Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879

Experimental Study of Exhaust Manifold Water Injection on Emission of CI Engine Fueled with Madhuca Longifolia and Diesel Blends

Asfakahemad Shekh[1], Nikul Patel[2], Bhavesh Pathak[3,*]

[1] Department of Mechanical Engineering, Faculty of Technology & Engineering, M S University of Baroda, Gujarat, 390001, India

ARTICLE INFO

Article history:
Received 18 September 2023
Received in revised form 29 November 2023
Accepted 13 December 2023
Available online 31 December 2023

Keywords:
Diesel engine; biodiesel; emission; exhaust manifold; Madhuca Longifolia; water injection; compression ratio

ABSTRACT

Nitrogen dioxide (NO_2) is the ubiquitous chemical structure of NO_x in the ambience that is initiated by anthropogenic (human) acts. NO_2 is also reacts in the surrounding to result in ozone (O_3) and the main culprits for acid rain. Captured proportion of NO_x by moisture forms acid rain. Acid rain severely affects certain ecosystems. The facts mentioned indicate necessity to reduce NO_x pollution. When any of these oxides disintegrate in H_2O and breakup, they result in nitric acid (HNO_3) or nitrous acid (HNO_2). Automobiles is one of the major sources of the NO_x that is emitted. Here in this experimental based research effort has been made to reduce emissions of NO_x and CO emitted by the diesel based engine powered by Madhuca longifolia as a biodiesel blended with diesel (B10, B20, B30) by injecting water after exhaust gas manifold to get reaction so as oxides disintegrate in H_2O and breakup, they result in nitric acid (HNO_3) or nitrous acid (HNO_2). Experimental work conducted on Mono-cylinder CRDI engine. Trials were taken with different blends of Madhuca longifolia by setting CR 15,16, 17 and 18 with water injected at 3 different mass flow rates (38.7, 82.7, 130.4 CC/min). Results shows average reduction in NO_x by 7.89%, 12.26%, and 17.73% respectively.

1. Introduction

Huge demand of power and transportation leads to ever increasing demands for internal combustion vehicles. Due to huge population of which NO_x and greenhouse gas emissions is increases exponentially. Ever high cost of crude based fossil fuel and implacable emission laws force the investigator to find other option of diesel like biodiesel [1]. Biofuel has a potential to mitigate usage of fossil fuels. It is replicable, is not detrimental to the environment, and might be manufactured in tiny quantities in countryside regions. In a localized manner in rural areas, biofuel is also capable of providing a green and efficient source of power. Use of biofuels does not add to atmospheric CO_2 because any greenhouse gas emissions resulting from burning is taken in and utilized by the crop for vegetation [2]. Plenty of investigations have been performed regarding oil gained from different raw materials and it interacts as biofuel for assessing performance and emissions [3,4]. The majority of investigations have noticed that when compared to diesel-powered engines, the thermal

---

[*] *Corresponding author.*
E-mail address: dzbhavesh@gmail.com

https://doi.org/10.37934/arfmts.112.2.116136

performance of biodiesel-powered machines is found to be much lower, yet the levels of NO_x are higher and oxide and dioxides of carbon and hydrocarbons (HC) released are smaller [5-7]. All nations need to establish their transportation systems if they are to advance economically. The main concern for the world's transportation sector at the present time is energy generation, which relies on petroleum-based fuels like petrol and diesel. The global average use of energy in the field of transportation has gone up by 1.1 percent annually as a result of the development of the motorization industry. Only the automotive sector will account for 63 % of the rise in worldwide liquid fuel consumption for next three decades from 2010 [8].

2. Biodiesel

The American Society for Testing and Materials details that biodiesel is a fuel which contains mono alkyl esters of long-chain fatty acids produces from renewable lipid feedstock [9]. Renewable and sustainable fuels, such as oil obtained from vegetables, seeds, and fats, are required as the best substitution for the fossil fuel [10,11]. Here are a few illustrations of oil extraction: The oils from species including soy bean, sunflower, palm, rapeseed, canola, cottonseed, and jatropha demonstrate greatest potential and have been used extensively to produce biofuels [12]. In India, there are a variety of trees, bushes, and plants which can be utilised to extract oil and produce bio-diesel. There are 77 non-edible plants of India with a seed, fruit, or nut that contains 30% or more oil as listed in Table 1 [13,14]. Non-edible species Botanical names summarizes the botanical labels of 77 plants that have been recognized as possible non-edible seeds, fruits, or nuts for biodiesel production in India.

Table 1
NO_x elements

Formula	Properties
N_2O (Nitrous Oxide)	Colourless gas, soluble in water
NO (Nitric Oxide)	Colourless gas, soluble in water
N_2O_2 (Dinitrogen dioxide)	
N_2O_3 (Dinitrogen trioxide)	Soluble in water, decomposes in water
NO_2 (Nitrogen dioxide)	Red-brown gas, very soluble in water,
N_2O_4 (Dinitrogen tetroxide)	decomposes in water
N_2O_5 Dinitrogen pentoxide	Very soluble in water, decomposes in water

3. NO_x

NO_x usually means both NO and NO_2. They are equally detrimental to human wellness and the ecosystem [15]. NO_x in general holds NO as main component with a tiny participation of NO_2. Nitrogen results in other formations with oxides like N_2O, NO_3 and N_2O_5 are much limited which can be ignore. The three most relevant NO_x compositions are thermal NO_x, prompt NO_x, and fuel NO_x. The Zeldovich mechanism, which occurs at high temperatures, results in thermal NO_x. The thermal NO_x has the highest contribution to overall NO_x generation in an IC engine. Prompt NO_x is originating when hydrocarbon elements come collectively to form it. It is also called as fenimore NO_x. HC components are essential for quick NO_x generation and it is feasible when fuel-rich conditions be found, quick NO_x is formed when these components participate. Fuel NO_x gets generated in the combustion process as a result of the oxidation of nitrogen-containing fuel components. When excessive concentrations of nitrogen-containing fuel additives contribute reaction than only fuel NO_x is produced [16]. As NO_x emissions are so harmful restrictions limiting the quantity of these gases can be emitted are becoming stronger through governing rules [17]. Earth surface-level ozone generation, smog and Acid precipitation are the events which initiated by NO_x emissions [15].

4. NO_x Reduction Techniques

4.1 Exhaust Gas Recirculation

EGR technique is supposed to be helpful method of lowering NO_x emissions from diesel fuel gases. Basically, EGR technique replaces oxygen and nitrogen by dioxides of carbon and aqua vapour in new air entering the combustion chamber as shown in Figure 1 [18]. The heat storage capacity of a mixture is increased when a part of an emission gases is recirculated through intake airline, while lowering the oxygen concentration. When these two factors are combined, NO_x emissions are significantly reduced. The proportion of emission gas which has to be mixed (MEGR) in the overall intake mixture is specified as EGR (percentage) [1].

$$\%EGR = \frac{(Amount\ of\ air\ permitted\ w/o\ EGR - Amount\ of\ air\ permitted\ with\ EGR)}{Amount\ of\ air\ permitted\ w/o\ EGR} \tag{1}$$

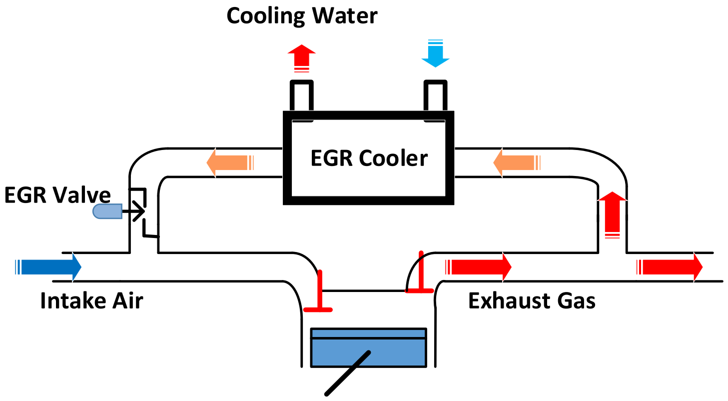

Fig. 1. EGR Technique

Although employing EGR in a CI engine to minimise NO_x emissions is an effective technology, it has a number of disadvantages, including a significant increase in smoke, HC, CO, and fuel usage, as well as a drop in thermal efficiency unless properly tuned. MSD15 blend of mustard feedstock is prepared. Experiment done without EGR and with 10% EGR. It has been found that NO_x has decrease by 12 % in case of 10% EGR but carbon monoxide, hydrocarbon, and smoke exhaust rise compare to non EGR test [18]. Kawano *et al.,* [19] selected B100 Rapeseed oil methyl ester (RME) as fuel to CI engines along with Bi pressure loop (High and Low) EGR setup. A rise in HPL EGR rate lowered NO_x emission while having little effect on PM emission. A rise in the amount of LPL EGR, NO_x and smoke emissions are being reduced at the same time. Prakash *et al.,* [1] has done an investigation of a diesel engine fuelled with a 20 % biodiesel blend and varied recirculation (EGR) rates (10%, 20%, and 30%). The rate of released heat and pressure inside cylinder were monitored and estimated. According to the outcome of the experiments, a Pongamia biodiesel blend of 20% and a 20% EGR rate lowered BTE, raised SFC, and reduces NO_x emissions. Other pollutants, such as smoke, hydrocarbons and monoxides have raised slightly. With a rise in rate of EGR for the biodiesel, the pressure inside the cylinder and HRR were observed to decline. Elavarasan and Duraisamy [18] has prepared mustard oil biofuel blends by mixing with diesel in the proportion of 5%, 10%, and 15%. The investigations were performed with a CI engine at various loads and the emissions were matched to those of a diesel fuelled engine. The outcomes revealed that with the rise in the mix, smoke, hydrocarbons and monoxides output reduced while nitrogen oxides discharges increased. The increase in oxygen concentration in the mixture explains the improved igniting method and also a reduction was observed in smoke, hydrocarbons and monoxides. Furthermore, with the help of 10% exhaust gas recirculation, a down trend of 12 percent in case of NO_x emissions was obtained.

