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Performance and Emission Analysis of a Modern Small DI Diesel Engine Using Biodiesel-Diesel Blends and Additives with EGR

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ABSTRACT
This study investigated the effects of EGR on performance and emission of a twin cylinder HATZ 2G40 light-duty engine at different speeds (1000 rpm, 2100 rpm and 3000 rpm) at different load conditions (20%, 50% and 80%) at each speed. Biodiesel-diesel blends with additives are considered the fuels in this study. The biodiesel was produced from pure canola oil using the transesterification process. Additives such as methanol (5% and 10% by volume) and diethyl ether (5% by volume) were mixed together to use in a diesel-biodiesel blends of B20 (20 vol.% biodiesel and 80% diesel), B50 (50 vol.% biodiesel and 50% diesel), and B100. Brake thermal efficiency (BTE) and brake-specific energy consumption (BSEC) were measured as the engine performance parameters, and those were increased when increasing the percentage of biodiesel and additives in the mixture. In emissions, carbon monoxide (CO), unburned hydrocarbon (HC), oxides of nitrogen (NOx) and smoke were measured. Increasing the percentage of biodiesel decreased HC and CO emissions and increased NOx, whereas increasing the methanol percentage increased HC and CO emission in the diethyl ether-biodiesel-diesel blend when compared with a diesel-biodiesel blend. This was still less than diesel, except for the B20 series, which showed a 20-22% decrease in NOx emission for methanol 10%, diethyl ether 5% in B20 (M10D5B20). However, the use of exhaust gas recirculation (EGR) shows a significant decrease in BSEC and increase in BTE. In terms of emissions, the use of EGR decreases smoke opacity and NO_x emission but increases CO and HC emissions.

Keywords-Biodiesel, canola oil, diesel engine, diethyl-ether, EGR, emissions, methanol, transesterification

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I. INTRODUCTION

The availability of oil reserves is diminishing, and the environmental regulations and norms are becoming more stringent day by day for the use of natural resources as fuels [1]. Petrochemical resources, such as coal and natural gases, have been the main source of energy for the worlds energy needs [2]. Diesel engines have many advantages over spark ignition engine like lower brake specific fuel consumption and HC formation but at the same time also produces high amount of NO, soot and CO_2 emissions [3].These environmental consequences of exhaust gases from petroleum fueled engines with the increase in demand for fuel led to the research and production of an alternative fuel which is sustainable as well as renewable. Hence, the renewable and clean alternative fuels have established most important desirability for present and future consumption [4]. Vegetable oil are found to be a possible source of energy that can be used as an alternative fuel in diesel engine as they have properties similar to that of diesel [3,4]. However, these vegetable oils are not suitable for

direct use in diesel engine due to their high viscosity and low volatility, low cetane number and high boiling point which leads to engine oil contamination, incomplete combustion and higher smoke emission [5]. These problems can be either reduced or eliminated through a process known as transesterification of vegetable oil to form methyl esters, which is commonly known as biodiesel [5–7].

As biodiesel is a non-toxic, biodegradable, and renewable fuel, it is receiving immense attention as an alternative fuel [8]. Biodiesel has a higher cetane number than diesel fuel with no aromatics and sulphur content [9], and contains 10-11% of oxygen by weight. Use of biodiesel in internal combustion engine results in reduction of unburnt hydrocarbons, sulphur oxides, carbon monoxide and particulate material (PM) [1]. But at the same time it also increases the NO_x emissions which are considered to be the most harmful gas of all mentioned above [10]. According to Sun et al. [11], biodiesel produces higher NOx due to following reasons: high oxygen content, advancement of ignition timing, increase in ignition delay period, and higher degree of unsaturation. In addition, a significant reduction in HC and CO has been observed by many researchers [8–12].

Biodiesel is the basic term for all types of fatty acid methyl esters that can be easily used in any diesel engine with little or no modifications [12,13]. The total global production of biodiesel attained an estimated 19 billion liters in 2010, a 12% increase from the previous year. That same year, the European Union was recognized as the world's largest biodiesel-producing region [14].

