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Effects ofEGR onPerformance andEmissions ofaLight-DutyModern DI Diesel Engine Fueled with Blends of Diesel, Kerosene, andBiodiesel

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ABSTRACT-The extensive research on a light-duty modern 2-cylinder direct injection (DI) diesel engine was conducted with and without exhaust gas recirculation (EGR), using different blends of diesel, kerosene and biodiesel.The engine was operated at three speeds (1000,2100 and3000 rpm), and at each speed, three different loads(low load ≈ 20%;medium load ≈50%; and high load ≈80%) were applied. Three EGRconditions were investigated non-EGR (0%),10% EGR,and 15% EGR.The effect of EGR on the performance parameterssuch as brake-specific energy consumption (BSEC) and brake thermal efficiency (BTE), and on emission parameters such as nitrogen oxides (NO_X),carbon monoxide(CO), unburned hydrocarbons(HC) and smoke was investigated at various engine operating conditions. The main objective of thework was to reduce NO_X emissions of a diesel engine fueled with different blends of diesel,kerosene and biodiesel, by using different EGR rates,and to improve other performance and emission parameters.

KEYWORDS-EGR, Diesel engine, Base fuel, Biodiesel, Performance and emissions

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Nomenclature

B0	Diesel
BF	Base fuel (50 vol % diesel + 50 vol % kerosene)
B20	Base fuel with 20 vol % biodiesel
B50	Base fuel with 50 vol % biodiesel
B100	Biodiesel
BSEC	Brake-specific energy consumption
BSFC	Brake-specific fuel consumption
BTE	Brake thermal efficiency
cc	Cubic centimeter
CI	Compression ignition
CO	Carbon monoxide
CO_2	Carbon dioxide
cSt	Centistoke
°C	Degree Celsius
EGT	Exhaust gas temperature
EGR	Exhaust gas recirculation
GHG	Greenhouse gas
HC	Hydrocarbon
kg/m^3	Kilogram per cubic meter
kJ/kg	Kilojoule per kilogram
kW	Kilowatt
mg/m^3	Milligram per cubic meter
ml/min	Milliliter per minute
mm	Millimeter
MJ/kWh	Mega Joule per Kilowatt-hour
NO	Nitric oxide
NO_2	Nitrogendioxide
NO_X	Oxides of nitrogen

PM	Particulate matter
ppm	Parts per million
rpm	Revolutions per minute
SI	Spark ignition
US EPA	United States Environmental Protection Agency

I. INTRODUCTION

Population growth and industrial development have led to a surge in the global demand for energy in recent years, due to which many researchers and government are investing their time and money in the research and development of the alternative fuels. In comparison to gasoline engines(SI),diesel engines(CI) are more popular energy conversion devices because of their higher fuel conversion efficiency, greater torque capability, superior durability, and lower HC and CO emissions. Due to more pros than cons,the extensive use of the compression ignition (CI) engine in mining, construction and transportation, as well as new emissions regulations have increased interest in developing cleaner diesel engines. Biodiesel has become a promising alternative to conventional diesel fuel due to its ability to run in CI engines with little to no modification andit emits less greenhouse gas (GHG) and other pollutants. On a lifecycle basis when compared to conventional diesel, biodiesel can reduce net carbon-dioxide emissions by 78% [1]. United States Environmental Protection Agency (US EPA) has done a comprehensive analysis of biodiesel impacts on exhaust emissions [2], and it is shown that pure biodiesel can reduce HC as high as 70% and PM and CO about 50% when compared with conventional diesel fuel.

Apart from the above advantages of biodiesel fuel, an engine fueled with biodieselhas high NO_X emissions, which renders it difficult to meet emission regulations. There are two main methods of alleviating NOx emissions: pre-treatment and post-treatment technology.This research paper focuses mainly on EGR(a post-treatment) effects on NOx as well as performance and other emissions.

Future vehicles demand engine modifications as well as high-quality energy sources(fuels) to be compliant with stringent emission norms. It is deduced that EGR has become an essential control technique for both advanced combustion engines (SI and CI)and alternately-fueled engine applications [3,4].Thermal and prompt mechanisms of NOx formation are important in biodiesel combustion [5]. Thermal NO_X is formed from high local temperatures due to excessive hydrocarbon(HC) oxidation.Prompt NO_X is produced by the formation of free radicals in front flame. It has been reported that NO_X concentration is mainly affected by the prompt mechanism in biodiesel combustion [6].Although biodiesel and EGR have been studiedseparately in many researches [7-13], the combination of these two technologies is relatively uncommon.The common trend of biodiesel results is lower CO, HC and PM with a slight increase in NOx, and with EGR, the NOx is reduced.

In the following references [14-20], current research works of biodiesel in diesel engine combined with EGR is presented.Biodiesel with cetane improver under 20% EGR reduces NO_xemissions by 33% when compared to baseline fuel without EGR [14]. However CO, HC and smoke emissions increase with an increase in percentage of EGR.In ref. [15], it is mentioned that NO_x emissions are higher for fish oil biodiesel and its blends. The percentage increase of NO_x emission is higher for higher percentages of biodiesel in the blend. EGR flow-rates of 10%, 20% and 30% were used in the work. It was found that 20% EGR rate is optimum for 20% biodiesel blend considering the emissions of NO_x and Soot.The results show that *Simaroubaglauca*biodiesel decreases HC, CO and smoke emissions with slight increase of NOx [16]. At EGR rate 20% there is substantial increase in HC, CO, and opacity and NOx values are lesser than the diesel operation. It is optimized that 15% EGR rate and B10 biodiesel blend gives better performance and lower emissions for all operating conditions. In ref. [17], 15% EGR rate is attempted for different biodiesel-diesel blends. With B50 and B100 at high load conditions approximately 25-30% NOx reduction is obtained than non-EGR. A recent publication [20] shows the results of EGR with palm biodiesel in a diesel engine at a constant engine speed of 2500 rpm in full load condition. The results showed that, from the simulated and experimental works, palm biodiesel significantly increased fuel consumption, increased NOx and slightly decreases in other emissions including CO_2, CO, and HC. However, the use of EGR shows a significant reduction in the NOx emission and exhaust temperature but increases in fueleconomy, CO, CO_2, and HC emissions.

