Influence of Water-in-Diesel Emulsion Fuel and Compression Ratio on Combustion, Performance and Emission Characteristics of Diesel Engine

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Abstract: The emission characteristics of diesel engine have drawn much interest in the study of eco-friendly fuels since enhanced environmental and human health are of concern. To improve the emission qualities, researchers endeavor to create changes in existing diesel fuel and engine operating conditions. The current study focuses the modification of existing diesel fuel in the form of water-in-diesel emulsion and analyzes its effect on combustion, performance and emission characteristics in a diesel engine with different CRs. The experiments are conducted in two phases. In the first phase, various concentration of W/D emulsion fuels (5%, 10%, 15% and 20%) are prepared at a high speed of agitation, stabilized by a non-ionic surfactant, and its properties are measured. The results revealed that the concentration of water in excess of 10% in diesel failed to meet the standard diesel fuel requirements. In the second phase, the combustion, performance and emission characteristics of BD and W/D emulsion fuels (5% and 10%) are studied under different loading conditions (25%, 50%, 75% and full load) with CR of 15 and 18. The results showed that ICP and NHR are increased and MGT is decreased with increase in water concentration. In addition, marginal increases in IDP is observed for W/D emulsion fuels at a CR 18, whereas significant increases is observed with CR 15. The diesel engine performance and emission parameters such as BSFC, BTE and NO emission showed good improvement with W/D emulsion fuels for both CRs, irrespective of load conditions. In addition, marginal increase in HC and CO emissions are observed with high CR, and considerable increases are noted at low CR.

Keywords: Combustion characteristics, emission characteristics, emulsion fuel properties, performance characteristics, water-in-diesel emulsion fuel

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1 Introduction

Diesel engines are dominating in transportation and power generation sectors due to their enhanced fuel economy and better engine performance. Despite the fact that diesel engines are the major sources of atmospheric pollutants such as NOx and PM, which are the contributors of ground level ozone and photochemical smog. In order to obtain the best emission characteristics in diesel engines, continuous efforts have been taken in in-cylinder and engine-based design changes, fuel modifications and after treatment systems. As a result, the fuel modification techniques have been preferred for the existing diesel engines since the desired emission characteristics can be achieved without any added cost [1]. Several investigations are carried out to improve the emission characteristics in diesel engines by fuel modification. Out of these, the introduction of water in diesel fuel has generated much interest since it reduces the peak flame temperature inside the combustion chamber that directly promotes the low-level NOx formation [2].

The inclusion of water in the diesel engine combustion zone was initially proposed by Hopkinson to reduce the exhaust emissions and promote better intercooling of the gas engine [3]. The following methods are preferred to initiate the water in diesel engines: (i) direct injection of water into the combustion chamber (ii) fumigating the water into the engine intake air and (iii) in the form of W/D emulsion fuel. Ghojel *et al*. [1] concluded that the W/D emulsion fuels displayed better emission characteristics without any engine modification. There are two types of emulsion: (i) W/D and (ii) Diesel-in-water (D/W). Panayiotis *et al*. [4] reported that W/D emulsion fuels has favorable fuel characteristics, such as large fragmentation, less change in viscosity, and micro-explosion phenomena of the water droplet in contrast to D/W emulsion fuels.

Forming a kinetically stable W/D emulsion for a long period is the main challenge to implementing emulsion fuels in diesel engine. It can be achieved through the selection of suitable surfactants and emulsification methods [5]. Morozumi *et al*. [6] noticed that a non-ionic surfactants has the desired fuel characteristics, such as burning with no soot and free of sulfur and nitrogen, over cationic and anionic surfactants. The emulsification method includes high-shear stirring, high-pressure homogenizers, ultrasonic and supersonic vibrations. As per Lin [7] statement, mechanical homogenization has more positive effect over ultrasonic and supersonic vibrations, as far as the smoke and NOx emissions are concerned. In the previous phase of this study, it is concluded that Sorbitan monolaurate (a non-ionic surfactant of hydrophilic-lipophilic balance - HLB 8.6) at high speed of agitation (15000 rpm) provided better emulsion stability with a minor occurrence of creamy layer and coalescence zone.