Reports from numerous studies on alcohol-biodiesel-diesel blends focused mainly on ethanol as an alcohol component in this ternary blend; however very little research has been conducted on methanol [15-16]. Hafizil et al. [16] carried out a comparative study on biodiesel-methanol-diesel low proportion blends, and concluded that the brake specific fuel consumption (BSFC) of biodiesel-methanol-diesel blends is higher compared to mineral diesel, and the lower methanol concentrations (5%) have lower BSFC compared to 10% methanol concentrations. Higher methanol concentrations decrease NOx emissions, while slightly increasing CO emissions as well as exhaust gas temperature with an increased load. Similar performance and emission results were investigated by Y. Datta [13] with increasing HC and CO emission with decreasing NO_x. Yilmaz and Sanchez [17]analyzed operating a diesel engine on biodiesel-methanol and biodiesel-ethanol using both the alcohol blends at 15%. They concluded that the BSFC of the biodiesel alcohol blends had higher increases with methanol than with ethanol. Although the blends reduced NOx emission but increased CO and HC emissions, it was determined that the ethanol-biodiesel blend was more effective than the methanol-biodiesel blend. Later, Nadir Yilmaz [18] studied the effects of preheating the intake air and fuel blend ratios of biodiesel-methanol blends in a diesel engine. Methanol-biodiesel fuels were blended with several blend ratios to understand how overall performance was affected by the blend ratios. According to him, preheating the intake air is a key factor that affects the vaporization process, because it provides additional energy to methanol or biodiesel–methanol blends. It was shown that exhaust gas temperature increased as the concentration of methanol in biodiesel-methanol increased, because part of the biodiesel-methanol vaporized and underwent combustion during the exhaust cycle, which in turn slightly increased the exhaust gas temperature. This preheating effect reduced the NOx emission when increasing the percentage of methanol, whereas it also reduced HC and CO emissions. Biodiesel blended with 5%, 10% and 15% (vol%) methanol fuel was numerically modelled by H. An et al. [12] to study the influence of methanol addition on the combustion, emission and performance characteristics of a diesel engine fueled by biodiesel. Simulated results revealed that the indicated thermal efficiency linearly increased with the increase in methanol ratio under all load conditions, which improved the combustion process due to its lower viscosity and higher oxygen content.

Different types of additives such as metal-based, oxygenated fuel, cetane improver, antioxidant, etc., were used to reduce the NOx emissions from biodiesel combustion. It decreased the maximum combustion temperature, which suppressed NOx formation [19]. Among the ethers group, diethyl ether and dimethyl ether were used on a large scale due to their structure with lower carbon chain atoms and ignition-improving qualities. The production cost of diethyl ether is very low compared to dimethyl ether, and it is easily available. It also has various favorable properties for use in diesel engines, such as higher oxygen content, moderate energy density, and lower auto-ignition temperature [20]. Qi et al. [21] studied the effects of ethanol and diethyl ether on combustion and emission of a biodiesel-diesel blended fuel engine. They concluded that both ethanol and diethyl ether showed lower BSFC with B30, as well as a drastic reduction in smoke, HC and CO due to high oxygen content, which helped in complete combustion with an increase in NO_x. Ismet Sezer [22] investigated the thermodynamic, performance and emission of diethyl ether and dimethyl ether, and concluded that the engine performance decreased with an increase in fuel consumption and higher BSFC due to low calorific value and higher brake thermal efficiency. Zhan et al. [23] investigated the spray characteristics of ethanol and diethyl ether under high injection pressure, and found that adding 20% biodiesel into diesel increased the characteristics droplet size. Further, adding 20% ethanol decreased the droplet size, and adding 20% diethyl ether reduced the droplet size even more. Srihari and Thirumalini [24] conducted an experimental study on the performance and emission of a diesel engine fueled with a diethyl ether-biodiesel-diesel blend. They found a significant reduction in HC, CO and NOx, as well as an increase in BSFC and brake thermal efficiency. Meshack et al. [25] studied the effects of performance and emission of diesel-piloted biogas engine, and found 7.6% reduction in exhaust gas temperature with increase in CO and HC.

The main objective of this research work was to study the influence of methanol on the ternary blend of diethyl ether, biodiesel and diesel at different rpm and load conditions with blends of B20, B50 and B100 with EGR.

II. METHODS AND MATERIALS

2.1 Materials

Materials used for experimentation include winter diesel purchased from a local fuel station throughout the experiment, and pure canola oil purchased from a local supermarket. The main ingredients for producing biodiesel are methanol (100% purity), sodium hydroxide pellets (99% purity), and diethyl ether (99.5% purity), all of which were obtained through the Chemistry Lab at Lakehead University. The chemical properties of the additives are listed in Table 1.

Table 1: Chemical properties of additives

Properties	**Methanol**	**Di-Ethyl Ether**
Chemical formula	CH_3OH	$C_4H_{10}O$
Molecular weight (g/mol)	32.04	74.12
Flash point (˚C)	12	-45
Boiling point(˚C)	64.5	34.6
Auto-ignition temperature (˚C)	385-475	150-160
Density (kg/m^3)	773	695
Purity (%)	100	99.5
Vapour pressure (mmHg)	97 @ 20 ˚C	440.28 @ 20 ˚C
Oxygen content (% by mass)	49.93	21.6