In our research, a base fuel (BF), which is 50 vol% winter diesel and 50 vol.% kerosene is used to prepare biodiesel blends. BF is used with biodiesel to extend biodiesel blends use in severe cold conditions like in Canadian winter. To our knowledge, there is no research with this BF and blends with biodiesel and EGR combination. This paper presents a comprehensive review of the impact of different percentages of EGR on performance and emissions, including details of engine and operating conditions. 10% EGR and 15% EGR are tested. The main objectives of this work are to provide information to engineers, industrialists and researchers who are interested in biodiesel and EGR, and to emphasize the application of EGR and the use of different blend of biodiesel,diesel and kerosene to benefit from the advantages of biodiesel and EGR technology.The other purpose of using kerosene indiesel to make BF is because it drastically reduces viscosity of the whole fuel blend, which will improve injection and combustion.This work is an addition to the scientific literature, with substantial investigation into diesel engine performance and emissions with biodiesel and EGR.

II. MATERIALS AND METHODS

2.1 MATERIALS

The following materials were used in the comprehensive research:

● The fundamental materials (low-sulfur diesel, canola oil and kerosene)were purchasedfrom a local gas station;

● Methanol, sodium hydroxide pelletswere obtained from Lakehead University's chemistry lab.

● The EGR attachment, radiator (heat exchanger) and exhaust filters were purchased from Canadian tire.

2.2 BIODIESEL PRODUCTION

Oils and fats can be converted into biodiesel through various processes, i.e., direct blending (dilution), micro-emulsion, catalytic cracking and transesterification.In this research work,the base catalyzed transesterification method was used to produce biodiesel.Transesterification was used because it is the most economical process, requiring only low temperature and pressure which were easily attainable in the given facility. The procedure to make biodieselfollowed in this study is similar to that described in [21].The volumetric collection efficiency of biodiesel was calculated to approximately 80%.ASTM 6751 method is used to determine thequality of biodiesel. All the properties are satisfactory according to ASTM limit [22].

2.3 ENGINE SETUP

An air-cooled, 2-cylinder, 4-stroke light-duty (HATZ 2G40) diesel engine with a direct fuel injection system was used; its specifications are shown in Table 1.For circulation of exhaust gases into the intake manifold, an EGR setup with a control valve was built. In order to obtain cold EGR, a radiator was attached and was immersed in the chilled water.A schematic diagram for the diesel engine is outlined in Figure 1.

Table 1: Engine Specifications

Engine make and model	HATZ 2G40
Engine type	4-stroke, air-cooled
Number of cylinders	2
Bore/stroke	92 mm/75 mm
Displacement	997 cc
Compressions ratio	20.5:1
Rated power	17 kW @ 3600 rpm

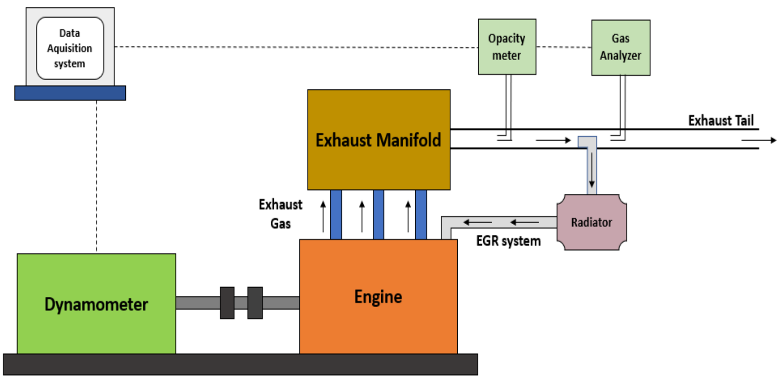

Fig. 1: Schematic diagram of experimental setup

2.4EXHAUST GAS RECIRCULATION (EGR)

EGR is a technique used to reduce $NO_X$by reducing the cylinder temperature and front flame temperature**.**In the EGR technique,a portion of the exhaust gas is recirculated back to the engine cylinderand involves replacing the oxygen and nitrogen from the fresh air entering the combustion chamber with the carbon dioxide and water vapor from the engine exhaust. This resulted in the dilution of the O_2 in the incoming air stream. The burnt gas introduced is inert, and therefore it did not contribute to the burning, nor did it produce more heat; rather, it acted as an absorbent of the combustion heat to reduce the temperature in the cylinder and front flame; this resulted in NO_Xreduction. The recirculation of a portion of the exhaust gases into the engine intake air increased the specific heat capacity of the mixture and reduced the oxygen concentration of the intake mixture. The combination of these two factors led to a significant reduction in NOx emissions. The amount of exhaust gas recirculated was calculated using the following formula:

$$\%\ \text{EGR} = \frac{\text{MASS OF EGR}}{\text{TOTAL INTAKE CHARGE IN THE CYLINDER}} * 100$$

2.4.1 EGR SETUP

In this research work, cooled EGR was used to allow the greater mass of recirculated gas. The hot exhaust gas was cooled with the heat exchanger, and then the cooled exhaust gas was recirculated in the engine cylinder. The exhaust gas was cooled because cooled EGR has more heat energy to absorb in the engine cylinder. There are two outlets available for using technology, or for attaching or mounting a component onto the engine; one of which was used to recirculate the cooled EGR in the cylinder (the amount of EGR is governed with the help of a valve mounted near the exhaust to regulate the definite percentage of EGR to bleed from the exhaust manifold). A portion of the exhaust is channeled through an EGR control valve and proceeds to the EGR cooler. From the cooler, EGR flows to a throttle valve assembly where it is mixed with filtered, high-pressure, fresh combustion air that has been cooled by an intercooler to recover some of its density. The mixture of air and EGR is then inducted into the engine through the intake manifold.