Several investigations are conducted to study the performance and emission characteristics of W/D emulsion fuels. As far as combustion and performance characteristics are concerned, the reports were inconsistent in the area of W/D emulsion fuels due to complexity of analyzing the combustion phenomena.

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Suresh and Amirthagadeswaran [8] reported that the micro-explosion behavior of evaporating droplets in W/D emulsion fuels promoted the combustion efficiency. Wang *et al* [9] and Basha and Anand [10] also reported that the BP, torque and BSFC are increased with increase in water concentration. Yang *et al*. [11] and Selim [12] reported some contradictory results of the above terms. On the other hand, majority of studies reported the consistent improvements in emission characteristics of W/D emulsion fuels. Attia and Kulchitskiy [13] reported that 25% of W/D emulsion fuel reduced 30% of NOx emission at normal condition. Ashok *et al*. [14], Suresh and Amirthagadeswaran [15], and Yuh *et al*. [16] also stated that the presence of water in diesel fuel brings a considerable reduction in NOx and PM emissions. Ochoterena *et al*. [17] and Subramanian [18] commented that the HC and CO has faintly increased by using W/D emulsion fuels.

The use of W/D emulsion fuels in existing diesel engines has been an active field of inquiry in the past decade. Most of the written reports are based on the measurement of brake specific fuel consumption, brake thermal efficiency and emission characteristics. However, not much efforts have been attempted to develop the systematic protocols of W/D emulsion formulation, emulsion stability measurement and emulsion fuels property variations. The present study addresses the above issues, and experiments are conducted to study the characteristics of W/D emulsion fuels in VCR, single cylinder and four-stroke diesel engine under fluctuating load conditions.

2 Materials and Methods

2.1 *Materials*

In this work, high-speed diesel (Bharath Petroleum Corporation Limited, India) is used as the continuous phase of the emulsion. Sorbitan monolaurate (HLB: 8.6) is used as the surfactant (Estelle Chemicals (P) Limited, India). Double distilled filtered water is used as the dispersed phase of the emulsion.

2.2 *Emulsion Fuel Preparation, Stability Analysis and Properties Measurement*

To prepare W/D emulsion fuels, the desired quantity of water and surfactants (1% in total volume) are added drop by drop inside the diesel container with high speed of agitation (15000 rpm) and stirred constantly for about 30 mins. The water concentration is limited to 20% since the excessive amount of water lead to premature failure of injection systems [12].

The stability period is analyzed based on the segregation of emulsion fuels with respect to time using the photonic circuit. The laser beam is allowed to travel in emulsion surface top to bottom without any hindrance. The penetrated laser beam from the emulsion surface is focused in the photo resistor and the signal is sent to multi-meter. The prepared emulsion fuel has uniform density

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throughout the surface at initial condition and showed unique value in multi-meter display. The destabilization of water from diesel causes the variation in density level of emulsion surface (higher density at bottom surface and lower density at top surface), and intensity of laser light penetration. The variation in laser light transfuse on emulsion surface is recorded by multi-meter. The entire experiment is carried out in a dark status to maintain the accuracy. The photographic view of the emulsion stability analysis setup is shown in Figure 1. The properties of standard diesel and prepared emulsion fuels are measured in compliance with the European standard of automotive fuel requirements (EN 590:2009).

2.3 Engine Testing Setup

The engine used in this experiment is a computerized single cylinder, four stroke and VCR diesel engine with an eddy current dynamometer. The fuel injection timing is maintained at 23 degrees before top dead centre (BTDC). ICEnginesoft_9.0 software is used to record and analyze the combustion parameters. AVL digas gas analyzer is used to measure the NO, HC, CO, CO_2 and oxygen (O_2). The detailed specifications of the engine and gas analyzer are listed in Table 1. The photographic view of the engine test setup is shown in Figure 2. In order to analyze the effect of CR, high CR 18 and low CR 15 are adopted in this study, since the lower CR for W/D emulsion fuels damages the combustion systems, and its functioning will fail [12].

