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Experimental Investigation on Performance and Emissions of Emulsified Biodiesel Operated Diesel Engine at Various Engine Operating Conditions

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Abstract- An experimental investigation on a light-duty diesel enginewas conducted to determine the effect of emulsified biodiesel's performance and emissions. Biodiesel was produced on site by a transesterification process from canola oil, emulsified with 5vol% and 10vol%of water. In order to prepare the emulsified fuel, two different types of emulsifiers, Sorbian Monooleate (Span 80) and Polyoxymethylene Sorbian Monooleate (Tween 80), were used. The engine was operated at three different speeds 1000, 2100 and 3000 rpm and at each speed, three loads were applied: low (≈20%), medium (≈50%) andhigh(>80%).Properties such as density, viscosity and calorific value of emulsified fuel were measured. Brake thermal efficiency (BTE) and brake-specific energy consumption(BSEC) were tested as the performance parameters. Regulated emissions carbon monoxide (CO), hydrocarbon (HC), oxides of nitrogen (NO_x) and smoke were measured. Performance and emissions of emulsified biodiesel were compared to that of petroleum diesel. Improved NO_x and smoke were achieved by using emulsified biodiesel over diesel.

Keywords- Biodiesel, Emulsification, Emissions and Performance, Diesel Engine,Transesterification process, Fuel properties.

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Nomenclature

B0	100vol% diesel
BF	Base fuel (50 vol % diesel + 50 vol % kerosene)
B20	Base fuel with 20vol % biodiesel
B50	Base fuel with 50 vol % biodiesel
B100	100% biodiesel
BSEC	Brake-specific energy consumption
BSFC	Brake-specific fuel consumption
BTE	Brake thermal efficiency
cc	Cubic centimetre
CO	Carbon monoxide
CO_2	Carbon dioxide
cSt	Centistoke
ºC	Degree Celsius
EB	Emulsified biodiesel
MJ/kWh	Mega Joule per Kilowatt-hour
Kg/L	Kilogram per liter
HC	Hydrocarbon
HLB	Hydrophile-lipophile balance
kg/m^3	Kilogram per cubic meter
kJ/kg	Kilojoule per kilogram
kW	Kilowatt
mg/m^3	Milligram per cubic meter
ml/min	Milliliter per minute
mm	Millimeter
NaOH	Sodium hydroxide
NO	Nitricoxide

NO_2	Nitrogendioxide
NOx	Oxides of nitrogen
O_2	Oxygen
O/W	Oil-in-water
O/W/O	Oil-in-water-in-oil
PM	Particulate matter
ppm	Parts per million
rpm	Revolution per minute
Span80	SorbianMonooleate
Tween80	PolyoxymethyleneSorbianMonooleate
W/O	Water-in-oil
W/O/W	Water-in-oil-in-water

I. INTRODUCTION

Biodiesel, being renewable in nature and offering a hope of some measure of independence, has been highlighted and researched during the last decade as one of the feasible alternative fuels for diesel engines.Production of biodiesel is usually obtained from vegetable oils, used cooking oils, or animal fats by transesterification [1]. Biofuels, which are used as alternative fuels, can be very effective in reducing engine emissions along with other benefits including energy security, lower toxicity, higher lubrication, local availability, and sustainability [2].Biodiesel can be used with some precautions in diesel engines in many sectors including on-road vehicles, off-road mobile equipment, and vehicles and stationary equipment such as transportation [3]. The main pollutants emitted from diesel engines that contribute to environmental pollution include HC, CO, NO_x, and particulate matter(PM) or smoke from the combustion process [4-6]. However, the only drawback reported in using biodiesel in diesel engine is the increased production of NO_x due to the availability of increased oxygen and higher temperature. This problem can be overcome by applying two important measures:delaying the injection timing (which needs engine modification), or by using an exhaust gas recirculation (EGR) system in the engine; however, volumetric efficiency will be reduced due to the higher temperature of the mixture. Hence, the other possibility of reducing NO_x emission from an engine running on biodiesel could be by using its emulsion with water [7].One of the biggest advantagesof water-diesel emulsions in diesel engines is a significant decrease in NO_x emissions [8, 9]. It was discovered that the presence of water vapor in reactants influenced the physics and chemical kinetics of combustion [10]. Combustion efficiency, engine power and engine torque were significantly improved with the addition of water in the form of emulsion [11]. The viscosity and calorific value of an emulsion fuel are two important indicators affected by water content of the emulsified fuel.Fuel with higher viscosity than diesel fuel resulted in a reduction in the injection rate, power, fuel atomization, and vaporization; consequently, an incomplete combustion, which resulted in higher soot emissions [12-13]. Research conducted by Zhang et al. [14] concluded that an increase in water content increases viscosity in an emulsified fuel. Qi et al. [15] reported that an increase in the percentage of water concentration in the emulsion fuel decreases the heating value of the emulsified fuel and raises the ignition delay of diesel engines. Hsieh et al. [16] focused their study on finding a combination between hydrophile-lipophile balance (HLB) of emulsifiers and gross heating value. The relationship was found to be linear, and the maximum HLB value indicated the minimum gross heating value.