2.5 MEASUREMENTAPPARATUS

2.5.1 EMISSION MEASUREMENTS

For emission testing, several devices were used: NovaGas 7466K for regular emissions, DWYER 1205A analyzer for CO emission, a Smart 1500 opacity meter to measure the amount of smoke produced,anda J-type thermocoupleto measure the exhaust gas temperatures. The specifications of the emission measurement devices are shown inTable 2.

Table 2: Specifications of Emission Measurement Devices

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

2.5.2BOMB CALORIMETER

The bomb calorimeter is a type of constant-volume calorimeter used for measuring the heat of combustion of a particularreaction. A plain jacket-type bomb calorimeter was used in this experiment.

2.5.3 OSTWALDVISCOMETER

An Ostwald viscometer wasused in this study to measure the viscosity of different fuel samples. Fuel is allowed to flow through its capillary tube between two marks, and the time of flow of the fuel is measured using a stopwatch. The comparison of the times for different fuels deduces the viscosity.

2.6. ENGINE TEST PROCEDURE

The engine was tested at three speed conditions: 1000rpm, 2100rpm, and 3000rpm. CO, CO_2,NO, NO_2, HC, O_2, exhaust temperature and opacity readings were taken. The probe was inserted for 2 minutes for each test, which was the length of time we observed to be the best in order to achieve a stable reading of exhaust gas components. We tested the engine in three different times for three readings; the average of these three readings of performance and emission parameters is presented in the next sections.

III. RESULT AND DISCUSSION

3.1 FUELPROPERTY

All the fuel property is illustrated in the Table 3.

Table 3 Properties of various fuels

Fuels	Fuel composition	H.V. (MJ/kg)	Density (kg/m^3)	Viscosity (cSt @ 40°C)
B0	Diesel 100%	44.806	844	2.62
Base Fuel (BF)	50% kerosene + 50% diesel	45.388	827	2.08
K100	Kerosene 100%	46.456	795	1.53
B20	Biodiesel 20% + Base fuel 80%	44.376	827	2.61
B50	Biodiesel 50% + Base fuel 50%	42.866	856	3.40
B100	Biodiesel 100%	40.334	886	4.72

3.1.1 CALORIFIC VALUE

The calorific value is a very important property of fuels to be used in an engine for combustion because the power output is fairly dependent on calorific value. Different fuels have different calorific value. It was found that the calorific value of biodiesel is lower (40.334 MJ/kg) compared to diesel fuel (44.806 MJ/kg) and kerosene(46.450 MJ/kg). As the concentration of the biodiesel increased in the blend, the heating value of the whole fuel blend decreased.

3.1.2 CLOUD AND POUR POINT

Cloud and pour point are the important fuel properties when assessing performance at a low ambient temperature. It is critical for cooled fuel to flow rather than transforming into a cloud of wax crystal, because solidification of fuel will block the fuel filter and fuel line, and will damage the engine. The cold weather performance of biodiesel is comparatively lower than diesel fuel[23]. Moreover, in cold weather conditions, the pour point and the cloud point become more crucial complications when using biodiesel. Biodiesel has higher cloud and pour point than diesel, kerosene andbase fuel(BF)due to a higher amount of fatty acid. Therefore, the increase of biodiesel concentration in the blend will contribute to the increase of cloud and pour point. Winter diesel's CP is -40˚C and that of kerosene's -78˚C. The BF shows CP of -50˚C. Our produced canola biodiesel's CP is only -2.6˚C.

3.1.3 KINEMATIC VISCOSITY

Kinematic viscosity is defined as the resistance of liquid to flow. Viscosity is also an importantparameter for fuel to be selected as it is directly related to the quality of IC engine combustion, including atomization and spray characteristics [24]. Lower fuel viscosity increases wear and leakage due to the insufficient lubrication. Also, high viscosity results in incomplete combustion and more difficulties in cold weather because when the temperature decreases, viscosity increases.High viscosity may lead to the formation of soot and engine deposits due to insufficient fuel atomization. It was found that the kinematic viscosity of biodiesel is much higher than diesel(B0), kerosene(K100)and base fuel(BF). Therefore, the increase of biodiesel concentration in the blend will contribute to the increase of kinematic viscosity of the whole fuel blend. Viscosity of B100 is 4.72 cSt, whereas the BF's viscosity is 2.08 cSt.

3.2. ENGINE PERFORMANCE

3.2.1. BRAKE-SPECIFICENERGY CONSUMPTION (BSEC)

Figure2 represents a comparison of BSEC for all different fuels using EGR with baseline data. BSEC ranges from 9-11 MJ/kWh for different fuels and engine conditions. There is a very slight increase in BSEC of BF compared to diesel at all non-EGR conditions. It was observed that as the EGR rate increased, the BSEC decreased. It was also observed that BSEC was less with EGR than without EGR, which could be due to the improvement in BTE. At 3000 rpm, BSEC's are about 6-7% less than that of 1000 and 2100 rpm due to higher in-cylinder temperatures and better combustion. There is no significant change in BSEC among different fuel blends for similar engine condition. This suggests that the thermal efficiency is pretty much similar for all fuel blends in a similar engine condition. Another observation is that at higher load the BSEC is lower due to higher fuel supply and increased in-cylinder temperature.