Figure 1 Photographic view of the emulsion stability analysis setup.

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Table 1 Specification of the engine and emission analyzer.

(a) Engine specifications	
Parameter	**Specification**
Engine type	Computerized, 4-Stroke, Single cylinder, VCR diesel engine
Bore × Stroke (m)	0.0875 × 0.11
Displacement volume (cc)	661.45
Max. power	3.5 kW at 1500 rpm
CR range	12–18
Dynamometer	Eddy current dynamometer (max. load of 7.5 kW)

(b) Gas analyzer specifications		
Measured quality	**Measuring range**	**Resolution**
NO	0 to 5000 ppm vol	1 ppm vol
HC	0 to 20000 ppm vol	≤ 2000: 1 ppm vol, > 2000: 10 ppm vol
CO	0 to 10% vol	0.01% vol
CO_2	0 to 20% vol	0.1% vol
O_2	0 to 22% vol	0.01% vol

Figure 2 Photographic view of engine setup.

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3 Result and Discussions

3.1 Emulsion Fuels Stability and its Property

The stability profile of W/D emulsion fuels with respect to water concentration and stirrer speed is shown in Figure 3. The process variables, namely water concentration and stirrer speeds are entailed in the emulsion stability. At lower water concentration, the dispersed water droplets are spaced out to interact among each other and improved the emulsion stability. On the other hand, the droplet-droplet interaction become high with increase in water concentration and reduce the emulsion stability. An increase in the mixing speed of the stirrer decreases the droplet size of water in emulsion phase and improve the emulsion stability. At a speed of 15000 rpm, emulsion fuels exhibit a better emulsion stability period for all concentrations of water.

The properties of BD and W/D emulsion fuels are listed in Table 2 and compared with EN590:2009. From the measured values, it is observed that the density of emulsion fuels increased with increase in water concentration due to the higher density of water over diesel fuel. 15% and 20% of W/D surpassed the permissible limit of density. In addition, the increase in water concentration promotes the water droplets' interaction and increase the viscosity of fuels. Viscosity of 5% and 10% of W/D emulsion fuels fall within the permissible limit. The high value of fuel viscosity with 15% and 20% W/D emulsion fuels will lead to poor atomization of droplets inside the combustion chamber. For neat diesel, the flash point is around 62 °C. The value is increased with increase in water concentration. Water containing diesel fuels are more fire resistant than neat diesel even at a temperature above the flash point [19]. All the W/D emulsion fuels has a higher flash point over BD. Corrosion property of emulsion fuels showed that BD, 5% and 10% of W/D emulsion fuels, exhibited the

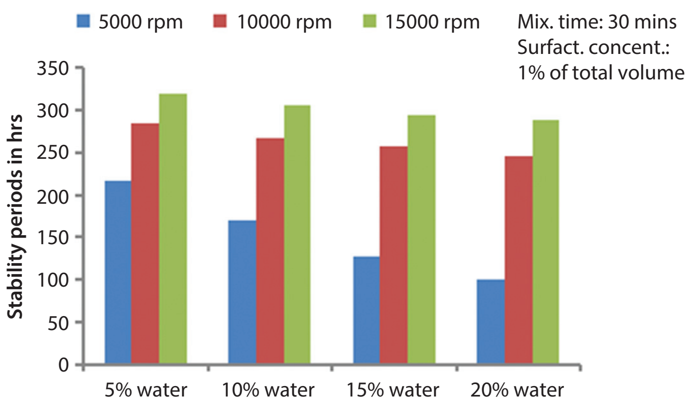

Figure 3 Stability profile of W/D emulsion fuels.

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Table 2 Properties of BD and W/D emulsion fuels.