Emulsified fuel is a blend of fuel(which is non-polar liquid), and water (polar liquid) with various emulsifiers such as Tween80 and Span80, which usually consists of two surfactants that can reduce the surface tension between immiscible liquids [7]. The surfactant that has more affinity towards polar liquid is called hydrophilic, while the surfactant that has more affinity towards a non-polar liquid is considered as lipophilic. Every surfactant has a numerical value varying from 0 to 20,calledHLB [17]. The emulsion is mainly of two types: the first is named as two-phase emulsion in which they are subdivided in two types which is water-in-oil (W/O), or oil-in water(O/W) [18]; the second is named as three-phase emulsion which isalsosubdivided into water-in-oil-in-water(W/O/W), or oil-in-water-in-oil (O/W/O)[19].

The two most important phenomena attributed to emulsion combustion in a diesel engine aremicro-explosion and puffing. Micro-explosion is the process in which there is quick breakdown of droplets, which ultimately results in secondary droplet atomization [20]. The main reason is that water and oil have different boiling temperatures, which results in the water evaporating much faster than the oil in a hot combustion chamber. In water-in-oil emulsions, water droplets are the dispersed phase, surrounded by oil. The process of micro-explosion takes place in the hot combustion chamber where the water droplets reach superheating much faster than the oil; whereas, in the case of puffing, water leaves the oil droplets as a fine mist [20, 21].Most of the researchers have not agreed, however, on the occurrence of micro-explosions in diesel engines, as was outlined by Weibiao et al [22].

Water emulsified fuels have accorded more optimistic effects on diesel engines in terms of engine performance and emissions.Scarpete[23] studied emission of a diesel engine fuelled by emulsified diesel with a significant reduction in NO_x and PM emission when the diesel engine ran on emulsion fuel. According to Yang et al. [24],BTE is higher in diesel engine performance fuelledby emulsion fuel with nano-organic additives,compared to neat diesel. The experiment conducted by Senthil et al. [25] investigated diesel engine emissions and performance, and concluded that the emulsion fuel resulted in slightly higher BTE, adecrease in $NO_x$and smoke, and a significant increase in CO and HC emission. From the investigation conducted by Ogunkoya et al. [26], a diesel engine with three different types of emulsion fuel showed increased BSEC anda significant decrease in mechanical efficiency and output power compared to the base fuels.The water, which is added to the fuel, normally acts as a diluent as it lowers the combustiontemperature and thus suppresses NO_x formation.In the case of experiments by Zaid et al., an increase in water content resulted in an increase in BTE, an increase in brake-specific fuel consumption (BSFC), and a decrease in exhaust gas temperature [27]. It was found in ref. [26] that significant reductions in carbon and hydrogen deposits are possible as water content in emulsions is increased.

In this research work, a two-phase emulsion of base fuel (BF), biodiesel-BF blends of B0,B20, B50 was carried outusing two different levels of water concentration (5%and 10%), with Span 80 and Tween 80 in a modern small unmodified diesel engine. The base fuel is the blend of 50 vol% kerosene (kerosene's cloud point is -78˚C) with 50 vol% winter diesel (winter diesel's cloud point is -40˚C), whose cloud point is -50˚C, lower than winter diesel by 10˚C. To our knowledge, this base fuel with biodiesel and emulsification is the first research to test a diesel engine for performance and emissions. The emulsion characteristics, engine performance, and engine emissions at various operating conditions of the enginewere investigated.Increasing the concentration of water compared to pure blend has the additional benefit of reduction of fuel consumption.

II. MATERIALS AND METHODS

2.1 MATERIALS

The following materials were used for the production of biodiesel and its emulsification and for engine test:

1) Diesel,having low sulphur content,was purchased from a local gas station in Thunder Bay;
2) Canola oil from a local supermarket to producebiodiesel on site;
3) Methanol and sodium hydroxide(NaOH)were obtained from Lakehead University'sChemistry lab;
4) Span 80 and Tween 80 were purchased from a Canadian supplier.

2.2 BIODIESELPRODUCTION

Biodiesel can be producedthrough various processes, namely direct blending (dilution), micro-emulsion, catalytic cracking and transesterification [28,29]. In this research work,a base-catalyzed transesterification method was used with sodium hydroxide as the catalyst and methanol as the base.Our lab developed a biodiesel production method, and tested biodiesel quality according to ASTM standards; we also produced biodiesel which conforms to ASTM 6751 standards [30]. The biodiesel production process efficiency averaged 80% volume collection of pure biodiesel, which means that from 1 L of canola oil, we produced 800 mL of pure biodiesel.

