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Performance and Emissions of a Modern Small DI Diesel Engine Fueled by Diesel-Biodiesel-Iso-Butanol Blends with EGR

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ABSTRACT
Iso-butanol is one of the next-generation biofuels that has the ability to help alleviate the energy crisis and environmental problems. The prime objective of this work is to experimentally investigate the performance and emissions of a modern light-duty diesel engine fueled by diesel-biodiesel-iso-butanol blends, and to compare the results to those of petroleum diesel. Biodiesel that varied between0% (pure diesel) and90%, as well as 10% iso-butanol, was examined. The engine speeds selected for the operation were low speed (1000 rpm), high torque speed (2100 rpm) and high power speed (3000 rpm). At each engine speed, three loads were tested: low (≈20%), medium (≈50%), and high (≈80%).In addition, the exhaust gas recirculation (EGR) was used to investigate its effect on the performance and emissions of the fuel blends. An EGR, up to 15% was attempted. Engine performance (brake-specific energy consumption and brake thermal efficiency) and regulated emissions: carbon monoxide (CO), hydrocarbon (HC), oxides of nitrogen (NO_x), and smoke emission were investigated. The results show that the addition of 10% iso-butanol to blends of diesel and biodiesel increased brake thermal efficiency. There was a significant reduction of regulated emissions (NO_x, HC and CO) with an increase of the proportion of biodiesel. The addition of the EGR method delivered a similar effect, which increased brake thermal efficiency and reduced emissions.
Keywords- Biodiesel, Diesel Engine, EGR, Iso-butanol, Performance and Emissions.

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I. INTRODUCTION

Internal combustion (IC) engines are one of most graceful inventions of humankind that had a great impact on society, on the economy, and on the environment. Since its invention in the 19thcentury, this magnificent innovation played a vital role in the engines, especially in automobile systems, due to its attractiveness such as reliability, ease of handling, and operational efficiency. The late 20thcentury created the necessity to improve combustion engines in terms of performance and reduction of exhaust emissions due to stringent environmental regulations put forward by various nations worldwide [1]. Since alterations in engine structure are limited due to constraints such as cost, level of complexity, size limitations, etc., studies are mainly focused on improving performance and regulated emissions in IC engines through the use of alternate fuels with minimal modification to the engine's characteristics within the system [2-5].

Diesel and gasoline engines constitute the lion's share of internal combustion engines due to portability, which is its major advantage. The developments in these engines changed from two-stroke to four-stroke overtime. Along with improvements in other factors such as ignition system, fuel systems, engine configuration, engine capacity, lubrication systems, etc., a diesel engine is more advantageous for commercial purposes due to its economic benefit and ease of manufacturing a wide range of engines sizes. Diesel engine generates exhaust gases containing harmful emissions during combustion, such as particulate matters (PM) or smoke, carbon monoxide (CO), unburned hydrocarbons (UHC), and oxides of nitrogen (NOx) [6 - 9].

IC engines are powered mainly by fossil fuels, which fulfil 80% of the world's energy needs, making it the most powerful source of energy [10-11]. As a non-renewable source, fossil fuels have disadvantages such as market price fluctuations and emissions that cause pollution, resulting in global warming. The day-to-day depletion of this resource, and the increase in its demand, intensifies the momentum in fuel price. Availability of fossil fuels in the future remains a mystery.

These days, there is an increased emphasis on research into alternative fuels to address the crisis of reducing the impact of global warming effects, as well as the potential lack of fossil fuels. Renewable fuels, which have begun replacing fossil fuels, have the ability to reduce greenhouse gas emissions emitted from vehicles and heavy equipment. Until now, they were used in proportions or blends with fossil fuels due to bounded production regulations, which is an actual tool to increase the use of green fuels [12]. Biofuels are being improved and used in automobiles by more than 3.5% worldwide [13]. The most common green fuels known to the public are bioethanol and biodiesel.