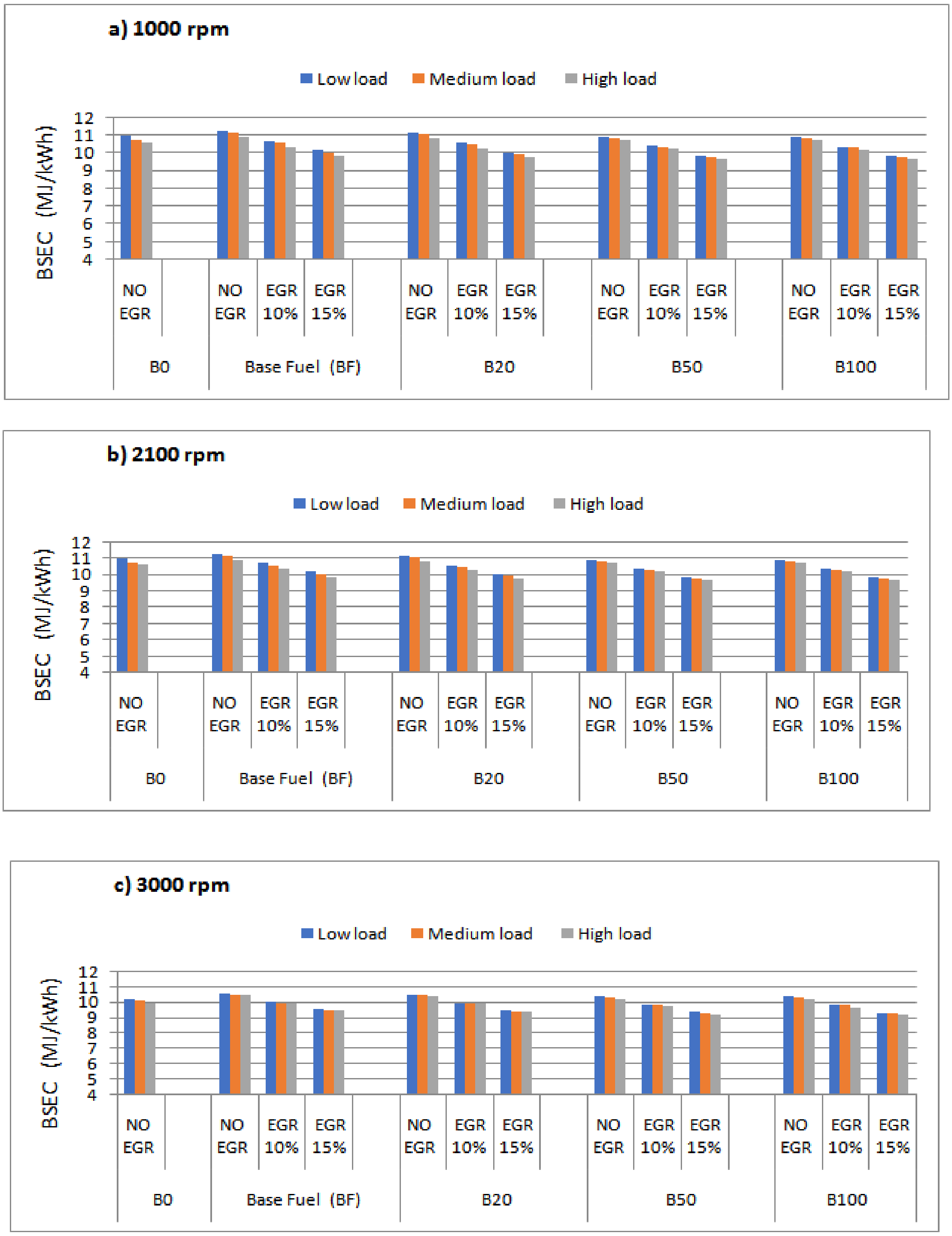

Fig. 2: BSEC of different fuel blends with and without EGR at (a) 1000 rpm, (b) 2100 rpm, and (c) 3000 rpm

3.2.2. BRAKE THERMAL EFFICIENCY

The trends of the thermal efficiency are shown in Figure3. Thermal efficiency was found to be slightly increased as the EGR percentage increased.The possible reason may be re-burning of HCs that enter the combustion chamber with the recirculated exhaust gases. Also, EGR increased intake charge temperature, which in turn increased the rate of combustion. However, the recirculation of too much exhaust gases displaces much of the necessary air for combustion, hence maydecrease the thermal efficiency. The low percentage of EGR (up to 15%) in this research seems created positive environment inside the cylinder for better combustion in this small diesel engine. As the load increased, BTE also increased. The results show that by introducing EGR, the brake thermal efficiency increased, and 15%EGR had higher BTE (1-2% higher) than 10% EGR and about 3-4% higher than without EGR.When the engine was operated on biodiesel blends with EGR, there is no significant increase in thermal efficiency up to B50, however, B100 shows about 1-2% BTE increase than other fuel blends.This may be due to oxygen content of biodiesel which helps better combustion. Higher engine speed and load showed a little higher BTE for all the fuels and engine conditions due to higher temperature and better air fuel mixing.