2.3EMULSIFICATION OF FUELS

An emulsion is a combination of two or more liquids immiscible in nature, one present as droplet or dispersed phase distributed throughout the other, or the continuous phase. It is generated by means of mechanical agitation in the presence of surface active agents, sometimes called emulsifiers or surfactants. The most commonsurfactants used in the water-in-diesel emulsion are Sorbian monooleate (Span 80)and polyethylene glycol Sorbian monooleate (polysorbate 80).Emulsified fuel was prepared using the external force method. The fuels used were diesel and biodiesel-diesel blends, namely B0,base fuel (BF), B20, B50, and B100. Once various kinds of blends were prepared, two levels of water concentration (5% and 10%) in emulsion were investigated. Emulsified fuels properties are shown in Table 1.

2.4 ENGINE SETUP

An air-cooled, 2-cylinder, 4-stroke light-duty (HATZ 2G40) diesel engine with a direct fuel injection system was used; its specifications are shown in Table 2. A schematic diagram of the experimental system is outlined in Figure 1.In the engine, smoke was measured using a device calledSmart 1500 opacity meter, and various kinds of gas such as NO, NO_2, CO, CO_2, O_2were measured using a Nova Gas analyzer and DWYER 1205A analyzer for precise CO emission. The engine is also connected to a dynamometer, which measures brake power.

Table 1: Fuel Properties

Fuels	**Fuel composition**	**Calorific value (MJ/kg)**	**Density (kg/m^3)**	**Viscosity (cSt @ 40 °C)**
B0	Diesel	44.806	844	2.62
B0W5%	Emulsion of diesel with 5% water	42.893	865	2.92
B0W10%	Emulsion of diesel with 10% water	40.781	873	2.99
BF(D50K50)	50% kerosene with 50% diesel	45.380	827	2.08
EBFW5%	Emulsion of Base fuel with 5% water	43.893	874	2.65
EBFW10%	Emulsion of Base fuel with 10% water	41.205	886	2.70
B100	Biodiesel	40.334	886	4.72
EB100W5%	Emulsion of Biodiesel with 5%water	37.869	912	5.23
EB100W10%	Emulsion of Biodiesel with 10% water	36.221	931	5.67
B20	Base fuel with 20 vol % biodiesel	44.371	839	2.59
EB20W5%	Emulsion of B20 with 5% water	44.652	858	2.85
EB20W10%	Emulsion of B20 with 10% water	40.587	874	2.93
B50	Base fuel with 50 vol % biodiesel	41.327	857	3.26
EB50W5%	Emulsion of B50 with 5% water	39.213	868	3.73
EB50W10%	Emulsion of B50 with 10% water	36.993	879	4.52

Table 2: Engine Specifications

Engine make and model	HATZ 2G40
Engine type	Four-stroke, air-cooled
Number of cylinders	2
Bore/stroke	92 mm/75 mm
Displacement	997 cc
Compressions ratio	20.5:1
Rated power	17 kW @ 3600 rpm

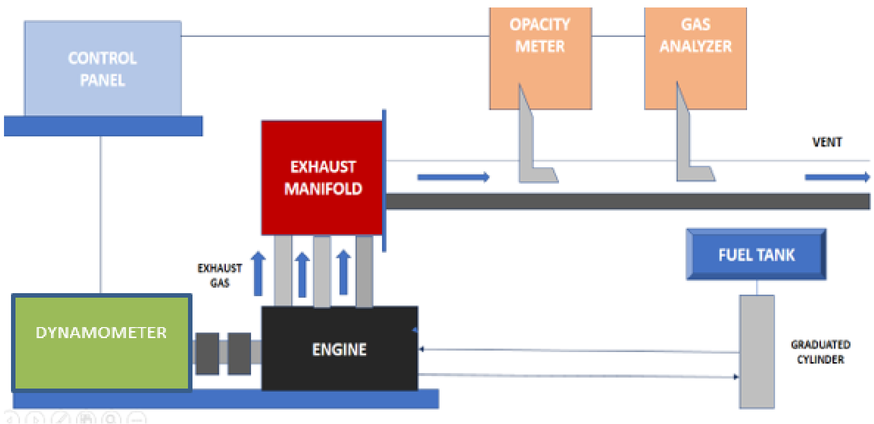

Figure 1: Schematic diagram of experimental setup

2.5 MEASUREMENT APPARATUS

A capillary u-tube viscometer was used to determine the kinematic viscosity for various types of fuels following ASTM D445 standard. A plain jacket bomb calorimeter was used to measure the heating value of the fuels and blends. Pure biodiesel (B100) had the viscosity of 4.72 cSt; with 5% and 10% water, it had 5.23

cStand 5.6 cSt, respectively. Base fuel (BF) had the lowest viscosity of 2.08 cSt; with 5% and 10% water, it had 2.65cSt and 2.70cSt, respectively.Pure diesel hadthe highest heating value of 44.806MJ/kg; with 5% and 10% water, it had42.893MJ/kg and 40.781MJ/kg, whereas biodieselhadlowestheating value of 40.334MJ/kg; with 5% and 10% water, it had 37.869MJ/kg and 36.221MJ/kg, respectively.

