Title: NOx Reduction of Biodiesel Operated Diesel Engine Using Different Techniques: (EGR, Steam Injection and Emulsification)

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May, 2018

A thesis submitted in partial fulfilment of the requirement of

the MSc degree in

Mechanical Engineering

Faculty of Engineering

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Abstract

The increase in world population has led to the growth in energy demand. The primary sources of this energy come from the combustion of conventional fuels, which are contributing to polluting the environment. Biodiesel offers a solution as an alternative fuel for internal combustion engines, however it emits higher (nitrogen oxides) NOx emission. Exhaust gas recirculation (EGR) systems, as well as methods that supply steam into the intake air system of diesel engines, are used to lower NOx emissions. This study focuses on determining the effects of EGR, methods that supply steam into the intake air systems, canola biodiesel, and emulsions consisting of diesel-biodiesel blends with additives on diesel engine performance and emissions. Experiments using two modern diesel engines (a light-duty and a heavy-duty) were investigated at various operating conditions. The results showed that canola biodiesel increased fuel consumption and NOx, but decreased other emissions including carbon monoxide (CO) and hydrocarbon (HC) emissions. The use of both EGR, methods that supply steam into the intake air system, and emulsion consisting of diesel-biodiesel blend with diethyl ether (DEE) showed a significant reduction in NOx emission and exhaust temperature; however, there were slight increases in fuel consumption, CO, and HC emissions.

Acknowledgments

A special thank to Dr. Murari Mohon Roy, Associate Professor in the Department of Mechanical Engineering at Lakehead University. The door to Dr. Roy’s office was always open whenever I ran into a trouble spot or had a question about my research. He consistently allowed this research to be my own work, but steered me in the right direction whenever he thought I needed it.

I would also like to acknowledge Dr. Birbal Singh, Professor in the Mechanical Engineering Department at Lakehead University, and Dr. Leila Pakzad, Assistant Professors in the Chemical Engineering Department at Lakehead University, as the second readers of this thesis, and I am gratefully indebted to their very valuable comments and suggestions.

Finally, I must express my very profound gratitude to my parents, wife and daughters for providing me with unfailing support and continuous encouragement throughout my journey at Lakehead University. This accomplishment would not have been possible without my family. Thank you.

Contents

Nomenclature

ASTM	American Society of Testing and Materials
BSFC	Brake specific fuel consumption
BTE	Brake thermal efficiency
FAME	Fatty acid methyl ester
cc	Cubic centimeter
CN	Cetane number
CO	Carbon monoxide
CR	Compression ratio
cSt	Centistoke
˚C	Degree Celsius
DEE	Diethyl ether
DOC	Diesel oxidation catalyst
DPF	Diesel particle filter
EGR	Exhaust gas recirculation
EB	Emulsified biodiesel
EGT	Exhaust gas temperature
g/kWh	Gram per kilowatt-hour
g/L	Gram per liter
HC	Hydrocarbons
HLB	Hydrophile-lipophile balance
kg/m^3	Kilogram per cubic meter
kJ/kg	Kilojoule per kilogram
kW	Kilowatt
MP	Melting point
mg/m^3	Milligram per cubic meter
ml/min	Milliliter per minute
mm	Millimeter
µm	Micrometer
NO	Nitric oxide
NO_2	Nitrogen dioxide

NOx	Oxides of nitrogen
NSC	NOx storage catalyst
O_2	Oxygen
PM	Particulate matter
ppm	Part per million
rpm	Revolution per minute
Span 80	Sorbitan monoleate
Tween 80	Polyoxyethylene sorbitan monoleate

Caption for Figures

Caption for Tables

Chapter 1
Introduction

1.1 Overview

The growing worldwide energy demand is directly attributed to the rising global population. In line with this increased energy demand, more conventional fuel sources have been consumed, which has caused fossil fuel depletion, leading to an energy crisis in different parts of the world. Thus, many governments around the globe have been attempting to shift towards alternative sources.

Until recently, global energy use was derived primarily from hydrocarbon-based fuels. These fuels, such as diesel and gasoline, are generally consumed by internal combustion engines. The dependency on diesel and gasoline contributes to environmental pollution since the main emissions exhausted from the engines that function on those fuels include:

- carbon monoxide (CO);
- nitrogen oxides (NOx);
- unburned hydrocarbon (HC); and
- particulate matters (PM).

Emissions from those types of fuels are leading human civilization to near catastrophic ozone depletion and climate change, as never seen before. While those resources remain the leading source of energy, newer sources of energy are gradually being developed and used in many countries. Multiple alternative fuels have been proposed, one of which being biodiesel, which has been largely touted as a viable alternative for fueling compression ignition (CI) engines.

The skyrocketing growth in the world's population over last century has heightened the demand for conventional fuel resources. Currently, the worldwide consumption of conventional petroleum products (oil and liquid fuels) is approximately 96 million barrels per day [1], [2]. Canada consumed approximately 1.9 million barrels of refined petroleum products per day in 2015 [3]. In that same year, the net sales of diesel and gasoline fuels were 17.98 and 44.58 million liters per year, which equates to 420,000 and 993,000 barrels per day, respectively [4]. Diesel is commonly used as a fuel for compression ignition (CI) engines, while gasoline is used as a fuel for spark ignition (SI) engines. In addition to the pollution issue, increasing the demand on conventional fuel, which has an end-date, will result in it no longer being a viable option in the future.

Generally, diesel engines have advantages of high-energy conversion and economic power source over gasoline engines, especially for the same power output. Therefore, a diesel engine emits lower CO and HC [5]. Additionally, there is low maintenance required for diesel engines since they have no ignition or carburetor systems. Furthermore, a diesel engine has more flexibility over fuel choice [6]. Thanks to these advantages, diesel engine use is wide-spread in many applications such as transportation, agricultural machines, and mining equipment. Although a diesel engine has lower emissions compared to a gasoline engine, public and regulatory agencies in both developed and developing countries put more pressure on diesel engine emission control.

Extensive research has been conducted on emission reduction in diesel engines. Such potential technologies include reducing in-cylinder temperature and after-treatment of engine exhaust gases. Reducing in-cylinder temperature using exhaust gas recirculation (EGR) is an effective way to reduce NOx emissions. This system recirculates a portion of the exhaust gases back into the engine's cylinder, thus reducing the amount of oxygen that is available for combustion in the cylinder [7]. After-treatment systems include [8]: a diesel oxidation catalyst (DOC), designed to reduce CO and HC emissions; a diesel particulate filter (DPF), designed to remove PM or soot emission; and NOx storage catalysts (NSC) and selective catalytic reduction (SCR), both designed to control NOx emissions.

Biodiesel is an alternative fuel derived from biomass defined as mono alkyl esters of long chain fatty acids. Biodiesel has several advantages, such as it reduces the dependency on petroleum fuels, it can be used as fuel for diesel engines with little modification to engine fuel system, it emits lower HC, CO and PM, and it has higher CN [9]–[11], [12]–[14]. However, biodiesel also has downsides such as lower heat content; inferior cold flow properties, and a slight increase in NOx emissions [15]–[17].

Chapter 2

Literature Review and Thesis Objective

This chapter covers a summary of previous works on biodiesel. A brief literature on engine performance and emissions are mentioned, followed by a short review on the effect of introducing water into combustion chamber fuel. Finally, highlighting the objective of this study concludes the chapter.

A number of studies have been applied in literature to support the current results. Various authors have performed work on introducing water into the combustion chamber to control diesel engine emissions. Numerous studies focused on the effects of EGR system on diesel engine regulated emissions. Many investigations showed that the use of biodiesel can result in a substantial reduction in PM, CO and HC emissions.

2.1 Engine Performance

The engine performance when fueled with biodiesel is dependent on many factors, such as fuel injection and biodiesel's fuel properties (oxygen content, lower heating value, and higher viscosity). These factors influence the spray formation and combustion of fuel. BSFC is the ratio between mass fuel consumption and brake power. Brake-specific fuel consumption (BSFC) for a particular fuel is inversely proportional to thermal efficiency. Verma et al.[18] discovered that brake-specific fuel consumption of biodiesel produced from cotton seed oil decreased as the load on the engine increased. It was also found that as the percentage of biodiesel in the blend increased, BSFC also tended to increase. Roy et al. [11] investigated the effects of canola biodiesel on a 2-cylinder, 4-stroke DI diesel engine for performance under different load conditions, and found that there was no significant effect on BSFC when using up to 10% of biodiesel blends. The BSFC of pure biodiesel increased to approximately 5% at low load, and 9% at high load. The study concluded that biodiesel has higher fuel conversion efficiency than that of diesel fuel. A similar study [19] revealed that there was no effect of BSFC up to 5% blend of biodiesel or canola oil in diesel fuel, however there was a 1.1% to 2.3% increase of BSFC when using 20% blends at different speeds.

Due to biodiesel's lower calorific value, BSFC for higher biodiesel blends is higher than diesel fuel [20]. It is interesting to note that the BSFC is the actual mass of the consumed fuel to produce 1kW, however a large amount of fuel is consumed to produce the same amount using biodiesel, which would cause a tremendous increase in the BSFC [21]. Ozener et al.[22] studied the performance characteristics of conventional diesel fuel and biodiesel produced from soybean oil and its blends. Compared to diesel fuel, the average brake torque decreased when increasing the biodiesel concentration over the entire speed range under full load condition. The study concluded that the average BSFC values at all engine speeds for B100, B50, B20 and B10 blends were 9%, 7%, 4% and 2% higher, respectively, than the values when using diesel fuel. Liaquat et al.[23] examined the effects of coconut biodiesel blended fuels on engine performance. The tests were carried out at full load using biodiesel blends (B5, B15) and diesel fuel, at variable speeds of 1500 to 2400 rpm at intervals of 100 rpm. The experiments revealed that the engine torque and brake power for biodiesel blends were lower compared to diesel fuel because of its lower heating value. The BSFC values for biodiesel blends increased due to higher densities compared to conventional diesel fuel. In another study, Liaquat et al.[24] employed biodiesel-diesel blend (B20) produced from palm oil on a single cylinder, 4-stroke diesel engine during an endurance test, which was carried out for 250 hours at 2000 rpm and 10 Nm load. The test results showed that B20 blend had higher BSFC compared to diesel fuel. The average increase in BSFC was 3.88% during endurance testing for B20 when compared with diesel fuel. The increased fuel consumption for B20 was due to higher oxygen content, which resulted in lower heating value.

Habibullah et al.[25] evaluated the performance of coconut and palm oil, and their blends with diesel on a single cylinder, 4-stroke, direct injection diesel engine under full load at varying speeds. The average BSFC for PB30, CB30 and PB15CB15 were 8.58%, 9.03% and 8.55% higher, respectively, than that of diesel fuel. This was due to biodiesel's low heating value, as it contains a higher concentration of oxygen. On the other hand, the BTE values for PB30, CB30 and PB15CB15 were lower by approximately 5.03%, 3.84% and 3.97%, respectively, than diesel fuel. The results indicated that the reduction in BTE was due to higher viscosity, density and low heating value of biodiesel than diesel fuel. Fattah et al.[26] studied the performance and emission characteristics of a diesel engine with coconut and jatropha biodiesel-diesel blends (B20) using antioxidants. The BSFC values for the B20 blends were higher by 4.76-5.02% compared to diesel fuel, and the addition of antioxidants lowered the BSFC by 0.55-0.79% depending on the feedstock. The use of antioxidants resulted in a significant reduction in NOx emissions.

Das et al. [27] experimented on a diesel engine using biodiesel from pongamia oil under various load conditions. The results showed that as the load increased, the fuel consumption for different blends of biodiesel decreased. This could be due to incomplete fuel combustion at lower loads as a result of low cylinder gas temperature and lean fuel air mixture. At higher loads, increased wall temperature helped reduce ignition delay, which improved the combustion process and reduced fuel consumption. A subsequent study on engine performance conducted by Hasan et al.[28], using jatropha biodiesel blends, showed that BSFC for B10 was 4% lower than diesel fuel, and B20 showed similar results with diesel. However, B30, B40 and B50 showed 3.4%, 5.7% and 7.5% higher, respectively, than diesel fuel. The reason for similar BSFC values for B20 with diesel was due to the presence of inherent oxygen in the fuel dominating over lower calorific value for improved combustion.

2.2 Engine Emissions

In general, pure biodiesel and biodiesel blends reduce PM, HC, partially burned or unburned HC, CO_2, and CO emissions. However, there is usually a slight increase in NOx emissions compared to diesel fuels [13]. Armas et al.[29] tested biodiesel on a 4-cylinder, 4-stroke, turbocharged, intercooled diesel engine. The oxygenated biofuel was extracted from animal fats. The results showed lower HC, CO and PM emissions. In terms of NOx emissions, a slight decrease was achieved using biodiesel as an alternate fuel. Singh et al.[30] investigated the emissions from a diesel engine powered by biodiesel and hydroprocessed renewable diesel (HRD). Both were produced from the same feedstock, i.e., jatrophacurcas oil, using different processes. Using the European stationary cycle, an idle condition was trialed as one of the thirteen modes. Using biodiesel, they were able to reduce PM, CO and HC more effectively, although HRD reduced NOx by 29% and BSFC compared to conventional diesel fuel. An et al. [31] carried out testing on the effects of emissions from a diesel engine with biodiesel produced from waste cooking oils under multiple idling conditions at 800 and 1200 rpm. The tests revealed that higher HC and NOx emissions were emitted at idle conditions, but not at high rpm, stating that low engine speed had a significant effect on emissions when using biodiesel. Another experiment was conducted by An et al. [32] on a common rail fuel injection diesel engine using an ultra low sulfur diesel engine, biodiesel, and their blends. They concluded that partial load and idle conditions had a major influence on BTE, BSFC and CO emissions.

Cheik et al. conducted experiments using biodiesel blends on a naturally-aspirated, direct injection diesel engine under different loads at 2500 rpm. The results revealed that the variation of engine speed and load had a great influence on engine emissions. Increasing the engine speed led to increased HC emissions. However, increasing the engine load resulted in higher emissions of CO and PM. Due to the higher amount of oxygen content in biodiesel blends, NOx emissions increased slightly. Rahman et al. [33] used jatropha biodiesel and their blends (B10 and B20), along with diesel fuel, on an inline 4-cylinder CI engine at various engine speeds and loads. The results revealed that with higher percentages of blends, CO and HC emissions decreased. However, as blend percentages increased, NOx emissions increased significantly. The experiment also revealed that compared to pure diesel fuel, fuel consumption increased for biodiesel-diesel blends when increasing the amount of blend percentage. Yang et al. [34] performed experiments on a common-rail fuel injection diesel engine using diesel fuel, biodiesel and their blends (B10, B20 and B50) under various loads. They noticed that engine load had an impact on CO emissions. At higher engine loads, CO emissions increased when decreasing the biodiesel blend ratio and increasing engine speeds. Yang et al. [31] conducted another test on a Euro IV diesel engine with biodiesel produced from waste cooking oil and its blends at four different engine speeds and under three different loads. The study revealed that low engine speed had a significant effect on the formation of CO, HC and NOx emissions.

Habibullah et al. [25] studied the effects of 20% palm biodiesel or coconut biodiesel blend, their combination (5-15%), and diesel fuel on performance and emissions of a single cylinder, 4-stroke direct injection diesel engine under full load conditions at varying speeds from 1400 to 2400 rpm. They found that the coconut biodiesel blends showed lower break power of 1.72% due to low heating value, and an increase in NOx emissions by 4.49% due to high oxygen content of coconut. It was concluded that the addition of palm biodiesel (5-15 vol. %) could significantly improve the low BP output and high NOx emissions in coconut biodiesel-diesel blends. The CO and HC emissions from all the biodiesel blends decreased from 3.36% to 7.01%, and from 13.54% to 23.79%, respectively, compared to diesel fuel. An investigation [35] was carried out on performance and emissions of a 4-stoke, turbocharged, direct injection, 4-cylinder, high-pressure common rail diesel engine with coconut biodiesel (B10, B20, B30 and B50) under different loads. The BSFC was higher at all load conditions due to lower calorific value. Carbon monoxide emissions decreased, and NOx emissions increased when increasing the biodiesel concentration in the blend and engine load. At all load conditions, smoke emissions were lower with coconut biodiesel blends compared to conventional diesel fuel. At B50 and 0.86 MPa, the smoke opacity was reduced to 52.4%. This was due to lower carbon and high fuel borne oxygen content in biodiesel, which helped achieve more complete combustion, and limited the formation of smoke.

Rahman et al. [36] explored the blend properties of moringa oleifera biodiesel (5 and 10 vol. %) and compared it with palm biodiesel and diesel fuel. The performance evaluation of all the fuel blends were conducted on a multi-cylinder diesel engine at various engine speeds and under full load condition, however the emission were measured under full load and half load conditions. The study exhibited lower brake power for biodiesel blends (PB5, MB5, PB10 and MB10) with 1.38%, 2.27%, 3.16% and 4.22% reduction, respectively, compared to diesel fuel. BSFC was higher with 0.69%, 2.56%, 2.02% and 5.13% increase for PB5, MB5, PB10 and MB10, respectively, compared to diesel. Moringa oleifera biodiesel blends produced lower CO and HC emissions compared to diesel fuels, and therefore, the study emphasized that these blends could be replaced with diesel fuel to lower exhaust emissions into the environment. Rahman et al. [37] conducted another test on the effect of jatropha curcas and moringa oleifera biodiesel blends on the performance of a 4-cylinder diesel engine, and on its emissions at full load condition at different engine speeds. The study depicted that the brake of MB10 and JB10 were 4% and 5% lower than those of diesel fuel. Compared to diesel fuel, MB10 and JB10 decreased HC emissions by 12% and 16%, and CO emissions by 11% and 14%, respectively. In addition, MB10 and JB10 increased NOx emissions by 9% and 10%, respectively, and CO2 emissions by 5% and 7%, respectively.

Zhu et al. [38] investigated the performance and emissions of a 4-cylinder direct injection diesel engine fueled with diesel and biodiesel fuels blended with 5%, 10% and 15% by volume of methanol and ethanol. The BSFC increased with higher amounts of alcohol in the fuel due to its lower heat values. CO and HC emissions increased, and NOx emissions decreased, with the percentage of methanol and ethanol in the blended fuel. Moreover, methanol blends proved more effective than ethanol in decreasing PM and NOx emissions due to methanol's higher latent heat of evaporation. Yilmaz et al.[39] studied the effects of emissions on a 2-cylinder, 4-cycle, DI diesel engine generator with biodiesel-ethanol-diesel blends. Ethanol concentrations were varied at 3%, 5%, 15% and 25% in biodiesel-diesel blends. Engine tests were conducted from no load to high load. The main factors affecting the emission reduction were due to superior cooling effects and oxygen content of alcohols. The experiments showed that the blends increased the CO emissions compared to diesel at low load conditions, however, there was no significant change in CO emissions at high loads based on fuel types or blends. Ethanol-blended fuels reduced NOx emissions in all concentrations. HC emissions were dependent on both ethanol concentrations and operating conditions. With an increasing amount of ethanol blends, HC emissions increased up to 50% load. Nevertheless, above 50% load, ethanol decreased HC emissions in all concentrations.

In study [35], 2.5%, 5% and 7.5% by volume of ethanol was blended with neat biodiesel from animal fat to test on a single cylinder, naturally-aspirated, water-cooled DI diesel engine at different loads and at a constant speed of 1500 rpm. The addition of ethanol reduced CO, HC and smoke emissions when compared to neat biodiesel, with a greater reduction at higher load conditions. HC reduction was achieved with a higher amount of ethanol additives in the biodiesel blends. However, NOx emissions increased tremendously by increasing the ethanol at higher loads. Biodiesel with an ethanol additive was tested on a supercharged DI diesel engine at an engine speed of 1500 rpm with loads ranging from 20% to 100%. NOx emissions increased with the loads, whereas blending with ethanol helped reduce NOx emissions. It was found that CO and HC increased with the addition of ethanol at all load conditions [40]. However, these increases were minimized when the engine was supercharged. Two engines were used to test the fuel emissions in [41], whereby ethanol-biodiesel blends were tested on a multi-cylinder, turbocharged, common rail injection system with an exhaust gas recirculation system (EGR), as well as on a single cylinder, direct injection, 4-stroke diesel engine running in low temperature condition. Three conditions were tested: 1500 rpm at 3-bar brake mean effective pressure (BMEP); 2500 rpm and 6-bar of BMEP; and 4000 rpm at full load. It was noted that higher NOx and smoke, and lower CO and HC were obtained at higher load and higher speed condition (2500 rpm, 6-bar) than at lower load, lower speed condition (1500 rpm, 3-bar) for all fuel blends. However, ethanol-blended fuel showed lower NOx and higher CO and HC emissions than diesel fuel. The weak sooting tendency of ethanol blends allowed higher EGR rates in the reduction of NOx emissions. Ethanol blends allowed for an increase in operating range at low temperature condition mode in the single cylinder diesel engine due to lower smoke emissions.