Recently, biodiesel was the first choice for investigators in this field, and has been chosen as a reasonable alternative for diesel fuel, since its properties are similar to those of diesel fuel. Also, it can be mixed with diesel in a varied range of proportions without any modifications to compression ignition engines [14]. Vegetable oils, which consist of edible and non-edible oils, are the main sources of biodiesel production by roughly 95% [15]. Biodiesel has the ability to reduce the quantity of regulated emissions (CO, HC and PM). On the other hand, there is general agreement that indicates that biodiesel has a negative side whereby the proportion of NOx is slightly increased. However, biodiesel can be incorporated with new technologies such as catalysts, particulate traps, exhaust gas recirculation, cetane improver and emulsion in order to resolve this issue [16-18]. Other alternatives include adding alcohols such as methanol, ethanol, pentanol, kerosene, propanol and iso-butanol in proportions with diesel and biodiesel as fuel additives [19-23]. In addition, they are oxygenated fuels which in turn reduce many diesel engine emissions including soot [24-25].Alcohol, which belongs in the organic molecules family, can be used in diesel engines due to a reduction in emissions and to reduce the consumption of fossil fuels. Adding alcohol is a desirable option to enhance biodiesel properties with minimal NOx emissions [26]. Bayındır et al. [22] tested fuels which were prepared from diesel, biodiesel and kerosene. They found that the fuels consisting of10% kerosene had the exact same combustion characteristics as pure diesel. In addition, NOx emissions decreased with the blends. Using 5% pentanol with blends of diesel and biodiesel, Yilmaza et al. [21] indicated that exhaust gas temperature, CO and NOx emissions decreased. Ref. [27] made a comparison of three fuels: 80% diesel/20% biodiesel, 80% diesel/10% biodiesel/10% n-butanol with ultra-low sulfur diesel. This study showed that CO and NOx emissions decreased at low load condition, whereas thermal efficiency increased. For the propanol, Atmanli [23] conducted experiments on blends containing 20% propanol of the total volume of the blend. Those studies revealed that the blends have the capability of reducing NOx emissions.

Iso-butanol is one of the best alcohol types for use as a fuel additive in diesel engines [28]. Studies show that alcohols have higher latent heat of vaporization compared to diesel fuel. Iso-butanol is one among four isomers of butanol. The main difference between these isomers is the location of the hydroxyl group (OH) and the carbon chain structure [29]. By adding butanol in biodiesel of palm oil in a diesel engine, Sharon et al. [30] improved brake thermal efficiency (BTE) and reduced NOx emissions. Tüccar et al. [31] stated that using butanol in diesel-microalgae biodiesel blends reduces NOx and CO emissions. In ref. [32], they reported a decrease in power and BTE when fueled in a single cylinder diesel engine by up to 40% volume of iso-butanol in diesel fuel. The results of the studies conducted by Karabektas et al. [33] declared that the brake power and BTE decreased, while increasing brake specific fuel consumption (BSFC). They used four different blends of iso-butanol and diesel, in which each blend contained up to 20% iso-butanol by volume. Moreover, Yang et al. [29] tested various mixtures of diesel/biodiesel (up to 40%)/iso-butanol (10% of volume). They appeared to reduce the emissions of NOx, CO and PM and increase the brake-specific fuel consumption (BSFC). Furthermore, the scientists mentioned that if the higher proportion of iso-butanol was used in the blends, it would have produced worse fuel economy.

In a nutshell, the majority of literature reported a notable decrease in NOx emissions, as well as a decrease in CO when butanol, or one of its isomers, is added to either diesel fuel or diesel/biodiesel blends [29-31]. Some of them proclaim that adding butanol to diesel fuel or diesel/biodiesel blends resulted in increased brake-specific fuel consumption (BSFC) and decreased brake power [29-35]. From another view, some authors [32-33] reveal that the brake thermal efficiency (BTE) decreased when adding a portion of butanol to their blends. However, others [29, 34, 35] reported that the brake thermal efficiency (BTE) increased with the percentage of butanol or its isomers. These conflicts can be explained, as the effect of adding butanol or its isomers on the emissions and engine performance may vary depending on many conditions such as engine specifications, the proportion of butanol or its isomers in fuel blends, and operating conditions. As a remedy for these inconsistencies, this work uses iso-butanol in a constant percentage (10% of volume) and is tested as an alternative additive for diesel engines in order to understand its impact on emissions and engine performance.

There is not much research on iso-butanol in biodiesel with EGR. In ref. [36], one attempt was done, however that is only at a constant engine speed. This study is an addition to the scientific literature about iso-butanol in biodiesel with EGR at different engine speeds and loads, which is a milestone in this research direction. The aim of this study is to experimentally examine and compare the effects of using iso-butanol/biodiesel/diesel blends with and without EGR over a varied engine loads and speeds on a diesel engine's performance and regulated emissions.

II. METHODOLOGY AND EXPERIMENTAL SETUP

2.1 Materials

The materials used in this work are low-sulfur diesel bought from a local gas station, canola oil purchased from a local supermarket; methanol, sodium hydroxide and Iso-butanol from Lakehead University's chemistry department facility.