2.5.1EMISSION MEASUREMENTS

For emission testing, several devices were used: Nova Gas 7466K for emissions of NO, NO_2, CO, CO_2, O_2, a DWYER 1205A analyzer for precise CO emission, a Smart 1500 opacity meter to measure the amount of smoke produced, and a J-type thermocouple to measure the exhaust gas temperatures. The specifications of emission measurement devices are shown in Table 3.

Table 3: Specifications of Emission Measurement Devices

Measurement devices and method of detection	Species	Measured Unit	Range	Resolution	Accuracy
Nova Gas 7466K:					
Electro Chemical/Infrared detector	CO	%	0-10%	0.10%	±1%
Infrared Detector	CO_2	%	0-20%	0.10%	±1%
Electro Chemical	NO	ppm	0-2000 ppm	1 ppm	±2%
Electro Chemical	NO_2	ppm	0-800 ppm	1 ppm	±2%
Electro Chemical	O_2	%	0-25%	0.10%	±1%
Dwyer 1205A:					
Electro Chemical	CO	ppm	0-2000	1 ppm	±5%
ExTech EA10:					
	Temp.	0.1 ˚C	-200˚C to 1360˚C	0.1˚C	±0.3%
SMART 1500:					
	Opacity	%	0-100%	0.10%	±0.5%
	Soot density	mg/m^3	0-10 mg/m^3	0.00001	±0.5%

III. RESULTS AND DISCUSSIONS

The performance and emissions of a diesel engine using biodiesel and base fuel with their emulsions at different engine operating conditions were investigated. A mixture of 50 vol% diesel and 50 vol% kerosene was used as the base fuel (BF) for this research.This BF hada lower cloud point (-50˚C) compared to diesel (-40˚C). Therefore, biodiesel blends with base fuel is more efficientthan blending it with diesel in severe Canadian winters. Three engine speeds were selected: low (1000 rpm), medium for maximum torque (2100 rpm), and high for maximum power (3000 rpm), as well as loads such as low, medium and high at each engine speed. A totalof six fuels and their emulsions were tested, namely diesel (B0), BF, B20, B50, B100, K100 with 5% and 10%water concentration in emulsions.

3.1 EMULSION FUEL PROPERTIES

From Table 1, it is clearthat the fuel viscosity for a particular blend increasedwith the increase in water content in the blend.For example**,**pure diesel(B0) had kinematicviscosity of 2.62 cSt, whereas for diesel with 5% and 10%,itwas 2.92cSt and 2.99cSt, respectively.Density also changed due to emulsification [31-33].For example, the density of pure diesel was 0.832 kg/L, whereas for 5%and 10% emulsion of diesel, itwas 0.852 kg/L and 0.859kg/L, respectively. It was observed that water addition reduced the heating value of the emulsion [31,34].It was found that the heating value of pure diesel was 44.81 MJ/kg,whereas diesel with 5%and 10% water had heating values 42.57 MJ/kg and 40.33 MJ/kg, respectively.

3.2 ENGINE PERFORMANCE

3.2.1BRAKE-SPECIFICENERGYCONSUMPTION(BSEC)

Brake-specific energy consumption is defined as the product of brake-specific fuel consumption and calorific value.BSEC is better suited than BSFC for testing different fuel types and their performance. Figure 2represents BSEC of different fuels and their emulsions at various engine loads andspeeds.There is no significant change in BSEC for no water and water up to 10% at all engine conditions. Also from the graph, it is clearly depicted that the BSECs decreased with the increase in engine load and speed, as higher loads [35] and speeds have higher burning efficiency.

3.2.2 BRAKE THERMAL EFFICIENCY (BTE)

Figure 3 shows BTE for different emulsified fuels. Base fuel blends with biodiesel had slightly higher BTE compared to diesel at all engine conditions, as oxygen content in biodiesel promotes burning efficiency. We did not see significant change in BTE at different engine speeds up to B50 without and with emulsification. However, there is 3-4% BTE increase for B100 without and with emulsification. Higher oxygen content of B100, and micro-explosion with emulsified fuels may have helped the combustion. As micro explosion takes place in the emulsion fuels, which improves the air fuel mixture and thus enhances improvement in combustion efficiency, this is one of the reasons for increasing BTE in emulsified fuels compared to pure fuel blends [36].

3.3 ENGINE EMISSIONS

3.3.1 NO_x EMISSION

Figure 4 compares NO_x emission of various kinds of fuels and their emulsions at various speeds and loads.It was observed that NO_x emissions increase with the increased load and biodiesel content for all fuels as the combustion temperature was higher at higher load due to the increased fuel supply and with higher biodiesel content, higher oxygen was available for the combustion. Water addition in the blend shows NOx reduction and the higher the water percentage, the higher the reduction is for all engine loads and speeds. 10% water shows about 30-35% NOx reduction compared to no water case. This is due to the water's heat energy absorption, which led to a reduction in peak flame temperature.Similar results were obtained by Buyukkaya [37] and Man et al. [38].