Zhang et al. [42] investigated the particulate emission characteristics of a single cylinder, direct injection diesel engine fueled with blends of butanol and pentanol in biodiesel at 10% and 20% by volume. The engine ran at a constant speed of 3000 rpm and at three engine loads (25%, 50% and 75%). Organic carbon and water soluble organic carbon decreased significantly with the loads, whereas elemental carbon increased. Both alcohol blends were able to effectively reduce particulate mass, elemental carbon emissions, and polycyclic aromatic hydrocarbons at all loads. Park et al. [43] studied the effects of biodiesel in bioethanol-blended diesel fuel. The test engine was operated at 1200 rpm and at an injection pressure of 120 MPa. The biodiesel blending effect resulted in reductions of HC, CO and soot emissions at early injection timing. Rakopoulos [44] experimented on a HSDI diesel engine using blends of diesel fuel with ethanol, butanol and diethyl ether at different volume percentages for emission analysis. He found that by increasing the percentage of all biofuels in the blends, he achieved a significant reduction of smoke opacity (mainly higher for butanol blend), a reduction of NOx emissions (mainly higher for diethyl ether blends), as well as a reduction of CO emissions compared to diesel fuel. A study conducted by Lanjekar et al. [45] concluded that coconut and palm kernel oils, which have a high content of lauric acid, produced lower NOx emissions, had better oxidative stability, and improved cold flow properties.

2.3 Introducing Into Combustion Chamber

Much work has been performed to control engine emission by reducing combustion temperature. An effective approach was noted by introducing water into the engine, whether as steam into the air intake system, or in the fuel as emulsion fuel.

2.3.1 Steam:

Kokkuiunk et al. [46] conducted theoretical and experimental investigations of steam injected into a diesel engine, and concluded that NOx emissions dramatically decreased with a slight increase in specific fuel consumption. Gonca et al. [47] reported that introducing steam into a combustion chamber reduced both NOx and PM emissions, whereas HC and CO emissions increased.

2.3.2 Emulsion Fuel:

Emulsion fuel is a mixture of polar liquid (water) and nonpolar liquid (fuel) that is blended with emulsifiers [48]. Adding water to fuel reduced both NOx and PM emissions. Additionally, emulsion fuel produced higher thermal efficiency due to better atomization caused by evaporating the water particles inside the cylinder, which led to lower fuel particles; hence improved combustion efficiency. Elsanusi et al. [49], investigated the effect of fuel emulsion with different levels of water content in the emulsion on diesel engine regulated emissions; they obtained significantly low NOx emissions with the highest water content in emulsified fuel. On the other hand, they also obtained a significant increase in CO emissions with higher water content.

2.4 Thesis Objective

As discussed in the aforementioned literature review, although there have been a number of studies on performance and emissions of biodiesel fuel, the main problem remains limiting biodiesel's NOx emissions. The objective of this study is to reduce both NOx and PM emissions of biodiesel, as well as to control HC and CO emissions. In this study, different blends of biodiesel were tested to compare the emissions with two different diesel fuels used as reference fuels. Furthermore, chemical additive DEE was used to improve emulsion fuel's CN. Moreover, an EGR and steam injection system was designed, and their effects were tested on diesel engine emissions. In this study, tests were carried out on two separate engines; a heavy-duty diesel engine at two idling conditions (1000 and 1200 rpm) and a light-duty, 2-cylinder diesel engine with varying engine loads at different engine speeds to compare the performance and emissions with diesel fuel.

Chapter 3

Methodology

3.1 Introduction

This chapter includes a list of all materials used, as well as an explanation of the preparation of biodiesel and emulsion fuel. We also describe the engines that were tested, the measurement apertures, and the engine testing procedure.

Firstly, canola oil was used to produce biodiesel via the transesterification method. Thereafter, the emulsion preparation method will be explained, followed by a description of the engine that was tested and the apparatus used, and a brief summary of the engine testing procedure.

3.2 Biodiesel Production

Biodiesel produced in the lab using the transesterification method, which is simply a chemical reaction of oil and alcohol with the help of a catalyst that accelerates the reaction to produce biodiesel [50], [51]. The method of producing biodiesel began by mixing the two components: sodium hydroxide (which acts as the catalyst), and methanol. These were added in a proportion of 200 ml methanol and 3.5 gm of catalyst, placed in an air-tight container, and mixed until the catalyst was properly dissolved. The canola oil was then heated to 65°C, after which the mixture of methanol and catalyst were poured into the blender. This solution was then left to blend at high speed for at least 50 minutes to ensure adequate mixing (the speed of the blender was high enough to properly mix it). During blending, the process was inspected at equal intervals to monitor the temperature, because methanol's boiling point is approximately 65°C. Therefore, the temperature of the mixture had to remain below that point. When the single-phase solution was ready, it was poured into a 2-litre bottle, where it remained for one day. After 24 hours, two major products were formed: glycerin, which is known as the by-product of the biodiesel, and the biodiesel itself. By separating the glycine and washing the biodiesel twice, the final biodiesel product was obtained by heating it to 65°C. The volumetric collection efficiency of biodiesel was calculated to be approximately 75%, and its quality under ASTM6751 can be found in table 3.1.

Table 3.1 Canola biodiesel properties.

Test Name	Test Method	ASTM limit	Results
Free Glycerin (mass%)	ASTM D6584	Max. 0.02	0
Total Glycerin (mass%)	ASTM D6584	Max. 0.24	0.112
Flash Point, Closed Cup (^{0}C)	ASTM D93	Min. 130	169
Water & Sediment (vol.%)	ASTM D2709	Max. 0.050	0
TAN (mg KOH/g)	ASTM D664	Max. 0.5	0.14
Sim. Dist., 50% recovery (^{0}C)	ASTM D2887	N/A	359.8
Cetane Index	ASTM D976 (2 variables formula)	N/A	50
Copper Corrosion, 3h @ 50^{0}C (rating)	ASTM D130	Max. 3a	1a

3.3 Designing EGR System

EGR system is a NOx emissions reduction technique used in internal combustion engines. EGR works by recirculating a portion of the exhaust gas back into the engine's cylinder, which replaces the amount of oxygen inside the cylinder; hence lower combustion temperature and NOx emission. In this research, two sets of EGR were applied: half open. and full open. The percentages of half open and full open investigated at each speed were calculated using a manometer, and are presented in Table 3.2. A sample of EGR% of full open for 1000 rpm engine speed at low load is presented below:

$$EGR\% = \frac{Total\ Mass\ \ without\ EGR_{intake} - Mass\ of\ air\ with\ EGR_{intake}}{Total\ Mass\ \ without\ EGR_{intake}} \qquad (1)$$

Log linear rule was used to calculate the manometer reading deflection, and the average was considered; it was 0.002m. Then, the velocity of intake air was calculated using the equation below; it was 5.754 m/s.

$$V = \sqrt{(2g * \rho * \Delta h)} \qquad (2)$$

Where:

ρ is the air density,

Δh the difference in manometer reading

Consequently, the volumetric flow rate was calculated by multiplying the velocity by the intake area, which was 0.00956 m^3/s. Thereafter, the total mass flow rate of intake air and fuel consumption (without ERG) was calculated to be 0.0113839 kg/s. The mass flow rate of intake air with EGR was calculated as 0.0105161 kg/s.

Finally, the full open EGR% at engine conditions of 1000 rpm speed and low load was 7.62%. The same procedure was undertaken for all engine conditions, and the percentages are shown in Table 3.2.

Table 3.2 EGR% at various engine conditions.

	Half open valve of EGR % at different loads			Full open valve of EGR % at different loads		
Speed (rpm)	Low	Medium	High	Low	Medium	High
1000	2.51	4.13	5.77	7.62	8.72	9.93
2100	7.2	8.52	9.75	11.99	13.86	15.58
3000	8.08	10.09	12.36	12.77	15.43	17.94

3.4 Introducing Water into Combustion Chamber

A fixed percentage of steam into the intake air system was investigated to determine the effects on a diesel engine's performance and emissions. First, the intake air mass flow rate is calculated using the manometer as in EGR system. The mass flow rate of engine intake air can be found in table 3.3a.

Table 3.3a Mass flow rate of engine intake air at all engine operating conditions

	Mass flow rate of intake air (kg/s)		
Speed (rpm)	Low load	Medium load	High load
1000	0.01138	0.011912	0.012971
2100	0.01606	0.017001	0.01718
3000	0.02884	0.028849	0.02998

Thereafter, the steam flow rate required was multiplied by the intake mass flow rate. The percentages were obtained by calculating 5% and 10% of the intake air system. The mass flow rate of steam at each engine condition was calculated as below:

$$\dot{m}_{steam} = Total\ mass\ flow\ rate\ at\ intake\ air * steam\ \% \quad (3)$$

The mass flow rate of steam for all engine conditions investigated can be found in Table 3.3b.

Table 3.3b Mass flow rate of 5% steam at various engine conditions.

	Mass flow rate of 5% steam (kg/s)		
Speed (rpm)	Low load	Medium load	High load
1000	0.000569	0.0005956	0.00064855
2100	0.000803	0.00085005	0.000859
3000	0.001442	0.00144245	0.001499
Speed (rpm)	Mass flow rate of 10% steam (kg/s)		
1000	0.001138	0.001191	0.001297
2100	0.001606	0.0017	0.001718
3000	0.002884	0.002885	0.002998

3.5 Selection of Fuels and Fuel Blends

In this study, ultra-low sulfur diesel and canola biodiesel were used as the main fuels. The diesel and biodiesel were blended by a volumetric ratio of 20% biodiesel and 80% diesel (B20, B40, B50 and B100). The proposed additives to B40 are ethanol, methanol, DEE and water, and their addition by volumetric percentage of 15. The ethanol, methanol and DEE were simply added to blend B40 with normal mixing, however to add water, the emulsifying process was required to obtain a stable emulsified fuel. Emulsion fuel is a blend of immiscible liquids with emulsifiers [48], [49], [52]. The fuel properties are shown in Table 3.4.

3.6 Emulsion Fuel Preparation Process

Emulsified fuel was prepared using the external force method. In total, 16 emulsion diesel, biodiesel, and diesel-biodiesel blends were prepared. The materials used were Span 80, Tween 80, canola biodiesel, distilled water, and a blender. The preparation process is explained in the following steps:

1. Blend Span 80 and Tween 80 in portions that produce HLB of 8, using the following formula [53]:

$$Tween\ 80\ \% = \frac{100\ (X - HLB_{Span\ 80})}{HLB_{Tween\ 80} - HLB_{SPan\ 80}} \quad (4)$$

$$Span\ 80\ \% = 100 - Tween\ 80\ \% \quad (5)$$

Where,

X= required HLB value (8),

$HLB_{Tween\ 80}$ is given for Tween 80 to be 15 [54],

$HLB_{SPan\ 80}$ is given for Span 80 to be 4.3 [55].

The HLB is a weight percentage indication of the hydrophilic portion in a surfactant. The surfactant is called lipophilic when it has an HLB value lower than 9, while it is named hydrophilic when its HLB value is higher than 11

2. Pour the fuel into the blender; turn on the blender.
3. Add the distilled water in the blender (different water levels of 5%, 10%, and 15% of the total emulsion volume were investigated).
4. Add the Span 80 and Tween 80 mixture to the blender (2% of the total volume).
5. Run the blender for 15 minutes.

The results were milky emulsified fuels. The fuels used were biodiesel-diesel blend B40, with three different levels of water concentration (15%). Another emulsion was prepared following the previous steps with the same concentration of water (15%), but this time DEE was added by 15%. Refer to Table 3.4 for fuel properties.

Table 3.4 Fuel compositions and properties.

	Composition	H.V (kJ/kg)	Density (kg/m^3)	Viscosity (cSt @ 40°C)	CN	Latent heat of vaporization (kJ/kg @ 25°C)
B0	Diesel	44890	827	1.97	48	232
B20	(80 vol.% Diesel, 20 vol.% B100)	44399	839	2.4	48.4	235
B40	(60 vol.% Diesel, 40 vol.% B100)	43032	848	2.99	48.7	239
B50	(50 vol.% Diesel, 50 vol.% B100)	42879	852	3.2	49	243
B100	Biodiesel	40523	889	4.21	50	250
Methanol	Methanol	18200	791	0.687	5	1167
Ethanol	Ethanol	29700	800	0.8	5-8	921
DEE	Diethyl ether	36892	710	0.23	125	368.2
W	Water	0	1000	0.6591	-	2260
Span 80	Sorbitan Monoleate	-	990	(@ 25°C) 1000-2000		-
Tween 80	Polyoxyethylene Sorbitan Monoleate	-	1000.9	(@ 25°C) 300-500		-
EB40W15%	15 vol.% water in B40	36264	878	4.66	-	-
EB40WDEE15%	(15 vol.% water, 15 vol.% DEE) in B40	36071	863	4.42	-	-
B40M15	(85 vol.% B40, 15 vol.% methanol)	39217	839	2.39	-	-
B40E15	(85 vol.% B40, 15 vol.% ethanol)	39453	841	2.61	-	-
B40DEE15	(85 vol.% B40, 15 vol.% DEE)	40021	833	1.9	-	-

3.7 Engine under Study

Two different engines were tested in this study. A heavy-duty (Figure 3.1) Cummins engine is a 4-cylinder turbocharged diesel engine with a high pressure common rail injection system. This type of engine is used mainly in agriculture, mining and construction. It consists of a cooled EGR system and a diesel oxidation catalyst (DOC)/diesel particulate filter (DPF). A dual tank fuel system was installed for switching between various fuel blends. Figure 3.2 shows a schematic diagram of the experimental test setup. The engine specification is shown in Table 3.5.

Table 3.5 Engine specification for heavy-duty engine.

Engine Make and Model	Cummins QSB 4.5 T4I
Engine Type	Inline 4-cylinder
Number of Cylinders	4
Bore * Stroke	102mm * 138mm
Swept Volume	4.5 l
Compressions Ratio	17.3:1
Rated Power	97KW @ 2300 RPM

Figure 3.1: Heavy-duty engine test setup

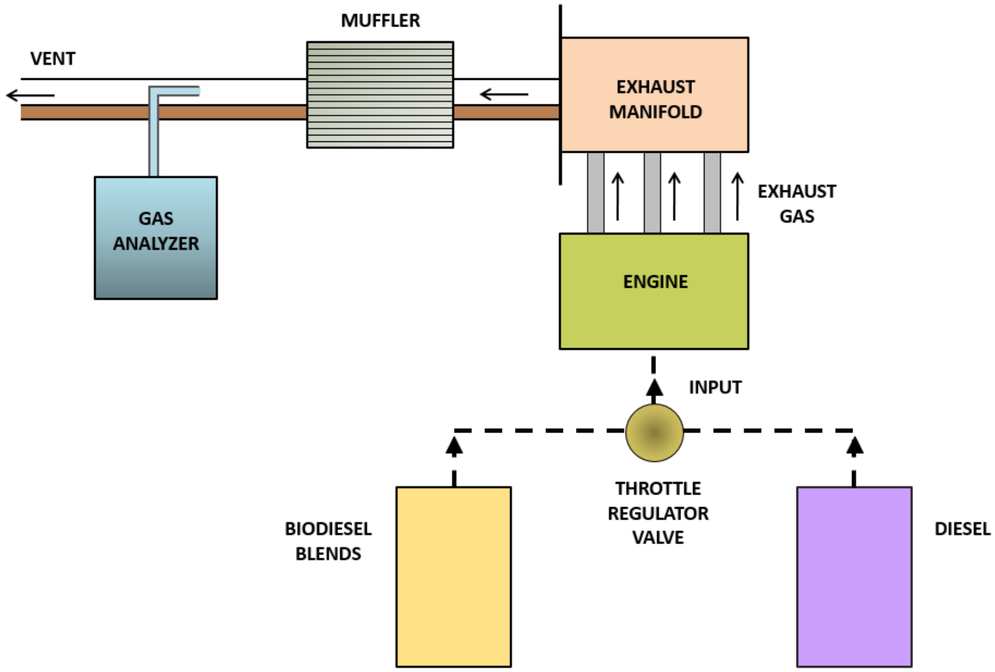

Figure 3.2: Schematic diagram of heavy-duty engine test setup

A light-duty diesel engine (Figure 3.3) was also being used at variable engine loads and speeds. Hatz 2G 40 is an air-cooled 2-cylinder, 4-stroke diesel engine that is rated for Tier 4 regulations. Figure 3. Outlines the schematic diagram of the experimental test setup for the light-duty engine.

Table 3.6 Engine Specifications for Light-duty engine.

Engine Make and Model	Hatz 2G40/2G40H
Engine Type	4-stroke
Number of Cylinders	2
Bore/Stroke	92mm/75mm
Displacement	997 cm^3
Rated Power	17 kW @ 3000 rpm

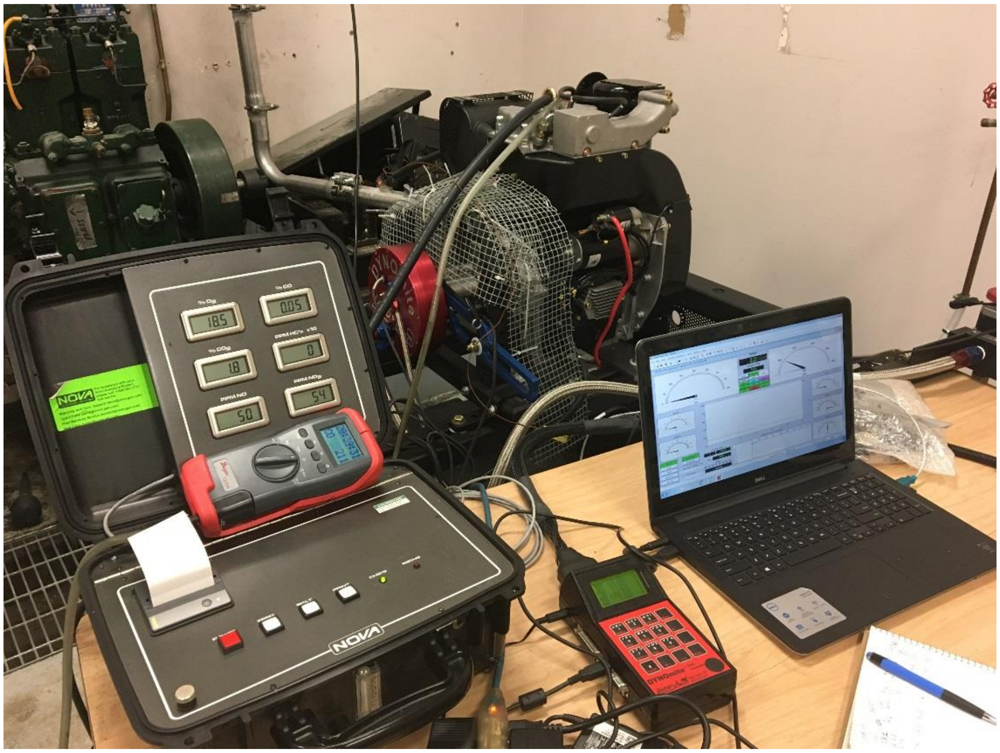

Figure 3.3: Light-duty engine test setup

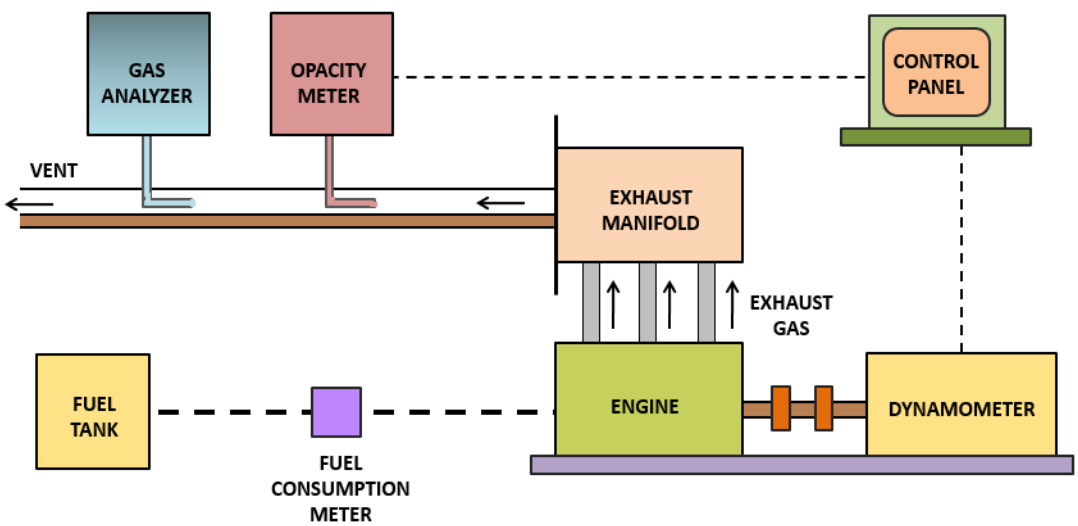

Figure 3.4: Schematic diagram of the experimental test setup for the light-duty diesel engine

3.8 Measurement Apparatus

3.8.1 Emission Measurement:

For emission testing, several devices were used, including a NovaGas 7466K unit, which measures six different exhaust gases (NO, NO_2, CO, CO_2, HC and O_2.), and a DWYER 1205A analyzer for measuring CO emissions. The results from both devices were measured manually. Finally, a Smart 1500 opacity meter was used to measure the amount of smoke produced. This device uses software that can be installed on a PC that uses Windows software (refer to the computer screen illustrated in Figure 3.5). The specifications of emission measurement devices are described in Table 3.7.