2.2 Biodiesel Production

Transesterification of vegetable oils and fats is the most common method of biodiesel production. In this process, using methanol (CH_3OH) with sodium hydroxide (NaOH) as a catalyst produces biodiesel following ref. [37].

2.3 Test Fuel Blends

This study emphasized three blends as shown in Table1: IBU10B20 (Iso-butanol 10% with B20); IBU10B50 (Iso-butanol 10% with B50) and IBU10B90 (Iso-butanol 10% with B90). B20, B50 and B90 were produced by adding 20%, 50% and 90% biodiesel in the blends, respectively with diesel. All these blends were compared with pure diesel.

2.4 Exhaust Gas Recirculation (EGR)

EGR is a technique to control mainly NO_x from IC engines. It works by recirculation a portion of the engine's exhaust gas back into the intake air. EGR contains valve which is used to control the flow of exhaust gas. There are two kinds of exhaust gas recirculation: hot EGR and cold EGR. In this study, cold EGR was used due to its more NO_x reducing capability compared to the hot type. By using U-tube manometer, mass flow rate of intake air without and with EGR is calculated. Two EGR settings were used in this study, 10% EGR and 15% EGR. The following equation is used to calculate the percentage of EGR.

EGR% = (Mass of recirculated exhaust/Mass of total intake mixture) × 100

2.5 Diesel Engine and Measurement Devices

A light-duty HATZ engine 2G40 (2-cylinder) was used in this study for tests at three engine speeds (1000, 2100 and 3000 rpm), each with three different loads: low load (LL), medium load (ML) and high load (HL), respectively. Table 2 shows the engine's specifications, and Figure 1 is the schematic diagram of the experimental setup. Two type of software (Dyno 2010 and MB1-SMART1500 OPACITY) were used to measure important parameters such as torque, brake power, speed and smoke opacity. Specialized equipment was used to detect the regulated emissions (CO, NO_x, CO_2 and HC) which includes NovaGas 7466K analyzer, Dwyer 1205A (special analyzer for CO emission), and Smart 1500 opacity meter to measure the quantity of smoke produced. The specifications of emission measurement devices are shown in Table 3.

Table 1: Properties of fuels

Fuel	Heating value (MJ/kg)	Density (kg/m^3)	Viscosity@ 40ºC (cSt)
Diesel	45.05	835	1.92
Biodiesel	39.52	881	4.33
Iso-butanol	34.09	808	2.63
IBU10 B20	42.85	841	2.06
IBU10 B50	41.19	855	2.58
IBU10 B90	38.98	873	3.51

Table 2: Engine specifications

Engine make & model	HATZ 2G40
Engine type	4-stroke, air-cooled
Number of cylinders	2
Bore/stroke	92mm/75mm
Displacement	997cc
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

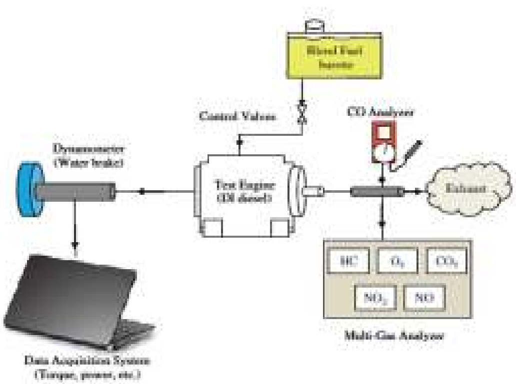

Fig 1: Schematic diagram of experimental setup

Table 3: Specifications of emission measurement devices

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

III. RESULTS AND DISCUSSION

Diesel engine emission and performance were measured from diesel and biodiesel/diesel/iso-butanol blends under various engine operating conditions. The test matrix is shown in Table 4. Four fuels are tested. For each fuel, three engine speeds were used: 1000rpm, 2100 rpm, and 3000rpm. At each speed, three loads were applied: low load (20%), medium load (50%), and high load (80%). In addition, at each test condition, three steps of EGR were applied, no-EGR, 10% EGR and 15% EGR.

3.1 Engine Performance

BSEC and BTE are measured to present the performance of the test engine at different conditions.

3.1.1 Brake Specific Energy Consumption

Brake-specific energy consumption (BSEC) measures the amount of input energy required to develop one-kilowatt hour output. Figure 2 depicts the BSEC of four test fuels. It was observed that the BSEC values declined with an increase in biodiesel concentrations in the blends. Moreover, it is clear that the results of BSEC decreased with increases in speed and load. At No-EGR condition, the peak value was 17.34 MJ/kWh for pure diesel (B0); the bottom point at IBU10 B90differed by 31.35%.