Fuel Properties					
Fuel	**Density at 15 °C (kg/m³)**	**Viscosity at 40 °C (mm²/s)**	**Flash point °C**	**Heating value (MJ/kg)**	**Copper strip corrosion resistance**
BD	831.4	2.4	62	43.8	Class I
5% W/D	839.8	4.2	69	42.9	Class I
10% W/D	845.1	4.4	74	42.1	Class I
15% W/D	853.4	4.7	78	41.2	Class II
20% W/D	857.2	4.9	83	40.4	Class II
EN 590:2009	820–845	2–4.5	Above 55	NA	Class I

acceptable limit (class 1 - light orange), whereas 15% and 20% of W/D emulsion fuels exhibited class 2 (claret red). Heating value of the emulsion fuels is reduced with increase in water concentration due to the endothermic reaction of water.

3.2 Combustion Characteristics

3.2.1 In-cylinder Pressure Rise

Variation of ICP is the critical factor to analyse the engine combustion characteristics. Figure 4 (a–d) shows the ICP rise with respect to CA for BD, 5% and 10% of W/D emulsion fuels with CRs of 15 and 18 under varying load conditions (25%, 50%, 75% and 100%). The graphs indicated that the ICP is increased with increase in water concentration. This may be due to the micro-explosion of water particles during combustion and the additional force acted on the piston surface [20]. It is also observed that the peak pressure rise is little bit late for W/D emulsion fuels due to longer IDP. An increases of 18.5% in peak pressure is noted with 10% W/D emulsion fuel over BD at a CR 18 under full load condition. The peak pressure for CR 18 is higher than CR 15 due to high overall cycle pressure. In CR 18, 12.6% increases in peak pressure is noted for BD over CR 15 at full load condition, whereas 13.8% is noticed for 10% W/D emulsion fuel. At low load conditions, the charge temperature is low during the starting of ignition and leads to prolonged IDP and lower ICP at a later degree of CA. At high load conditions, more quantity of fuel and higher charge temperature lead to high ICP and advanced pressure rise with respect to CA [21].

3.2.2 Net Heat Release Rate

Figure 5 (a–d) shows the NHR, with respect to crank angle, for BD, 5% and 10% of W/D emulsion fuels. It is noted that the increase in water concentration increases

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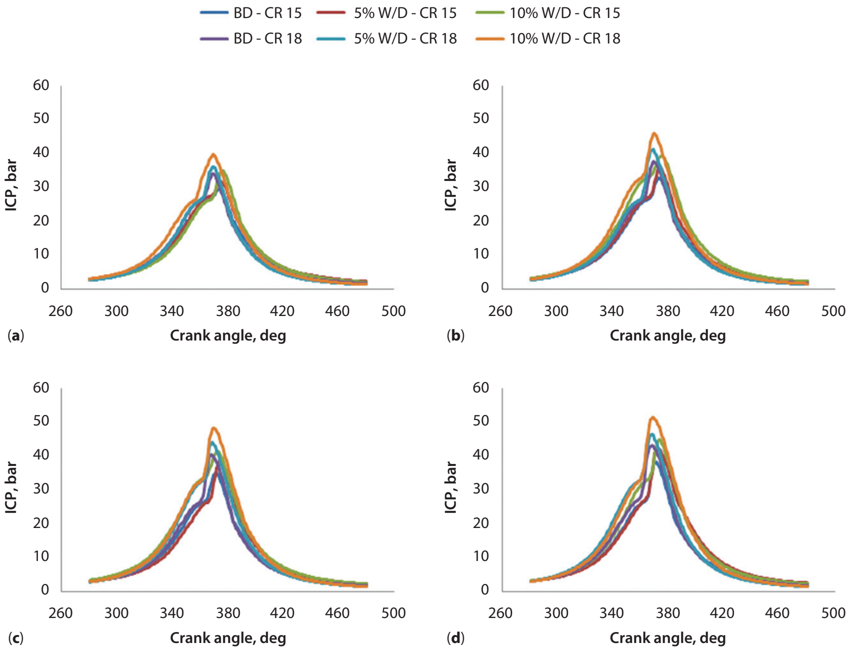

Figure 4 ICP rise of BD, 5% and 10% W/D emulsion fuels with different CR; (**a**) 25% load (**b**) 50% load (**c**) 75% load and (**d**) 100% load.