3.3.2 SMOKE EMISSION

Figure 5 depicts smoke opacity of different fuels and their emulsions at various engine loads and speeds. It is observed from the figure that smoke opacity was higher with higher biodiesel content in the blends. Although there is a general perception that biodiesel reduces smoke, it did not happen in our small modern unmodified diesel engine. Higher viscosity of biodiesel and its blends adversely affected the smoke emissions. Due to a shorter penetration length of the spray (from the tip of the nozzle to the combustion chamber walls) of this small diesel engine, there was a higher chance of a larger amount of fuel adherence to the combustion chamber walls; this is part, together with higher viscosity, might be responsible for higher smoke formation. Reduction in smoke with higher water concentration was observed due to micro-explosion of emulsion fuel and better fuel mixing and vaporization in the combustion chamber.From Figure 5, it was found that smoke opacity reduction at 10% water concentration for all emulsion fuels averaged between 10% and 15%, compared to their fuel bases at the same engine load condition.

3.3.3 CO AND HC EMISSION

Figure 6 outlines CO emission of different fuels and their emulsions at various engine loads and speeds. CO is mainly formed byincomplete combustion. The reduction in CO emission is due to higher combustion efficiency and temperature therefore, the biodiesel-diesel blends decreased CO emission compared to pure diesel. CO was also reduced by adequate turbulence and high temperature environment with an increase in load. As there was lower combustion temperature created by water content in the emulsions, CO emissions increased with an increase in water concentration. From Figure 6, we see that there was a considerable decrease (60-70%) in average CO emission of B100 than B0 in different load and speed conditions. On the other hand, we see that with an increase in water concentration, there was an increase in CO emissions (i.e., with 10% water, CO increased by 20-40% compared to base fuel of same type at all load and speed conditions).

Figure 7 shows HC emission of different fuels and their emulsions at various engine loads and speeds. Improvement in combustion efficiency and higher oxygen content in the biodiesel blends also emitted lower HC than diesel. Correspondingly, HC emission was observed to decline with an increase in engine load and speed. HC increases with an increase in water concentration, and the HC emission is the highest for blends with 10% water. Figure 7 shows that the average HC reduction of B20, B50 and B100 is 20%, 30% and 60%, respectively, compared to the petroleum diesel.