2.2 Biodiesel Production Process

Biodiesel can be produced chemically with any natural oil or fat with an alcohol such as methanol, ethanol, or even methyl acetate. The most commonly used alcohol in the commercial production of biodiesel is methanol. Chuah et al. studied ultrasonic

assisted transesterification with different oil and catalyst [26]. As per the study, canola oil can undergo transesterification with methanol in the presence of a catalyst (NaOH or KOH), but the conversion rate with NaOH (98%) is higher than with KOH (85%). In this study, biodiesel was produced by the transesterification of oil with methanol in the presence of a catalyst (NaOH). For everyone litre batch of canola oil, the molar ratio of oil-to-alcohol was 1:5 (200 ml of methanol in 1000 ml of canola oil) and 3.5 g of NaOH pellets. Initially, sodium hydroxide was dissolved in methanol, and the canola oil was heated to 60^{o}C separately to reduce itsviscosity and to make it soluble with methanol and sodium hydroxide. Canola oil temperature was kept to 60^{o}C to avoid evaporation of methanol whose boiling point is 64.5^{o}C. After heating, this mixture was blended for 45 minutes and kept aside in an air-tight container for a day. After 8-10 hours, the by-product of this transesterification process settled down and its by-product (glycerine) was separated from the oil. This oil was then washed with 500 mL of water in the first wash and with 300 mL of water in the second wash to remove the fatty acids from the oil. After the second wash, the oil was heated to more than 100^{o}C to evaporate any remaining water particles until the oil turned golden yellow in colour. The final collection efficiency was 84%.

2.3 Tested Fuels and Their Properties

In this study, ten fuels were studied at 0% and 20% EGR: B0 (diesel), B20 (20% biodiesel in diesel), B50 (50% biodiesel in diesel), B100 (100% biodiesel), M5D5B20 (methanol 5% and diethyl ether 5% in B20), M10D5B20 (methanol 10% and diethyl ether 5% in B20), M5D5B50 (methanol 5% and diethyl ether 5% in B50), M10D5B50 (methanol 10% and diethyl ether 5% in B50), M5D5B100 (methanol 5% and diethyl ether 5% in B100), and M10D5B100 (methanol 10% and diethyl ether 5% in B100). The density of all the fuels were tested at room temperature, whereas the kinematic viscosity was tested at 40^{o}C using a capillary U-tube viscometer. Viscosity is an important factor that influences the fuel atomization and should be within the ASTM limit of less than 6cSt for diesel engine fuel. The calorific value of each fuel was tested using a bomb calorimeter: highest for diesel (44.825 MJ/kg), and lowest for M10D5B100 (35.478 MJ/kg). The fuel properties for all the tested fuels blends are provided in Table 2.

Table 2:Properties of different fuels and their blends

Fuel	Density (kg/m^3)	Calorific Value (MJ/kg)	Viscosity @ 40˚C (cSt)
D100	835	44.825	3.15
B20	842	43.758	3.98
5DEE5M-B20	831	42.223	3.62
5DEE10M-B20	827	41.033	3.41
B50	853	42.157	4.56
5DEE5M-B50	841	40.792	4.24
5DEE10M-B50	837	39.692	3.99
B100	871	39.49	5.24
5DEE5M-B100	857	38.388	5.07

5DEE10M-B100	852	37.418	4.92
M100	773	20.075	0.50
DEE100	695	36.844	0.24

2.4 Engine Specifications

The engine used in this study was a light-duty HATZ 2G40, which was an air-cooled, twin-cylinder, 4-stroke, naturally-aspirated diesel engine. It was comprised of a direct fuel injection system with a maximum torque at 2100 rpm. The engine specifications are shown in Table 3.

Table 3: Engine specifications

Engine make & model	HATZ 2G40
Engine type	4-stroke, air-cooled
Number of cylinders	2
Bore/stroke	92 mm/75 mm
Displacement	997 cc
Compression ratio	20.5:1
Fuel injection timing	8°BTDC (≤2250 rpm); 10°BTDC (≥2300 rpm)
Fuel injection pressure	26 MPa
Continuous maximum-rated power	13.7 kW @ 3000 rpm
Maximum-rated power	17 kW @ 3600 rpm

2.5 Engine Test Procedure

The engine was coupled with a dynamometer and different loads were applied to carry out the experiments at different engine speeds. The schematic diagram for the setup of the engine is shown in Fig. 1. In order to conduct the experiments, three different engine speeds were used: 1000 rpm (low), 2100 rpm (medium) and 3000 rpm (high), with 20% (low), 50% (medium) and 80% (high) loads without EGR (0% EGR) and with 20% EGR rate. The test for maximum torque and maximum power are associated with medium and high speeds of the engine respectively. A water dynamometer was used to measure these loads. In order to conduct the experiments, the engine was made to run to warmedup with winter diesel for half an hour. To be able to calculate the brake specific fuel consumption (BSFC), brake thermal efficiency (BTE) and brake specific energy consumption (BSEC), the load on the engine, fuel consumption and brake power were measured. To ensure complete combustion of the residual fuel, the engine was flushed with winterdiesel before using the next test fuel. To measure the CO, CO_2 and O_2 (in %), and NO, NO_2 and HC (in ppm), the NOVA 7466 PK type multi-gas analyser was used. To measure CO precisely in terms of ppm, Dwyer 1205A was used separately. To measure the smoke, the SMART 1500 smoke opacity meter (computerized with automated system) was used. The exhaust gas temperatures were measured using digital thermostats. The specifications of different analysers are shown in Table 4.