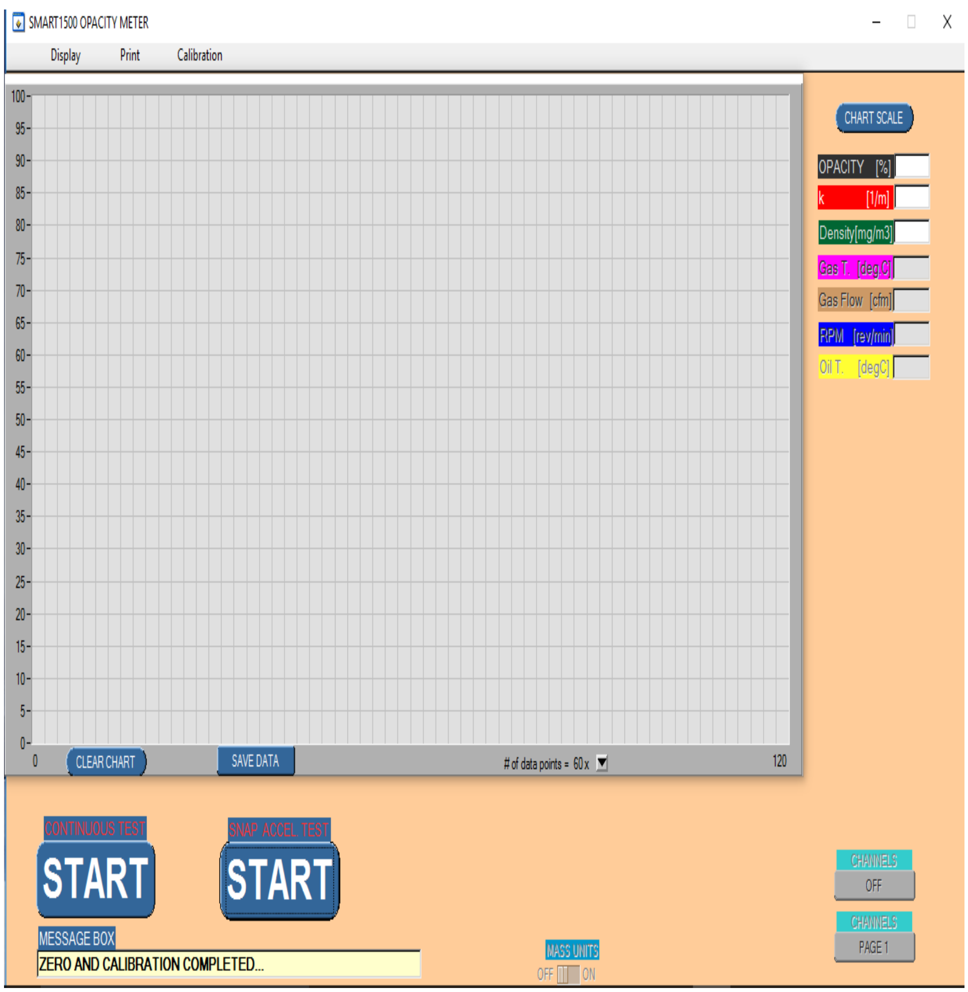

Figure 3.5 Smart 1500 software window

Table 3.7 Specifications of emission measurement devices.

Method of Detection	Species	Measured Unit	Range	Resolution	Accuracy
NovaGas 7466K					
ElectroChemical/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%
Infrared Detector	HC	ppm x 10	0-20000 ppm	10 ppm	±1%
Dwyer 1205A					
Electro Chemical	CO	ppm	0-2000	1 ppm	±5%
ExTech EA10	Temp	0.1 ^{0}C	(-)200^{0}C to 1360^{0}C	0.1^{0}C	±0.3%
Smart 1500	Opacity	%	0-100%	0.1%	±2%
	Soot Density	mg/m^3	0-10 mg/m^3	0.00001	±2%

3.8.2 Performance Measurement:

A dyno-meter was installed on the engine. It has a capacity of 15 to 800 Hp, torque of between 2 lb/ft and over 5000 lb/ft, and rpm ranging from 1000 to over 10000. Water-brake load valves control the engine load. It was equipped with a software option called DYNO-MAX, which can be installed on a Windows-run PC. Its features include a real-time trace graph display, adjustable voice/color limit warnings, push-button controls, and user-configurable analog and digital gauge ranges. Publication-quality color graphs and detailed reports are available for printing (displayed in Figure 3.6). The engine load can be controlled either manually or automatically using the computer. Several parameters can be obtained from the software including engine rpm, exhaust gas temperature, ambient temperature, engine load, engine torque, and operation time. Moreover, the software automatically records up to 1000 readings per second. The following formulas were used for calculating the engine BSFC and BTE:

$$BSFC = \frac{\dot{m}_f}{B_p}, \left(\frac{g}{kWh}\right) \quad (6)$$

$$BTE = \frac{3600}{BSFC * HHV}, (\%) \quad (7)$$

Where,

$\dot{m}_f$= fuel consumption (g/h),

B_p= brake power (kW).

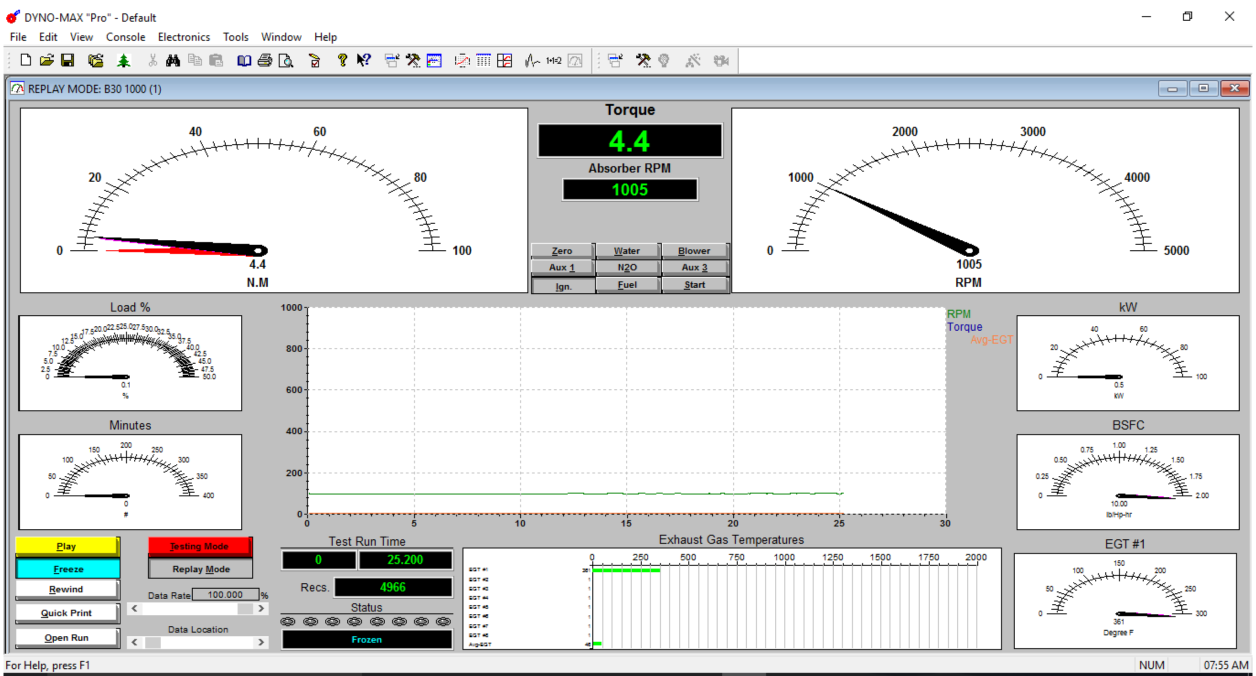

Figure 3.6 DYNO-MAX software window and the parameter recorded

3.9 Engine Test Procedure

3.9.1 Heavy-Duty Engine:

This engine was tested at two idling conditions: 1200 rpm and 1500 rpm, with no engine load. The engine was tested for 30 minutes, starting from a cold start for each test. CO, CO2, NOx, HC, and exhaust temperature readings were taken at 0, 2, 4, 6, 8, 10, 15, 20, 25 and 30-minute intervals. The engine was tested outdoors, with an ambient temperature ranging between 5^{o}C and 25^{o}C.

3.10 Light-Duty Engine

The light-duty diesel engine was tested at three different loads (low: 20%, medium: 50%, and high: 100%) and at three different speeds (1000 rpm, 2100 rpm, and 3000 rpm). The engine was warmed up for approximately 10 minutes. The test duration for all engine operating conditions/fuels was about 45 minutes. Five different fuels were tested in this engine; all are described in Table 3.4. The engine was tested indoors, at a constant ambient temperature of 25^{o}C.

Chapter 4

Results and Discussion

In this chapter, we examine the results obtained throughout the study. The emission results obtained from a heavy-duty diesel engine powered by various fuels at two idling conditions will be discussed. Finally, the effects of EGR and steam into the intake air system on a light-duty diesel engine's performance and emission under various operating conditions will be described.

4.1 Light-Duty Diesel Engine Performance:

Engine performance was tested under three different speeds and loads. The engine speeds were 1000 rpm, 2100 rpm and 3000 rpm; the engine loads were set at 20%, 50% and 80%. Several fuels and fuel series were used in this study.

4.1.1 EGR System:

Two sets of EGR systems were tested in this study (half open and full open). The fuels investigated were B0, B20, B50, and B100. The results outlined in this section will be for half open and full open EGR at engine conditions of 2100 rpm and three different loads. The remaining results can be found in the appendix.

4.1.2 Brake-Specific Fuel Consumption

The variation of BSFC for all tested fuels (half open and full open EGR) with engine loads at 2100 rpm engine speed is shown in Figure 4.1 and Figure 4.2. The BSFC decreased with increases in engine load and speed, which signifies higher burning efficiency. On the other hand, BSFC increased with an increased amount of biodiesel in the blend (B100 had the highest BSFC). This increase is due to the lower heat content in biodiesel compared to conventional diesel. The increase for B100 at low load and speed of 2100 rpm for half open EGR was higher by 4.2% than conventional diesel. The full open EGR provided slightly higher BSFC at all engine conditions and fuel types than half open EGR, which might be because full open EGR provides lower burning efficiency than half open EGR, since the higher amount of oxygen was replaced by the exhaust gases. The BSFC of B0 half open EGR at low load and 2100 rpm was lower by approximately 1.5% than full open EGR at the same operating conditions.

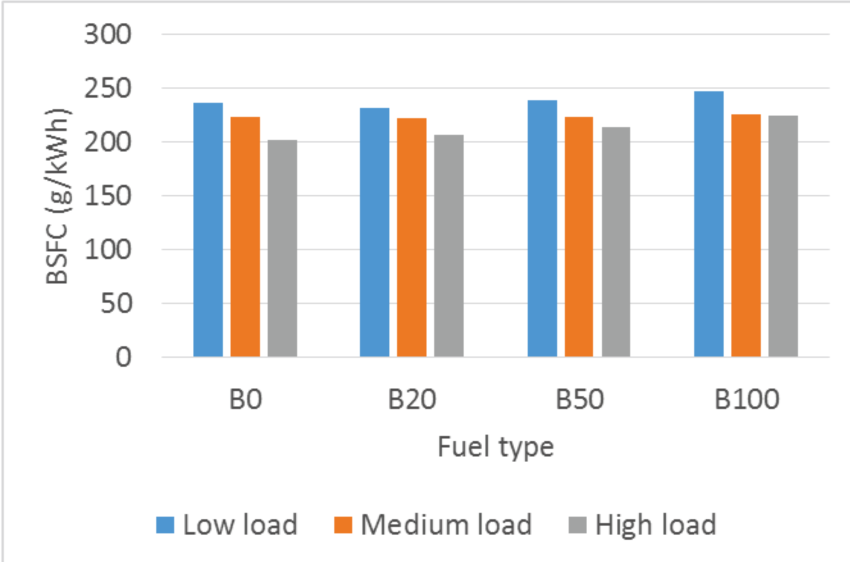

Figure 4.1 BSFC of half open EGR system for various fuel blends.

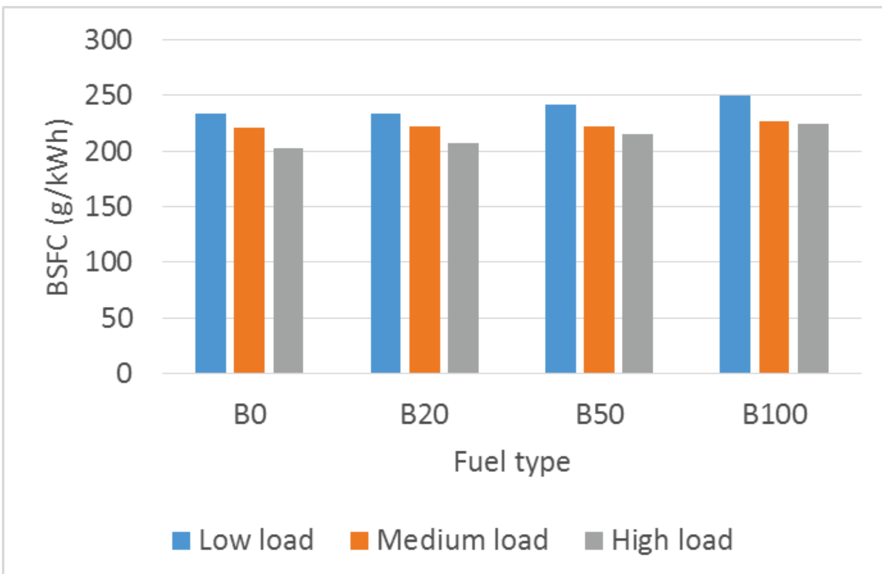

Figure 4.2 BSFC of full open EGR system for various fuel blends.

a) Brake Thermal Efficiency

The engine's brake thermal efficiency (BTE) indicates how efficiently the fuel is converted into mechanical output. Figure 4.3 and Figure 4.2 illustrate BTE of different fuels for half open and full open EGR at various engine loads. BTE rose with the increased engine load. Although biodiesel-diesel blends have a lower heating value than pure diesel, the oxygen content in biodiesel promotes burning efficiency. Therefore, biodiesel-diesel blends had slightly higher BTE compared to diesel at all engine conditions. Full open EGR provided slightly lower BTE than half open EGR at all engine conditions. The BTE of B50 half open EGR was higher than full open by 0.37% at low load at 2100 rpm.

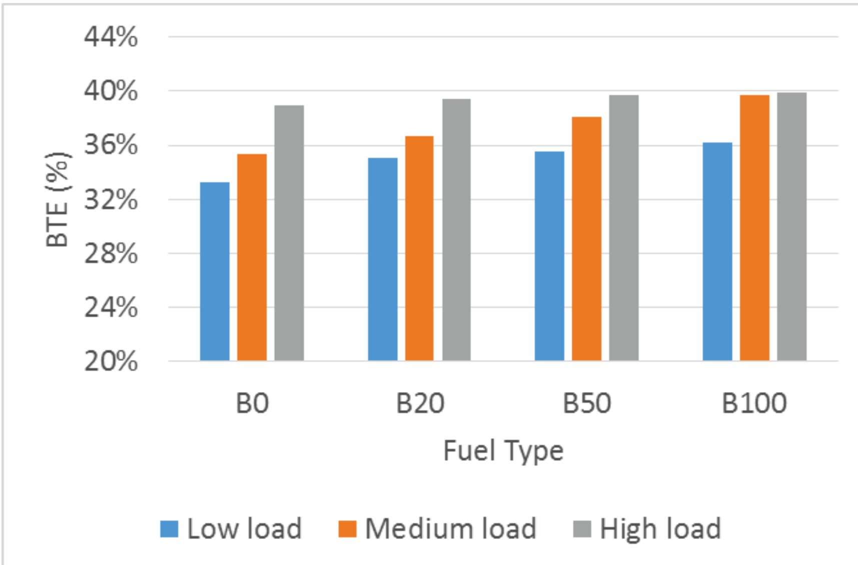

Figure 4.3 BTE of various fuel blends for half open EGR at 2100 rpm and three different loads.

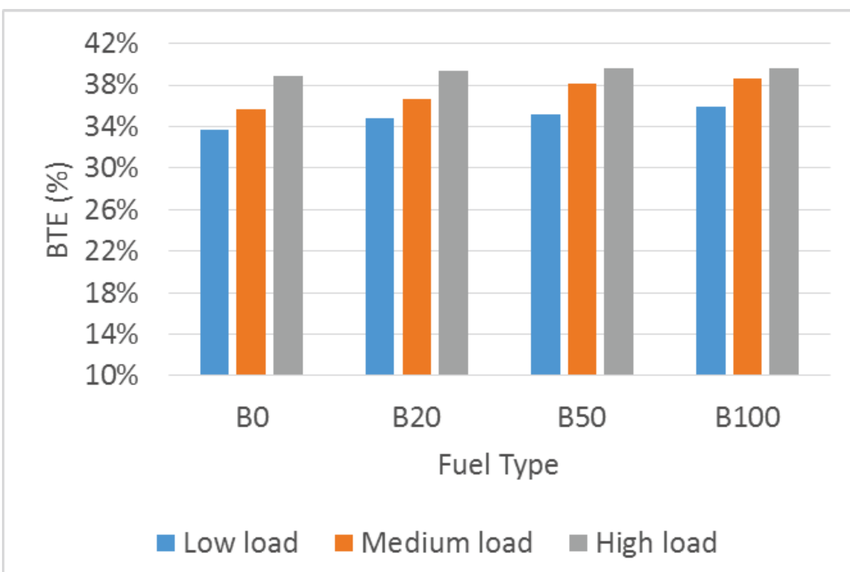

Figure 4.4 BTE of various fuel blends for full open EGR at 2100 rpm and three different loads.

4.1.3 Steam System:

Steam was supplied to the engine at 5% and 10% through the intake air. The fuels investigated were B0, B20, B50, and B100. The results shown in this section are for 5% and 10% steam at engine condition of 2100 rpm and three different loads. The remaining results can be found in the appendix.

b) Brake-Specific Fuel Consumption

Figure 4.5 and Figure 4.6 depict the variation of BSFC for various fuel blends with the engine load for 5% and 10% steam into the intake air, at engine speed of 2100 rpm. At medium load and 5% steam, the BSFC of B0, B20, B50 and B100 fuels were 219, 222.079, 223.22 and 225.89 (g/kWh), respectively. At the same load conditions for the same fuel, 10% steam provided higher BSFC than 5%, averaged at 0.76% for all fuel blends at medium load at 2100 rpm.

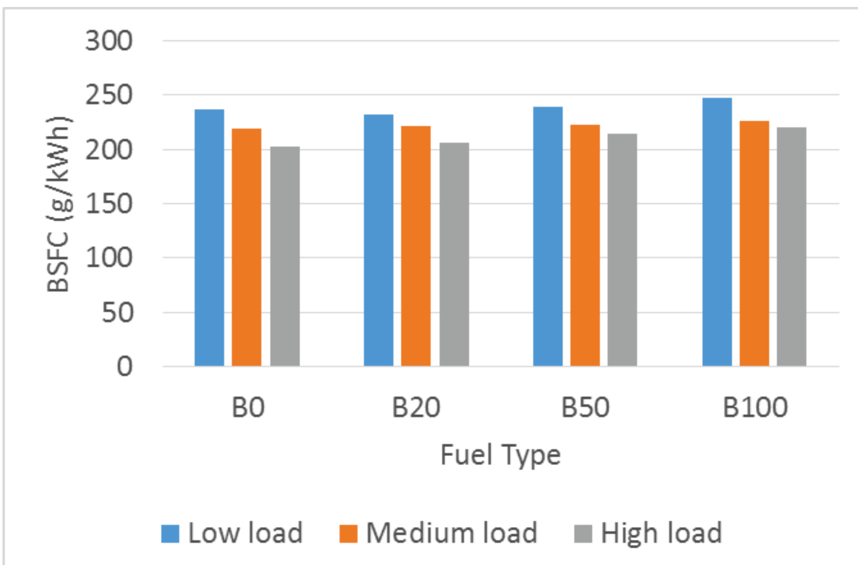

Figure 4.5 BSFC of various fuel blends with 5% steam at various engine loads.