4.2 Water Emulsion

In this process, portion of the heat generated is soaked up by atoms of H_2O (L) in the cylinder during fuel burning process, reducing the temperature gradient of chamber cutting down the NO_x emissions. An emulsion is formed by two moderately miscible liquids, one of which is water, which is disseminated in its counterpart (biodiesel). The presence of aqua portion in the emulsified biodiesel enhances expansion, which provides more force and so improves brake thermal efficiency [20].

4.2.1 Micro-explosion

Inside the combustion chamber, larger drops of fuel are transformed into smaller droplets [21]. With the help of the surfactant, the oil and water combined quickly. In the beginning of the procedure, the droplets of fuel which contains water droplets can be transformed into smaller droplets by increasing the temperature (rapid evaporation) [22]. The graph depicts the transformation of fine droplets via micro-emulsion. This phenomenon presented in Figure 2.

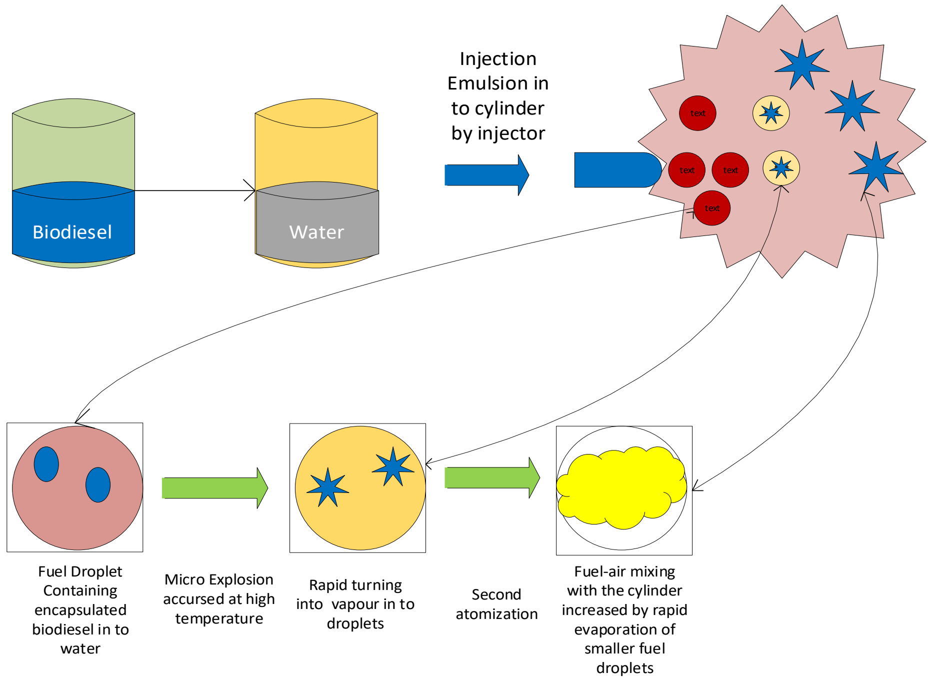

Fig. 2. Transformation of fine droplet via micro-emulsion [23]

The non-homogeneous system of water drops scattered in diesel fuel is known as emulsion fuel. Surfactant improves the stability of this system, which is quite unstable. Reduced emulsion water drops are another effective approach to emulsion fuel instability. Emulsions are classified into three classes based on the size of the water droplets [24]: macro-emulsion, micro-emulsion, and Nano-emulsion. The colour of macro emulsions is opaque, and the drop size is more than 400 nm. If the water droplets having size of 100–400 nm, it is called micro-emulsion, and if the water droplets having size less than 100 nm, it is called Nano-emulsion. Micro-emulsions and Nano-emulsions are transparent, unlike creamy-coloured macro-emulsions. Stability in micro- and nano-emulsions can be obtained in a matter of months, making them suitable for use in diesel engines. Different experts have carried study on a range of emulsion fuels in CI engines. As an example, the emulsified Nerium biodiesel created by blending it along with a tiny number of atoms of water in the proportions of 5-7%, 10-12%, and 15-18% by volume. When compared to base fuel, the combination of 60-62 % diesel, 18-20% Nerium biodiesel, 15-17 % water, and 3-5% surfactant resulted in upper side values for BTE and P_{cyl} nearly 14 % and 12.5 %, respectively. In addition, while the values and results are compared with diesel, CO, NO_x, smoke opacity, and HC emissions of the aforesaid fuel blend dropped by 43 %, 6.5 %, 13 %, and 32 %, respectively. The results showed that using emulsified gasoline in typical engines without any changes in, it provides a considerable improvement and advantage [23]. The water-emulsified soybean biodiesel along with alumina nano-additive found capable to be used as a fuel. As 10% water is added to soybean biodiesel, the specific fuel and energy consumption values increase approximately by 4.2% and 10.3%, respectively, compared to diesel-based engines. Nitrogen oxides, Hydrocarbon, monoxide of carbon, and smoke opacity are reduced by 21.3 %, 16.6 %, 16.8 %, and 11.7 %, respectively. The addition of aluminium nanoparticles to emulsified biofuel reduces the pollutants like NO_x and carbon, hydrocarbon, and smoke emissions while increasing CO_2 [24]. Canola biodiesel-diesel blends were emulsified with 3 unique mixing proportions of water concentration (5%, 10% and 15%). Increased water content in emulsions concluded in rise of BTE and also drop in EGT was attained. The rise in water content in the emulsion lowered nitrogen oxides and smoke emissions significantly when compared to their bases. CO emissions were found to be much greater in emulsion fuels with a higher water content [25]. In general, the availability of aqua proportion in the emulsion enhances the expansion of the emulsification process and provides more force, hence boosting the thermal efficiency of the brakes. Nevertheless, there is a rise in values of BTE, decrease in portion of nitrogen oxides-based emissions but due to the lower value of temperature in combustion process, there is a rise in CO and HC emissions. It also has issues with stability. Emulsified biodiesel demands the installation of an emulsifier system on the vehicle. It comes at an extra expense. Emulsion can alter the physical properties of the fuel; hence emulsified biodiesel could influence the fuel injection system's performance [20].

4.3 Water/Steam Injection

There are two ways of Water Injection has identified: Water injection at inlet manifold and water injection directly inside the cylinder [26-28]. Although WI technology reduced NO_x, it has several drawbacks, such as considerably increasing CO-HC emissions, as well as specific fuel consumption, when the engine is running at minimum load and at minimum combustion temperature. Either Injection of water directly inside the chamber, or through the intake manifold, is an essential approach for reducing nitrogen oxides emissions from a diesel engine. WI (water injection) has the advantage of being able to mitigate nitrogen oxides for all the engine load range while having small rise of PM emissions [27]. Water absorbs the heat of evaporation from the adjacent adiabatic flame, lowering the temperature as a result, NO_x emissions are lowered [26]. The study of investigation for the outcome of steam injection was carried out for diesel-canola oil methyl ester blends as a fuel. The B10-S10 combo has been shown to reduce NO_x emissions significantly. At 1200 rpm, B10-S10 reduced NO_x emissions by 22%, while B20-S10 reduced NO_x emissions by 18% [29]. For lowering NO_x values to control emissions for sunflower oil methyl ester powered engine, direct water injection with electronics control is employed (SOME). Injecting water directly reduces NO_x emissions by 54-58 % but also rises in other emissions components [30]. The methyl ester of residues of chicken frying oil (10 %) was combined with diesel fuel (90%) and utilised as B-10 in CI engine. The steam injection method was utilised to mitigate NO_x emissions values which is generated by the usage of biodiesel. At varied ratios, steam was introduced into the intake manifold. According to the study's findings, the most reduction in NO_x emissions was 13.7 % [31]. Table 4 shows some of the research work done to reduce NO_x emission through water and steam injection technique.