2.6 Exhaust Gas Recirculation

EGR is a useful method for reducing NO_x emissions in engines. The EGR rate can be obtained from the following equation measuring the concentration of CO_2 in exhaust gas and the concentration of CO_2 in intake air that increased due to recirculation of exhaust gas.

$$\% \, EGR = \frac{CO_{2(in)} - CO_{2(amb)}}{CO_{2(exh)} - CO_{2(amb)}}$$

In EGR technique, 20% of the exhaust gases are recirculated back into the inlet manifold where it mixes with the fresh air. This helps in reducing the amount of O_2 available for combustion. This dilutes the intake charge by reducing the concentration of O_2 and reduces the peak combustion temperature inside the combustion chamber which will restrict the formation of NO_x[27].

III. RESULTS AND DISCUSSION

3.1 Engine Performance

All the experiments were carried out at 1000 rpm, 2100 rpm and 3000 rpm, at three different load conditions (low, medium and high). The data obtained from the experiments were used to evaluate the performance of diesel engine; the performance parameters studied were brake-specific energy consumption and brake thermal efficiency.

3.1.1 Brake Specific Energy Consumption (BSEC)

Brake-specific energy consumption is defined as the amount of energy consumed by the engine per kilowatt of power developed in one hour. Figure 2shows BSEC of different fuel blends at different engine conditions. It was observed that the BSEC decreased with increased load for all fuels. Higher load caused higher in-cylinder temperature, which consequently helped better fuel evaporation and combustion. Therefore, better thermal efficiency is expected, which will be discussed in the next figure. With 20% EGR a substantial decrease in BSEC was observed for all the fuels when compared with 0% EGR. The decrease in BSEC with EGR is due to increase in intake charge temperature which increases the rate of combustion of the fuel which causes a decrease in BSEC. As per the results showed in Fig. 2, the BSEC of B20, B50 and B100 blends increased by approximately 3%, 7% and 11%, respectively, at 0% EGR, in comparison to diesel fuel at lower speed and load due to lower heating values and higher viscosity of biodiesel, resulting in increased BSEC. By adding methanol and diethyl ether, a further increase in BSEC was observed due to the very low heating value of methanol, which consumed more energy as the methanol percentage increased. The highest BSEC was observed for M10D5B100 at 0% EGR, which was 13% higher than diesel.

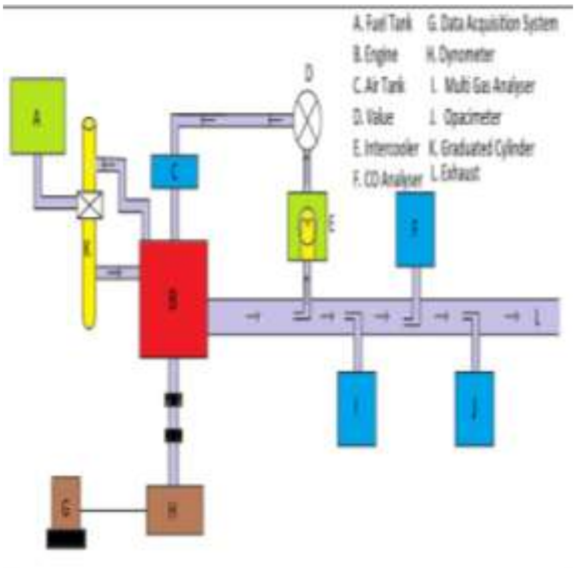

Fig. 1: Schematic layout of engine setup

Measurement device Species	Method of detection	Measurement unit	Resolution	Range	Accuracy
Nova Gas 7466 PK					
CO	Electrochemical	%	0.10%	0 – 10 %	±1%
CO_2	Infrared detector	%	0.10%	0 – 20 %	±1%
NO	Electrochemical	ppm	1 ppm	0 – 2000 ppm	±2%
NO_2	Electrochemical	ppm	1 ppm	0 – 800 ppm	±2%
O_2	Electrochemical	%	0.10%	0 – 25%	±1%
HC	Infrared detector	ppm	10 ppm	0 - 20,000 ppm	±1%
Dwyer 1205 A					
CO	Electrochemical	ppm	1 ppm	0-2000	±5%
Smart 1500					
Opacity		%	0.10%	0-100%	±2%