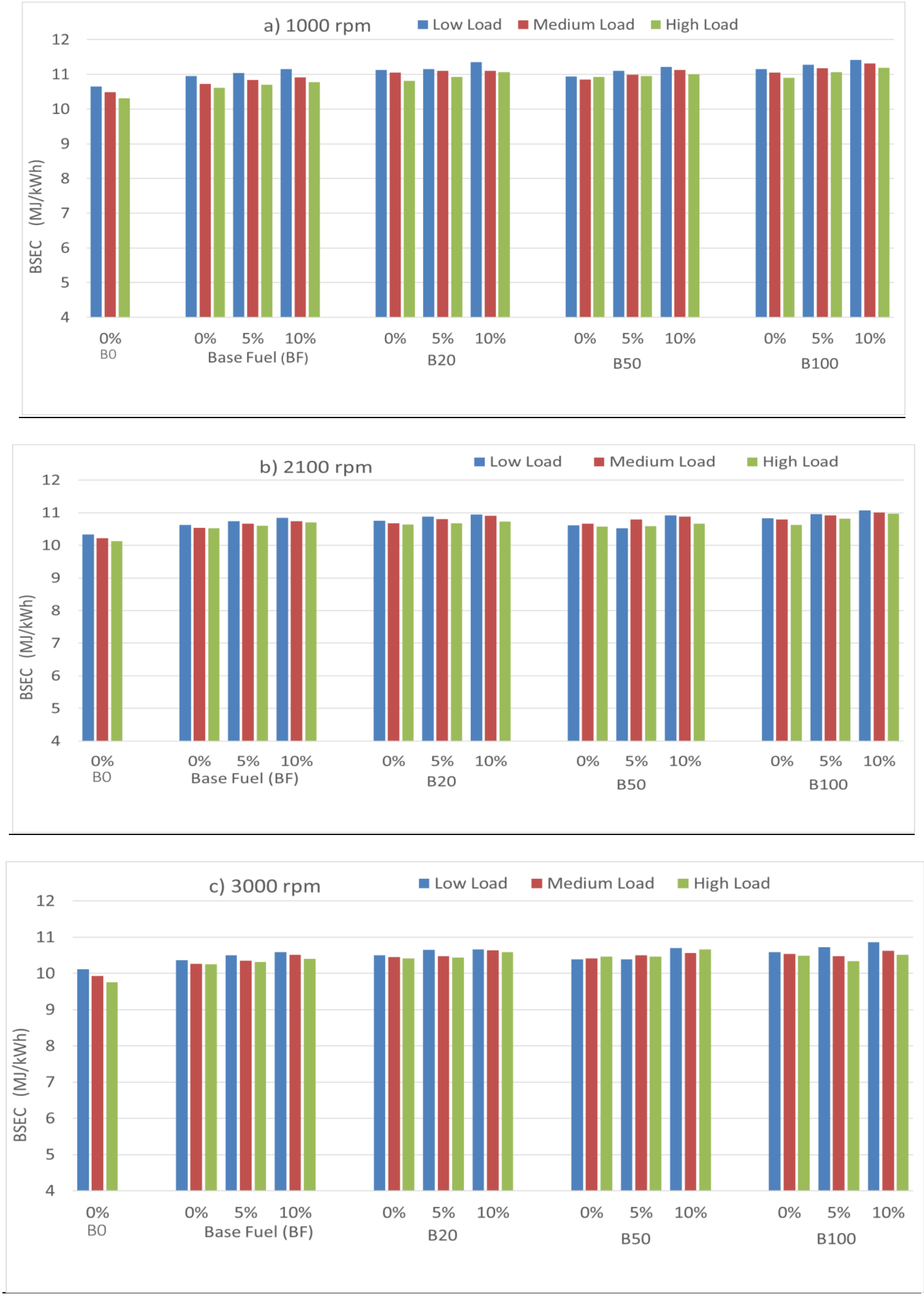

Figure 2: BSEC of different fuel blends with 5% and 10% emulsification at a) 1000 rpm, b) 2100 rpm, and c) 3000 rpm

Figure 3: BTE of different fuel blends with 5% and 10% emulsification at a) 1000 rpm, b) 2100 rpm, and c) 3000 rpm

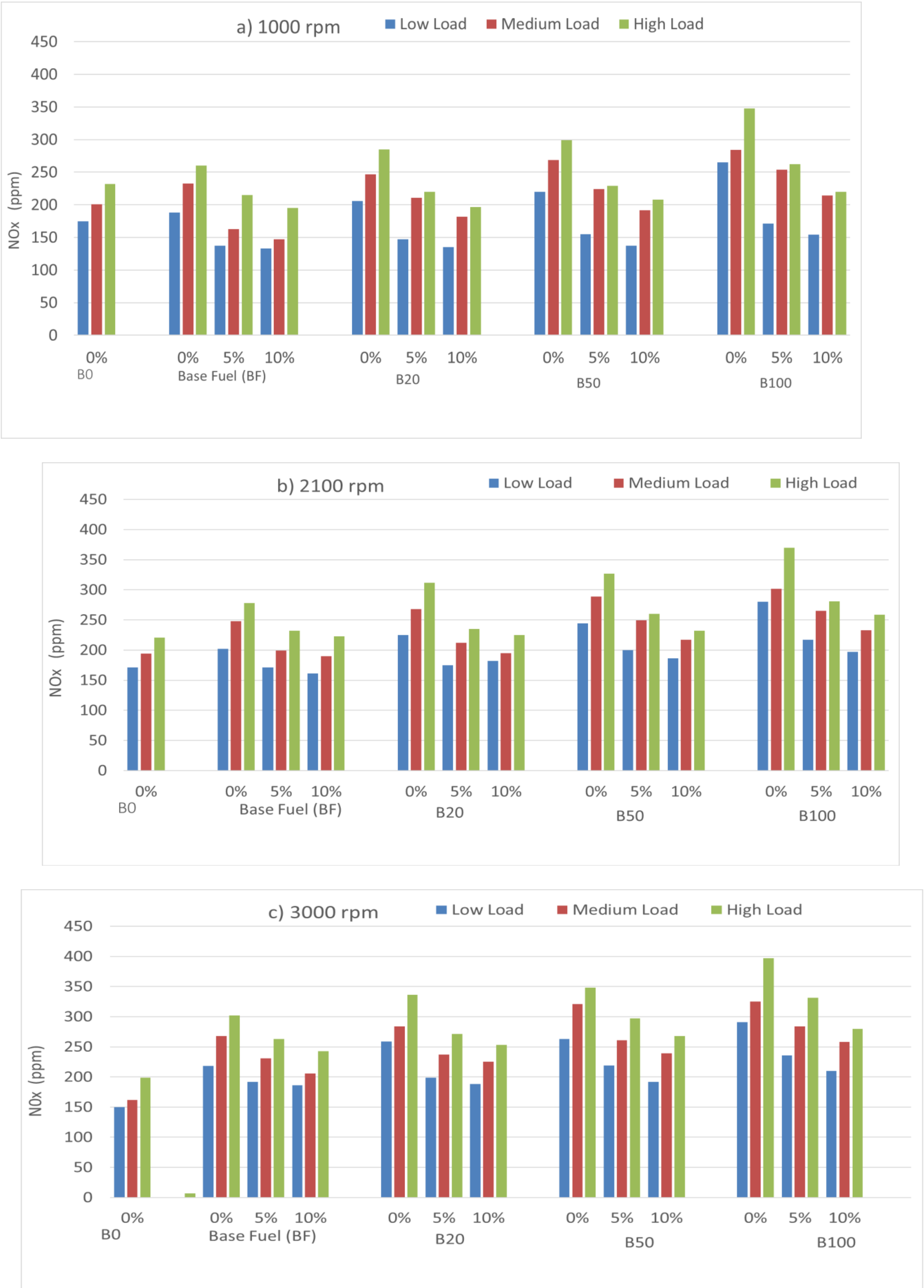

Figure 4: NOx emissions of different fuel blends with 5% and 10% emulsification at a) 1000 rpm, b) 2100 rpm, and c) 3000 rpm