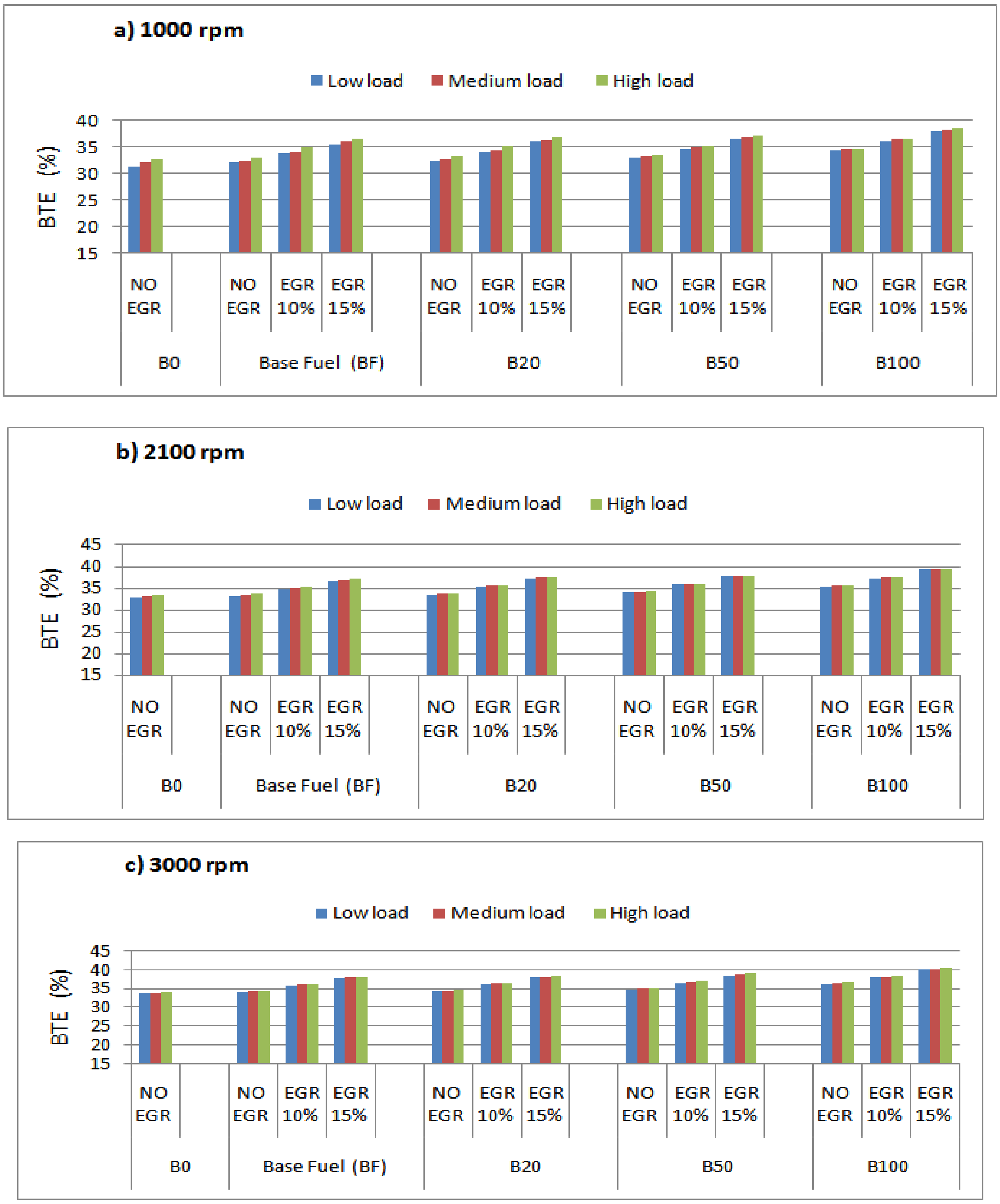

Fig. 3: BTE of different fuel blends with and without EGR at (a) 1000 rpm, (b) 2100 rpm, and (c) 3000 rpm

3.4 ENGINE EMISSIONS

3.4.1 NO_x EMISSION

Figure 4 shows NOx emissions for different fuel blends with and without EGR at differentengine speeds and loads. For all the fuel blends, the NO_X emission increased with the increased load at all three engine speeds. At medium load, NOx is about 15% increased than low load and at high load it is approximately 30% higher than low load condition. The main reason for this increase at higher loads is that the higher temperature generation in the combustion chamber was due to the increased fuel injection at high load conditions. Addition of biodiesel with BF shows an increase in NOx emissions and for no EGR, B100 increased approximately 20-25% NOx than BF and 30-40% than diesel. Fuel-bound oxygen of biodiesel helps to increase the NOx emissions for biodiesel blends.