the NHR rate. This may be due to the enhanced micro-explosion of water droplets that promoted better atomization of the fuel mixture and formed better combustible charges during ignition [22]. In addition, the increase in water content increases the IDP, and resulting in higher amount of fuel accumulation at pre-flame combustion phase. The maximum NHR is closer to TDC for BD and a later degree of CA for W/D emulsion fuels due to longer ignition delays. An increases of 12.5% in NHR is recorded with 10% W/D emulsion fuel over BD at CR 18 under full load condition. The NHR is increased with increase in CR, and closer to TDC for BD and W/D emulsion fuels at a CR of 18. NHR is increased by 12% with 10% W/D, and 10.4% with 5% W/D emulsion fuel at full load condition. Up to 50% of load conditions, the NHR is increased with increase in load for all sample fuels. Beyond 50% of load conditions, not much variation in NHR is recorded due to the effect of lean air-fuel mixer at high load conditions.

3.2.3 Mean Gas Temperature

MGT of BD and W/D emulsion fuels with different CRs under varying load conditions is shown in Figure 6. It can be observed that the MGT is low for W/D emulsion fuels over BD at all CRs due to the lower energy content of emulsion

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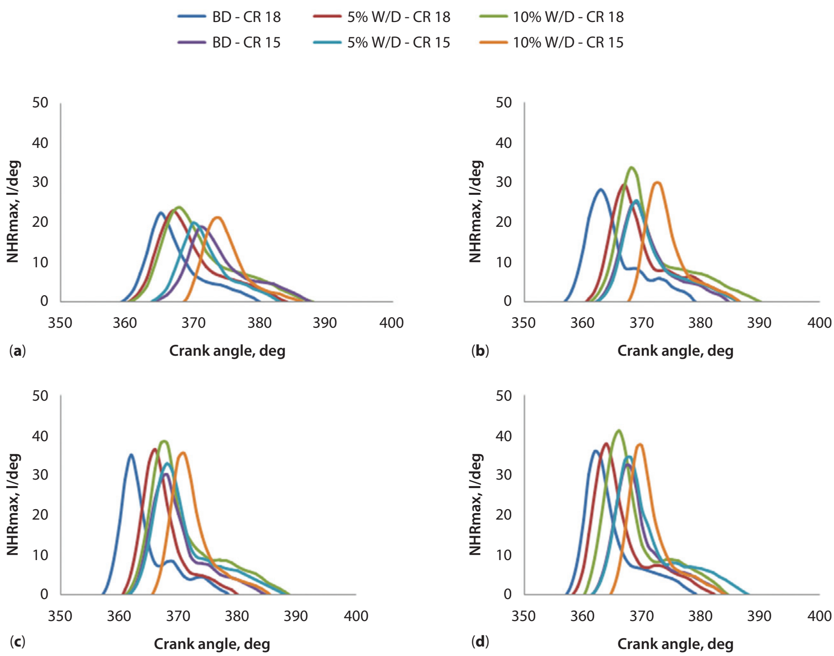

Figure 5 NHRmax of BD, 5% and 10% W/D emulsion fuels with different CR; (**a**) 25% load (**b**) 50% load (**c**) 75% load and (**d**) 100% load.

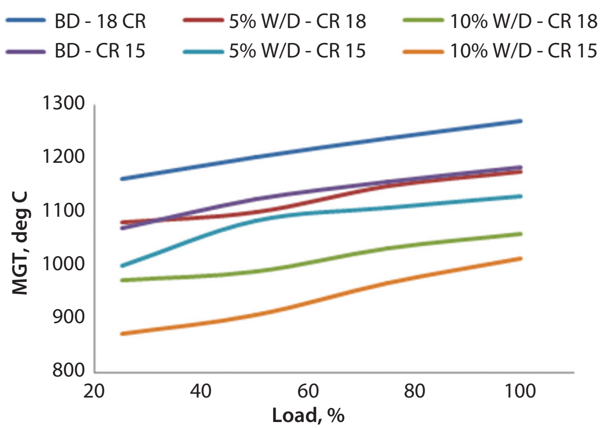

Figure 6 MGT of BD and W/D emulsion fuels.