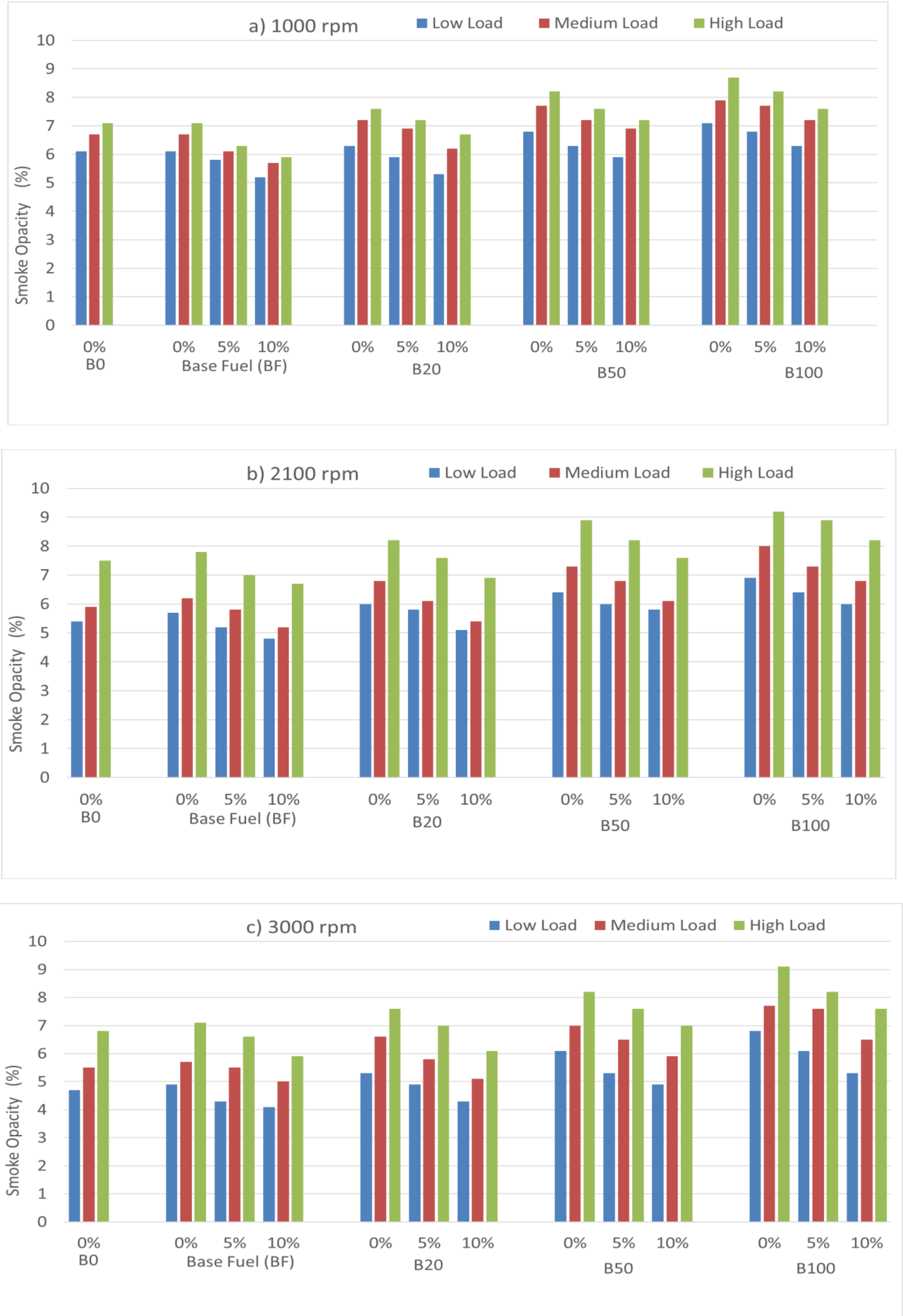

Figure 5: Smoke emissions of different fuel blends with 5% and 10% emulsification at a) 1000 rpm, b) 2100 rpm, and c) 3000 rpm