4.4 Fuel Additives

Fuel additives most widely used for various reasons like whether it's an additive to change the burn rate of a fuel, enhance surface area, avoid corrosive effects, or simply change the colour. Researchers have developed a variety of additives over the past few decades that provide base fuels an additional attribute that meets a pressing customer demand. Additives added to petroleum-based fuels are commonly associated with climate protection, pollutants reduction, and increased mileage. Additive technology has a wider impact based on changeability, altercation, or improved specific attributes of a fuel, irrespective of phase of fuel like liquid, solid, or gas. Additives supposed to be developed for boosting combustion rates, act as anti-oxidants, affect burn rates, allow fuels to operate at high temperatures, minimise toxic emissions, and more [32]. A tiny amount of several distinct fuel additives is capable of decreasing the nitrogen-oxide emissions, in accordance with experimental findings from a running diesel engine [33]. The Reduxco® additive decreases particulate matter emissions by raising the diffusion combustion rate while marginally increasing the NO_x content in engine exhaust flow. Cumene (CU)—an antioxidant, diglyme (DGE)—a cetane enhancer, and eugenol (EU) and acetone (A)—bio-additives—are applied 10% by volume with Camphor Oil to enhance ignition characteristics and minimize NO_x emissions [34]. The oxidation feature of biodiesel causes its quality to deteriorate. This problem can be rectified by adding appropriate antioxidants, which increases the fuel's oxidation stability. Natural antioxidants compensate for the shortcomings of antioxidants based on synthetic structure since they are reproducible, safe, and economical. The studies are carried out in a test rig using jamun oil methyl ester (JOME) by adding Albizia Lebbeck (AL), a natural leaf extract additive. It is concluded that JOME20 at and around thousand ppm AL reduced NO_x emissions by up to 8-9 % as compared to diesel. Biodiesel's oxidation stability is also observed to be greatly improved [35].

4.5 Selective Catalytic Reduction (SCR)

To changing structure of dangerous NO_x emissions from toxic to non-toxic N_2 structure, the SCR process is used. It is made up of catalyst along with certain NO_x reducing agents. Ammonia is often used as NO_x reduction agent (NH_3) (Figure 3). Under lean conditions, ammonia selectively reacts with NO_x along with catalyst to form N_2 [36]. The NH3-SCR technique is unfeasible for use in automotive diesel engines since storing toxic NH_3 (in gaseous form) is unsafe [37]. As a result, urea-SCR was proposed, where ammonia is created on-vehicle by urea decomposition. Urea first decomposes into NH_3, which then interacts with NO_x to form N_2 [38]. SCR conversion rates are typically in the 70-90 percent range. Higher rates of reduction are also achievable, but they are not cost effective.

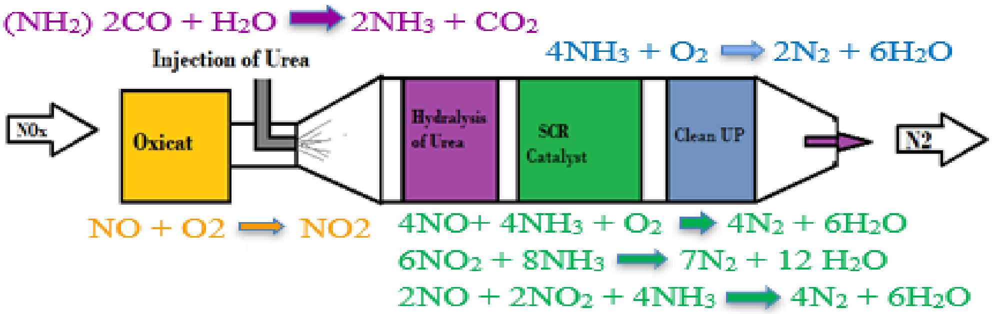

Fig. 3. Schematic View of SCR System

5. NO_x and CO Emission Reactions with Water

5.1 NO_x Emission

Mahmoud Bady and colleagues conduct a test to examine the impact of water injection at the inlet and exhaust manifold on the CI engine's performance and emission metrics. Injection of water into the exhaust and intake manifolds at a rate of 40 mg/cycle was tried. The findings demonstrate that, in comparison to intake manifold water injection, water injection into exhaust manifold enhances engine performance and combustion properties while lowering emission [39].

5.1.1 Oxidation of NO_x

In water, nitric oxide reacts with oxygen. The reaction is thought to proceed via the following stoichiometry [39]:

N_2O_3 and water reaction:

$$N_2O_2 + H_2O \rightarrow 2HNO_2 \tag{2}$$

NO_2 and water reaction:

$$2NO_2 + H_2O \rightarrow HNO_3 + HNO_2 \tag{3}$$

NO and water reaction:

$$4NO + O_2 + 2H_2O \rightarrow 4HNO_2 \tag{4}$$

N_2O_4 and water reaction:

$$N_2O_4 + H_2O \rightarrow HNO_3 + HNO_2 \tag{5}$$

N_2O_5 and water reaction:

$$N_2O_5 + H_2O \rightarrow HNO_3 \tag{6}$$

5.2 CO Reaction with Water

The transformation of carbon monoxide and water vapour into CO_2 and H_2 is known as the water-gas shift reaction (WGSR):

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{7}$$

As all elements of NO_x are soluble with H_2O, the NO_x reactions with H_2O can be utilised to reduced NO_x from the emission of the CI engine.

6. Materials and Experimental Methods

6.1 Biodiesel: Madhuca Longifoliaa

Mahua grows in 84 distinct forms, five among which are native in India and may be differentiated by their distinctive leaf patterns [40,41]. The most common botanical names for Mahua are Madhuca longifolia, latifolia, butyracea, bourdillonii, and neriiolia [42,43]. The Mahua tree is known by different names in different geographical areas of the country. People in India call it Mahua, Mohua, Mahula, Mowrah, Moha, Mova, Mahuda, Dodi, and so on. These trees thrive in a variety of soil. A sandy-loam deep loamy soil with good drainage is best suited for increased development and productivity. The tree has a wide spreading strong root system that catches the soil lump together and prevents soil erosion [41].

6.1.1 Biodiesel properties

Understanding every aspect of biofuels is crucial in order to evaluate them with those of traditional petro-diesel. Properties of all the blends of Madhuca Longifolia has been investigated and compare with diesel as per ASTM standards. Table 2 shows properties of Madhuca Longifolia.

Table 2
Madhuca Longifolia fuel property

Sample/ Properties	Heating Capacity	Density At 25 °C	Acid Value	Flash Point	Fire Point	Kinematic Viscosity @ 40 °C	Dynamic Viscosity @ 40 °C
Unit	$\frac{kJ}{kg}$	$\frac{kg}{m^3}$	$\frac{Mg\ of\ KOH}{gm\ of\ Oil}$	°C	°C	cSt	cP
ASTM Standard	D4809	D287	D6751	D9358 T	D9358 T	D445	D445`
St. Diesel	45236	816	0.6	53	56	2.09	1.73
B10	44074	826	0.73	61	67	2.79	2.30
B20	42941	828	0.79	68	74	2.93	2.43
B30	42256	832	0.89	71	77	3.08	2.56
B100	42034	871	1.31	101	110	4.98	4.34
Raw Oil	39932	910	2.20	256	270	39.6	36.0

6.2 Experimental Procedure and Setup

A mono-cylinder test rig having CRDI VCR engine along with an eddy current-type dynamometer was used for experimentation. Engine specifications are mentioned in Table 3. In this test rig, compression ratio can be set without halting the engine or interrupting the combustion chamber geometry by using a tilting cylinder block mechanism.

Table 3
Test Rig Specifications

Engine	Make Kirloskar, Mono cylinder, water cooled, 4 stroke
Bore	87.5 mm
Stroke	110 mm
Power	3.5 KW
C Capacity	661 cc
Speed	1500 rpm
Comp. Ratio	12-18
Dynamometer	Eddy current, water jacketed
Common rail	With pressure sensor and pressure regulating valve

Figure 4 shows the schematic diagram of the setup and Figure 5 shows the experimental test rig. The various blends of Madhuca Longifolia and diesel are used as a fuel in VCR engine. Engine was initially run for 30 min to bring it to a steady state before any measurements. In present study, water is injected in the exhaust manifold and the effect of water injection on NO_x emission is investigated.