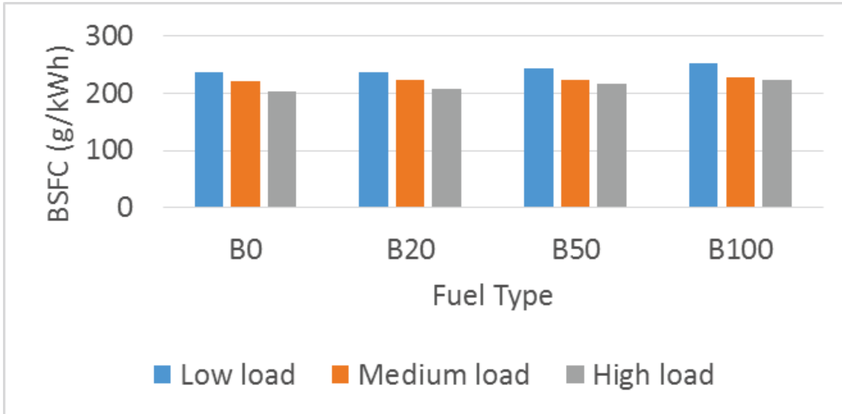

Figure 4.6 BSFC of various fuel blends with 10% steam at various engine loads.

c) Brake Thermal Efficiency

The BTE of 5% and 10% steam into the intake air for various fuel blends at three different loads and 2100 rpm speed are shown in Figure 4.7 and Figure 4.8. It is clear that a higher percentage of steam into the intake air provided lower BTE. The main reason could be the lower burning efficiency. B100 for 5% steam provided 1.2% higher BTE compared to 10% steam at engine conditions of high load and 2100 rpm speed.

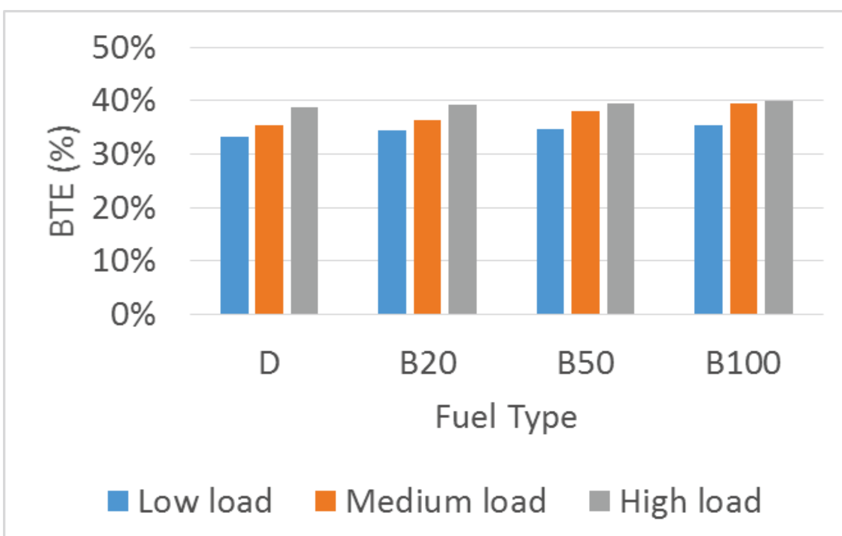

Figure 4.7 Variation of BTE for various fuel blends (5% steam) with engine load at 2100 rpm engine speed.

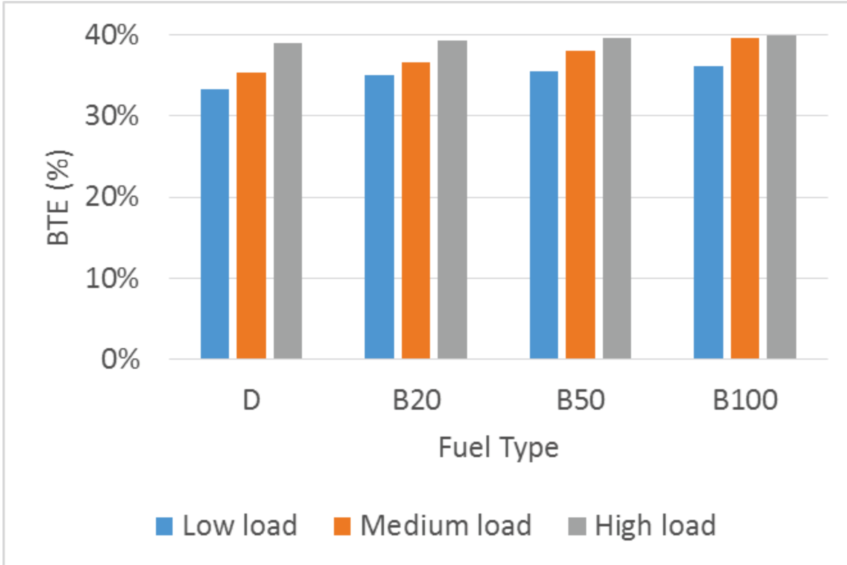

Figure 4.8 Variation of BTE for various fuel blends (10% steam) with engine load at 2100 rpm engine speed.

4.1.4 EGR System with Steam

There are two sets of tests conducted on EGR and steam in this study. The EGR was fixed at half open, while the steam percentage was changed from 5% to 10%. The results shown below are for fuel blends B0, B20, B50 and B100, at three different loads and 2100 rpm speed.

d) Brake-Specific Fuel Consumption:

The BSFC of half open EGR system with 5% and 10% steam into the intake air for various fuel blends are presented in Figure 4.9 and Figure 4.10. The half open EGR with 10% steam represented higher BSFC for all fuels investigated at all engine conditions. B20 of half open EGR and 10% steam provided 2.11% higher BSFC than B20 of half open EGR, and 5% steam at low load and 2100 rpm engine conditions.

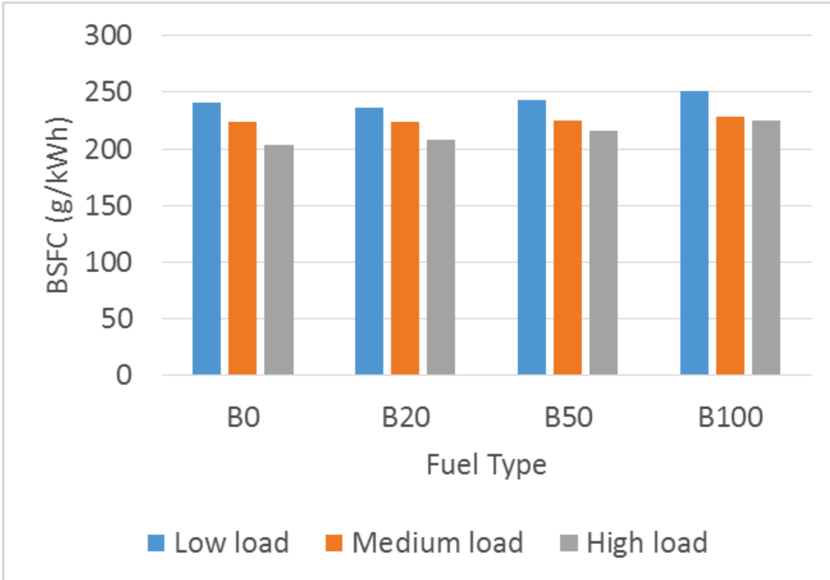

Figure 4.9 BSFC of half open EGR and 5% steam variation with engine load at speed of 2100 rpm.

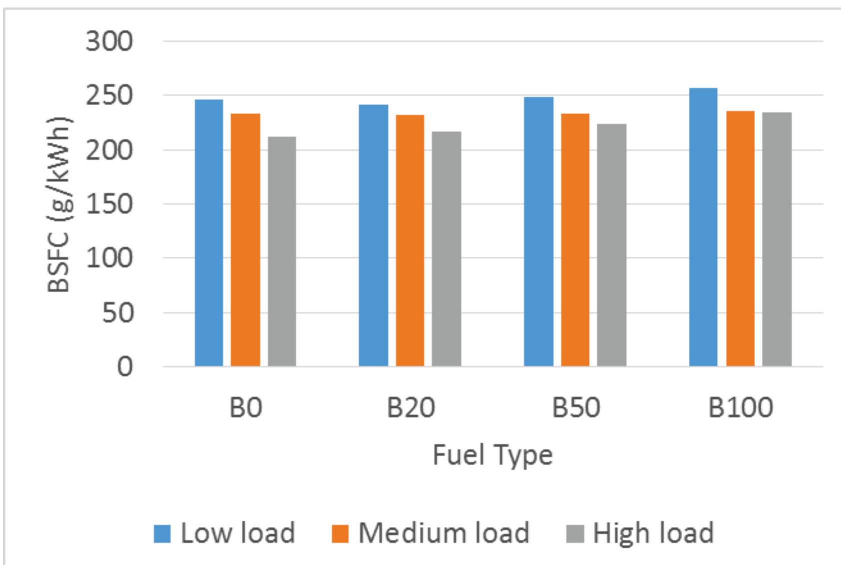

Figure 4.10 BSFC of half open EGR and 10 % steam variation with engine load at speed of 2100 rpm.

e) Brake Thermal Efficiency

The BTE of half open EGR with 5% and 10% steam into intake air for various fuel blends at three different loads and 2100 rpm speed are shown in Figure 4.11 and Figure 4.12. The half open EGR with 10% steam had lower BTE than half open EGR with 5%. B0 for half open EGR and 10% steam presented 1.33% lower BTE than B0 of half open EGR, and 5% steam at low load and 2100 rpm engine conditions.

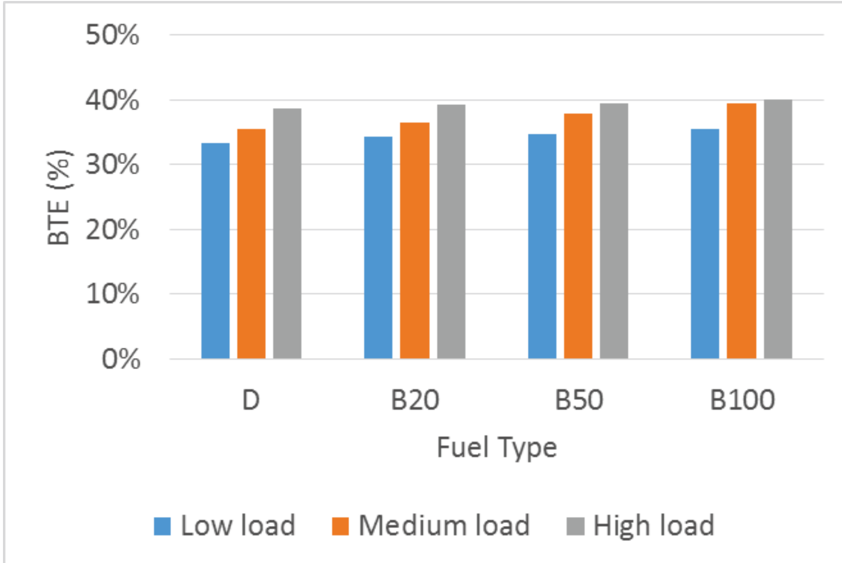

Figure 4.11 BTE of half open and 5% steam for various fuel blends at 2100 rpm engine speed.

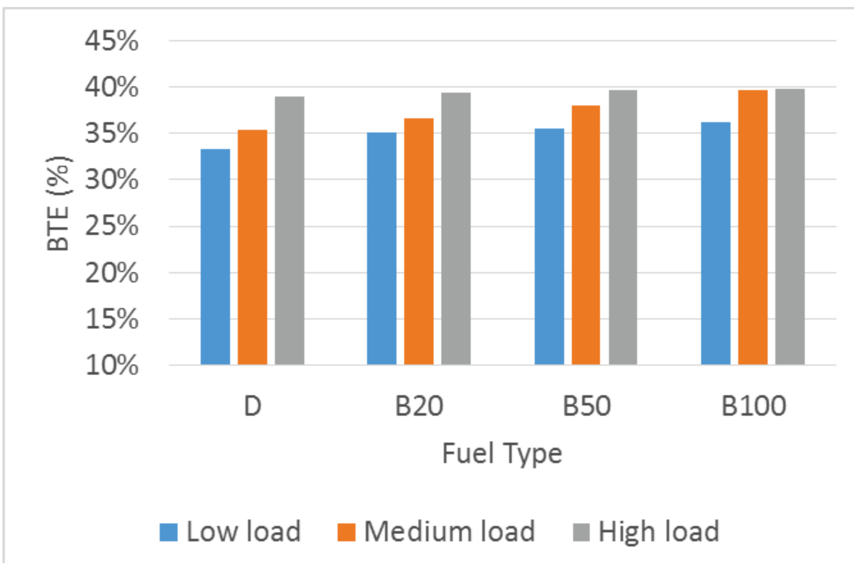

Figure 4.12 BTE of half open and 10% steam for various fuel blends at 2100 rpm engine speed.

4.2 Light-Duty Diesel Engine Emission

We investigated emissions of a diesel engine that ran on both diesel and biodiesel-diesel blends, operating at different operating conditions. For this experiment, the engines were operated at three different speeds: low (1000 rpm); medium (2100 rpm) for maximum torque; and high (3000 rpm) for utmost power. At each speed, we applied three engine loads: low (20%), medium (50%), and high (80%). Because the engine emissions from all fuels investigated demonstrated similar trends with load variation at each engine speed, we targeted the results in our figures at 2100 rpm. (For a complete list of results, refer to the tables in Appendices A, B, C and D). The emission results listed below refer to half open EGR, full open EGR, 5% steam, 10% steam, half open EGR with 5% steam, and half open EGR with 10% steam.

4.3.1 NOx Emissions

For all system setups, NOx emissions decreased with an increased engine load. Consequently, the increase in the amount of biodiesel in the blend attributed to slightly higher NOx emissions due to the high oxygen level in the biodiesel[56] (see Figure 4.13). However, the NOx emission decreased slightly with an increase in engine speed. The shorter ignition delay was due to an increase in both volumetric efficiency and inlet air motion, which enhanced air-fuel mixing at a higher speed; which could be one reason for the reduction in NOx emissions. In addition, for each engine cycle, the reaction time decreased with an increase in engine speed, resulting in a decrease in the residence time of fuel-air mixture within the cylinder at a high temperature; hence lower NOx emission [57], [58].

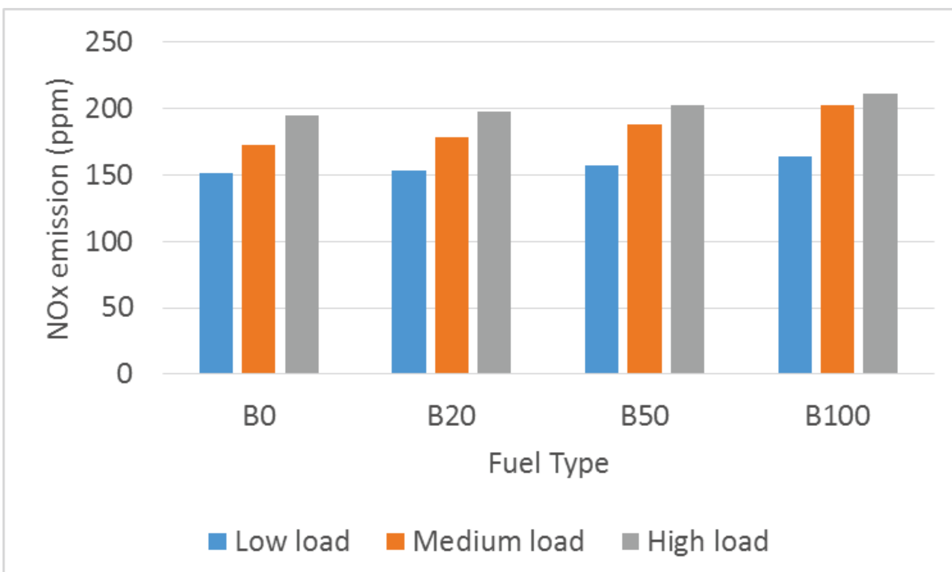

Figure 4.13 NOx emission variation with engine load for various fuel blends at 2100 rpm engine speed.

Figure 4.14 shows NOx emission variation with engine load of biodiesel-diesel blends for half open EGR at 2100 rpm engine speed. It is clear that half open EGR represented lower NOx emissions than without EGR, caused by a lower amount of oxygen inside the cylinder, which was replaced by exhaust gases returned into the combustion chamber; hence lower combustion temperature and lower NOx emission. B100 of half open EGR represented 13.15% lower NOx emission than B100 without EGR at low engine load. Similarly, full open EGR resulted in a further NOx emission reduction compared to half open EGR and full open EGR (see Figure 4.15). At medium engine load, B50 of full open EGR showed a 13.5% reduction in NOx emissions than half open ERG, and 21% lower than that without EGR.

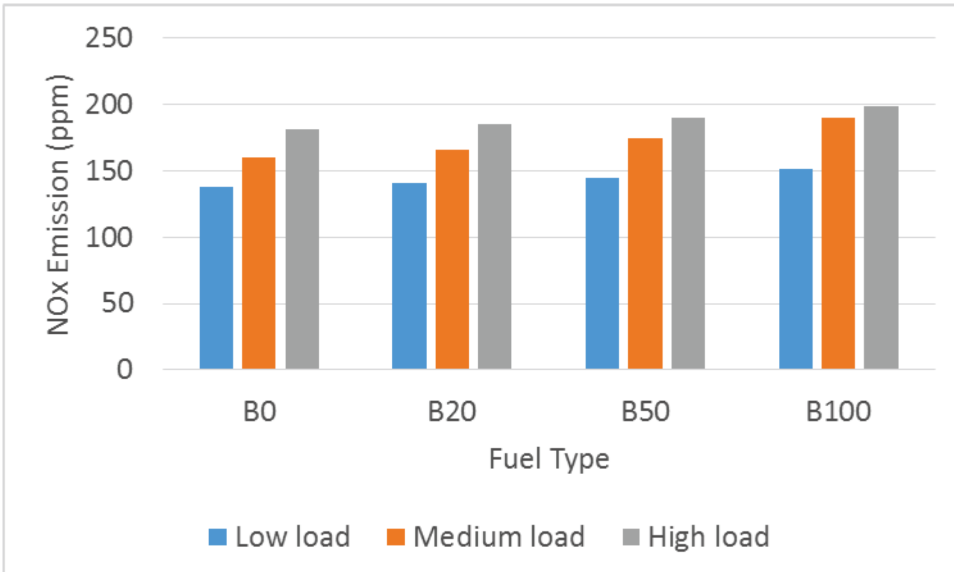

Figure 4.14 NOx emission variation with engine load of various fuel blends for half open EGR at 2100 rpm engine speed.

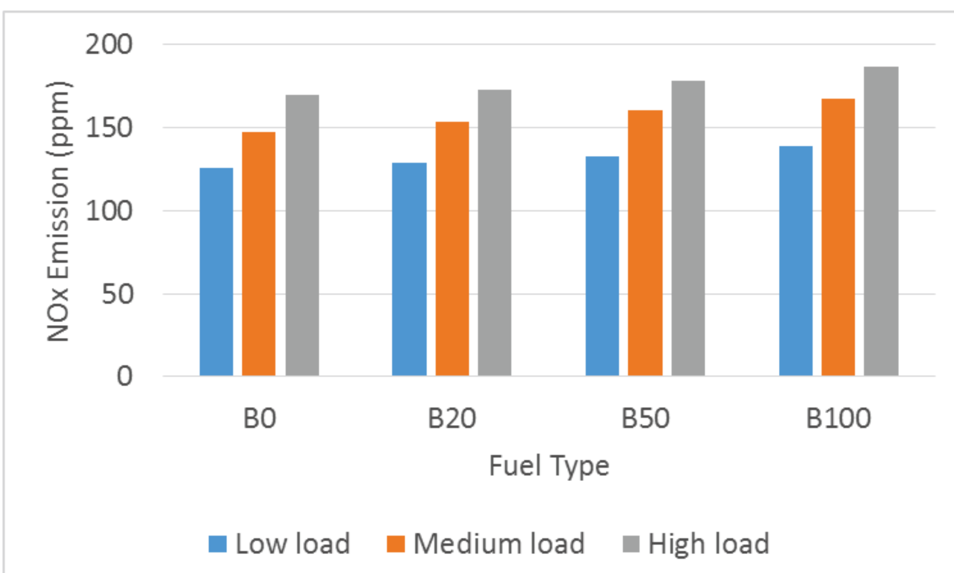

Figure 4.15 NOx emission variation with engine load of various fuel blends for full open EGR at 2100 rpm engine speed.

Steam into intake the air reduces combustion temperature, hence it lowers NOx emission (see Figure 4.16 and Figure 4.17). Test results with 5% steam into the intake air and half open EGR had similar NOx emissions at all engine condition. For example, NOx emission for B100 of 5% steam was 0.2589 g/kWh, whereas it was 0.2535 g/kWh for half open EGR at engine conditions of high load and 2100 rpm speed. 10% steam into the intake air presented lower NOx emissions than half open EGR, however it was still slightly higher than that of full open EGR at all engine conditions investigated. B20 with 10% steam into the intake air had lower NOx emission by approximately 7% than B20 of half open EGR at engine conditions of low load and 2100 rpm speed.

