pressure for all the tested fuels. The injected fuel droplet size is inversely proportional to the fuel injection pressure [6]. At lower injection pressure, atomized fuel droplet size is relatively larger which takes more time to mix with air to form a homogeneous mixture before the start of combustion. Also, the air contact surface area for larger fuel particles is less. On the other hand, when the injection pressure is higher, the ignition delay period becomes shorter due to the formation of a more homogeneous mixture which leads to higher combustion efficiency [16]. The peak net heat release rate was found to be maximum for an injection pressure of 210 bar. With the increase in injection pressure, the fuel penetration becomes longer and air–fuel mixture quality is improved [1]. This leads to higher combustion efficiency of fuel. More amount of fuel is accumulated in the case of a longer ignition delay period for physical and chemical reactions resulting in more combustion in premixed mode [36, 37]. Thus, the peak net heat release rate was noted to be higher for WED than for base diesel.

The net heat release rate curves depict that the peak heat release rate increases with the increase of injection pressure up to a certain limit using normal diesel as well as emulsified diesel. Maximum values were recorded at 210 bar for both types of tested fuels. But, at maximum injection pressure, i.e., at 250 bar, the peak heat release rate was lower than the other injection pressure. This can be attributed to the wastage of fuel due to the collision of spray tips with the cylinder wall at higher injection pressure [6, 17].

The variations of heat release rate with a crank angle using base diesel and emulsified diesel at only 210 bar of injection pressure is presented in Fig. 5 to show the different phases of combustion. For a direct injection of the diesel engine, the overall combustion process can be identified from the heat release rate diagram [38]. Ignition delay refers to the period of time from the start of fuel injection to the beginning of combustion. Figure 5 shows a longer ignition delay for emulsified diesel than base diesel. At the beginning of the combustion, the combustion chamber temperature is low where micro-explosion is not so significant. Its intensity increases with the increase in temperature [33]. The heat sink effect reduces in-cylinder temperature. The higher viscosity of the water-emulsified diesel fuel also significantly affects the fuel atomization [39]. The combined effect of these factors retards the atomization, evaporation, and subsequent formation of a combustible mixture of air and fuel. Thus, a longer ignition delay was observed in the case of WED when it was used as an alternative fuel for a CI engine.

In-cylinder pressure

A higher in-cylinder pressure and a shorter ignition delay were observed at higher fuel injection pressure. This can be explained by the fact that at higher injection pressure, smaller fuel droplets are formed which enhance the formation of a better air–fuel mixture resulting in improved combustion of the fuel [6]. Thus, the ignition delay becomes shorter due to the early ignition of fuel. However, a higher ignition delay was observed for emulsified diesel than neat diesel at all injection pressures. This can be attributed to the higher viscosity and the heat sink effect of the emulsified diesel [40, 41].

Brake thermal efficiency

The variations of brake thermal efficiency with load for different injection pressures showed the maximum efficiency at an injection pressure of 210 bar for both fuels. Thalari and Kumar [6] also found higher brake thermal efficiency when injection pressure was increased. With an increase in injection pressure, more fuel energy was released because the combustion efficiency was improved due to the formation of smaller fuel particles and also for more penetration of fuel spray. However, at very high injection pressure, some amount of fuel remains unburnt which strikes the cylinder wall without participating in the combustion process [6, 17]. It can also be observed that at lower loads, there was no significant difference in brake thermal efficiency for the tested fuels at all injection pressures. However, at higher loads, the same was noted to be higher when emulsified diesel was used as fuel instead of normal diesel. This was due to higher combustion chamber temperature and pressure at higher load when enhanced micro-explosion took place resulting in improved combustion of emulsified fuel than neat diesel [42, 43]. The maximum efficiency recorded using WED at an injection pressure of 210 bar was found to be 28.54% which was about 3.3% higher than that noted using normal diesel at the same injection pressure.

Brake-specific fuel consumption

The BSFC was noted to be higher using emulsified diesel at all fuel injection pressures due to its lower calorific value. The BSFC decreased with the increase of fuel injection pressure for both fuels. In this connection, it may be noted that Shehata et al. [44] reported a decrease in the BSFC with the increase in injection pressure for normal diesel and bio-diesel. At lower injection pressure, the injected fuel forms larger size fuel particles [15, 16] which lead to poor combustion resulting in higher BSFC. However, too high injection pressure leads to a situation where the fuel spray tip touches the cylinder wall. This collided part of fuel forms a layer on the cylinder wall resulting in less power generation [17]. Thus, BSFC increased at very high fuel injection pressure. Though BSFC increased using emulsified diesel, the neat BSFC using WED was found to be slightly lower compared to neat diesel at higher loads, if only the amount of diesel present in the emulsion was considered as the total fuel.