Table 4: Specifications of measuring instruments

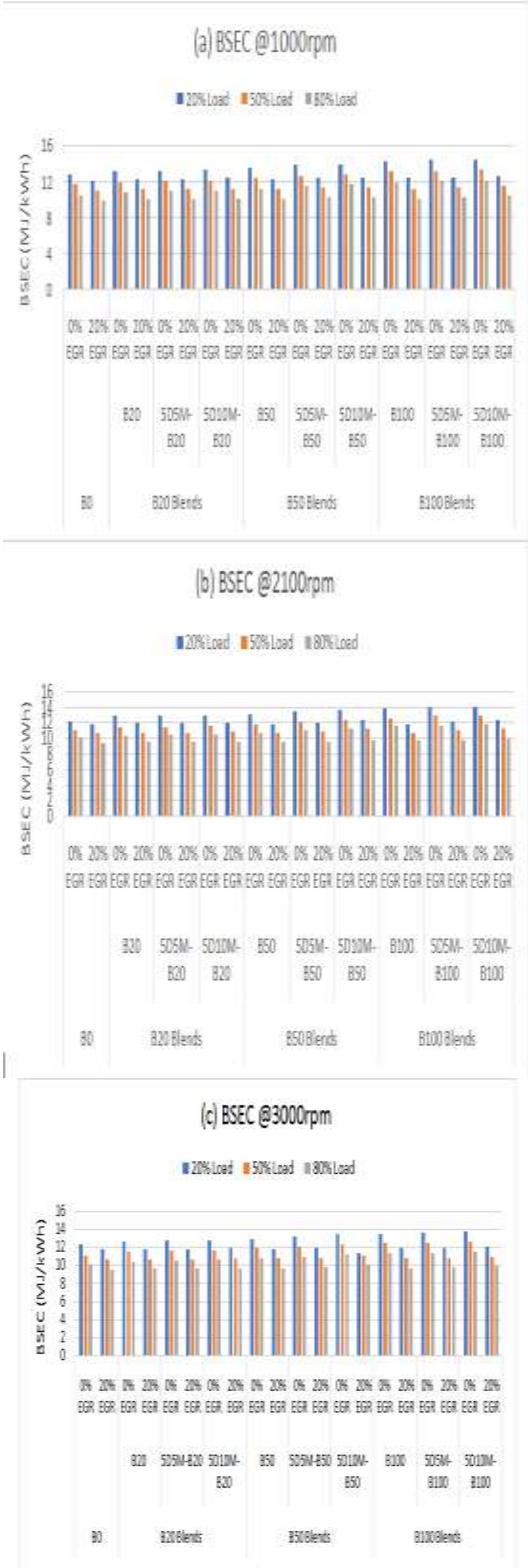

Fig. 2:BSEC of different fuel blends at 0% and 20% EGR. (a) 1000 rpm, (b) 2100 rpm, (c) 3000 rpm

3.1.2 Brake Thermal Efficiency (BTE)

The variation in BTE with varying engine load and speed for different combinations with diesel-biodiesel blend is shown in Fig. 3 at 0% and 20% EGR. The BTE varied from about 34% to 40%, and higher load showed higher BTE as expected. A significant increase in BTE was observed for all the fuels at 20% EGR due to increase in intake charge temperature which increases the rate of combustion of the fuel. The brake thermal efficiency of B20, B50 and B100 was higher than diesel, and similar results were observed by adding methanol and diethyl ether in diesel-biodiesel blend. This is attributed to the higher oxygen content in biodiesel, methanol and diethyl ether, which helped in improved combustion. Also, the addition of diethyl ether may have resulted in rapid evaporation, which easily mixed with air and formed a favourable charge due to its high volatility. The maximum BTE was observed for M5D5B100 at low speed and load, which was 8% and 10% more, respectively than diesel at 0% and 20% EGR.

3.2 Emissions Analysis

All the experiments were carried out at 1000 rpm, 2100 rpm and 3000 rpm at three different load conditions. The data obtained from the experiments were used to evaluate the diesel engine's emissions, i.e., carbon monoxide (CO), unburned hydrocarbon (HC), and oxides of nitrogen (NOx). Smoke results were taken at 2100 rpm for low, medium and high load.

3.2.1 Carbon Monoxide (CO)

Fig. 4 compares the variation in carbon monoxide at 1000 rpm, 2100rpm and 3000 rpm at low, medium and high load at 0% and 20% EGR. It is observed that at low engine speed the CO emissions are maximum, and it decreases with increase in load. At high speed, more fuel entered inside the combustion chamber, which led to high cylinder temperature that helps proper combustion and as a result less CO emissions. An increase in CO was observed for all the fuels at 20% EGR due to oxygen deficiency. A significant decrease in CO was observed for B20, B50 and B100 with about 8%, 23% and 36% reduction at 0% EGR as compared with diesel. Further, the addition of higher percentage of methanol in the diethyl ether-biodiesel-diesel blend increased the CO emissions, which were about 7% and 27% higher than diesel for M5D5B20 at 0% and 20% EGR for low speed and low load. Because the cetane number of methanol is very low, it increased the ignition delay followed by incomplete combustion with an increase in CO formation.