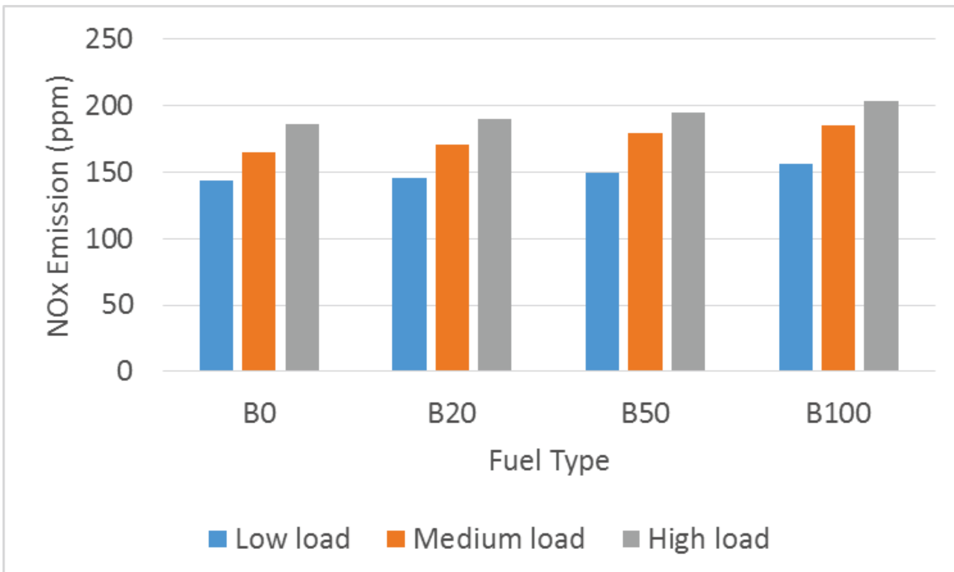

Figure 4.16 NOx emission variation with engine load of various fuel blends for 5% steam at 2100 rpm engine speed.

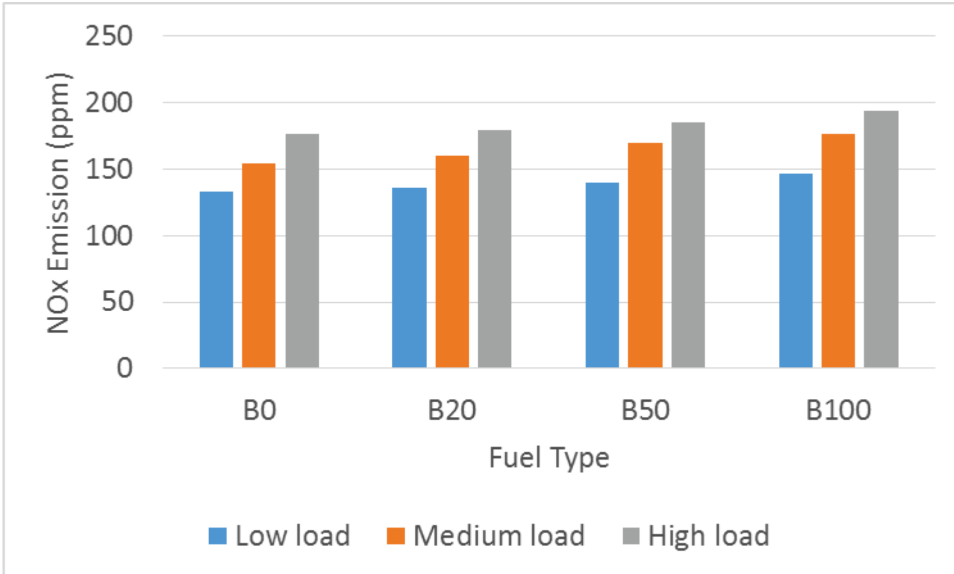

Figure 4.17 NOx emission variation with engine load of various fuel blends for 10% steam at 2100 rpm engine speed.

Combining EGR with steam provided a significant NOx emission reduction, with half open EGR with 10% steam producing the best results (refer to Figure 4.18 and Figure 4.19). B100 with 10% steam and half open EGR showed a NOx emission reduction of 28.93%, 22.42%, 10.97%, 20.7%, and 4.721% than without EGR, 5% steam, 10% steam, half open EGR and full open EGR, respectively, at engine conditions of high load and 2100 rpm speed.

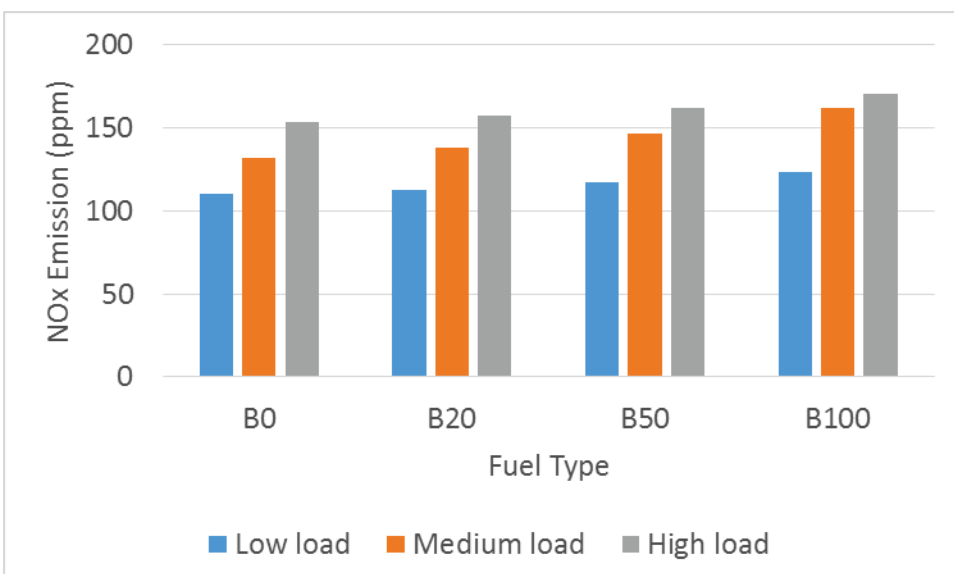

Figure 4.18 NOx emission variation with engine load of various fuel blends for 5% steam and half open EGR at 2100 rpm engine speed.

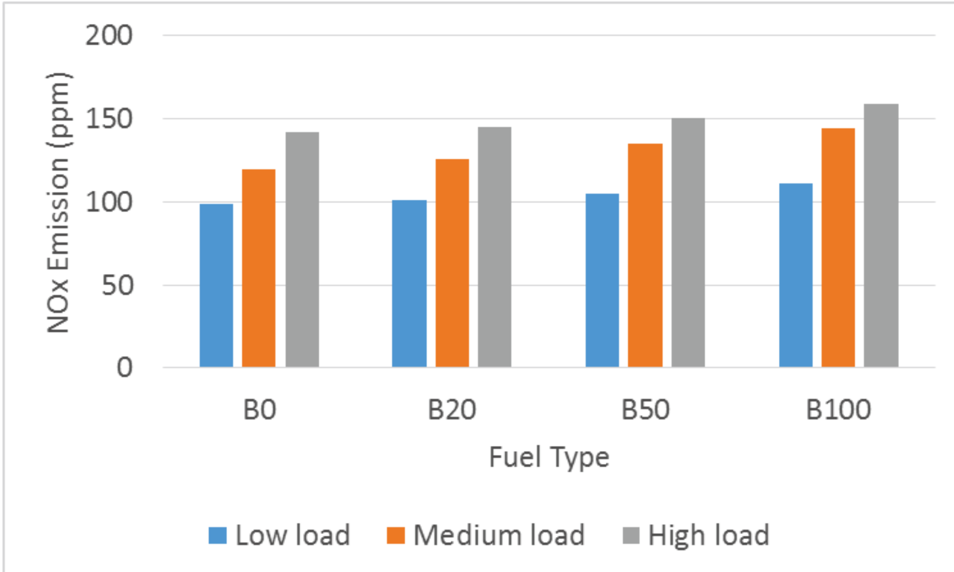

Figure 4.19 NOx emission variation with engine load of various fuel blends for 10% steam and half open EGR at 2100 rpm engine speed.

4.3.2 Smoke Opacity Emission

Soot content in the exhaust gas is indicated by the smoke opacity, therefore this parameter can be correlated with the fuels' tendency to form soot during combustion [59]. Diesel particulates are essentially combustion-generated carbonaceous material (soot) where some organic compounds remain absorbed and grow via the gas-to-particle conversion process [60], [61]. They are formed mainly due to incomplete combustion of hydrocarbon fuel; the composition of smoke generally depends on engine operating conditions and different fuel properties. Smoke opacity increased when increasing the biodiesel content in the fuel blends due to the higher viscosity of the fuels; it also increased with an increase in engine load (Figure 4.20). This may have increased the injection pressure, causing over-penetration of the fuel, which may have resulted in wall-quenching.

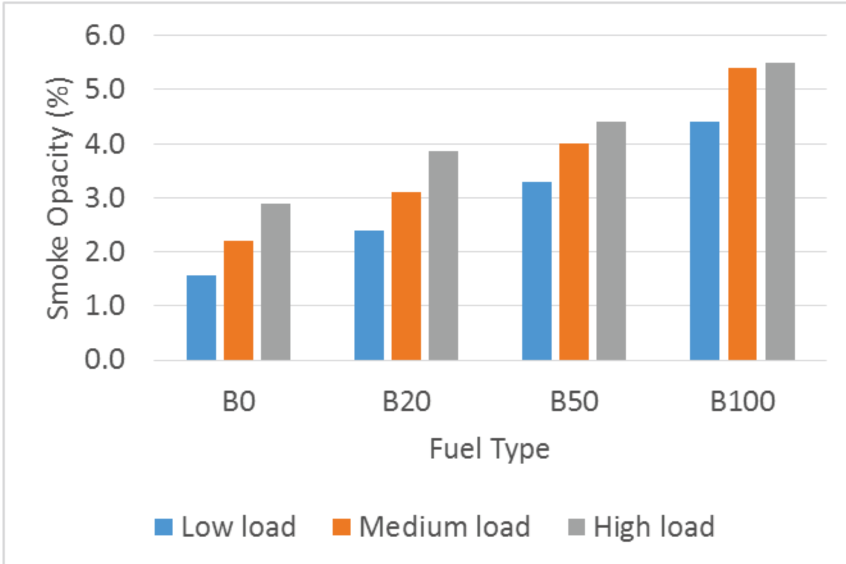

Figure 4.20 Smoke emission variation with engine load for various fuel blends at engine speed of 2100 rpm.

It can be clearly seen from Figure 4.21 and Figure 4.22 that smoke emission increased when the EGR was connected, and full open EGR represented an insignificant increase compared to half open EGR and without EGR results. Increasing the EGR rates decreased the oxygen concentration and increased the local equivalence ratio, causing incomplete combustion and promoting soot formation [62], [63]. The smoke opacity increment of B0 full open EGR was 36.9% higher than that obtained from B0 without EGR at high load and 2100 rpm engine speed.

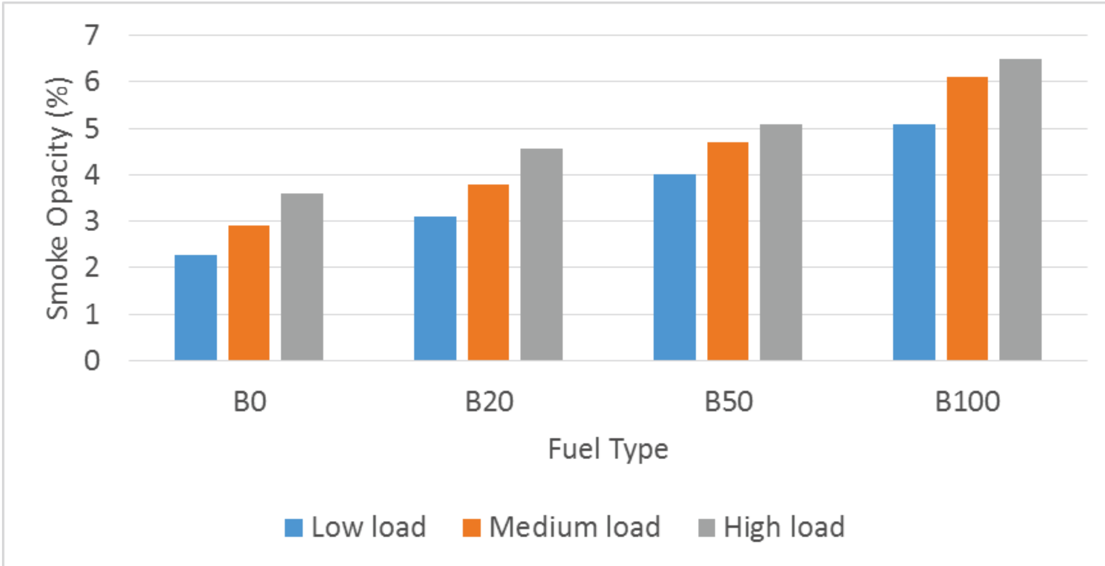

Figure 4.21 Smoke opacity emission variation with engine load of various fuel blends for half open EGR at 2100 rpm engine speed.

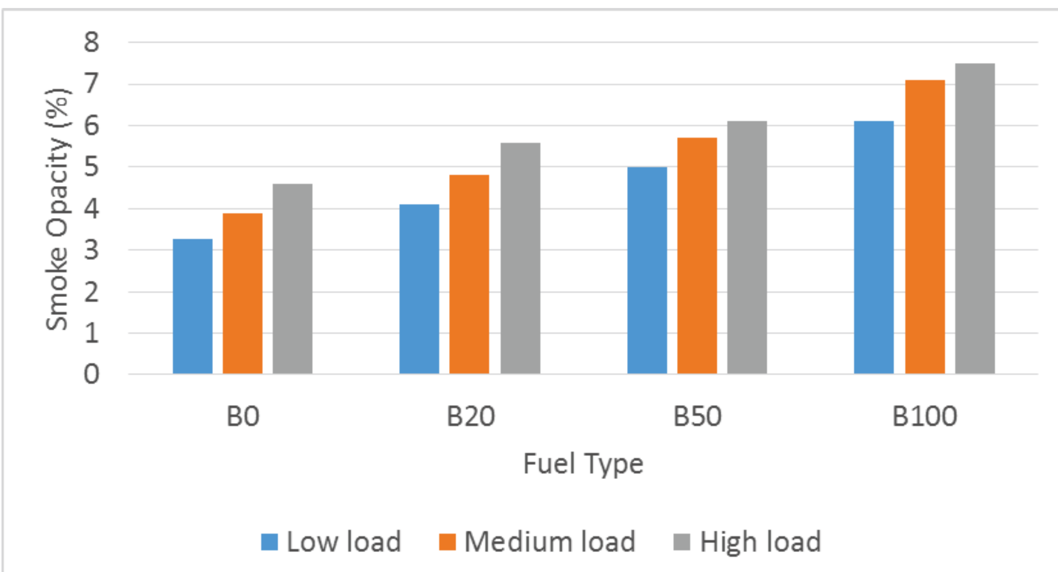

Figure 4.22 Smoke opacity emission variation with engine load of various fuel blends for full open EGR at 2100 rpm engine speed.

Similarly, the injection of steam into the intake air system increased the smoke opacity for the same reason (Figure 4.23 and Figure 4.24) [64]. The most significant increase in smoke opacity was formed when the engine was running in half open EGR with 10% steam. The smoke opacity of B100 at half open EGR and 10% steam was approximately 25% higher than B100 of 5% steam at medium load and 2100 rpm engine speed.

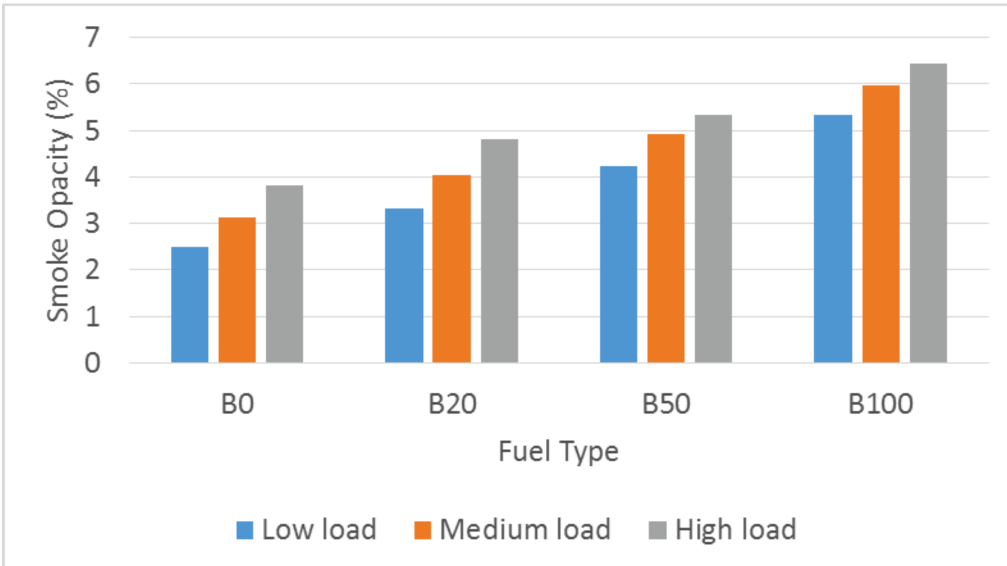

Figure 4.23 Smoke opacity emission variation with engine load of various fuel blends for 5% steam at 2100 rpm engine speed.

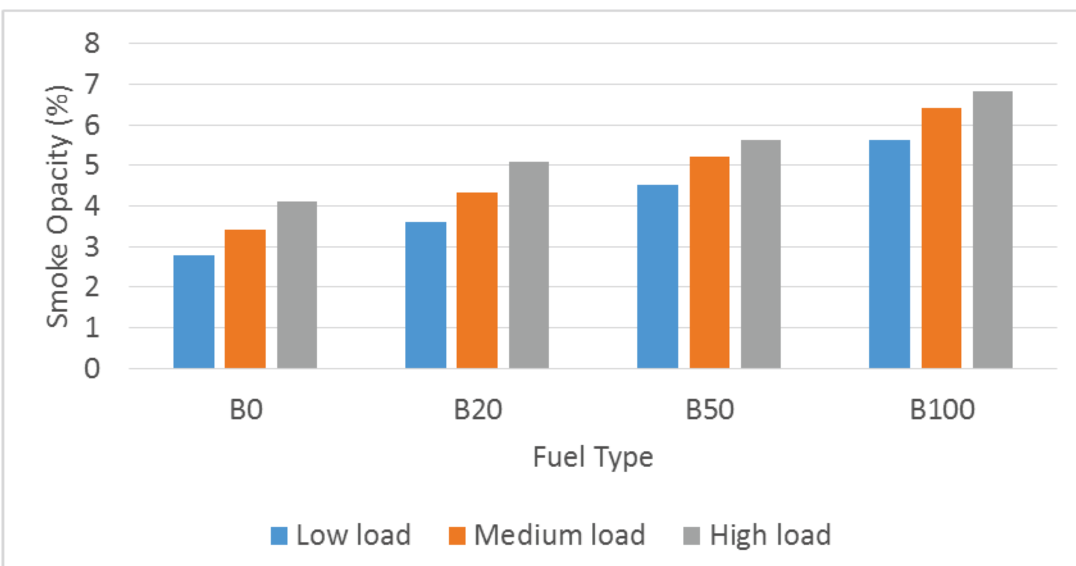

Figure 4.24 Smoke opacity emission variation with engine load of various fuel blends for 10% steam at 2100 rpm engine speed.

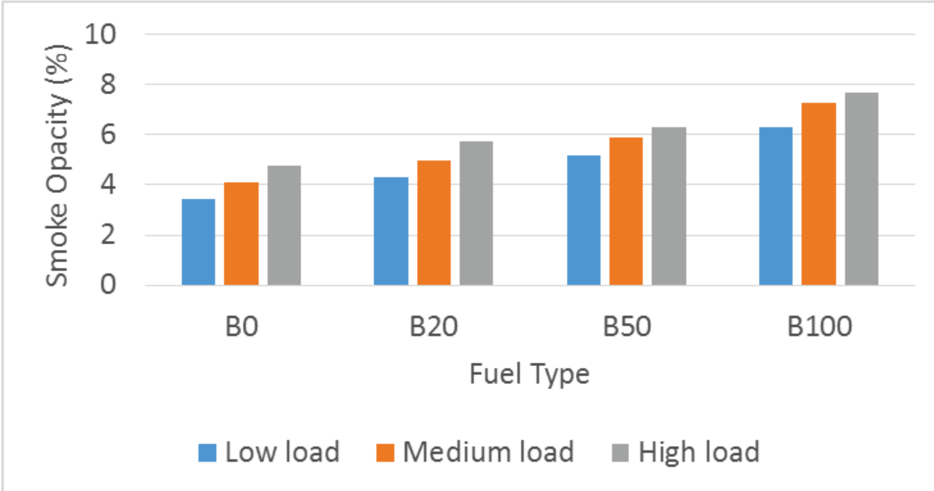

Figure 4.25 Smoke opacity emission variation with engine load of various fuel blends for half open EGR and 10% steam at 2100 rpm engine speed.

4.3.3 CO Emission

CO emission is one component of incomplete combustion. Many factors affect CO emissions such as engine speed, engine load, and fuel type. Increased engine load and speed results in decreased CO emissions due to the fact that combustion temperature increases with an increase in both engine load and speed, leading to oxygenated CO, thus forming CO_2 emissions [65]. Biodiesel has proven to have lower CO emission than conventional diesel, as can be seen in Figure 4.26.