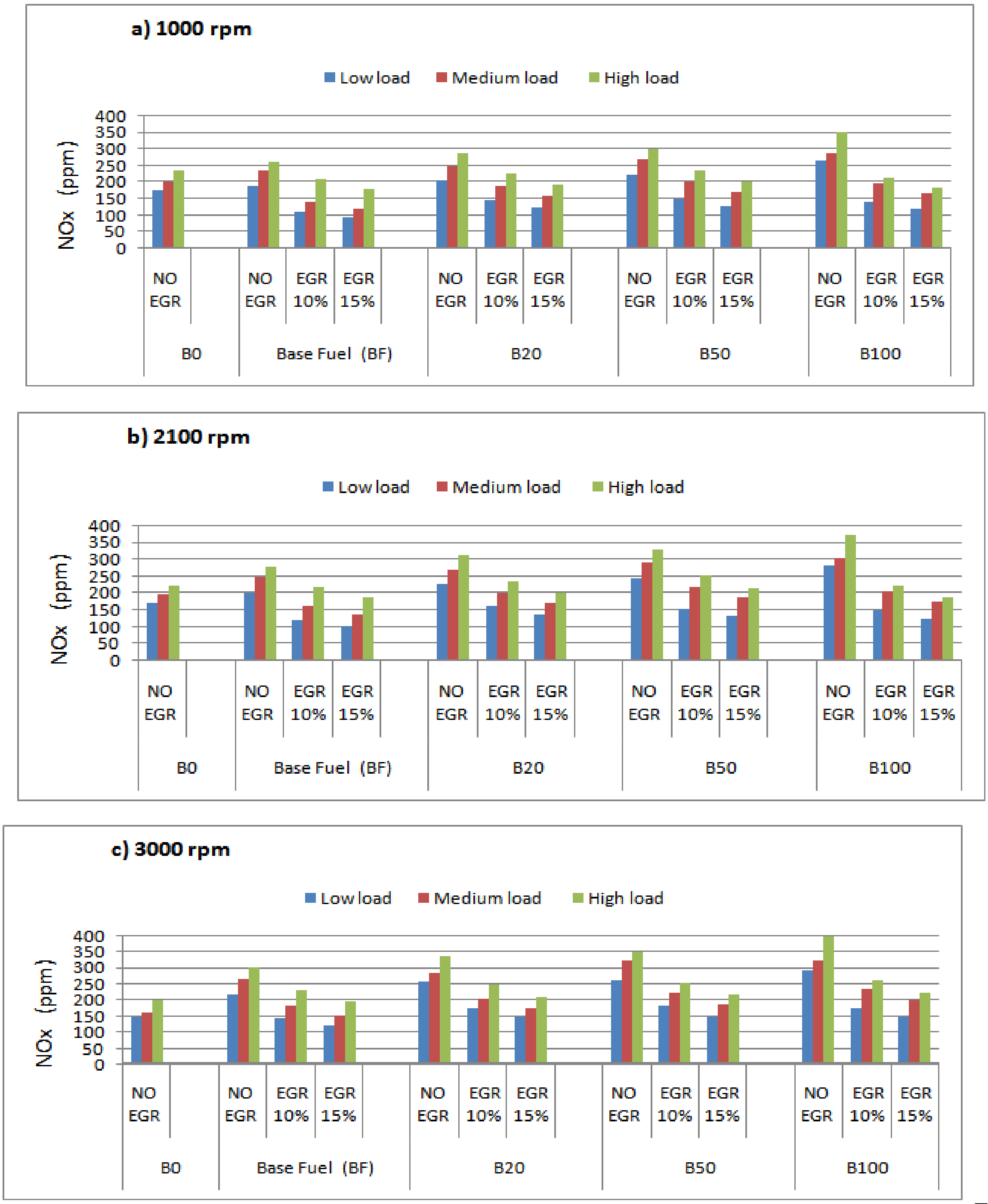

Fig. 4: NO_x emissions of different fuel blends with and without EGR at (a) 1000 rpm, (b) 2100 rpm, and (c) 3000 rpm

However, from figure 4, it is clearly understood the benefit of EGR to reduce NOx from diesel engine combustion. 10% EGR is found to reduce about 20% average NOx than non-EGR and 15% EGR showed about 30% NOx reduction than non-EGR. This is a significant reduction in NOx with low percentage of EGR, and this reduction is due to dilution of in-cylinder content due to EGR and subsequent temperature reduction in the cylinder.

3.4.2 SMOKE EMISSION

The smoke opacity is shown in figure 5 for different fuel blends with and without EGR at different load and speed. A significant smoke reduction (≈30%) is obtained for BF than diesel at all engine conditions. This shows the potential of kerosene to be used in diesel engine with low smoke emissions. A very slight increase in smoke is obtained with EGR than non-EGR. Usually the introduction of EGR reduced oxygen for combustion of fuel in the engine cylinder, which showed a negative impact on combustion and resulted in incomplete combustion and increased formation of PM in diesel operated engine. However, kerosene in the blend improves the combustion and lessens the negative effect of EGR. Smoke opacity for biodiesel blends without EGR was noticed to be generally higher than that of diesel (15-35% for B100 than BF), which should not be the result because biodiesel molecules contain oxygen, which is a reason why the combustion should have improved, thus resulting in lower smoke. However, the actual results contradict this. As there were no modifications made to the injection valve or to the injection system as the whole, it is observed that due to higher viscosity of biodiesel, there was an increase of injection pressure causing over-penetration of the fuel, which could cause wall-quenching for this small engine and resulting smoke increase for biodiesel blends.

3.4.3 CO AND HC EMISSION

Figure 6 shows the CO emission of different fuels. The CO emission is mainly a product of incomplete combustion. Higher combustion efficiency and temperature help reduce CO emission; therefore, the biodiesel-diesel blends reduced CO emission compared to pure diesel at all engine conditions investigated. Approximately 50% CO reduction was achieved with B100 than BF or diesel at all non-EGR conditions. An increase in the load led to an adequate turbulence and high temperature environment, which resulted in additional CO reduction. At high load on average more than 50% CO was reduced than that of low load at all engine conditions. At higher EGR rates, CO emissions were comparatively higher because of lower availability of oxygen due to EGR, leading to incomplete combustion results with an increase of CO emission. For example, Figure 6 shows that CO emission for B20 without EGR for mid load at 1000 rpm was 1100 ppm, whereas B20 with 10% and 15% EGR was 1500 ppm and 1600 ppm, respectively.

Figure 7 shows HC emission of different fuel blend with EGR and without EGR for different fuel blends. As the load increased, HC emission decreased because at higher load condition, high temperature conditions were generated resulting in more efficient combustion. By adding biodiesel to the diesel and kerosene blends, the oxygen availability from the fuel increased, resulting in a complete combustion and therefore the HC emission lowered as the concentration of biodiesel increased in the blend, and B100 reduced two-third or more HC than BF and diesel. As the EGR percentage increased, the HC emission also slightly increased because the introduction of EGR led to an increase of unburned HC in the combustion chamber.