3.2.2 Unburned Hydrocarbon (HC)

Fig. 5 illustrates the variation in total hydrocarbon at 1000 rpm, 2100 rpm and 3000 rpm for three different load conditions: low, medium and high, at 0% and 20% EGR. HC and CO both are by-products of incomplete combustion and it follows the same trend as CO (decreases with increase in speed and load). An increase in HC was observed for all the fuels at 20% EGR because of the deficiency of oxygen in the air-fuel mixture would have resulted in local incomplete combustion. As the percentage of biodiesel in diesel increases, HC startsdecreasing and this change was nearly 30% and 22% for B100 at 0% and 20% EGR when compared with diesel at low engine speed. This was because a higher percentage of oxygen in the air-fuel mixture enhanced the oxidation of the total unburned hydrocarbon. As soon as methanol and diethyl ether were added to the diesel-biodiesel blend, a further increase in HC was observed. This increase of HC may have been due to the higher latent heat of evaporation of diethyl ether, initiating lower combustion temperature, particularly the temperature near the cylinder walls throughout the mixture formation; more HC would be produced from the cylinder boundary [29]. As the percentage of methanol increased in this quaternary blend, an additional increase in HC was observed. The reason is that methanol, being an alcohol, resulted in a cooling effect of the blends, thereby reducing the combustion temperature which led to incomplete combustion and higher HC emission.

3.2.3 Oxides of Nitrogen (NO_x)

NOx is the generalized term for combined NO and NO_2. In fig. 6, the variation in NOx for various fuels at 1000 rpm, 2100 rpm and 3000 rpm for different load conditions for 0% and 20% EGR is presented. With 20% EGR, significant decrease in NO_x was observed for all the fuels as the EGR mechanism decreases the combustion temperature and decreases the air-fuel ratio because of the reduction of oxygen. The maximum decrease of 52% was observed for M10D5B20 blend at 1000 rpm and low load. As the percentage of biodiesel in diesel increases, NO_x emission also increases, and this trend is very commonly observed by many researcher [26–31]. This increase was 19%, 36% and 41% for B20, B50 and B100, respectively, for high speed and low load at 0% EGR. The existence of oxygen played a substantial role in NOx formation [32]. By adding methanol and diethyl ether, it was observed that it exhibited the lowest NOx at all engine speeds and loads. The influence of diethyl ether may have promoted low temperature combustion, which would have decreased the combustion duration resulting in lower NOx. As the percentage of methanol increased, a further reduction in NOx was observed; the lowest NOx was observed at 3000 rpm and 20% load for M10D5B20, which was approximately 20-22% and 34% less than diesel at 0% and 20% EGR.