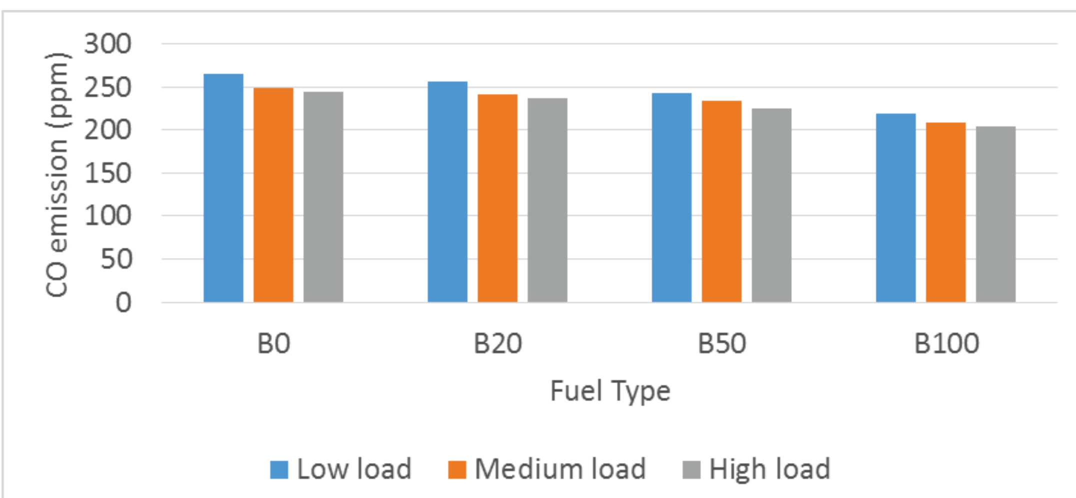

Figure 4.26 CO emission variation with engine load of various biodiesel-diesel blends at 2100 rpm engine speed.

The introduction of EGR prevents CO oxidation due to lower oxygen concentration inside the cylinder. As a result, CO emissions increased slightly by increasing the EGR rates, as seen in Figure 4.27 and Figure 4.28. Similar increases were reported involving EGR with alcohol diesel blends [61].

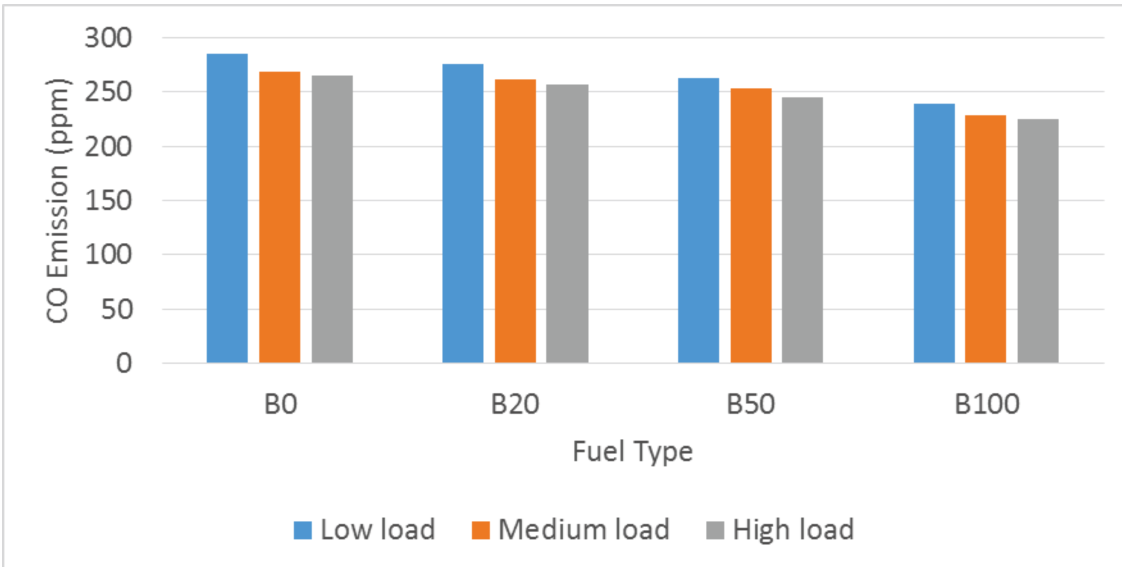

Figure 4.27 CO emission with engine load for half open EGR of various fuel blends at 2100 rpm engine speed.

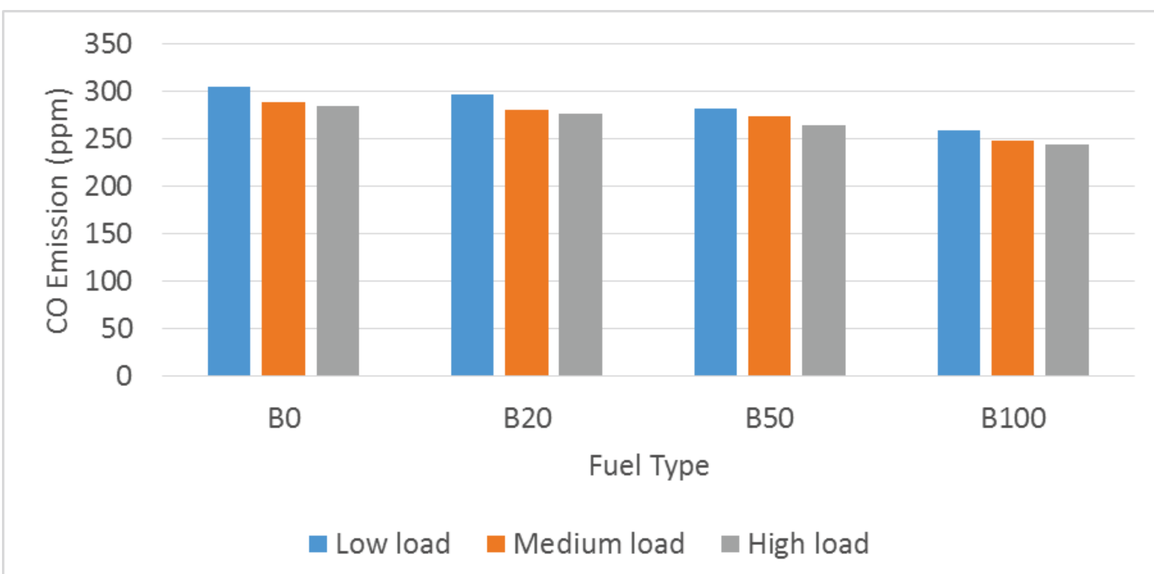

Figure 4.28 CO emission with engine load for full open EGR of various fuel blends at 2100 rpm engine speed.

Similarly, introducing steam into the intake air decreased the in-cylinder temperature due to its high latent heat of vaporization and reduction of the oxygen concentration inside the cylinder, thus preventing CO oxidation; hence, higher CO emission [66] (see Figure 4.29 and Figure 4.30).

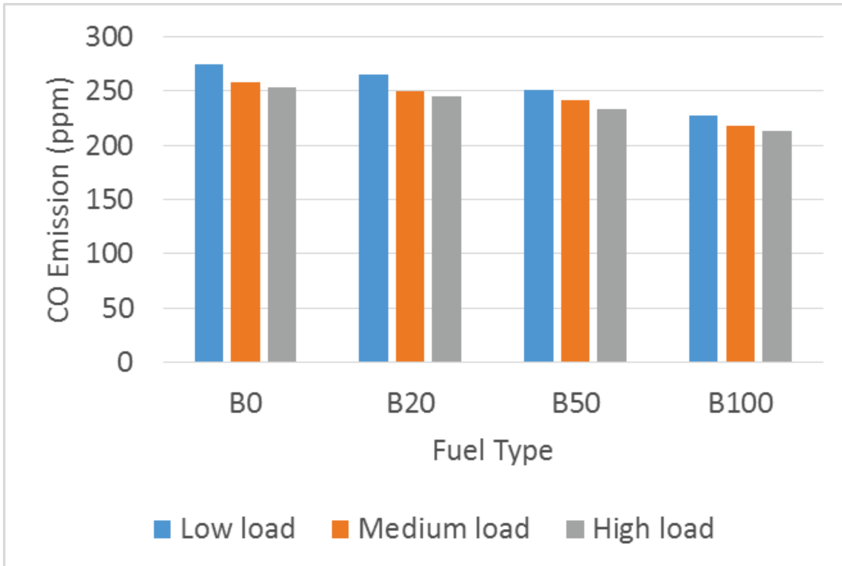

Figure 4.29 CO emission with engine load for 5% steam of various fuel blends at 2100 rpm engine speed.

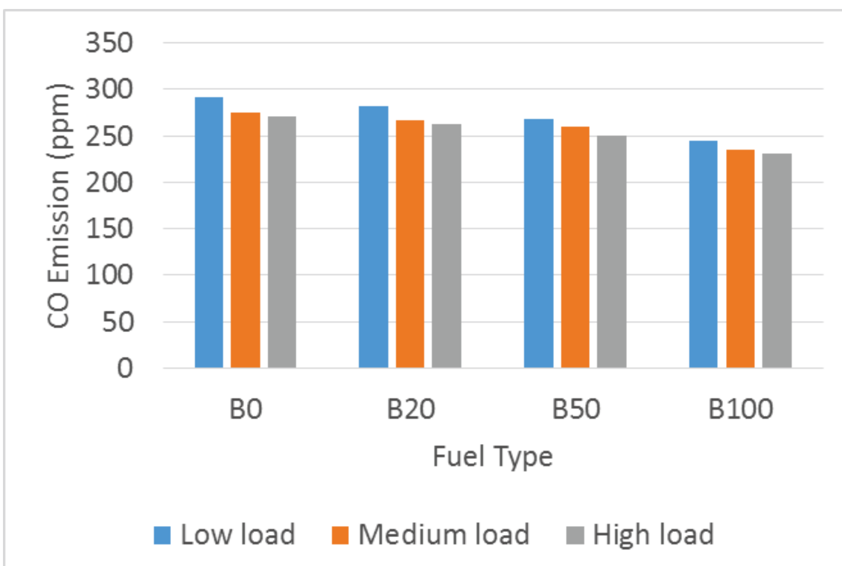

Figure 4.30 CO emission with engine load for 10% steam of various fuel blends at 2100 rpm engine speed.

Combining the EGR with steam resulted in further CO emission increment since they are both the main reasons for decreasing combustion temperature, leading to incomplete combustion, as seen in Figure 4.31 and Figure 4.32. B0 of half open EGR and 10% steam represented higher CO emission among all systems tested.

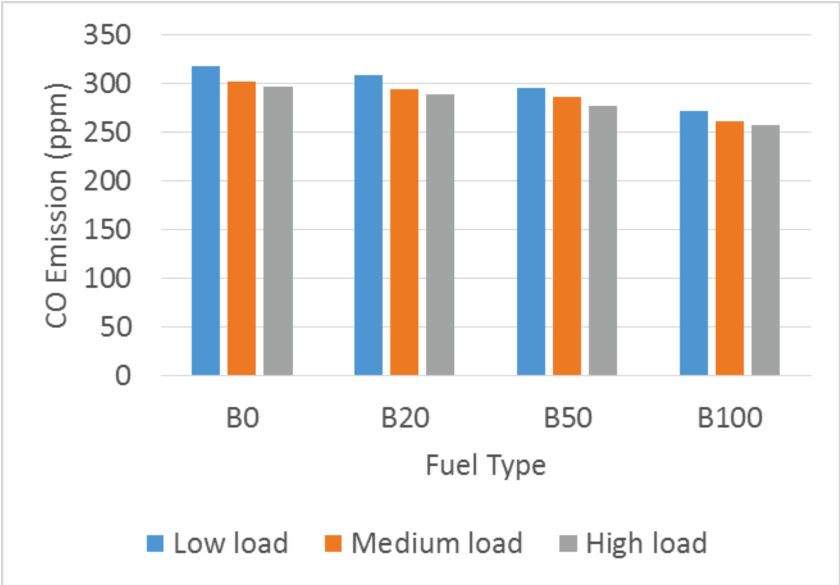

Figure 4.31 CO emission with engine load for half open EGR and 5% steam of various fuel blends at 2100 rpm engine speed.

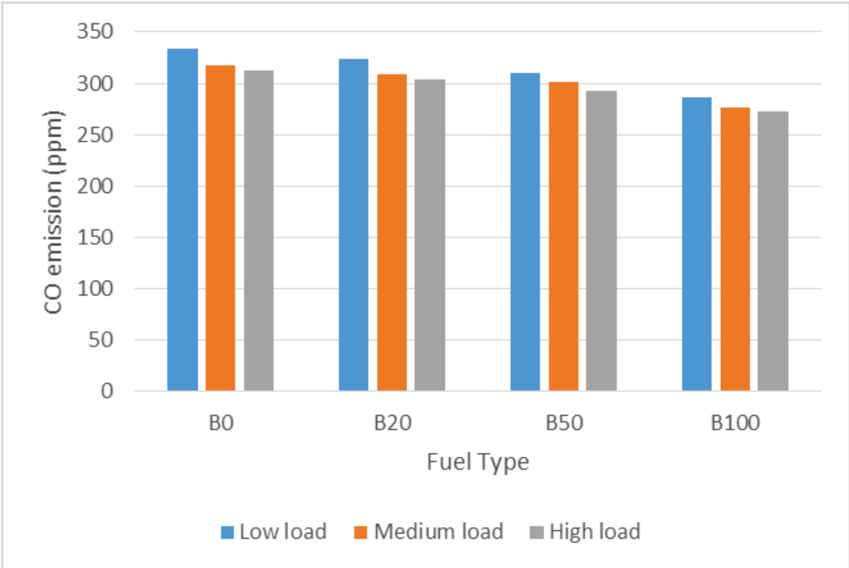

Figure 4.32 CO emission with engine load for half open EGR and 10% steam of various fuel blends at 2100 rpm engine speed.

4.3.4 HC Emission

The main causes of HC emission [67] include low temperature bulk quenching of oxidation reactions, locally over-lean or over-rich mixture, liquid wall films for excessive spray impingement, and incomplete fuel combustion. HC emissions were found to decrease with increased engine load and speed, due to an increase in the combustion temperature, as shown in Figure 4.33. The oxygen content in biodiesel enhanced combustion quality, thus producing lower HC emission. Therefore, HC emission was reduced by increasing the biodiesel content in the blend. B100 exposed the highest HC reduction among all biodiesel-diesel blends with 150 ppm at low load and medium speed engine conditions.

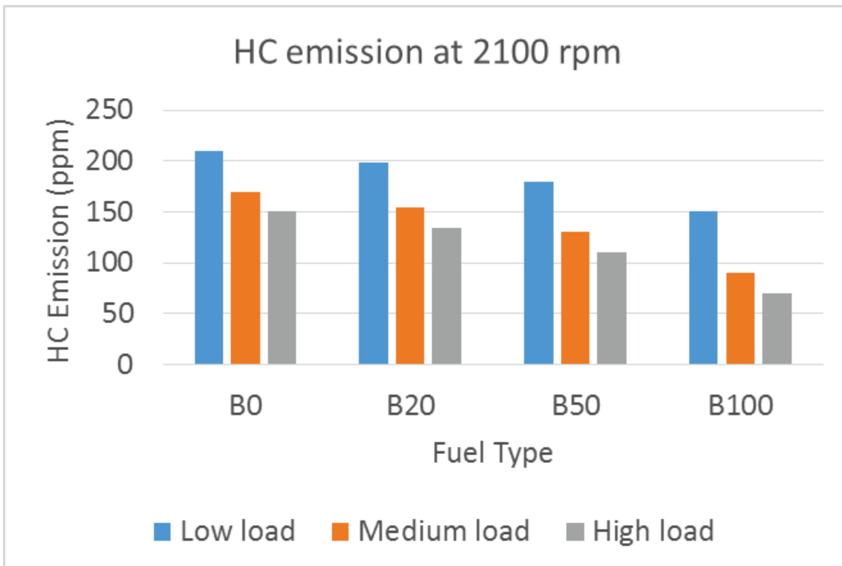

Figure 4.33 HC emission variation with engine load at constant engine speed of 2100 rpm.

Increasing both EGR and steam rates led to a reduced combustion temperature, causing incomplete combustion, and subsequently, higher HC emissions. The significant HC emission increase was noticed when the engine ran with half open EGR and 10% steam. B100 of half open EGR with 10% steam represented 37.5% higher HC emissions than that obtained when the engine ran without steam and EGR under low load and 2100 rpm engine speed conditions (see Figure 4.34).

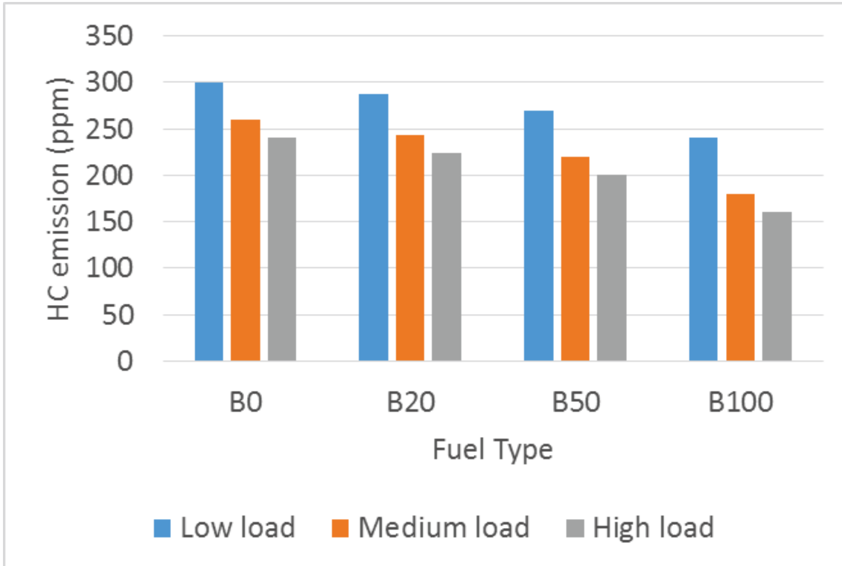

Figure 4.34 HC emission with engine load for half open EGR and 10% steam of various fuel blends at 2100 rpm engine speed.

4.3 Heavy-Duty Diesel Engine Results

4.4.1 Fuel Consumption

Figure 4.35 shows fuel consumption for diesel, biodiesel, and B40 with various additives. Fuel consumption increased when increasing the engine speed, as would be expected. B100 had higher fuel consumption by 4.86% at 1000 rpm engine speed compared to neat diesel, which could be due to the lower heat content of biodiesel, as well as higher density. All additives to B40 resulted in higher fuel consumption compared to B40, and EB40W15 had the highest fuel consumption. With respect to EB40DEEW15, all fuels with lower heat content had higher fuel consumption. Although EB40DEEW15 had lower HHV, it showed an average of 1.2% lower fuel consumption compared to EB40W15 at the two idling conditions, which could be for two reasons. Firstly, DEE has very high CN, which improves the total CN of the blend; hence lower ignition delay period and lower fuel consumption. The second reason could be because EB40DEEW15 had lower density compared to EB40W15, leading to less kg burned for the same volume.

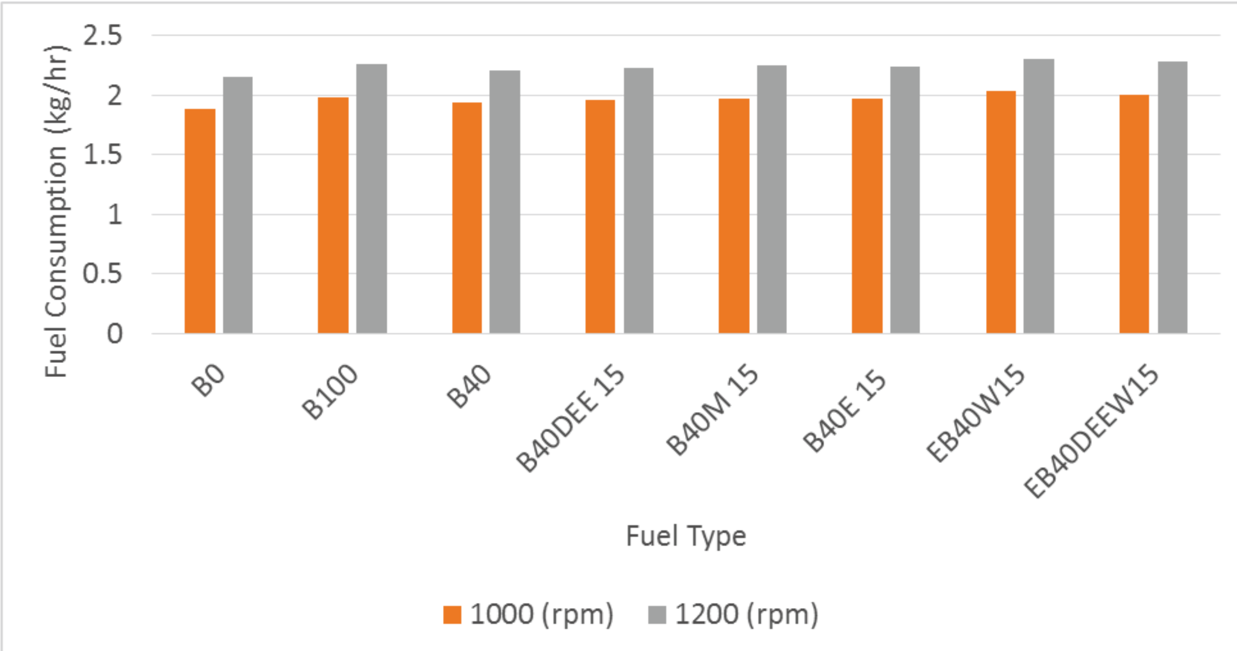

Figure 4.35 Fuel consumption for biodiesel and diesel with various additives at two different engine speeds.