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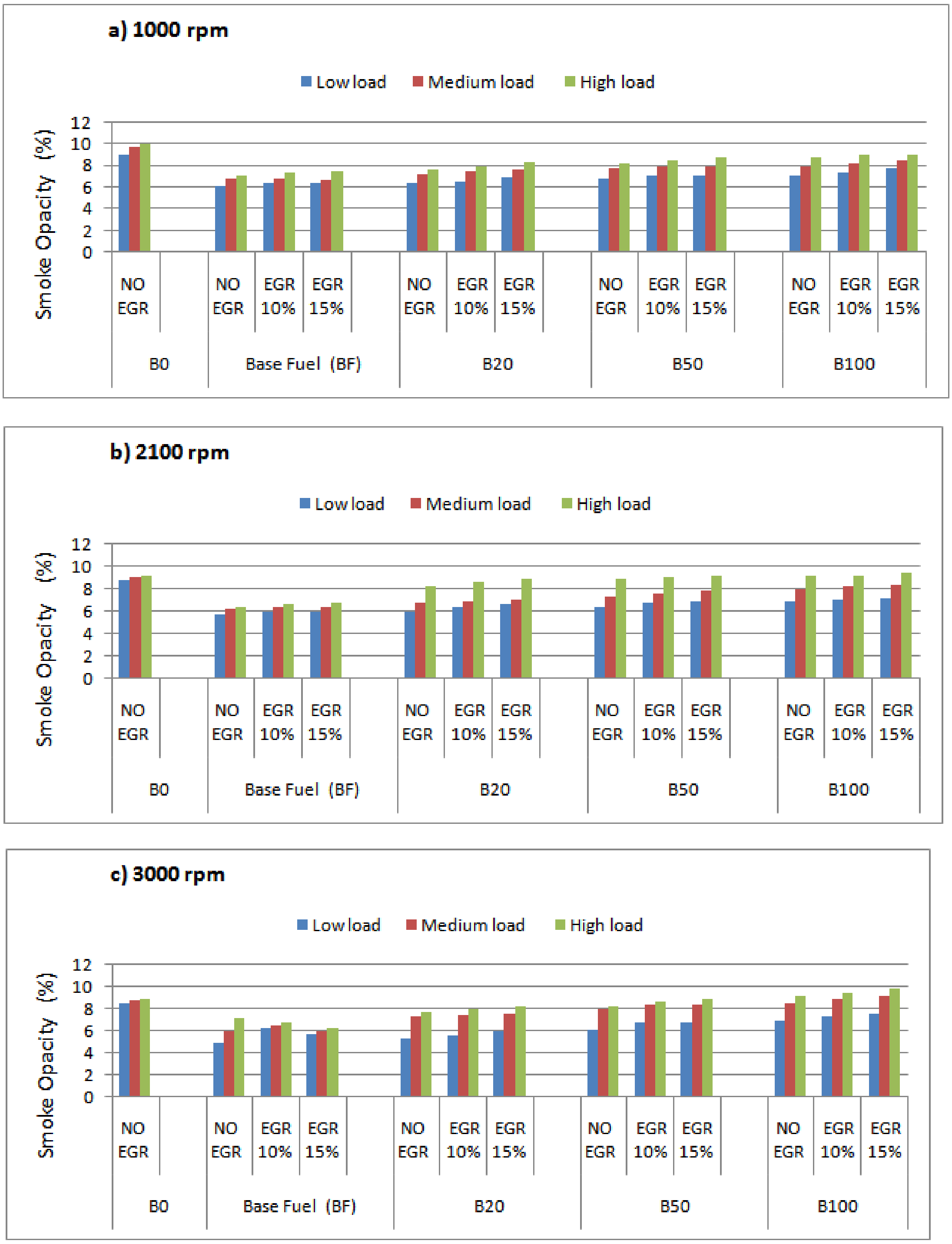

Fig. 5: Smoke opacity of different fuel blends with and without EGR at (a) 1000 rpm, (b) 2100 rpm, and (c) 3000 rpm

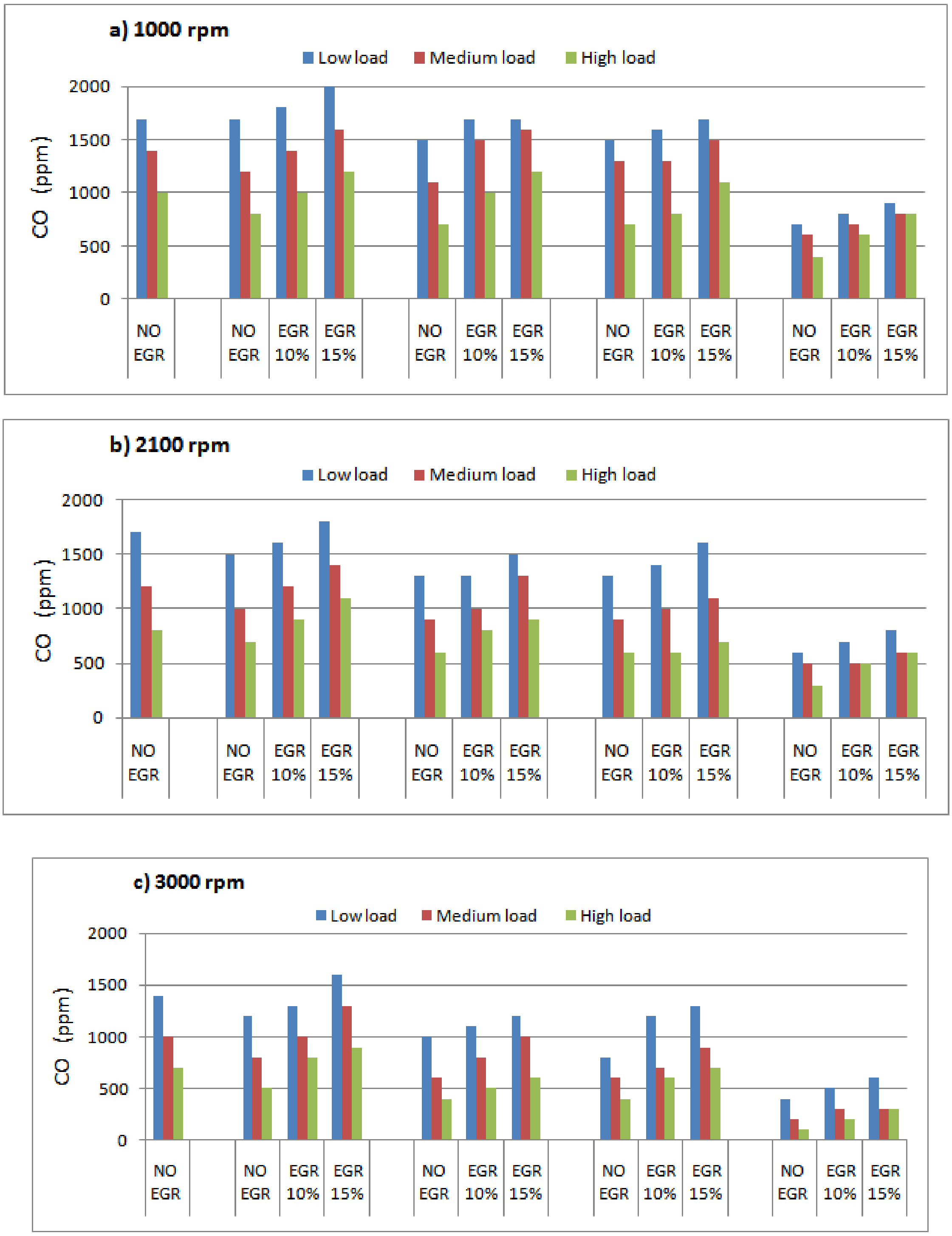

Fig. 6: CO emissions of different fuel blends with and without EGR at (a) 1000 rpm, (b) 2100 rpm, and (c) 3000 rpm