From an EGR standpoint, the results supported the fact that the BSEC trend goes down with the additional percentage of EGR. The high value of these results at 10% condition is 17.13 MJ/kWh for pure diesel (B0) at LL, while 12.5 MJ/kWh was the lower point for BSEC at HL at the same condition of EGR. In 15% condition, the results declined more than other conditions, which consisted of the lowest point in this graph (10.32 MJ/kWhforIBU10 B90) at HL. The average value for decreasing BSEC for one fuel was approximately 5% between 3000 and 1000 rpm. The reason is that blend fuels have very similar fuel properties to that of pure diesel with higher percentage of O_2 content values, which helped better combustion. To summarize, the blended fuel IBU10 B90 requires less input energy to developed one-kilowatt hour output of the engine than others. Therefore, it has an advantage in replacing conventional diesel.

3.1.2 Brake Thermal Efficiency (BTE)

Figure 3shows the BTE of different blends (diesel/biodiesel/10% iso-butanol) at various engine loads and speeds. The BTE increases with an increase in engine load and biodiesel content in the blends. The burning efficiency in the blends is higher than conventional diesel due to higher oxygen percentage. The peak point of BTE for all fuels is IBU10 B90 at high load for 2100 rpm, which is approximately 34%. The BTE of blends (IBU10 B20, IBU10 B50 and IBU10 B90) is increased by about 1%, 2% and 3.75%, respectively when compared to pure diesel at high load condition.

From EGR point, exhaust gas recirculation improves the BTE in all fuel blends. The graph illustrates that using EGR at 10% and 15% led to an increase the BTE compared to the results of BTE without using EGR. The increase in BTE with the EGR is due to the increase in combustion speed/burning efficiency, because EGR increases the intake charge temperature [36]. The proportion of BTE with EGR at high load and 2100 rpm for all blends (IBU10 B20, IBU10 B50, and IBU10 B90) increased on average at 10% condition by approximately 0.5%, and at 15% by approximately 0.75%, respectively compared to the results of BTE without EGR. The highest percentage of BTE with EGR is about 34.9% for IBU10 B90 blend. The results appear to be that the increase in BTE by using exhaust gas recirculation improved slightly at almost 1% at 10% condition, and by 2% at 15% condition. In brief, the IBU10 B90blend could substitute neat diesel fuel for improved BTE in diesel engines.

Table 4: Test matrix

Fuel type (4 fuels)	Speed (3 speeds)	Load (3 loads)	EGR (3 EGRs)	Performance (2 performance parameters)	Emissions (4 emissions)
1) B0 2) IBU10B20 3) IBU10B50 4) IBU10B90	1) 1000 rpm 2) 2100 rpm 3) 3000 rpm	1) 20% 2) 50% 3) 80%	1) No- EGR 2) 10% EGR 3) 15% EGR	1) BSEC 2) BTE	1) NOx 2) CO 3) HC 4) smoke