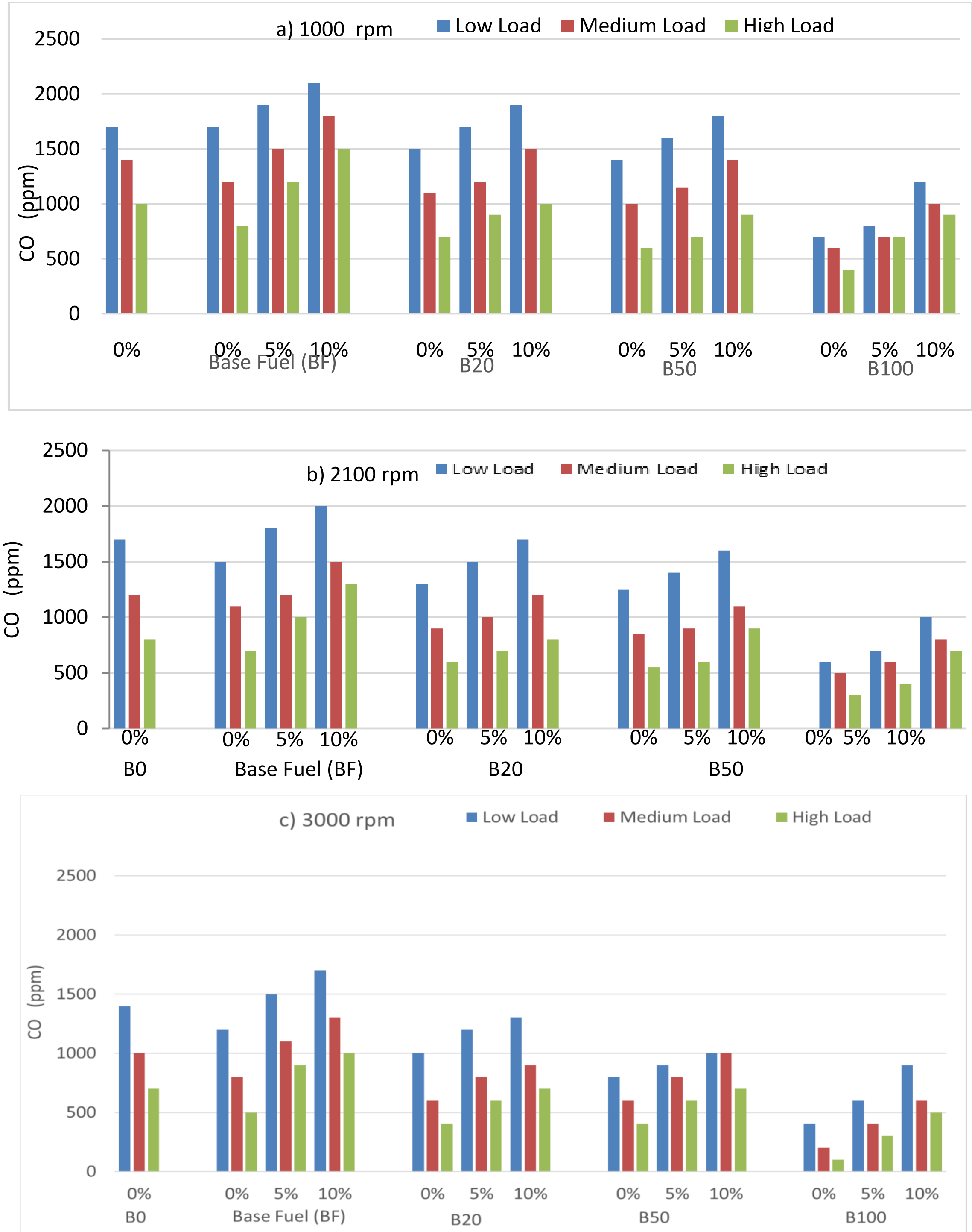

Figure 6: CO emissions of different fuel blends with 5% and 10% emulsification at a) 1000 rpm, b) 2100 rpm, and c) 3000 rpm

Figure 7: HC emissions of different fuel blends with 5% and 10% emulsification at a) 1000 rpm, b) 2100 rpm, and c) 3000 rpm

IV. CONCLUSIONS

The following are the conclusions from this experimental investigation.

The viscosity of emulsified fuel was higher than diesel and the base fuel, and the calorific value of emulsified fuels was far less than that of diesel and base fuel. For all engine conditions, there was no significant BSEC change of emulsion fuels up to B50 blends; however, the BTE of B100 fuel blends were 3-4% higher than diesel or base fuel. Due to emulsification, there was a decrease in NO_x and smoke emission, and the higher the water content, the higher the reductions. Maximum reduction of 35% in NO_x was obtained with blends with 10% water content. Water content in the fuel blends helped reducing smoke emissions, and at 10% water content, maximum smoke opacity reduction was found as 15%, compared to their fuel bases at the same engine load condition.There was about 60-70% CO reduction with B100 and blends than diesel or base fuel. CO emission for the blends with higher concentrations of water increased with an increase in percentage of water at all engine conditions.CO emission with 10% water content fuel blendswas 20-40%higher compared to the base fuel's CO emission. HC emission showeda similar trend to that of CO emission, but in a varying magnitude.HC emission with 10% water content fuel blends was 20-60% higher compared to that of fuel blends with no water.However, B100 emulsified blends show a significant HC reductions (≈50% for 5% water content and ≈15% for 10% water content).

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