4.4.2 Exhaust Gas Temperature

The engine design and fuel properties are two factors that affect the temperature of exhaust gases of a diesel engine. Generally, higher oxygen content in fuel results in higher EGT, whereas higher latent heat of vaporization has the opposite effect. Figure 4.36 depicts the EGT of a diesel engine running at 1000 and 1200 rpm with no load condition, obtained from various fuels. Among all fuels, B100 resulted in higher EGT at both engine speeds investigated. This noted increase in EGT is mainly due to the higher oxygen content and near similar latent heat of diesel vaporization. Methanol and ethanol are oxygenated additives; however, they showed lower EGT compared to B0, B40 and B100. B40E15 and B40M15 provided lower EGT by 6.75% and 8.55% compared to B40 at 1200 rpm engine speed. The lower CN and higher latent heat of vaporization of those additives are the main reason of this decrease [68], and B40DEE15 had a slight increase in EGT, where the DEE was a CN improver. Because fuel with a lower CN increases ignition delay, more fuel accumulated in the combustion chamber [69]. EB40W15 had the lowest EGT among all fuels investigated. Compared to B40, the EGT reduction was by 13.5% at low speed and 12.97% at high speed. At the onset of combustion, the amount of water in the emulsion absorbed the combustion heat and led to a drop in peak flame temperature[49].

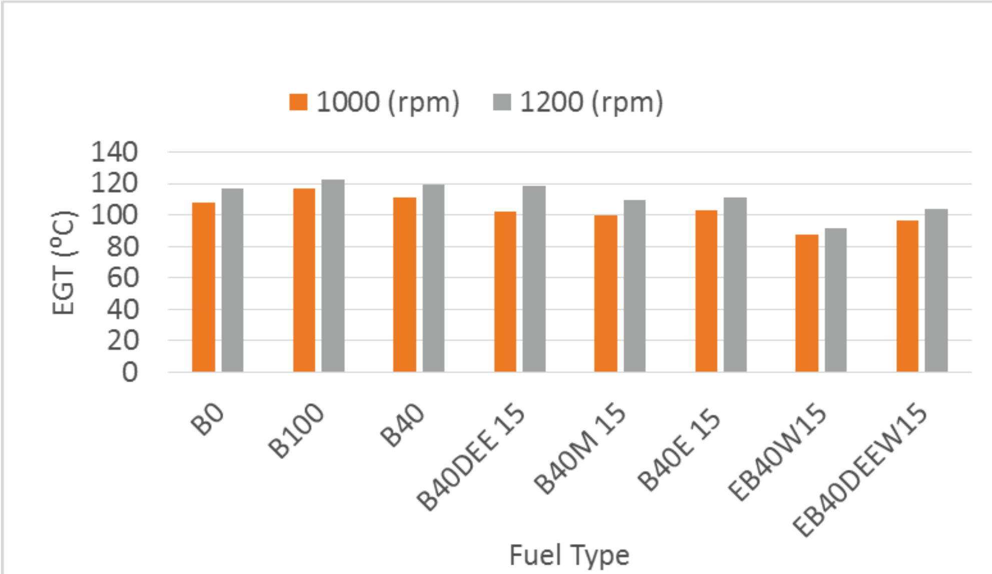

Figure 4.36 Average EGT of various fuel blends at two different engine speeds.

4.4.3 Emissions

a) NOx Emission

NOx formation depends on several parameters such as engine temperature, ignition delay, and fuel properties [70]. The variation in NOx emissions as a function of engine speed for all fuel types is represented in Figure 4.37. It was observed that NOx emissions increased by increasing the speed from 1000 rpm to 1200 rpm; the increase for B0 was 8.67%. Among all fuel types, B100 had the highest NOx emissions. Compared to B0, NOx emission was approximately 6% and 9% higher at 1000 rpm and 1200 rpm, respectively. This is due to the high level of oxygen that is present in biodiesel molecules, which improved the engine's combustion temperature [71], [72]. NOx emission of B40DEE15 was slightly lower than B40 by 3.14% at 1000 rpm. The higher CN in DEE, lowering the ignition delay period, helped reduced NOx emissions [73], [74]. Methanol and ethanol additives into B40 represented lower NOx emissions than the base fuel at the two engine speeds, as shown in Figure 4.37. This was obtained due to that the high evaporation enthalpy of methanol and ethanol, which reduced the combustion temperature; hence lower NOx formation [75]. There was a significant reduction of NOx emissions when the engine was operated with EB40W15. At 1000 rpm, NOx emissions were 8.8%, 12.04% and 14.2% lower for EB40W15 than B0, B40 and B100, respectively. The amount of water in the emulsified fuel is responsible for decreasing the peak flame temperature, which led to lower NOx emissions of EB40W15 [49]. The maximum NOx emission was observed at 1200 rpm (184 NO and 33 NO_2 for EB40DEEW15; and 236 NO and 40 NO_2 for B100). Additionally, EB40DEEW15 provided a slightly higher decrease (1.38%) in NOx emissions than EB40DEEW15 at 1000 rpm. The main reason of this reduction is that water has zero CN. By adding DEE, which has a CN of above 125, it enhanced the emulsion fuel's CN, leading to shorter ignition delay period.

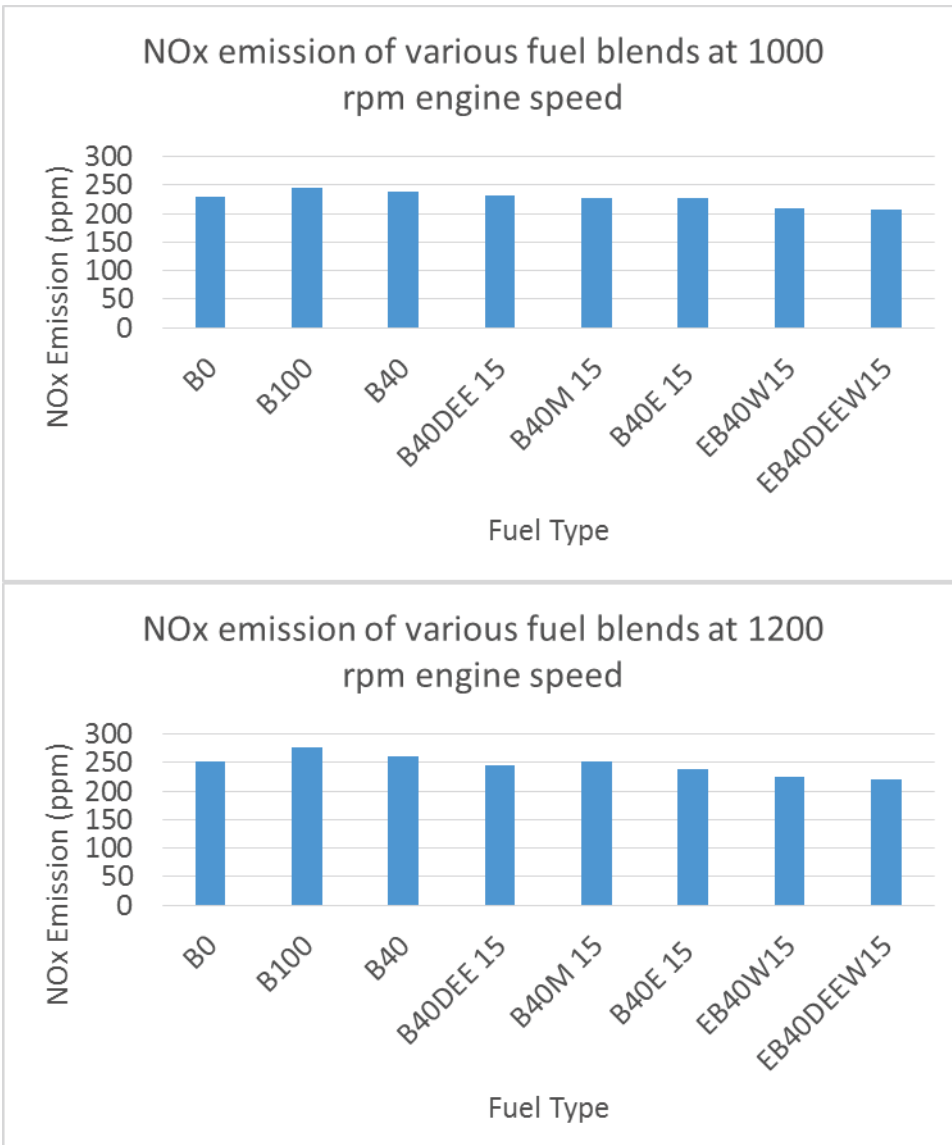

Figure 4.37 Average NOx emission variation with engine speed for different fuel blends.

b) CO and HC Emissions

Generally speaking, the incomplete combustion of fuel and insufficient presence of oxygen (lower combustion temperature) are the main reasons for producing CO and HC emissions. As a matter of fact, B100 had lower CO emissions compared to neat diesel at both engine operating conditions (refer to Figure 4.38). This reduction was observed to be 20.74% lower than that obtained from B0 at 1000 rpm. Another observation noticed was that an increase in engine speed decreased CO emissions, which could be due to the fact that the combustion temperature increased (as presented in Figure 4.36), attributing to oxygenated CO, thus forming CO_2 emissions. Figure 4.38 also depicts CO emission variation with speeds for several additives to B40. B40M50 and B40E15 had higher CO emissions than the base fuel. At 1200 rpm, CO emissions for B40M15 and B40E15 were 7.85% and 6.33% higher than B40, respectively. Even though methanol and ethanol are oxygenated additives, the low CN and high evaporation enthalpy of methanol and ethanol are responsible for the poor oxidation reaction rate of CO, leading to incomplete combustion; hence forming additional CO. Blending DEE with B40 provided 7.1% and 9.1% lower CO than B40 at 1000 and 1200 rpm, respectively. DEE has low latent heat of vaporization and very high CN, as well as high oxygen content, leading to acceleration of the reaction rate of CO to form additional CO_2. We observed the highest CO emission from EB40W15 among all fuels investigated, i.e., 17.15% higher than B40 at 1200 rpm. The very high latent heat of vaporization, as well as its low CN, are the main factors responsible for this increase. However, adding DEE to the emulsion improved the fuel. As a result, EB40DEEW15 had lower CO emissions by 11.557% and 5.29% than EB40W15 and B40M15, respectively, at an engine speed of 1000 rpm.

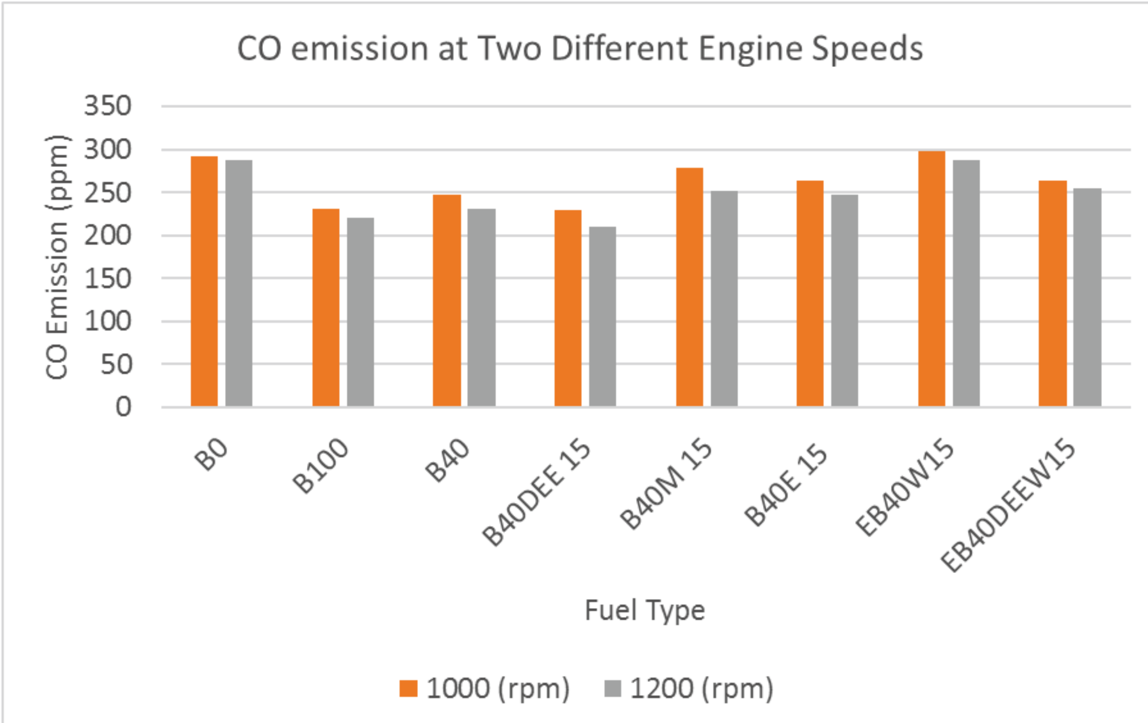

Figure 4.38 Average CO emission variation with engine speed for different fuel blends.

HC emission variation as a function of engine speed for different fuel blends is outlined in Figure 4.39. Generally, incomplete combustion is caused by very rich or very poor air-fuel ratio, flame quenching around the cylinder in cold regions, and heat loss; these are the main reasons of HC emission [76]. The oxygenated additives (methanol, ethanol and diethyl ether) attributed to higher HC emission due to excessive oxygen to complete the combustion [77], [78]. Therefore, B40M15, B40E15 and B40DEE15 had slightly higher HC emissions than B40 at the two idling conditions. EB40DEEW15 produced higher HC emissions among all fuels investigated at two idling conditions (12.963% higher than B100 at 1200 rpm). The reason for this increase could be attributed to the presence of water in the emulsion, leading to a long ignition delay period. Consequently, adding DEE to the emulsion enhanced its CN, for which a shorter ignition delay was obtained, thus leading to lower HC emissions, which was observed from EB40DEEW15. The HC emission of EB40DEEW15 was 3.7% less than that obtained from EB40W15, but it still had higher HC emissions than the other fuels investigated.

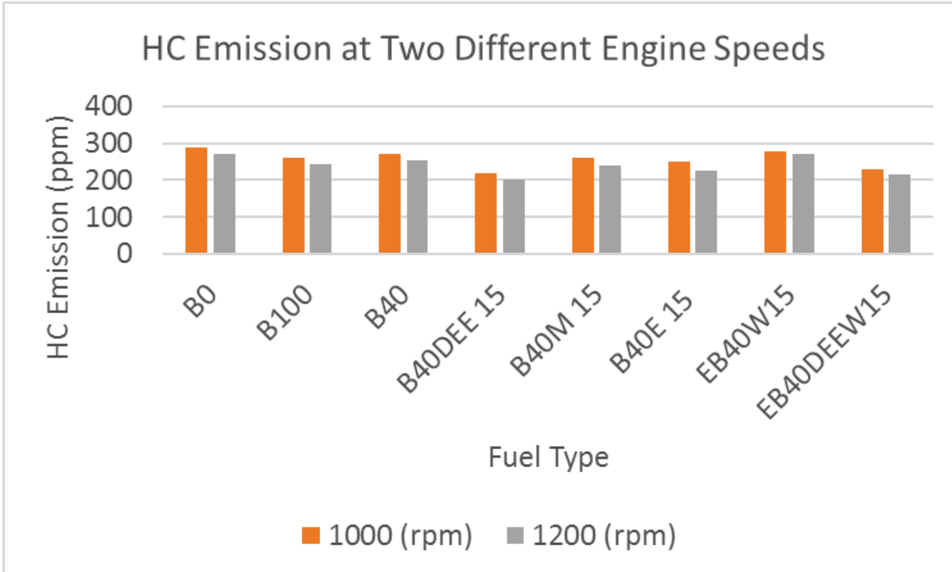

Figure 4.39 Average HC emission variation with engine speed for different fuel blends.

c) Smoke Opacity

Figure 4.40 shows smoke opacity variation with engine speed for different fuel blends. The optical properties of fuel smoke is measured by smoke opacity. The levels of viscosity and oxygen in the fuel are the main factors affecting smoke opacity [49], [79]. Smoke opacity of all additives was lower than their fuel bases. B40DEE15, B40E15 and B40M15 produced 19%, 14.28% and 10% lower smoke opacity at 1000 rpm, respectively, which might be due to the fact that additives reduce fuel viscosity and enhance combustion quality. At 1200 rpm, EB40W15 presented 28.57% lower smoke opacity than B40. Significant smoke intensity was obtained from EB40DEEW15 by approximately 38% than from B40. Better fuel mixing and fuel atomization, as well as emulsion micro-explosion, are the main reasons for smoke opacity reduction of emulsified fuel.

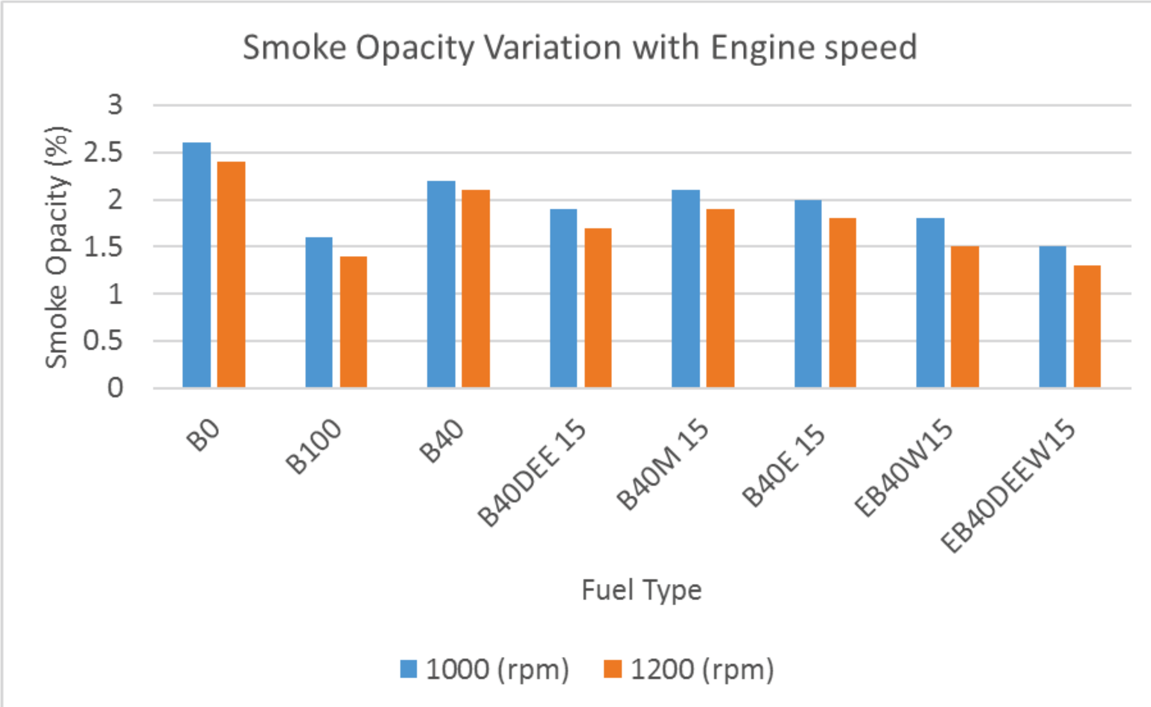

Figure 4.40 Average smoke opacity variation with engine speed for different fuel blends.

Chapter 5
Conclusion

In this study, biodiesel was produced from canola oil using the transesterification method, and was investigated in terms of quality and fuel characteristics. Additionally, a cold EGR system, which was designed for a light-duty diesel engine, produced favourable results. Furthermore, steam was supplied into the light-duty diesel engine's intake air system. The series of fuels investigated on the light-duty engine included B0, B20, B50 and B100. In addition to that experiment, we added ethanol, methanol, DEE and water to B40 to test a heavy-duty diesel engine's emissions, at two idling conditions. The results were compared to B0, B40 and B100, and the conclusions from the experimental studies were drawn as follows: favorable

5.1 Light-Duty Diesel Engine

The BSFC decreased with an increase in engine load and speed, but increased when increasing the amount of biodiesel in the blend. Additionally, the BSFC increased slightly with by increasing both EGR and steam rates, and the half open EGR with 10% steam represented higher BSFC for all fuels investigated, at all engine conditions. The BTE rose with the increased engine load, and an increase in the amount of biodiesel in the blend showed a BTE increase. Introducing EGR and steam into the diesel engine slightly decreased the engine's BTE.

NOx emissions decreased when increasing the engine load. Consequently, the increase in the amount of biodiesel in the blend attributed to slightly higher NOx emissions. The increase in EGR and steam rates led to decreased NOx emissions, with a significantly greater reduction when the engine was equipped with half open EGR and 10% steam. On the other hand, smoke emission increased with an increase in EGR and steam rates.