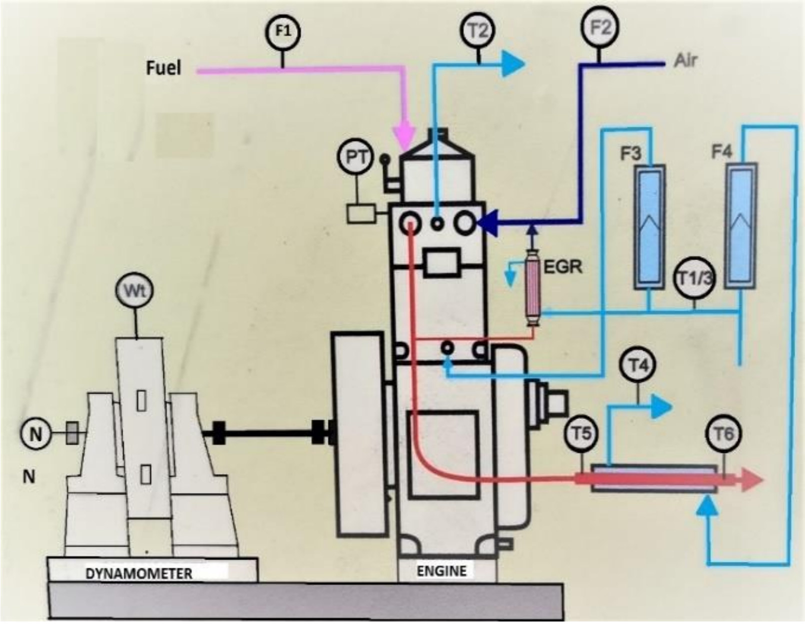

Fig. 4. Schematic diagram of the test rig

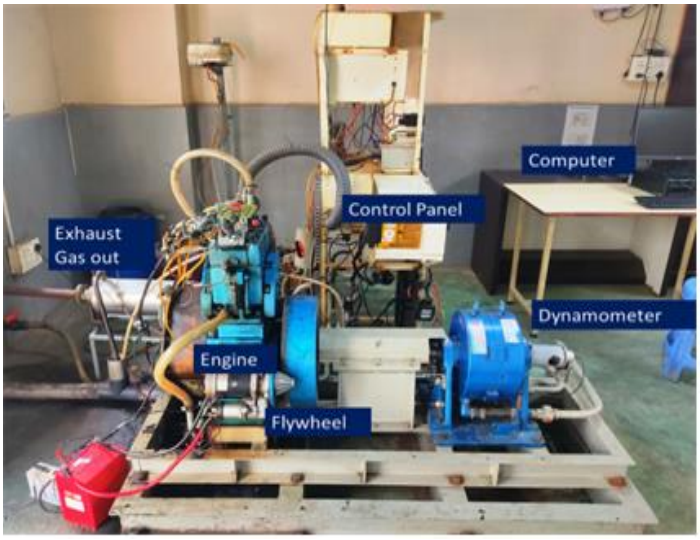

Fig. 5. Experimental setup

Figure 6 and Figure 7 show the emission and smoke measurement equipment. Engine speed was kept at 1500 rpm. As maximum NO_x emissions are generating at 9 kg (75%) and 12 kg (100%) loading of the engine so all the runs are taken at 75% and 100% loading of the engine. Water injection done for 38.7 cc/min, 82.7 cc/min and for 130.4 cci/min flow rates. The operating parameters are listed in Table 4. The AVS DIGAS 444 emission gas analyzer is connected to measure the emission elements like HC, CO, CO_2, NO_x. The measuring range is described in the Table 4. The various operating conditions are mention in Table 5.

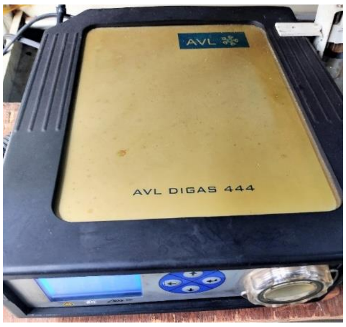

Fig. 6. Exhaust gas Analyser

Fig. 7. Smoke Meter

Table 4
Operating Parameters

Fuel	Compression Ratio	Load (%)	Water Flow rate (cc/min)
B10	15, 16, 17, 18	75, 100	0, 38.7, 82.7, 130.4
B20	15, 16, 17, 18	75, 100	0, 38.7, 82.7, 130.4
B30	15, 16, 17, 18	75, 100	0, 38.7, 82.7, 130.4

Table 5
AVL444N Gas Analyser Emissions Measurement Device Details

Parameter	Unit	Measurement	Resolution	Accuracy
CO	% Vol	0 to 15% Vol	0.01% Vol	<0.6 %: ±0.03 % Vol; ≥0.6 %: ±5 % ind. Val
HC	ppm Vol	0 to 20,000	1 ppm /10 ppm <2000 RPM / >2000RPM	<200ppm Vol: ±10 ppm Vol ≥200ppm Vol: ±5 % ind. Val
CO_2	% Vol	0 to 20	0.1 % Vol	<10%: ±0.5 % Vol; ≥10%: ±5 % ind. Vol
O_2	% Vol	0 to 25	0.01 % Vol	<2%: ±0.1 % Vol; ≥2%: ±5% ind. Vol
NO	ppm Vol	0 to 5000	1 ppm Vol	<500ppm Vol: ±50 ppm Vol ≥500ppm Vol: ±10% of ind. Val
Speed	RPM	400 to 6000 RPM	1 RPM	±1% of ind. Vol
Oil Temp	0C	0 to 125	1^0C	±4 ^{0}C
Lambda (λ)	-	0 to 9.999	0.001	Calculations of CO, CO_2, HC, O_2

6.3 Uncertainty Analysis

Various measuring instruments are used during the experimentation. Accuracy of all these instruments is shown in Table 6. AVL437 is a smoke opacity measuring instrument. Table 7 shows the detailed specifications of the AVL437. The uncertainty in NOx measurement has been calculated which is ± 68.49 ppm as mention in Table 8.

Table 6
Details of instruments and sensors attached to the experimental setup

Appliances	Accuracy
Pressure sensor	±1%
Analog temperature Transmitter	±0.5%
Speed indicator	± 0.05% F.S.
Encoder	± 0.25%
Load cell	± 0.25 % F.S. (± 0.125 kg)
Load indicator	± 0.2% F.S.
Differential pressure transmitter	±0.1%
Pressure transmitter	±0.5%
Rotameter	± 2% F.S.

Table 7
AVL437 Device Details

AVL437 Standard	Smoke Opacity measurement	
Measurement range	430 mm ±5 mm	
Measurement	Range	Resolution/Accuracy
Absorption (K Value)	0 to 99.99 m^{-1}	0.01 m^{-1}
Opacity	0 to 100%	0.1 %
Engine speed (RPM)	400 to 6000 min^{-1}	1 min^{-1}
Oil temperature	0 to 150 ^{0}C	1 ^{0}C
Linearity check	≈ 50% of the measured rang	

Table 8
Uncertainty in Results/Readings

Sr	Parameter	Uncertainty	Unit
1	NO_x (Nitric Oxide)	± 68.49	ppm

7. Result and Discussion

Experimentally investigated the effect of water on emission by injecting the water into the emission line of a test rig fueled with diesel biodiesel blends. Behavior of emissions elements like NO_x, CO and HC are discussed as follow.

7.1 Water Injection Effect on NO_x Emission

Oxides of nitrogen gas from an exhaust gas can be absorbed in aqueous solutions. The absorption process involves gas-phase and liquid-phase reactions and the diffusion of products and reactants to and from the two-phase boundary. Overall, NO_x in the gas phase reacts with water to form aqueous nitric acid.

Figure 8 to Figure 13 show the water injection effect on NO_x emission for different CR, different blends, and for different loading conditions which is a result of reaction between H_2O and NO_x. The effect of NO_x emission has observed for four different flow rates of water injection (38.7, 82.7, 130.4 CC/min).

Figure 8 and Figure 9 show water injection effect on NO_x emission for blend B10 for the CR 18, 17, 16 and 15 at 75% and 100% of engine loading condition. Water injected for three different flow rates, as a result, reduction in NO_x emission observed which is shown in Table 9.

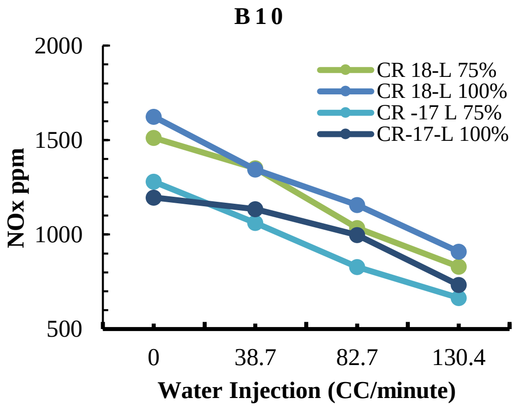

Fig. 8. Effect of Water Injection (B10, CR-17, 18)

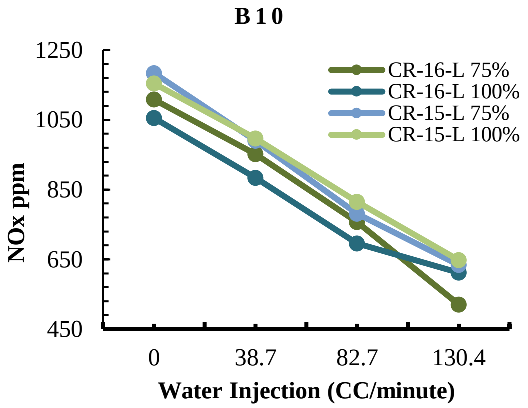

Fig. 9. Effect of Water Injection (B10, CR-15, 16)

As it is seen from Table 9, average reduction of NO_x emission for 38.7 cc/min, 82.7 cc/min and for 130.4 cc/min are 7.38%, 12.04% and 17.07% respectively.