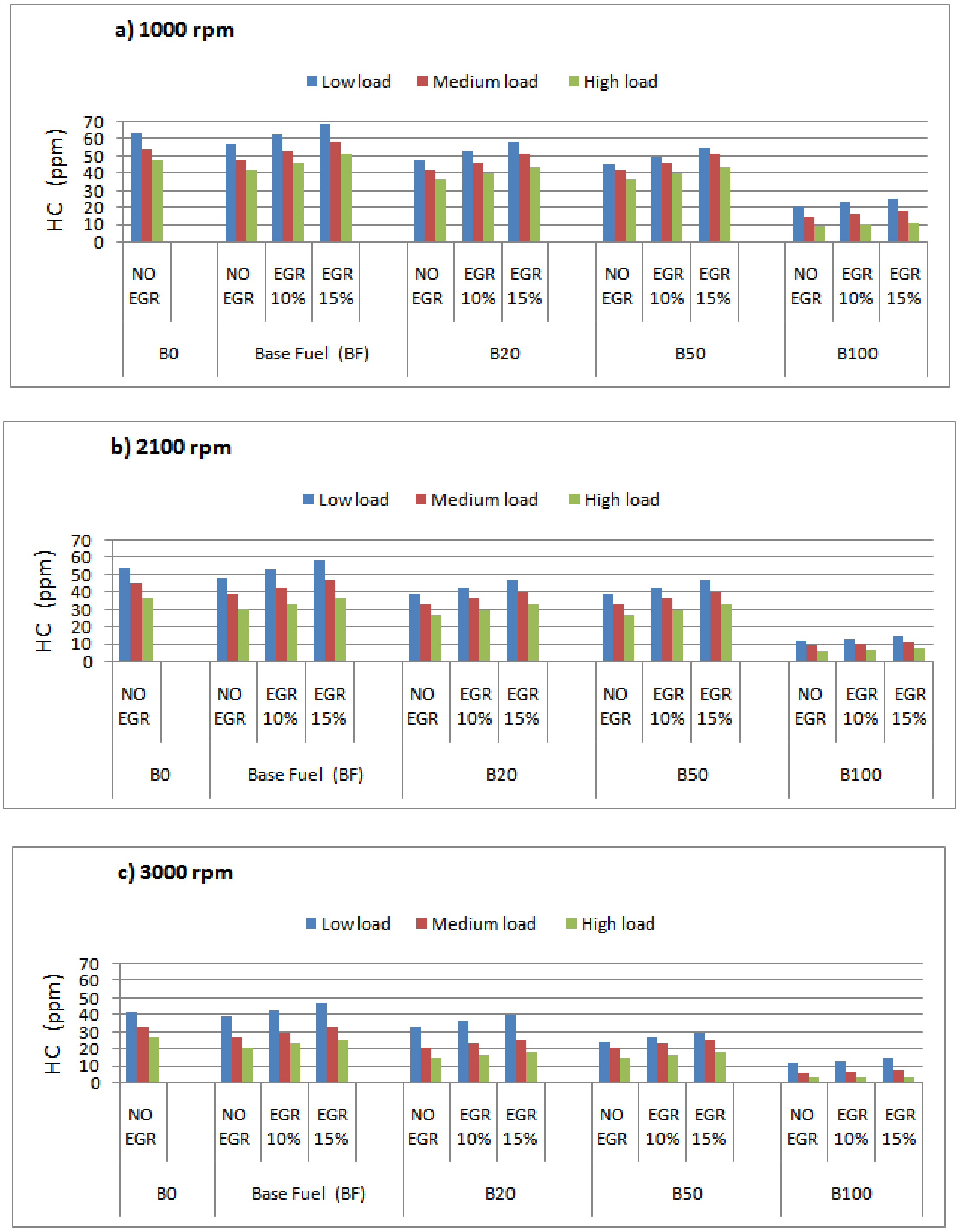

Fig. 7: HC emissions of different fuel blends with and without EGR at (a) 1000 rpm, (b) 2100 rpm, and (c) 3000 rpm

IV. CONCLUSION

The main conclusions from this study are outlined below:

● Therewas a considerable decrease of nitrogen oxides (NO_X)using EGR technology. NO_Xemission was less in 15% EGR compared to 10% EGR and without EGR. The reduction of NO_Xusing 10% EGR was approximately 20%; using 15% EGR provided about30% reduction.

● Hydrocarbons(HC) and carbon monoxide(CO) emissionsincreasedwith the introduction of EGR. It was noted that emission without EGR hadthe lowest HC and carbon monoxide(CO) than 10% and 15% EGR,and that 15% EGR had more HC and carbon monoxide(CO) in emission than 10% EGR. The increase of HC emission using

10% EGR was approximately 10%, whereas by using 15% EGR, the increase was about 20%.Secondly, the increase of CO emissionusing 10% EGR was about 6%, whereas using 15% EGR showed an increase of between 12%and 17%.

● EGR contributed to a marginal increase(0.1 to 0.5%)of the smoke level than without EGR.

● BTE increasedas EGR was introduced. In comparison with EGR and without EGR, the performance with EGR technology was better. The maximum BTE obtained for 15% EGR was 3-4% and for 10% EGR was 1-2% higher than non-EGR conditions.As BTE increasedwith the use of the EGR, BSEC decreased as the EGR rate increased.

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