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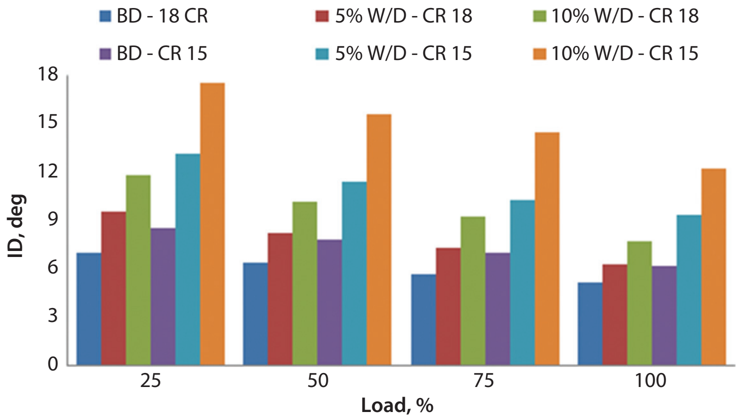

Figure 7 Ignition delay period of BD and W/D emulsion fuels.

fuels. In addition, some amount of heat is absorbed by the water particles during combustion. An increases in MGT is noted with increase in CR and load due to the enhancement in mixing and vaporization of fuel in the air. A drop of 16.6% in MGT is recorded with 10% W/D emulsion fuel over BD at a CR of 18 under full load condition, whereas 14.5% of the drop is noted at a CR of 15.

3.2.4 Ignition Delay Period

Figure 7 represents the ignition delay (ID) period of BD, 5% W/D and 10% W/D emulsion fuels. For W/D emulsion fuels, it is obvious that the starting of combustion occurs greater degree when compared to BD, due to the high viscosity of emulsion fuels and the endothermic reaction of water during the pre-mixed combustion stage. Almost 50% of increases in IDP is noted for 10% W/D emulsion fuel over BD at a CR of 18 under full load condition, whereas twice the above value is noted at CR of 15. Similarly, the high IDP is observed in CR 15 and low load conditions for all sample fuels due to lower charge temperature. This longer IDP lead to incomplete combustion and rough engine operation, which are the undesirable characteristics of diesel engine [12].

3.3 Performance Characteristics

3.3.1 Brake Specific Fuel Consumption

The BSFC of the engine under varying load conditions with CRs of 15 and 18 for BD, 5% and 10% W/D emulsion fuels, is shown in Figure 8 (a). In this observation, the total amount fuel is considered as the exact amount of diesel (without considering the amount of water). From the obtained results, it is noted that the BSFC is reduced with increase in water concentration. This can be attributed by

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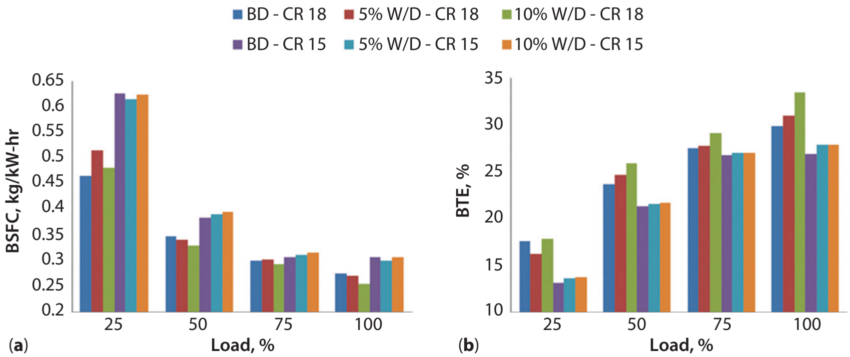

Figure 8 Performance Characteristics of BD, 5% and 10% W/D emulsion fuels with different CR; (**a**) BSFC (**b**) BTE.

the enhancement of fuel mixing and micro-explosion of water droplets. A drop of 7.2% in BSFC is observed with 10% W/D emulsion fuel over BD at a CR of 18 under full load condition, and 0.2% increase was noted at a CR of 15. In addition, BSFC reduced with increase in load due to the efficient combustion at high load conditions. The lower charge temperature and ICP at low CR increased the BSFC.