Table 9
Effect of Water Injection on NO_x emission for B10 Blend

Blend	CR	Load (%)	% Reduction in NO_x for cc/min Water injection		
			38.7	82.7	130.4
B10	18	75	7.34	10.71	17.66
	18	100	8.25	12.38	18.78
	17	75	8.13	12.58	16.56
	17	100	5.10	12.21	16.47
	16	75	7.67	10.65	16.88
	16	100	7.68	12.23	16.21
	15	75	7.01	11.99	16.39
	15	100	7.89	13.60	17.68

Figure 10 and Figure 11 show water injection effect on NO_x emission for blend B20 for the CR 18, 17, 16 and 15 at 75% and 100% of engine loading condition. Water injected for three different flow rates, as a result, reduction in NO_x emission observed which is shown in Table 10.

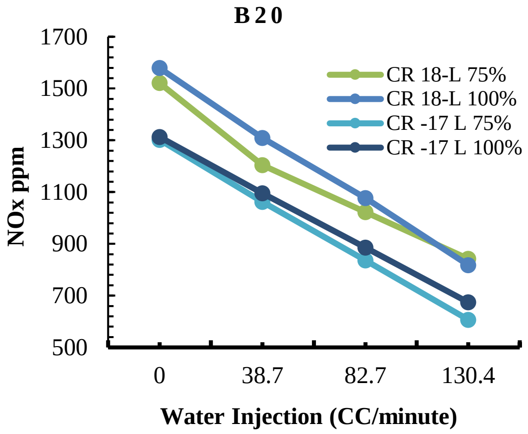

Fig. 10. Effect of Water Injection (B20, CR-17, 18)

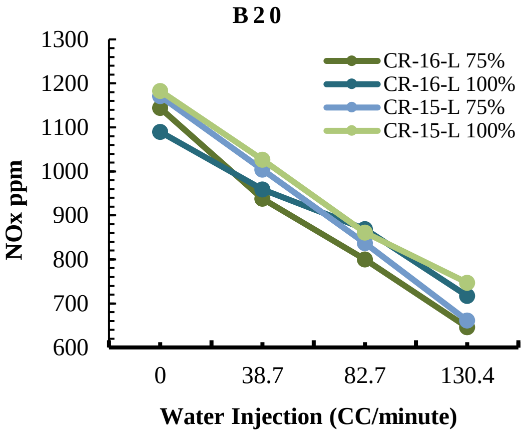

Fig. 11. Effect of Water Injection (B20, CR-15, 16)

As it is seen from Table 10, average reduction of NO_x emission for 38.7 cc/min, 82.7 cc/min and for 130.4 cc/min are 7.93%, 11.81% and 18.15% respectively.

Table 10
Effect of Water Injection on NO_x emission for B20 Blend

Blend	CR	Load (%)	% Reduction in NO_x for cc/min Water injection		
			38.7	82.7	130.4
B20	18	75	7.82	10.85	18.74
	18	100	8.73	12.03	17.10
	17	75	8.29	13.98	18.43
	17	100	7.77	12.41	19.73
	16	75	8.48	11.28	18.01
	16	100	7.43	12.02	18.17
	15	75	8.03	11.02	16.31
	15	100	6.93	10.90	18.75

Figure 12 and Figure 13 show water injection effect on NO_x emission for blend B30 for the CR 18, 17, 16 and 15 at 75% and 100% of engine loading condition. Water injected for three different flow rates, as a result, reduction in NO_x emission observed which is shown in Table 11.

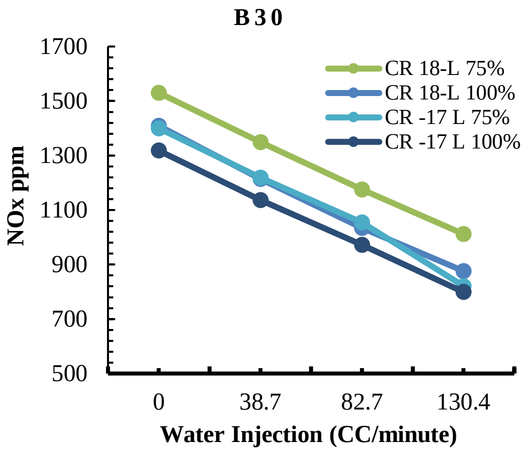

Fig. 12. Effect of Water Injection (B30, CR-17, 18)

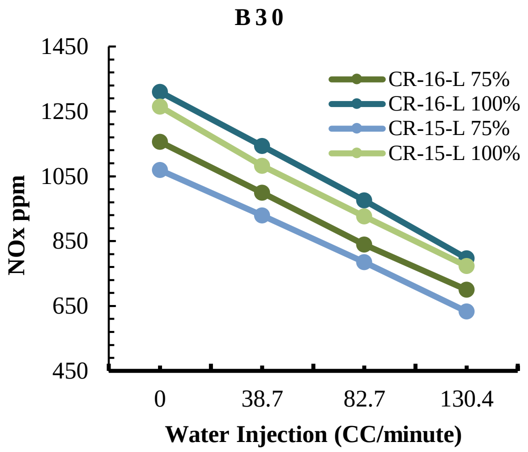

Fig. 13. Effect of Water Injection (B30, CR-15, 16)

As it is seen from Table 11, average reduction of NO_x emission for 38.7 cc/min, 82.7 cc/min and for 130.4 cc/min are 8.32%, 12.91% and 17.93% respectively.

Table 11
Effect of Water Injection on NO_x emission for B30 Blend

Blend	CR	Load (%)	% Reduction in NO_x for cc/min Water injection		
			38.7	82.7	130.4
B30	18	75	8.17	11.18	19.15
	18	100	7.74	13.84	18.38
	17	75	9	12.93	18.29
	17	100	8.19	13.81	17.37
	16	75	8.91	12.02	18.08
	16	100	8.40	12.75	18.78
	15	75	8.33	13.10	15.81
	15	100	7.83	13.68	17.63

The observations on plot shows reduction in NO_x values for all the readings. It seems for all the CR and load conditions NO_x reduction behaves almost linearly with respect to water injection and with same slop for said conditions. Further to this when fuel blends changed from B10 to B20 and B30 behavior of plot remains same only the value of slop of line changes. Line slops of B10 blends are higher and for B30 blend it found to be lower.

7.2 Water Injection Effect on CO Emission

According to water-gas shift (WGS) reaction, water (H_2O) particles when reacts with carbon monoxide (CO) converts CO into CO_2 and hydrogen. The reaction is exothermic. Figure 14 to Figure 18 show the effect of water injection on CO emission for different CR, different blends, and for different loading conditions which is a result of reaction between H_2O and CO. The effect of CO emission has observed for four different flow rates of water injection (38.7, 82.7, 130.4 CC/min).

Figure 14 and Figure 15 show effect of water injection on CO emission for blend B10 for the CR 18, 17, 16 and 15 at 75% and 100% of engine loading condition. Water injected for three different flow rates, as a result, reduction in CO emission observed which is shown in Table 12.

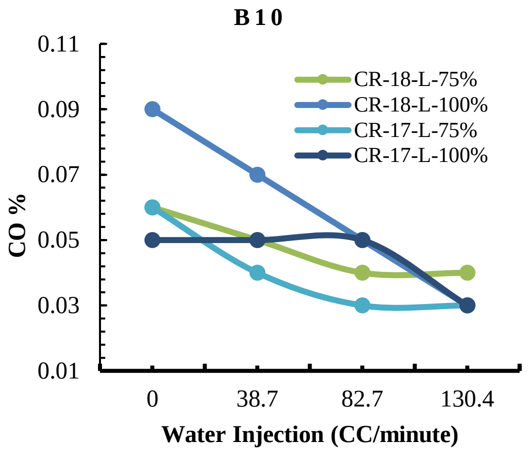

Fig. 14. Effect of Water Injection (B10, CR-17, 18)

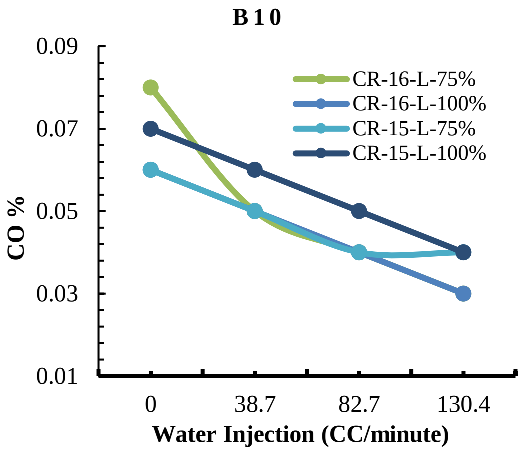

Fig. 15. Effect of Water Injection (B10, CR-15, 16)

As it is seen from Table 12, average reduction of CO emission for 38.7 cc/min, 82.7 cc/min and for 130.4 cc/min are 19.68%, 34.13% and 47.40% respectively.

Table 12
Effect of Water Injection on CO emission for B10 Blend

Blend	CR	Load (%)	% Reduction in CO for cc/min Water injection 38.7	82.7	130.4
B10	18	75	16.67	33.33	33.33
	18	100	22.22	44.47	66.70
	17	75	33.33	50.52	50.50
	17	100	0	0	40
	16	75	37.50	50.00	62.50
	16	100	16.65	33.30	50
	15	75	16.80	32.90	33.32
	15	100	14.29	28.57	42.86

Figure 16 and Figure 17 show water injection effect on CO emission for blend B20 for the CR 18, 17, 16 and 15 at 75% and 100% of engine loading condition. Water injected for three different flow rates, as a result, reduction in CO emission observed which is shown in Table 13.