Exhaust gas temperature

At higher loads, more amount of fuel was combusted resulting in a higher amount of heat release, and thus, the exhaust gas temperature increased. Also, the exhaust gas temperature is found to be higher at higher injection pressure. This can be attributed to the improved combustion at higher injection pressure which results in the release of more amount of heat [16]. As a result, the combustion chamber temperature increased with the increase of fuel injection pressure, and hence, the corresponding exhaust gas temperature increased as expected. It can also be seen from those two figures that the exhaust gas temperature was reduced using emulsified diesel instead of base diesel at any injection pressure. Suresh et al. [45] and Yang et al. [35] also observed lower exhaust gas temperatures using WED compared to base diesel. This is due to the presence of water in the emulsified diesel which results in a decrease in combustion chamber temperature [37].

Nitrogen oxide emissions

At all engine operating conditions, the NO_x emissions were observed to be reduced using WED than with neat diesel. During the combustion of fuel, the water present in the emulsified fuel absorbs sensible heat and latent heat of evaporation resulting in a reduction in the combustion chamber temperature [46]. Thus, the use of WED reduces the NO_x emissions compared to neat diesel as its formation is temperature-dependent [37, 47]. The NO_x emissions were also found to be higher at higher loads for both fuels. This is because, at a higher load, the combustion chamber temperature is higher than that at a lower load.

The average reductions in NO_x emissions using WED for the injection pressure of 160 bar, 190 bar, 210 bar, and 250 bar were noted to be 30.4%, 31.7%, 32.6%, and 32.3%, respectively compared to neat diesel. The above-mentioned values suggest that the effect of injection pressure on NOx emission is not so significant when WED is used as a fuel in a diesel engine. But, in the case of normal diesel, the influence of fuel injection pressure on NO_x emissions is not negligible. Other researchers [16] also reported an increase in NO_x emissions at higher injection pressure when normal diesel was used as a fuel. On the other hand, this study confirms a huge reduction of NO_x emissions at any injection pressure with the use of WED instead of neat diesel as fuel.

Carbon monoxide emissions

Celikten [16] also reported a reduction in CO emission at higher fuel injection pressure. This happens because the combustion efficiency increases due to the formation of smaller fuel particles in the atomized fuel at higher injection pressure [6]. Under this condition, the oxidation of CO to form CO_2 increases resulting in lower CO emissions. On the other hand, poor atomization of fuel takes place at lower injection pressure [1]. Thus, CO emissions increase at lower injection pressure because of incomplete combustion of fuel. The water particles present in the emulsified diesel evaporate absorbing sensible and latent heat of evaporation resulting in the heat sink effect [48]. The heat sink effect due to the presence of water in emulsified diesel reduces the combustion chamber temperature resulting in incomplete combustion of fuel. The combustion chamber temperature increased with the increase of engine load when more CO was oxidized to form CO2. Hence, at higher loads, CO emissions were found to be lower for both fuels at all fuel injection pressures. It can also be noted that at full load conditions, there was no significant difference in CO emissions between using base diesel and WED as a fuel.

Smoke emissions

The smoke emissions were noted to be remarkably lower using WED at all injection pressures. A reduction in smoke emissions at higher injection pressure was also noticed by Icingur and Altiparmak [48] and Fayad [49]. This can be attributed to the improved combustion of the fuels at a higher injection pressure. At higher pressure of fuel injection, smaller droplets of fuel are formed resulting better air–fuel mixture and thus the combustion efficiency of the fuel is improved [6]. Thus, smoke emission is reduced at higher injection pressure. The secondary atomization due to micro-explosion, more intense combustion in the premixed combustion phase due to longer ignition delay, and more air-entraining into the fuel spray due to higher momentum in the case of emulsified diesel result in the improvement in the overall combustion of fuel. The presence of OH radical available with the use of emulsified diesel also enhances the oxidation of soot and thus the smoke emissions are reduced [27].

Conclusions

Based on the results obtained from this experimental investigation, the following conclusions can be drawn. Improved combustion characteristics were observed at higher fuel injection pressure. However, at too high injection pressure, some fuel may be wasted due to the collision of spray tips with the cylinder wall. The maximum brake thermal efficiency was recorded using WED at an injection pressure of 210 bar, which was 3.3% higher than that noted using neat diesel at the same injection pressure. The neat BSFC considering only the amount of diesel present in the emulsion was shown to be less compared to neat diesel. The NO_x and smoke emissions increase and decrease, respectively, with an increase of injection pressure. However, they were noted to be lower using emulsified diesel compared to normal diesel. The maximum reductions in both NO_x and smoke emission using WED were recorded at 210 bar and the average reductions were found to be 32.6% and 51.9%, respectively. At full load, no remarkable difference in the emissions of CO was recorded using normal diesel and WED. Finally, it can be concluded that the emulsified diesel may be injected at a higher injection pressure to get improved combustion, performance, and emission characteristics of a compression ignition engine.

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Declarations

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