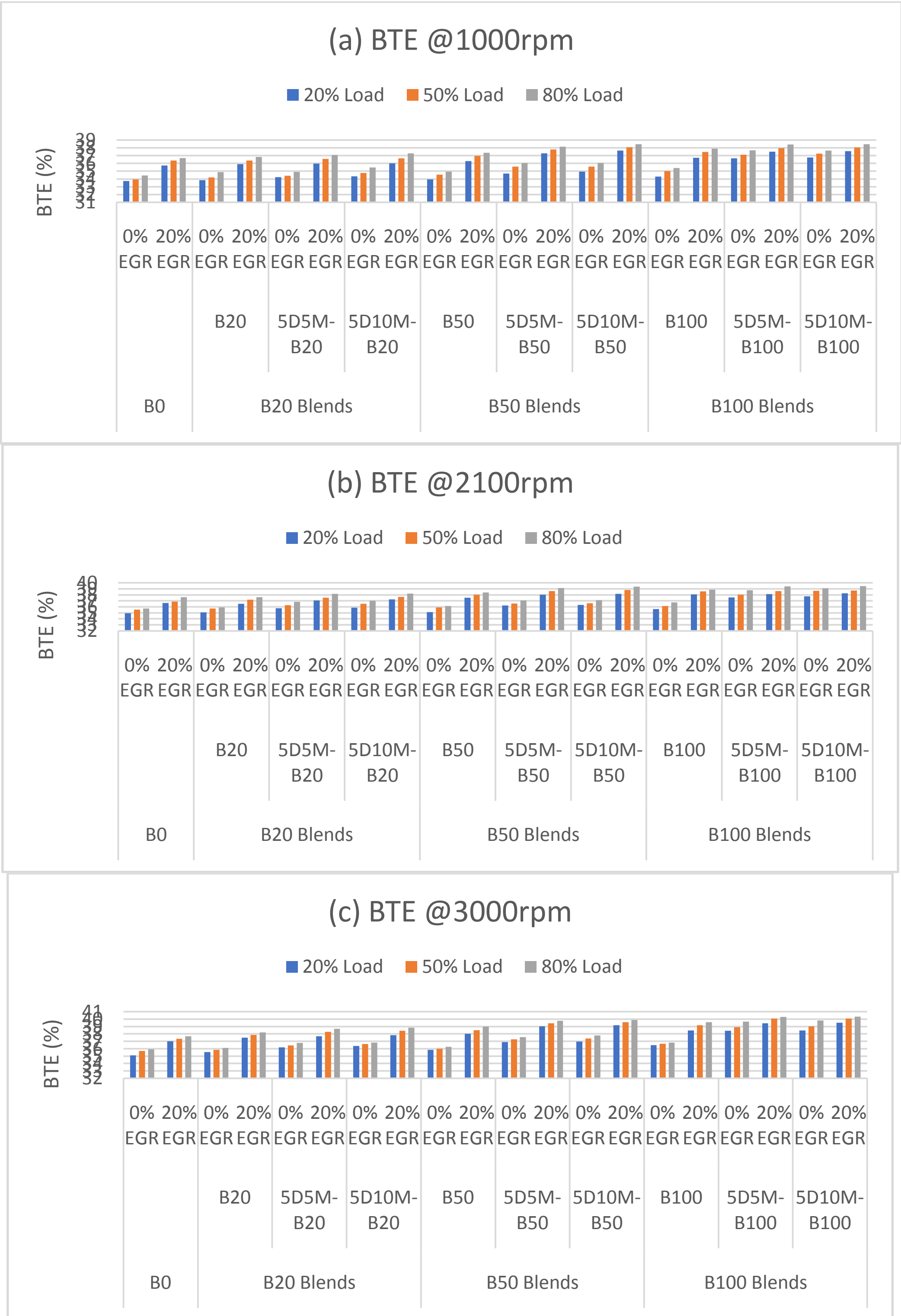

Fig. 3:BTE of different fuel blends at 0% and 20% EGR. (a) 1000 rpm, (b) 2100 rpm, (c) 3000 rpm

Fig. 4:CO emission of different fuel blends at 0% and 20% EGR. (a) 1000 rpm, (b) 2100 rpm, (c) 3000 rpm

Fig. 5:HC emission of different fuel blends at 0% and 20% EGR. (a) 1000 rpm, (b) 2100 rpm, (c) 3000 rpm