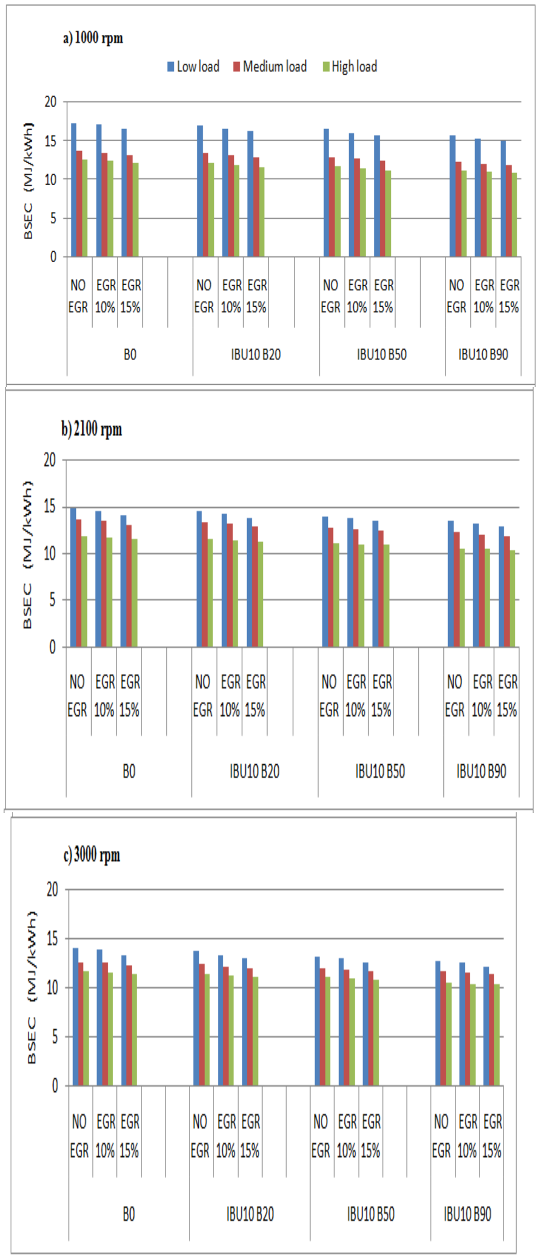

Fig.2: BSEC of different fuel blends with and without EGR at a) 1000 rpm; b) 2100 rpm; and c) 3000 rpm

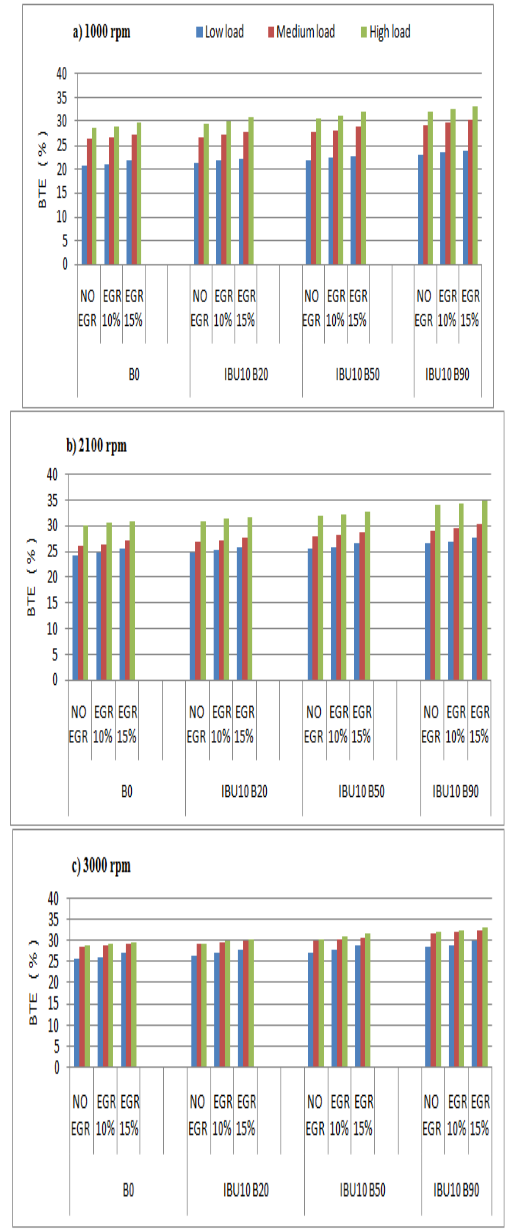

Fig.3: BTE of different fuel blends with and without EGR at a) 1000 rpm; b) 2100 rpm; and c) 3000 rpm

3.2 Engine Emissions

Four important regulated emissions: NO_x, CO, HC and smoke are reported in this study. However, O_2, CO_2 and the exhaust gas temperature are also measured and used in justification of the results.

3.2.1 NO_x Emission

Figure 4 indicates NO_x emissions of different blends at various engine loads and speeds. It is obvious that NO_x emission increases with the increase in load for all fuels investigated due to the higher combustion temperature, as well as the increased fuel supply. The fuel blends (IBU10 B20, IBU10 B50, and IBU10 B90) result in a significant reduction in NO_x emission by approximately 4%, 4.6% and 7%, respectively, compared to B0 at high load and 2100 rpm. The reason for this reduction is that iso-butanol works as a cetane improver, which reduces ignition delay and peak combustion temperature resulting for reducing NO_x. Similar NO_x reduction was obtained by Yang and Lin [29].

From EGR view, the rate of NO_x for fuels diminished more than the standard test result. For 10% EGR condition, the percentages of reduction were 3%, 6% and 7% for IBU10 B20, IBU10 B50 and IBU10 B90, respectively. For 15% EGR condition, the proportions of decrease were about 5%, 8% and 10 %, for IBU10 B20, IBU10 B50 and IBU10 B90, respectively. In conclusion, the iso-butanol drives to reduce the quantity of the NO_x with increase percentage of biodiesel in the blends. IBU10 B90 had a more significant decrease in NO_x emissions than other fuels.