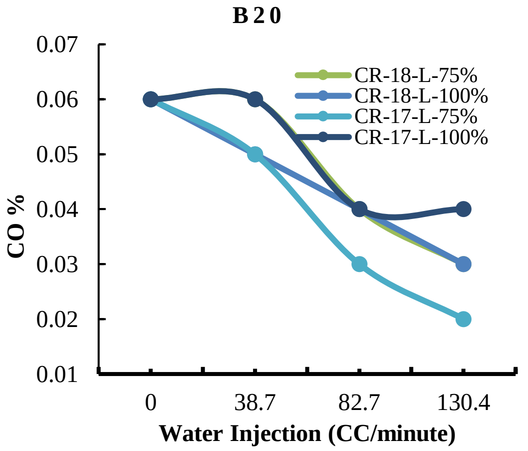

Fig. 16. Effect of Water Injection (B20, CR-17, 18)

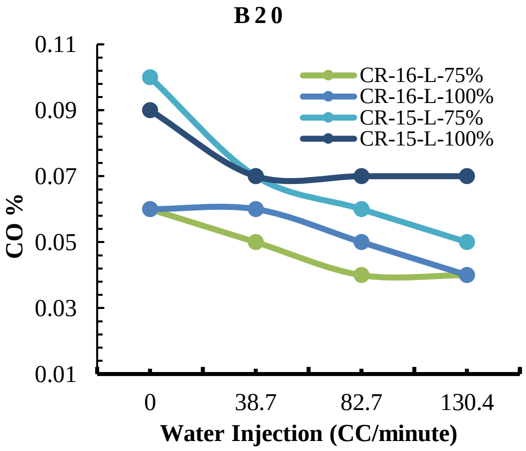

Fig. 17. Effect of Water Injection (B20, CR-15, 16)

As it is seen from Table 13, average reduction of CO emission for 38.7 cc/min, 82.7 cc/min and for 130.4 cc/min are 19.68%, 34.13% and 47.40% respectively.

Table 13
Effect of Water Injection on CO emission for B20 Blend

Blend	CR	Load (%)	% Reduction in CO for cc/min Water injection		
			38.7	82.7	130.4
B20	18	75	0	33.33	50.00
	18	100	16.67	33.33	50.00
	17	75	16.67	50	66.67
	17	100	0	33.33	33.33
	16	75	16.67	33.33	33.33
	16	100	0	16.67	33.33
	15	75	30	40	50
	15	100	22.22	22.22	22.22

Figure 18 and Figure 19 show water injection effect on CO emission for blend B30 for the CR 18, 17, 16 and 15 at 75% and 100% of engine loading condition. Water injected for three different flow rates, as a result, reduction in CO emission observed which is shown in Table 14.

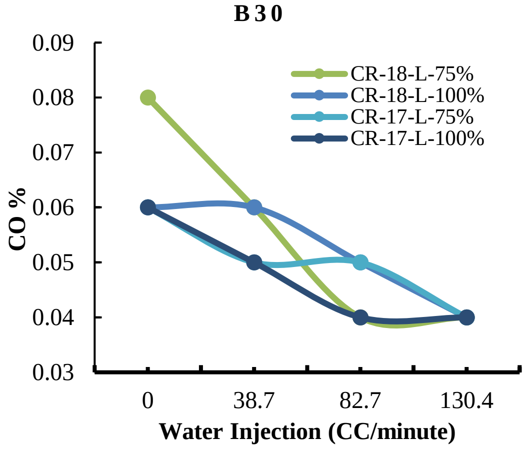

Fig. 18. Effect of Water Injection (B30, CR-17, 18)

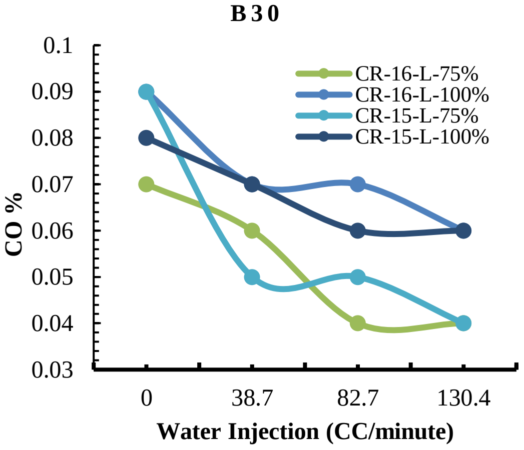

Fig. 19. Effect of Water Injection (B30, CR-15, 16)

As it is seen from Table 14, average reduction of CO emission for 38.7 cc/min, 82.7 cc/min and for 130.4 cc/min are 18.97%, 66.06% and 38.34% respectively. Overall observations derive reduction in percentage of CO when water injection rate is increased.

Table 14
Effect of Water Injection on CO emission for B30 Blend

Blend	CR	Load (%)	% Reduction in CO for cc/min Water injection		
			38.7	82.7	130.4
B30	18	75	25	50	50
	18	100	0	16.67	33.33
	17	75	16.67	163.67	33.33
	17	100	16.67	163.67	33.33
	16	75	14.29	42.86	42.86
	16	100	22.22	22.22	33.33
	15	75	44.44	44.44	55.56
	15	100	12.50	25	25

7.3 Water Injection Effect on HC Emission

Water (H_2O) particles when reacts with hydrocarbon (HC) converts HC into carbon monoxide (CO) and hydrogen (H_2) that called as water-carbon reaction. Further to this, CO when it reacts with water forms CO_2 as earlier explained according to water-gas shift (WGS) reaction. Figure 20 to Figure 25 show the behaviour of HC with respect to water injection.

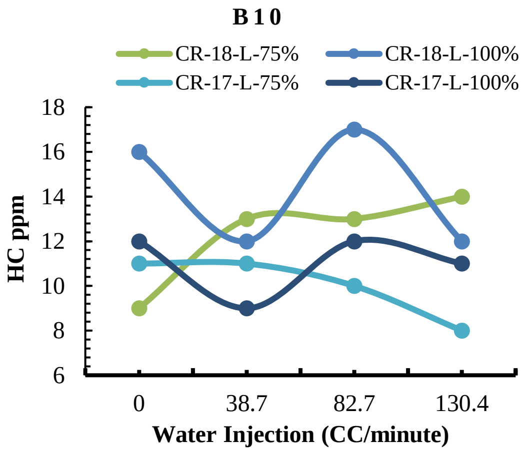

Fig. 20. Effect of Water Injection (B10, CR-17, 18)

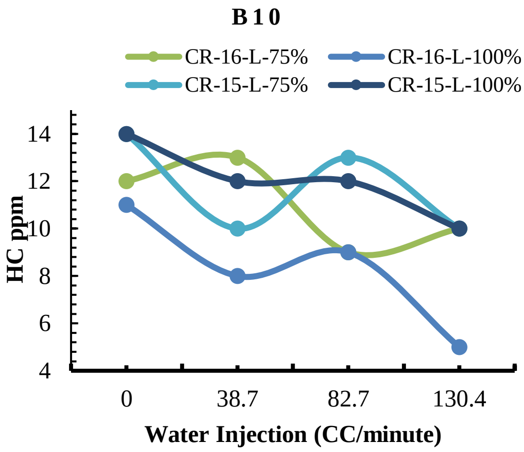

Fig. 21. Effect of Water Injection (B10, CR-15, 16)

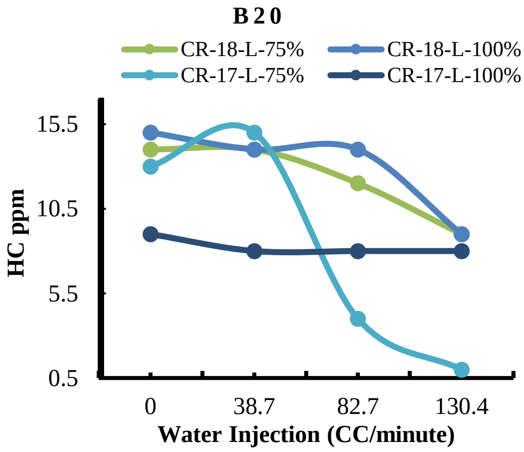

Fig. 22. Effect of Water Injection (B20, CR-17, 18)

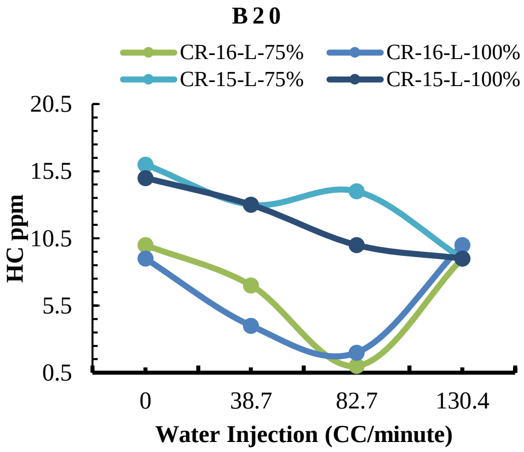

Fig. 23. Effect of Water Injection (B20, CR-15, 16)