3.3.2 Brake Thermal Efficiency

Figure 8 (b) represents the effect of W/D emulsion fuels on BTE under different load conditions. It is observed that the BTE is increased with increase in CR and water concentration due to the low BSFC at high CR and W/D emulsion fuels as discussed in 3.3.1. The average improvement in BTE with 10% W/D emulsion fuel over BD at full load condition are 12% and 3.7% at the CRs of 18 and 15 respectively.

3.4 Emission Characteristics

3.4.1 NO Emission

The formation of NO is due to high in-cylinder temperature and more oxygen availability during the combustion process [23]. The variations in NO emission characteristics of BD and W/D emulsion fuels with CR of 15 and 18 under varying load conditions are shown in Figure 9 (a). The figure indicated that NO gradually increased with increase in load due to the efficient burning of fuel and resulted in a higher amount of heat released at high load condition. The increment in fuel consumption at high load also leads to a high temperature inside the combustion chamber [24]. Similarly, at high CR the enhanced mixing and vaporization of fuel and air lead to a high heat release rate and a high formation of NO. At low CR, the NHR is lower due to the low pressure to initiate the combustion process [12].

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Furthermore, it is obvious that the increase in water concentration is directly proportional to a drop in NO formation, since the water particles absorbed the heat during the combustion process and reduced the peak flame temperature. The average reduction of NO at all load conditions for the CRs of 15 and 18 are 34% and 30% respectively.

3.4.2 HC Emission

Incomplete combustion of fuel inside the combustion chamber leads to the formation of un-burnt HC emission. Figure 9 (b) shows the HC emission variations with different CRs under varying load conditions. It is noted that the magnitude of HC drastically increased for low CR due to longer ignition delay, and the formation of a fuel-rich zone resulted in incomplete combustion. In addition, the increase in water concentration also increased the HC emission. This is due to longer ignition delay and high fuel consumption rate of emulsion fuels, which accumulated more fuel in the premixed combustion zone [24] and increased the magnitude of unburnt HC emissions. At high load conditions, the lower value of the ignition

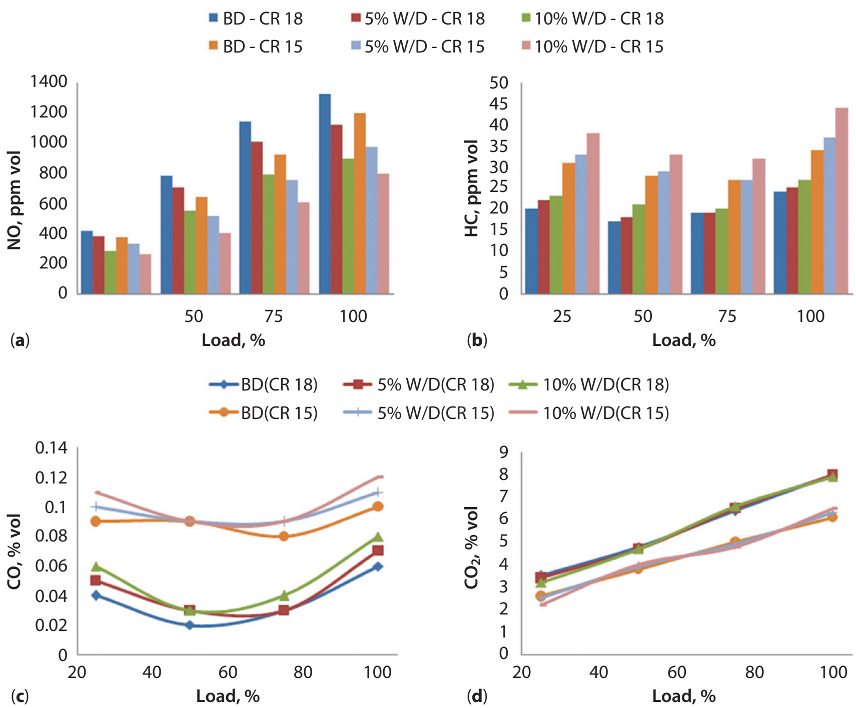

Figure 9 Variation in emission characteristics of BD, 5% and 10% W/D emulsion fuels with different CR under varying load conditions; (**a**) NO (**b**) HC (**c**) CO and (**d**) CO_2.