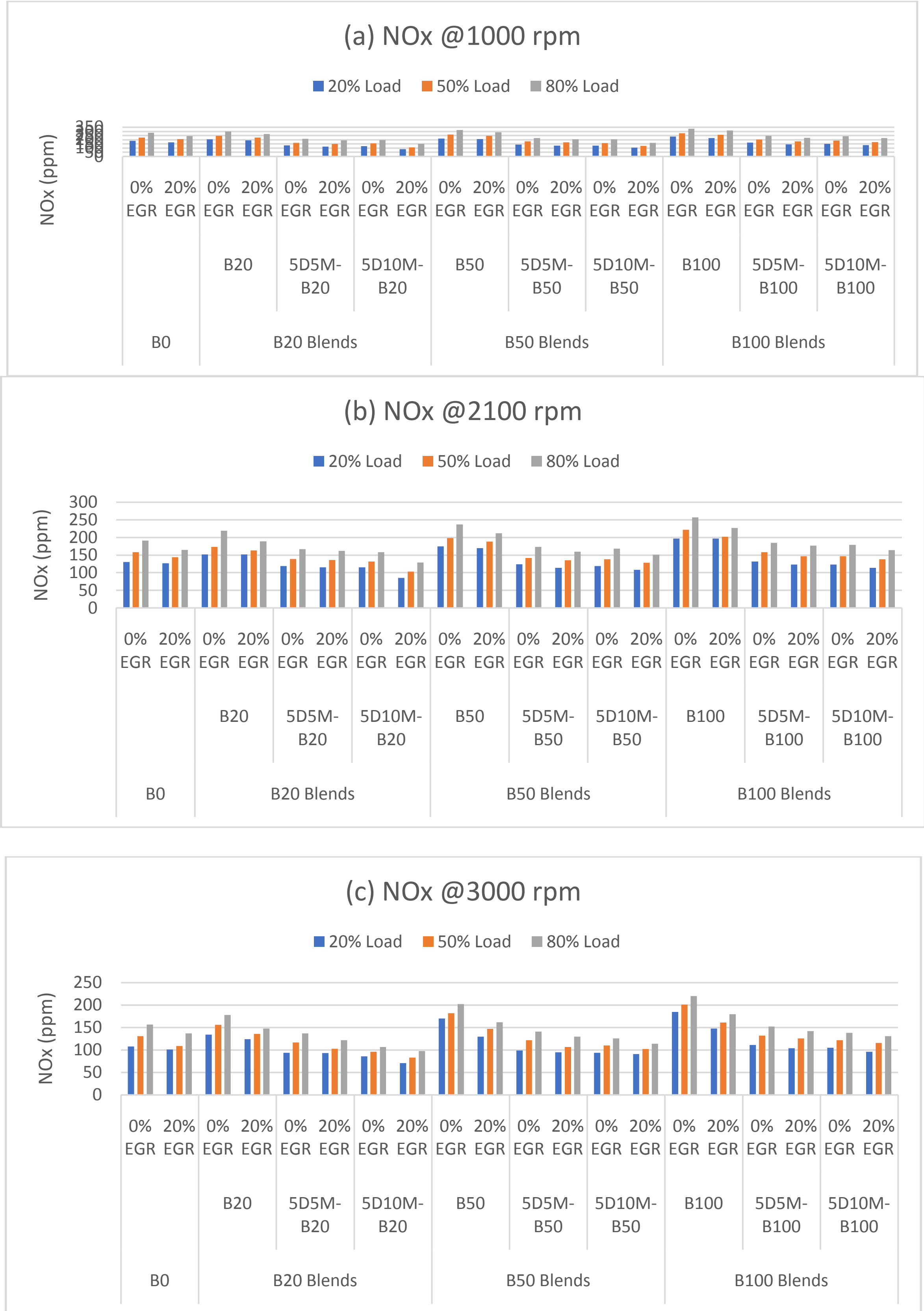

Fig. 6:NOx emission of different fuel blends at 0% and 20% EGR. (a) 1000 rpm, (b) 2100 rpm, (c) 3000 rpm

3.2.4 Smoke Opacity

The variation of smoke intensity for different fuels was measured at 0% and 20% EGR as shown in Fig.7. This smoke intensity was measured at 2100 rpm for three different load conditions: low, medium and high. It was observed that as the EGR percentage increased, smoke decreased due to proper mixing of fuel with burned gases. As the percentage of biodiesel increased in diesel, smoke opacity started increasing. The heavier molecules in the structure, and the higher viscosity of biodiesel slowed down the combustion process, which increased smoke emission in this small DI diesel engine. The maximum increase in smoke was observed at B100 (12.8% at high load), a change of approximately 35% more than diesel. Further addition of methanol and diethyl ether decreased smoke opacity, maybe due to better evaporation. The enhancement in spray atomization and fuel–air mixing with the addition of diethyl ether decreased the rich mixture region, which helped reduce the smoke emission [29]. Increasing the percentage of methanol decreased the percentage of smoke, mostly due to high volatility of methanol, which helped in better fuel mixing.

IV. CONCLUSION

An experimental investigation has been conducted to study the performance and emission of biodiesel, and ternary blend of methanol-diethyl ether-biodiesel in diesel using EGR. All the experiments were conducted on a light-duty Hatz 2G40, twin-cylinder engine at 1000 rpm, 2100 rpm and 3000 rpm at three load conditions at each speed: low, medium and high. Based on the experimental results from the engine testing, the results can be summarized as follows:

In terms of performance, the biodiesel series (B20, B50 & B100) showed an increase in BSEC and BTE. With respect to emissions, significant decreases (30-35% in CO, and 32-38% in HC) were observed for B100 at 0% EGR. Increases of 19%, 36% and 41% in NOx emissions at 0% EGR were observed for B20, B50 and B100 at high speed and low load. The highest smoke emission was observed at B100 (12.8% at high load).

The addition of methanol and diethyl ether at 5% resulted in an increase in BSEC and BTE, with maximum for B100 blends with additives. CO and HC emissions increased, whereas NOx and smoke emissions decreased compared to B20, B50 and B100.

Further addition of methanol up to 10% showed the same trend with maximum increase of 11% and 13% for CO and HC emission for M10D5B20 at 0% EGR and a significant reduction in smoke percentage were observed. At the same time, an extreme decrease in NO_x emission was observed for all the fuels with 10% methanol in it with the maximum decrease for M10D5B20 series blends.

In terms of performance, BTE increased, whereas BSEC decreased at 20% EGR. In terms of emissions, HC and CO increases whereas NO_x and smoke decreases using EGR at 20%. The maximum decrease of 52% in NO_x was observed for M10D5B20 at 20% EGR.

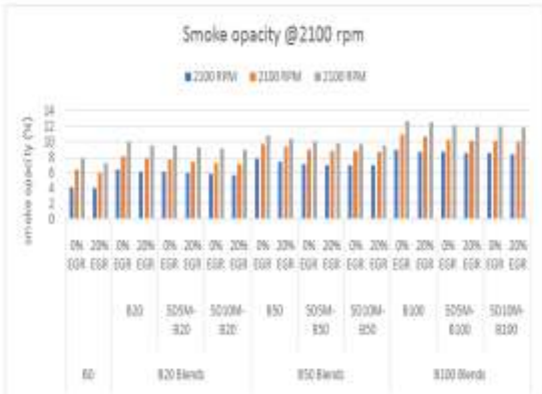

Fig. 7:Smoke emission of different fuel blends at 0% and 20% EGR

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