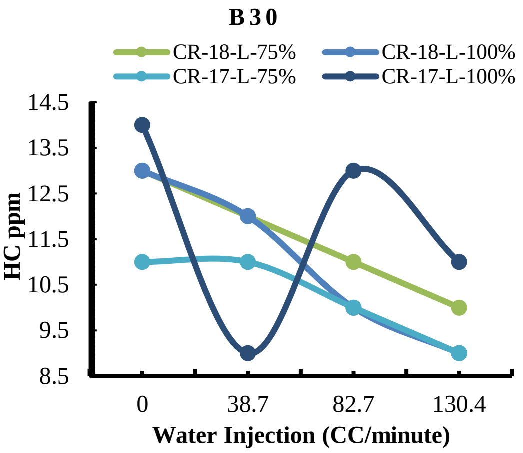

Fig. 24. Effect of Water Injection (B30, CR-17, 18)

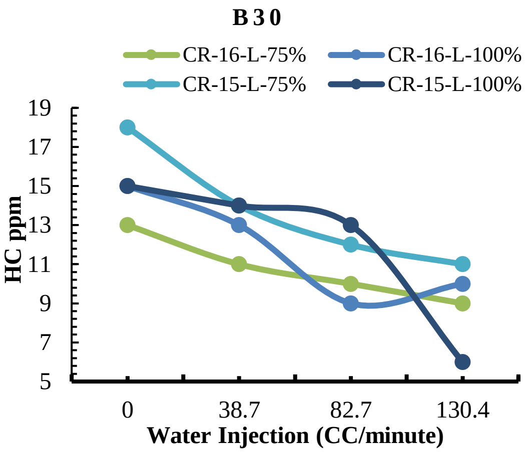

Fig. 25. Effect of Water Injection (B30, CR-15, 16)

Overall observation reveals there is not much notable reduction in HC achieved during trials. With or without water injection hardly much reduction in HC value found. In addition, whatever variation depicted it shows change in the reactions like shift from water-carbon to water-gas shift and vice versa.

8. Conclusion

The gas-phase reaction of NO_x, CO and HC with injected water was studied at exhaust manifold side for CIDI diesel engine test rig fueled by blends (B10, B20, B30) of ML biodiesel. NO_x formation tends to increase with an increase in intense combustion owing to higher combustion temperatures and longer residence time for flue gases. CO (%) and parts-per-million concentrations of NO_x and HC reacted with injected water. In present study, water is injected in the exhaust manifold and the effect of water injection on NO_x emission is investigated. Engine speed was kept at 1500 rpm. As maximum NO_x emissions are generating at 9 kg (75%) and 12 kg (100%) loading of the engine so all the runs are taken at 75% and 100% loading of the engine. However, main objective of study was to observe the effect of water injection on NO_x emissions at exhaust gas stream, but simultaneously effect on CO and HC were also investigated. Outcome of the experiment are as following:

i. NO_x emissions were reducing as water injection flow rate increases and the trend line of the same is almost linear in behavior. Same trend of NO_x emission reduction with increase in water injection flow rate has been observed for all the blends (B10, B20, B30), CR (15, 16, 17, 18) and for both the loading conditions (75% and 100%).
ii. Average reduction of the NO_x emissions for water injection flow rate of 38.7 cc/min, 82.7 cc/min and 130.4 cc/min are 7.89%, 12.26%, and 17.73% respectively.
iii. As water injected in the downstream of the engine, H_2O reacts with CO and converts the CO in to CO_2 and H_2.
iv. Few readings show abrupt behavior which is due to the influence of water-carbon reactions where HC reacts with water and produces more moles of CO.
v. CO emission reduces as water injection flow rate increases.by observing the trend, it seems to be following some empirical relation rather than following linearity.
vi. Average reduction of the CO emissions for water injection flow rate of 38.7 cc/min, 82.7 cc/min and 130.4 cc/min are 17.14%, 32.77%, and 42.68% respectively.
vii. HC emission found to be unaffected during all test runs irrespective of water injection

viii. In addition, whatever variation depicted it shows change in the chemical reactions like shift from water-carbon to water-gas shift and vice versa.

Acknowledgement

This research was not funded by any grant.

References

[1] Prakash, S., M. Prabhahar, and M. Saravana Kumar. "Experimental analysis of diesel engine behaviours using biodiesel with different exhaust gas recirculation rates." *International Journal of Ambient Energy* 43, no. 1 (2022): 1508-1517. https://doi.org/10.1080/01430750.2020.1712251

[2] Dhar, Atul, Roblet Kevin, and Avinash Kumar Agarwal. "Production of biodiesel from high-FFA neem oil and its performance, emission and combustion characterization in a single cylinder DICI engine." *Fuel Processing Technology* 97 (2012): 118-129. https://doi.org/10.1016/j.fuproc.2012.01.012

[3] Syahmi, Anwar, Mas Fawzi, Shahrul Azmir Osman, and Harrison Lau. "Engine Performance and Exhaust Emission Effect of Increasing Euro5 Diesel Fuel Blended with 7% to 30% Palm Biodiesel." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 28, no. 2 (2022): 34-40. https://doi.org/10.37934/araset.28.2.3440

[4] Pathak, Bhavesh, and Nikul Patel. "Thermodynamic Performance of an Engine by Modifying Piston Bowl Geometries Fuelled by SME-100, LA-100, KB-100 Biodiesel Blends, and Diesel." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 102, no. 1 (2023): 1-13. https://doi.org/10.37934/arfmts.102.1.113

[5] Gopal, K. Nantha, Arindam Pal, Sumit Sharma, Charan Samanchi, K. Sathyanarayanan, and T. Elango. "Investigation of emissions and combustion characteristics of a CI engine fueled with waste cooking oil methyl ester and diesel blends." Alexandria Engineering Journal 53, no. 2 (2014): 281-287. https://doi.org/10.1016/j.aej.2014.02.003

[6] Mahesh, Sneha E., Anand Ramanathan, KM Meera S. Begum, and Anantharaman Narayanan. "Biodiesel production from waste cooking oil using KBr impregnated CaO as catalyst." *Energy Conversion and Management* 91 (2015): 442-450. https://doi.org/10.1016/j.enconman.2014.12.031

[7] Vijayaraj, K., and A. P. Sathiyagnanam. "Experimental investigation of a diesel engine with methyl ester of mango seed oil and diesel blends." *Alexandria Engineering Journal* 55, no. 1 (2016): 215-221. https://doi.org/10.1016/j.aej.2015.12.001

[8] Mahmudul, H. M., F. Y. Hagos, R. Mamat, A. Abdul Adam, W. F. W. Ishak, and R. Alenezi. "Production, characterization and performance of biodiesel as an alternative fuel in diesel engines-A review." *Renewable and Sustainable Energy Reviews* 72 (2017): 497-509. https://doi.org/10.1016/j.rser.2017.01.001

[9] Rosca, Radu, Edward Rakosi, Gheorghe Manolache, and Marius Niculaua. *Fuel and injection characteristics for a biodiesel type fuel from waste cooking oil*. No. 2005-01-3674. SAE Technical Paper, 2005. https://doi.org/10.4271/2005-01-3674

[10] Sarwani, Muhamad Khairul Ilman, Mas Fawzi, Shahrul Azmir Osman, Anwar Syahmi, and Wira Jazair Yahya. "Calculation of Specific Exhaust Emissions of Compression Ignition Engine Fueled by Palm Biodiesel Blend." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 27, no. 1 (2022): 92-96. https://doi.org/10.37934/araset.27.1.9296

[11] Patel, Nikul K., Ragesh G. Kapadia, Romit Y. Gandhi, and Shailesh N. Shah. "Engine performance, emission and fluorescence study of fuel from plant oils." *Journal of Mechanical Engineering Research and Developments* 40, no. 4 (2017): 673-691.

[12] Singh, S. P., and Dipti Singh. "Biodiesel production through the use of different sources and characterization of oils and their esters as the substitute of diesel: a review." *Renewable and Sustainable Energy Reviews* 14, no. 1 (2010): 200-216. https://doi.org/10.1016/j.rser.2009.07.017

[13] Azam, M. Mohibbe, Amtul Waris, and N. M. Nahar. "Prospects and potential of fatty acid methyl esters of some non-traditional seed oils for use as biodiesel in India." *Biomass and Bioenergy* 29, no. 4 (2005): 293-302. https://doi.org/10.1016/j.biombioe.2005.05.001

[14] Patel, Nikul K., Padamanabhi S. Nagar, and Shailesh N. Shah. "Identification of non-edible seeds as potential feedstock for the production and application of bio-diesel." *Energy and Power* 3, no. 4 (2013): 67-78.