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delay period lead to complete combustion and reduce the formation of HC. In CR of 18, 5% of W/D emulsion fuel showed similar trends of HC emission with BD, and excess of 5% W/D emulsion fuel increased the magnitude of HC emission at all load conditions. At low CR, the formation of HC is higher for all the fuels irrespective of load conditions.

3.4.3 CO Emission

Lack of homogeneity, slow burning of the soot and incomplete oxidation leads to the formation of CO emission. Figure 9 (c) shows the formation of CO of all fuels under different loading conditions. It is observed that the increase in engine load reduces the CO emission due to the lean flame zone at low loads. At the load of 50% and 75%, low CO emission is noted, and 100% load showed marginal increases in CO emission. This is due to the lack of oxygen availability to convert CO into CO_2 and to burn the end portion fuels at full load condition [23]. For all W/D emulsion fuels, it is clear that CO emission is higher than BD at all load conditions owing to the insufficient temperature for the oxidation process. In addition, the low CR in engine increases the CO emission due to the agglomeration of fuel, and longer ignition delay period.

3.4.4 CO_2 Emission

Incomplete combustion usually reduces the CO_2 and increases the CO and HC. Figure 9 (d) shows the variation of CO_2 emission of all fuels under varying load conditions with CR of 15 and 18. It is clearly seen that at low load conditions the magnitude of CO_2 emission is low for all fuels that indicated the inefficient combustion. For higher CR, CO_2 emission increased due to lower IDP and high ICP. In addition, the increase in water concentration increases the agglomeration of fuel, which leads to longer combustion duration and resulting in less CO_2.

4 Conclusions

Various concentrations of W/D emulsion fuels are prepared and stabilized by Sorbitan monolaurate surfactant using a high speed of mechanical agitator, and its properties are measured and compared with the standard diesel requirements (EN 590:2009). A photonic system is developed to measure the emulsion stability. The combustion, performance and emission characteristics of BD and W/D emulsion fuels are investigated under varying load conditions in VCR diesel engine. The conclusions of the above findings are as follows:

- The properties of emulsion fuels exposed that the concentration of water in excess of 10% in diesel failed to meet the standard diesel fuel requirements.
- The developed laser beam assisted photonic system showed the accurate variation in emulsion stability.

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- The combustion parameters of W/D emulsion fuels, such as ICP, MGT and IDP are comparable with BD at a CR of 18 irrespective of load conditions. At a CR of 15, the combustion parameters, especially the delay in ignition, failed to afford complete combustion and smooth engine operation.
- The addition of water in diesel improved the performance characteristics (BSFC and BTE) at all load conditions.
- The emission characteristics of NO and CO_2 are significantly improved with W/D emulsion fuels in both CRs. The formations of HC and CO emission are marginally increased with CR of 18, and the significant increases are observed with CR of 15.

Based on the above findings, it may be recommended that W/D emulsion fuel has the potential to improve the performance and emission characteristics of the diesel engine, and high CR could be preferred to obtain the desired emission characteristics and smooth engine operation.

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Nomenclature

BD	Base Diesel	IDP	Ignition Delay Period
BSFC	Brake Specific Fuel Consumption	MGT	Mean Gas Temperature
BTE	Brake Thermal Efficiency	NHR	Net Heat Release Rate
CA	Crank Angle	NO	Nitric Oxide
CO	Carbon monoxide	NOx	Oxides of Nitrogen
CO_2	Carbon dioxide	PM	Particulate Matter
CR	Compression Ratio	VCR	Variable Compression ratio
HC	Hydro Carbon	W/D	Water-in-Diesel
ICP	In-Cylinder Pressure		

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