Increased engine load and speed resulted in a decrease in both of CO and HC emissions. However, they escalated when increasing EGR and steam rates. The half open EGR with 10% steam represented higher HC and CO emissions among all other experiments performed on the light-duty diesel engine.

5.2 Heavy-Duty Diesel Engine

All fuels with additives resulted in higher fuel consumption compared to B0, B40 and B100. EB40W15 consumed that largest quantity of fuel (6.35%, 4.22% and 1.6% higher than B0, B40 and B100, respectively) at 1200 rpm engine speed. The fuel additives provided lower EGT, with EB40W15 having the lowest EGT by 21.97% compared to B40 at 1000 rpm.

Biodiesel emitted higher NO_x levels than diesel by approximately 6% and 9%, at engine speeds of 1000 rpm and 1200 rpm, respectively. By adding methanol, ethanol, DEE and water, we achieved lower NO_x levels compared to all fuels investigated. The greatest reduction of NO_x was obtained by EB40DEEW15 (20.22% less than B100) at 1200 rpm engine speed. In terms of CO emissions, B40DEE15 had similar results to those obtained from B100 at two idling conditions; both had lower CO emissions than all other fuels investigated. Methanol, ethanol, and water tended to result in higher CO emissions than all other fuels tested, with the greatest CO emission obtained from EB40W15. However, the addition of DEE to the emulsion fuel resulted in a reduction of CO emission that was nearly equivalent to that obtained from B40E15 and B40M15. Among all fuels investigated, B100 provided lower HC emission, while the additives to B40 emitted slightly higher HC than B0, B40 and B100. The highest HC emission was produced by EB40W15, whereas the addition of 15% DEE to this fuel reduced HC emissions to provide results similar to those of B40. The fuel additives resulted in lower smoke opacity emission than their bases, and EB40DEEW15 emitted the lowest smoke compared to all fuels investigated (38% lower than B40) at an engine speed of 1200 rpm.

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Appendices

Appendix A: Biodiesel diesel blends performance and emission tested by light-duty diesel engine.

Table A.1 Engine performance and emissions of biodiesel diesel blends at all engine operating conditions

Load	Low load						Medium load						High load					
Fuel	BSFC (g/kWh)	BTE (%)	NOx (g/kWh)	Smoke (%)	CO (ppm)	HC (ppm)	BSFC (g/kWh)	BTE (%)	NOx (g/kWh)	Smoke (%)	CO (ppm)	HC (ppm)	BSFC (g/kWh)	BTE (%)	NOx (g/kWh)	Smoke (%)	CO (ppm)	HC (ppm)
Speed	1000 rpm																	
B0	251.7	0.31	1.54	2.8	351.3	230	219.7	0.36	0.83	4.3	305.0	210	210.2	0.38	0.67	5.8	308.3	190
B20	258.4	0.32	1.58	4.3	335.0	218	224.1	0.36	0.85	8.4	299.0	194	211.4	0.39	0.67	8.9	291.0	174
B50	263.6	0.32	1.61	8.7	317.4	200	225.9	0.38	0.86	10.7	277.8	170	218.3	0.39	0.69	12.6	271.0	150
B100	278.8	0.32	1.70	13.4	271.7	170	233.1	0.38	0.87	16.4	256.0	130	229.9	0.39	0.73	18.5	247.3	110
Speed	2100 rpm																	
B0	236.9	0.33	0.77	1.6	295.3	210	223.0	0.35	0.37	2.2	249.3	170	202.3	0.39	0.26	2.9	252.0	150
B20	232.3	0.35	0.77	2.4	285.9	198	222.1	0.37	0.38	3.1	241.2	154	206.8	0.39	0.27	3.9	245.7	144
B50	239.2	0.36	0.80	3.3	270.7	180	223.2	0.38	0.40	4.0	233.7	130	214.3	0.41	0.27	4.4	236.3	120
B100	247.3	0.36	0.83	4.4	245.1	150	225.9	0.39	0.43	5.4	208.9	90	224.6	0.42	0.28	5.5	220.5	80
speed	3000 rpm																	
B0	227.5	0.35	0.47	0.8	265.7	130	216.2	0.36	0.21	0.9	265.5	110	202.7	0.39	0.14	1.6	252.0	90
B20	231.4	0.35	0.48	1.0	256.4	118	217.9	0.37	0.213	1.4	257.0	98	207.8	0.40	0.15	1.9	245.7	78
B50	233.4	0.36	0.48	1.3	242.6	100	226.2	0.38	0.219	1.8	244.2	80	213.4	0.41	0.152	2.5	236.3	70
B100	240.4	0.37	0.49	2.0	219.3	70	232.6	0.39	0.22	2.4	222.9	65	222.9	0.42	0.16	3.2	220.5	60

Appendix B: Half open EGR results of light duty diesel engine running with diesel biodiesel blends.

Table B.1 Light duty diesel engine with half open EGR performance and emission results of various fuel blends at all engine operating conditions

Load	Low load						Medium load						High load					
Fuel	BSFC (g/kWh)	BTE (%)	NOx (g/kWh)	Smoke (%)	CO (ppm)	HC (ppm)	BSFC (g/kWh)	BTE (%)	NOx (g/kWh)	Smoke (%)	CO (ppm)	HC (ppm)	BSFC (g/kWh)	BTE (%)	NOx (g/kWh)	Smoke (%)	CO (ppm)	HC (ppm)
Speed	1000 rpm																	
B0	251.7	0.313	1.35	3.5	371	240	219.7	0.359	0.84	2.9	325	220	210.2	0.375	0.70	6.5	328	200
B20	258.4	0.315	1.38	5.0	355	228	224.1	0.363	0.85	3.8	319	204	211.4	0.385	0.71	9.6	311	184
B50	263.6	0.322	1.43	9.4	337	210	225.9	0.376	0.85	4.7	298	180	218.3	0.389	0.72	13.3	291	160
B100	278.8	0.321	1.50	13.4	292	180	233.1	0.384	0.87	6.1	276	140	229.9	0.390	0.76	19.2	267	120
Speed	2100 rpm																	
B0	236.9	0.333	0.66	2.3	286	220	202.3	0.353	0.32	2.9	286	180	202.3	0.390	0.23	3.6	272	160
B20	232.3	0.351	0.67	3.1	276	208	206.8	0.367	0.34	3.8	277	164	206.8	0.394	0.24	4.6	266	144
B50	239.2	0.355	0.69	4.0	263	190	214.3	0.381	0.35	4.7	264	140	214.3	0.397	0.24	5.1	256	120
B100	247.3	0.362	0.72	5.1	239	160	224.6	0.397	0.38	6.1	243	100	224.6	0.399	0.25	6.5	241	80
speed	3000 rpm																	
B0	227.5	0.347	1.00	1.5	315	140	202.7	0.365	0.46	1.6	269	120	202.7	0.389	0.33	2.3	265	100
B20	231.4	0.352	1.01	1.7	306	128	207.8	0.374	0.47	2.1	261	108	207.8	0.392	0.34	2.6	257	88
B50	233.4	0.364	1.03	2.0	291	110	213.4	0.376	0.47	2.5	254	90	213.4	0.398	0.34	3.2	245	70
B100	240.4	0.373	1.07	2.7	265	80	222.9	0.385	0.49	3.1	229	60	222.9	0.402	0.36	3.9	225	40

Appendix C: full half EGR results of light duty diesel engine running with diesel biodiesel blends.

Table C.1 Light duty diesel engine with full open EGR performance and emission results of various fuel blends at all engine operating conditions

Load	Low load						Medium load						High load					
Fuel	BSFC (g/kWh)	BTE (%)	NOx (g/kWh)	Smoke (%)	CO (ppm)	HC (ppm)	BSFC (g/kWh)	BTE (%)	NOx (g/kWh)	Smoke (%)	CO (ppm)	HC (ppm)	BSFC (g/kWh)	BTE (%)	NOx (g/kWh)	Smoke (%)	CO (ppm)	HC (ppm)
Speed	1000 rpm																	
B0	256.5	0.307	1.163	4.5	391	260	221.7	0.357	0.755	6.0	345	240	211.3	0.373	0.649	7.5	348	220
B20	259.0	0.314	1.191	6.0	375	248	223.1	0.366	0.761	10.1	339	224	213.2	0.382	0.659	10.6	331	204
B50	266.6	0.319	1.240	10.4	357	230	225.9	0.384	0.768	12.4	318	200	217.1	0.391	0.669	14.3	311	180
B100	278.8	0.321	1.309	15.1	312	200	230.9	0.396	0.779	18.1	296	160	227.2	0.394	0.706	20.2	287	140
Speed	2100 rpm																	
B0	233.6	0.357	0.640	3.3	335	240	220.9	0.357	0.288	3.9	289	200	202.7	0.389	0.196	4.6	292	180
B20	234.4	0.366	0.630	4.1	326	228	222.5	0.366	0.294	4.8	281	184	206.8	0.394	0.200	5.6	286	164
B50	241.4	0.384	0.646	5.0	311	210	222.8	0.384	0.306	5.7	274	160	214.8	0.396	0.203	6.1	276	140
B100	249.6	0.396	0.669	6.1	285	180	226.3	0.386	0.325	7.1	249	120	224.1	0.400	0.211	7.5	261	100
speed	3000 rpm																	
B0	225.9	0.366	0.855	2.5	306	160	215.6	0.366	0.403	2.6	306	140	202.5	0.389	0.296	3.3	285	120
B20	230.6	0.375	0.872	2.7	296	148	217.3	0.375	0.408	3.1	297	128	207.4	0.393	0.300	3.6	277	108
B50	234.2	0.376	0.891	3.0	283	130	225.9	0.376	0.417	3.5	284	110	212.5	0.400	0.306	4.2	265	90
B100	242.0	0.386	0.925	3.7	259	100	232.0	0.391	0.428	4.1	263	80	222.9	0.402	0.318	4.9	245	60

Appendix D: 5% steam results of light duty diesel engine running with diesel biodiesel blends.

Table D.1 Light duty diesel engine performance and emission results of various fuel blends running with 5% steam.

Load	Low load						Medium load						High load					
Fuel	BSFC (g/kWh)	BTE (%)	NOx (g/kWh)	Smoke (%)	CO (ppm)	HC (ppm)	BSFC (g/kWh)	BTE (%)	NOx (g/kWh)	Smoke (%)	CO (ppm)	HC (ppm)	BSFC (g/kWh)	BTE (%)	NOx (g/kWh)	Smoke (%)	CO (ppm)	HC (ppm)
Speed	1000 rpm																	
B0	260	0.300	1.43	3.2	364	240	226	0.351	0.87	4.7	316	220	213	0.370	0.72	6.2	317	200
B20	263	0.306	1.45	4.7	348	228	228	0.361	0.88	8.8	310	204	215	0.379	0.73	9.3	300	184
B50	270	0.311	1.50	9.1	330	210	231	0.372	0.89	11.1	289	180	219	0.388	0.74	13.0	280	160
B100	283	0.314	1.57	13.8	285	180	236	0.383	0.90	16.8	267	140	229	0.391	0.78	18.9	256	120
Speed	2100 rpm																	
B0	236	0.333	0.68	2.5	304	220	222	0.364	0.34	3.8	274	180	203	0.387	0.24	3.8	254	160
B20	237	0.343	0.68	3.3	294	208	224	0.373	0.35	4.8	266	164	207	0.392	0.24	4.8	245	144
B50	244	0.348	0.70	4.2	279	190	224	0.375	0.37	5.3	253	140	215	0.394	0.25	5.3	229	120
B100	252	0.375	0.74	5.3	254	160	227	0.385	0.40	6.4	231	100	224	0.400	0.26	6.4	254	80
speed	3000 rpm																	
B0	228	0.346	1.05	1.2	274	140	216	0.369	0.48	1.3	258	120	203	0.388	0.35	2.0	253	100
B20	236	0.344	1.07	1.4	265	128	218	0.374	0.49	1.8	250	108	208	0.392	0.35	2.3	245	88
B50	236	0.360	1.09	1.7	251	110	227	0.380	0.50	2.2	242	90	213	0.399	0.36	2.9	233	70
B100	244	0.367	1.12	2.4	228	80	233	0.391	0.51	2.8	217	60	223	0.401	0.37	3.6	213	40

Appendix E: 10% steam results of light duty diesel engine running with diesel biodiesel blends.

Table E.1 Light duty diesel engine performance and emission results of various fuel blends running with 10% steam.

Load	Low load						Medium load						High load					
Fuel	BSFC (g/kWh)	BTE (%)	NOx (g/kWh)	Smoke (%)	CO (ppm)	HC (ppm)	BSFC (g/kWh)	BTE (%)	NOx (g/kWh)	Smoke (%)	CO (ppm)	HC (ppm)	BSFC (g/kWh)	BTE (%)	NOx (g/kWh)	Smoke (%)	CO (ppm)	HC (ppm)
Speed	1000 rpm																	
B0	252	0.313	1.053	3.6	381	250	220	0.359	0.716	5.1	333	230	210	0.375	0.583	6.6	334	210
B20	258	0.315	1.135	5.1	365	238	224	0.363	0.722	9.2	327	214	211	0.385	0.617	9.7	317	194
B50	264	0.322	1.183	9.5	347	220	226	0.376	0.737	11.5	306	190	218	0.389	0.691	13.4	297	170
B100	272	0.321	1.013	14.2	302	190	235	0.384	0.779	17.2	284	150	230	0.390	0.711	19.3	273	130
Speed	2100 rpm																	
B0	237	0.333	0.616	2.8	321	230	219	0.349	0.305	3.4	291	190	202	0.370	0.220	4.1	278	170
B20	232	0.341	0.621	3.6	311	218	222	0.357	0.312	4.3	283	174	207	0.374	0.270	5.1	271	154
B50	239	0.355	0.635	4.5	296	200	223	0.369	0.328	5.2	270	150	214	0.387	0.298	5.6	262	130
B100	247	0.362	0.637	5.6	271	170	226	0.387	0.338	6.4	248	110	221	0.399	0.236	6.8	246	90
speed	3000 rpm																	
B0	227	0.347	0.799	1.6	291	150	216	0.365	0.385	1.7	275	130	203	0.389	0.271	0.8	270	110
B20	231	0.352	0.812	1.8	282	138	218	0.374	0.388	2.2	267	118	208	0.392	0.279	2.4	262	98
B50	233	0.364	0.831	2.1	268	120	226	0.376	0.394	2.6	259	100	213	0.398	0.285	2.7	250	80
B100	240	0.373	0.865	2.8	245	90	233	0.385	0.405	3.2	234	70	219	0.402	0.301	3.3	230	50

Appendix F: Half open EGR with 5% steam results of light duty diesel engine running with diesel biodiesel blends.

Table F.1 Engine performance and emissions of biodiesel diesel blends (half open EGR + 5% steam)

Load	Low load						Medium load						High load					
Fuel	BSFC (g/kWh)	BTE (%)	NOx (g/kWh)	Smoke (%)	CO (ppm)	HC (ppm)	BSFC (g/kWh)	BTE (%)	NOx (g/kWh)	Smoke (%)	CO (ppm)	HC (ppm)	BSFC (g/kWh)	BTE (%)	NOx (g/kWh)	Smoke (%)	CO (ppm)	HC (ppm)
Speed	1000 rpm																	
B0	262	0.301	1.13	3.7	408	305	223	0.354	0.75	5.2	360	285	213	0.370	0.66	6.7	361	265
B20	266	0.306	1.21	5.2	392	293	228	0.357	0.76	9.3	354	269	214	0.380	0.67	9.8	344	249
B50	273	0.312	1.26	9.6	374	275	229	0.372	0.77	11.6	333	245	221	0.385	0.72	13.5	324	225
B100	287	0.313	1.38	14.3	329	245	238	0.377	0.81	17.3	311	205	233	0.385	0.76	19.4	300	185
Speed	2100 rpm																	
B0	241	0.328	0.60	2.5	348	285	224	0.351	0.32	3.1	318	245	203	0.387	0.22	3.8	305	225
B20	237	0.344	0.61	3.3	338	273	224	0.364	0.33	4.0	310	229	208	0.387	0.22	4.8	298	209
B50	243	0.349	0.63	4.2	323	255	225	0.378	0.35	4.9	297	205	215	0.391	0.24	5.3	289	185
B100	251	0.356	0.76	5.3	348	225	228	0.390	0.42	6.3	318	165	225	0.398	0.26	6.4	273	145
speed	3000 rpm																	
B0	230	0.342	0.86	1.7	318	205	218	0.362	0.41	1.8	302	185	203	0.387	0.29	2.5	297	165
B20	238	0.342	0.87	1.9	309	193	219	0.371	0.41	2.3	294	173	209	0.390	0.29	2.8	289	153
B50	236	0.359	0.89	2.2	295	175	228	0.373	0.42	2.7	286	155	214	0.396	0.31	3.4	277	135
B100	244	0.367	0.92	2.9	272	145	234	0.362	0.47	1.8	261	185	224	0.400	0.33	4.1	257	165

Appendix G: half open EGR with 10% steam results of light duty diesel engine running with diesel biodiesel blends.

Table G.1 Engine performance and emissions of biodiesel diesel blends (half open EGR + 10% steam)

Load	Low load						Medium load						High load					
Fuel	BSFC (g/kWh)	BTE (%)	NOx (g/kWh)	Smoke (%)	CO (ppm)	HC (ppm)	BSFC (g/kWh)	BTE (%)	NOx (g/kWh)	Smoke (%)	CO (ppm)	HC (ppm)	BSFC (g/kWh)	BTE (%)	NOx (g/kWh)	Smoke (%)	CO (ppm)	HC (ppm)
Speed	1000 rpm																	
B0	250.68	0.31	1.02	4.17	423	325	219.29	0.36	0.70	5.7	375	305	209.91	0.38	0.62	7.2	376	285
B20	257.40	0.32	1.10	5.7	407	313	223.72	0.36	0.71	9.8	369	289	211.14	0.39	0.51	10.28	359	269
B50	262.65	0.32	1.15	10.1	389	295	225.50	0.38	0.72	12.1	348	265	218.08	0.39	0.68	14	339	245
B100	277.79	0.32	0.98	14.8	344	265	232.65	0.39	0.58	17.8	326	225	229.62	0.39	0.53	19.9	315	205
Speed	2100 rpm																	
B0	246.47	0.31	0.77	3.45	363	300	232.83	0.33	0.37	4.08	333	260	212.16	0.37	0.27	4.78	320	240
B20	241.87	0.33	0.78	4.28	353	288	231.91	0.35	0.38	4.98	325	244	216.68	0.37	0.28	5.75	313	224
B50	248.83	0.34	0.80	5.18	338	270	233.05	0.36	0.38	5.88	312	220	224.17	0.39	0.28	6.28	304	200
B100	256.86	0.34	0.84	6.28	313	240	235.72	0.38	0.39	7.28	290	180	234.54	0.39	0.29	7.68	288	160
Speed	3000 rpm																	
B0	227.16	0.35	0.60	2.2	333	220	216.04	0.36	0.28	2.3	317	200	202.62	0.39	0.19	3	312	180
B20	231.11	0.35	0.60	2.4	324	208	217.77	0.37	0.28	2.8	309	188	207.68	0.39	0.19	3.3	304	168
B50	233.10	0.36	0.61	2.7	310	190	226.11	0.38	0.30	3.2	301	170	213.32	0.40	0.20	3.9	292	150
B100	240.09	0.37	0.64	3.4	287	160	232.46	0.39	0.31	3.8	276	140	222.80	0.40	0.20	4.6	272	120

Appendix G: Measuring equipment used

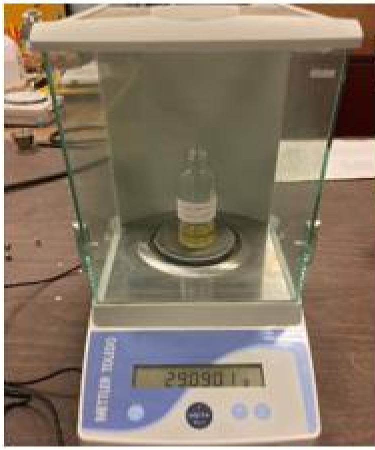

Figure G.1 Weighing scale

Figure G.2 Viscometer

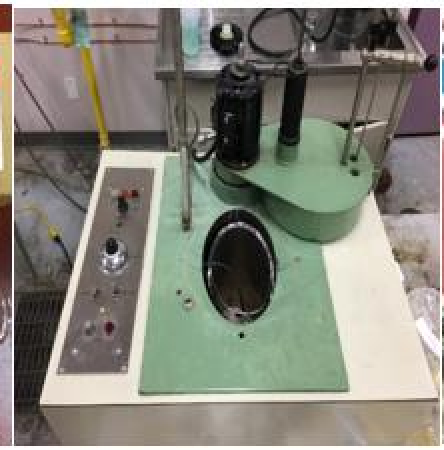

Figure G.3 Calorimeter

Figure G.4 Dynamometer

Figure G.5multi-gas analyzer.

Figure G.6 CO analyzer

Figure G.7. Smoke opacity meter

Figure G.8 Graduated cylinder.

Figure G.9 Thermometer