[15] Reşitoğlu, İbrahim Aslan, Kemal Altinişik, and Ali Keskin. "The pollutant emissions from diesel-engine vehicles and exhaust aftertreatment systems." *Clean Technologies and Environmental Policy* 17 (2015): 15-27. https://doi.org/10.1007/s10098-014-0793-9

[16] Hoekman, S. Kent, and Curtis Robbins. "Review of the effects of biodiesel on NO_x emissions." *Fuel Processing Technology* 96 (2012): 237-249. https://doi.org/10.1016/j.fuproc.2011.12.036

[17] Amaya, Andrés F. Duque, Adalberto Gabriel Díaz Torres, and Diego A. Acosta. "Control of emissions in an internal combustion engine: first approach for sustainable design." *International Journal on Interactive Design and Manufacturing (IJIDeM)* 10, no. 3 (2016): 275-289. https://doi.org/10.1007/s12008-016-0307-6

[18] Elavarasan, G., and Karthikeyan Duraisamy. "Effect of exhaust gas recirculation in the performance and emission characteristics of an oxygenated mustard oil biodiesel in a compression ignition engine." *Energy Sources Part A-Recovery Utilization and Environmental Effects* (2020).

[19] Kawano, Daisuke, Hajime Ishii, Yuichi Goto, Akira Noda, and Yuzo Aoyagi. *Effect of exhaust gas recirculation on exhaust emissions from diesel engines fuelled with biodiesel*. No. 2007-24-0128. SAE Technical Paper, 2007. https://doi.org/10.4271/2007-24-0128

[20] Jeevahan, Jeya, G. Mageshwaran, G. Britto Joseph, RB Durai Raj, and R. Thamarai Kannan. "Various strategies for reducing No x emissions of biodiesel fuel used in conventional diesel engines: A review." *Chemical Engineering Communications* 204, no. 10 (2017): 1202-1223. https://doi.org/10.1080/00986445.2017.1353500

[21] Elumalai, P. V., M. Nambiraj, M. Parthasarathy, Dhinesh Balasubramanian, V. Hariharan, and J. Jayakar. "Experimental investigation to reduce environmental pollutants using biofuel nano-water emulsion in thermal barrier coated engine." *Fuel* 285 (2021): 119200. https://doi.org/10.1016/j.fuel.2020.119200

[22] Perumal Venkatesan, Elumalai, Annamalai Kandhasamy, Arularasu Sivalingam, Appuraja Senthil Kumar, KrishnaMoorthy Ramalingam, Paul James Thadhani Joshua, and Dhinesh Balasubramanian. "Performance and emission reduction characteristics of cerium oxide nanoparticle-water emulsion biofuel in diesel engine with modified coated piston." *Environmental Science and Pollution Research* 26 (2019): 27362-27371. https://doi.org/10.1007/s11356-019-05773-z

[23] Elumalai, P. V., M. Parthasarathy, V. Hariharan, J. Jayakar, and S. Mohammed Iqbal. "Evaluation of water emulsion in biodiesel for engine performance and emission characteristics." *Journal of Thermal Analysis and Calorimetry* 147, no. 6 (2022): 4285-4301. https://doi.org/10.1007/s10973-021-10825-z

[24] Vellaiyan, Suresh, Arunkumar Subbiah, and Prabha Chockalingam. "Combustion, performance, and emission analysis of diesel engine fueled with water-biodiesel emulsion fuel and nanoadditive." *Environmental Science and Pollution Research* 25 (2018): 33478-33489. https://doi.org/10.1007/s11356-018-3216-3

[25] Elsanusi, Osama Ahmed, Murari Mohon Roy, and Manpreet Singh Sidhu. "Experimental investigation on a diesel engine fueled by diesel-biodiesel blends and their emulsions at various engine operating conditions." *Applied Energy* 203 (2017): 582-593. https://doi.org/10.1016/j.apenergy.2017.06.052

[26] Park, Jae W., Kang Y. Huh, and Kweon H. Park. "Experimental study on the combustion characteristics of emulsified diesel in a rapid compression and expansion machine." *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* 214, no. 5 (2000): 579-586. https://doi.org/10.1243/0954407001527862

[27] Tauzia, Xavier, Alain Maiboom, and Samiur Rahman Shah. "Experimental study of inlet manifold water injection on combustion and emissions of an automotive direct injection diesel engine." *Energy* 35, no. 9 (2010): 3628-3639. https://doi.org/10.1016/j.energy.2010.05.007

[28] Bedford, Fritz, Chris Rutland, Peter Dittrich, Alois Raab, and F. Wirbeleit. *Effects of direct water injection on DI diesel engine combustion*. No. 2000-01-2938. SAE Technical Paper, 2000. https://doi.org/10.4271/2000-01-2938

[29] Parlak, Adnan. "A study on performance and exhaust emissions of the steam injected DI diesel engine running with different diesel-conola oil methyl ester blends." *Journal of the Energy Institute* 92, no. 3 (2019): 717-729. https://doi.org/10.1016/j.joei.2018.03.001

[30] Ayhan, Vezir. "Investigation of electronic controlled direct water injection for performance and emissions of a diesel engine running on sunflower oil methyl ester." *Fuel* 275 (2020): 117992. https://doi.org/10.1016/j.fuel.2020.117992

[31] Cesur, Idris. "Investigation of the effects of steam injection on the emissions and performance of a diesel engine using waste chicken oil methyl ester." *Journal of Mechanical Science and Technology* 30 (2016): 4773-4779. https://doi.org/10.1007/s12206-016-0949-0

[32] Sreenivasulu, P., B. Durga Prasad, G. Naga Malleswar Rao, and S. Sudhakar Babu. "Importance and role of additives for estimating performance and emissions in CI engines using alcohol as fuels-A study." *International Journal of Innovative Research in Science, Engineering and Technology* 2, no. 8 (2013): 3827-3836.

[33] McCreath, C. G. "The effect of fuel additives on the exhaust emissions from diesel engines." *Combustion and Flame* 17, no. 3 (1971): 359-366. https://doi.org/10.1016/S0010-2180(71)80058-5

[34] Subramanian, Thiyagarajan, Edwin Geo Varuvel, Saravanan Ganapathy, S. Vedharaj, and R. Vallinayagam. "Role of fuel additives on reduction of NO_x emission from a diesel engine powered by camphor oil biofuel." *Environmental Science and Pollution Research* 25 (2018): 15368-15377. https://doi.org/10.1007/s11356-018-1745-4

[35] Senthil, Ramalingam, Ganesan Pranesh, and Rajendran Silambarasan. "Leaf extract additives: A solution for reduction of NO_x emission in a biodiesel operated compression ignition engine." *Energy* 175 (2019): 862-878. https://doi.org/10.1016/j.energy.2019.03.039

[36] Sharma, Shubham, Naveen Kumar, Sambhav Jain, and Sidhant Kumar. *Scope of Fe-ZSM5 zeolite based urea-SCR with fish oil bio-diesel fuel in compressed ignition engine*. No. 2014-01-1541. SAE Technical Paper, 2014. https://doi.org/10.4271/2014-01-1541

[37] Kim, T. Y., and S. H. Lee. "Combustion and emission characteristics of wood pyrolysis oil-butanol blended fuels in a DI diesel engine." *International Journal of Automotive Technology* 16 (2015): 903-912. https://doi.org/10.1007/s12239-015-0092-4

[38] An, H., W. M. Yang, J. Li, and D. Z. Zhou. "Modeling analysis of urea direct injection on the NO_x emission reduction of biodiesel fueled diesel engines." *Energy Conversion and Management* 101 (2015): 442-449. https://doi.org/10.1016/j.enconman.2015.06.008

[39] Farag, Mohamed, Hidenori Kosaka, Mahmoud Bady, and Ali K. Abdel-Rahman. "Effects of intake and exhaust manifold water injection on combustion and emission characteristics of a DI diesel engine." *Journal of Thermal Science and Technology* 12, no. 1 (2017): JTST0014-JTST0014. https://doi.org/10.1299/jtst.2017jtst0014

[40] Awasthi, Y. C., S. C. Bhatnager, and C. R. Mitra. "Chemurgy of Sapotaceous plants: Madhuca species of India." *Economic Botany* 29, no. 4 (1975): 380-389. https://doi.org/10.1007/BF02862185

[41] Kumar, M. Vijay, A. Veeresh Babu, and P. Ravi Kumar. "Experimental investigation on the effects of diesel and mahua biodiesel blended fuel in direct injection diesel engine modified by nozzle orifice diameters." *Renewable Energy* 119 (2018): 388-399. https://doi.org/10.1016/j.renene.2017.12.007

[42] Ghadge, Shashikant Vilas, and Hifjur Raheman. "Biodiesel production from mahua (Madhuca indica) oil having high free fatty acids." *Biomass and Bioenergy* 28, no. 6 (2005): 601-605. https://doi.org/10.1016/j.biombioe.2004.11.009

[43] Maksom, Mohammad Syahadan, Nurul Fitriah Nasir, Norzelawati Asmuin, Muhammad Faqhrurrazi Abd Rahman, and Riyadhthusollehan Khairulfuaad. "Biodiesel composition effects on density and viscosity of diesel-biodiesel blend: a CFD study." *CFD Letters* 12, no. 4 (2020): 100-109. https://doi.org/10.37934/cfdl.12.4.100109