3.2.2 CO Emission

CO emissions from various diesel/biodiesel/iso-butanol blends are presented in figure 5. The graph demonstrates that the percentage of CO emission decreases with an increase in the amount of biodiesel in blends (IBU10 B20, IBU10 B50, and IBU10 B90), which contain more O_2. They provide more O_2 in rich regions, which mixes with iso-butanol, making lean effect on blends which help to reduce the amount of CO. Also, when the blends have a high amount of bound oxygen, it affects the combustion temperature which increases oxidation from CO to CO_2 [29]. The amount of CO is further decreased due to use of EGR. In the 10% EGR condition, the percentage of reduction reached approximately 3.3%, 4.6% and 6%for blends IBU10 B20, IBU10 B50, and IBU10 B90, respectively when compared to the results without EGR. For the 15% condition, the reduction was increased by 6.3%, 9.3% and 9% for the similar blends compared to No-EGR condition. In general, IBU10 B90 had a high reduction in CO emission for all conditions (both with and without EGR). This blend has a better capability of reducing CO than diesel fuel.

3.2.3 HC Emission

It is clear in figure 6 that the HC emission declines with an increase in load and speed of the engine. The blends of diesel/biodiesel/10% iso-butanol emitted lower HC emission than diesel for all engine operating condition investigated (both with and without EGR), due to enhanced combustion efficiency and higher oxygen content in the blends. A similar reduction was noticed by Kiran et al. [36]. Higher cetane number of the blends with iso-butanol was reported to be responsible for this reduction too [38].

To summarize, the graph shows that HC emissions decrease with an increase in biodiesel proportion in the blends. In addition, the reduction increased with EGR. The results revealed that IBU10 B90 had the highest reduction of HC emissions at all conditions.

3.2.4 Smoke Emission

From figure 7, it is obvious that the amount of smoke in the exhaust gas increased significantly in the blends with high biodiesel content. The reason for this increase is that blends have a higher viscosity and may be the wall-quenching due to increasing the injection pressure, which causes over-penetration of the fuel increases smoke opacity of different blends at various engine loads. With EGR conditions, there was a reduction of approximately 25% at 10%EGR condition, and even further reduction in the15% EGR. This result is of same pattern to that in ref. [39].

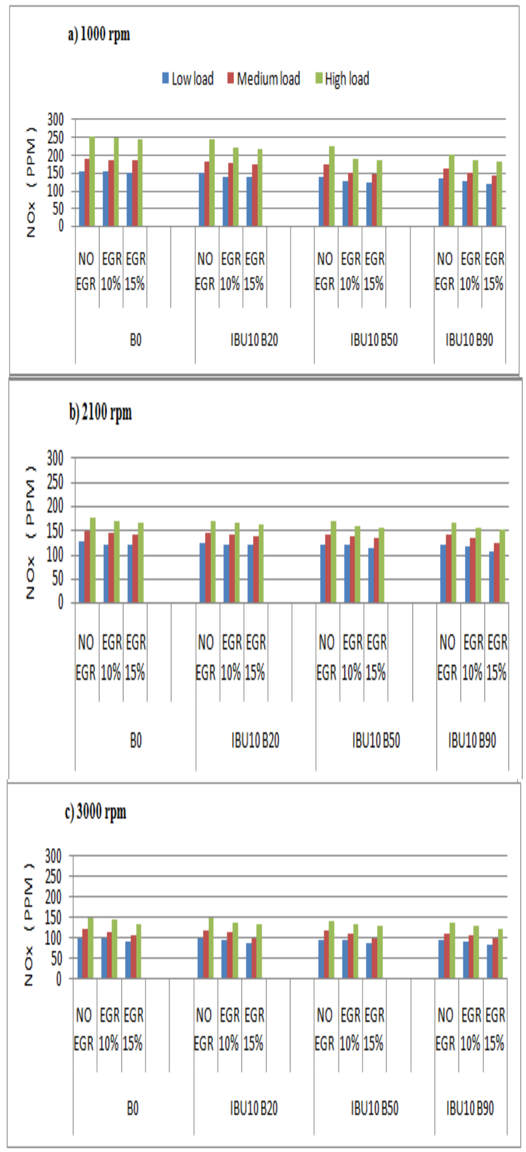

Fig.4: NO_x emissions of different fuel blends with and without EGR at a) 1000 rpm; b) 2100 rpm; and c) 3000 rpm

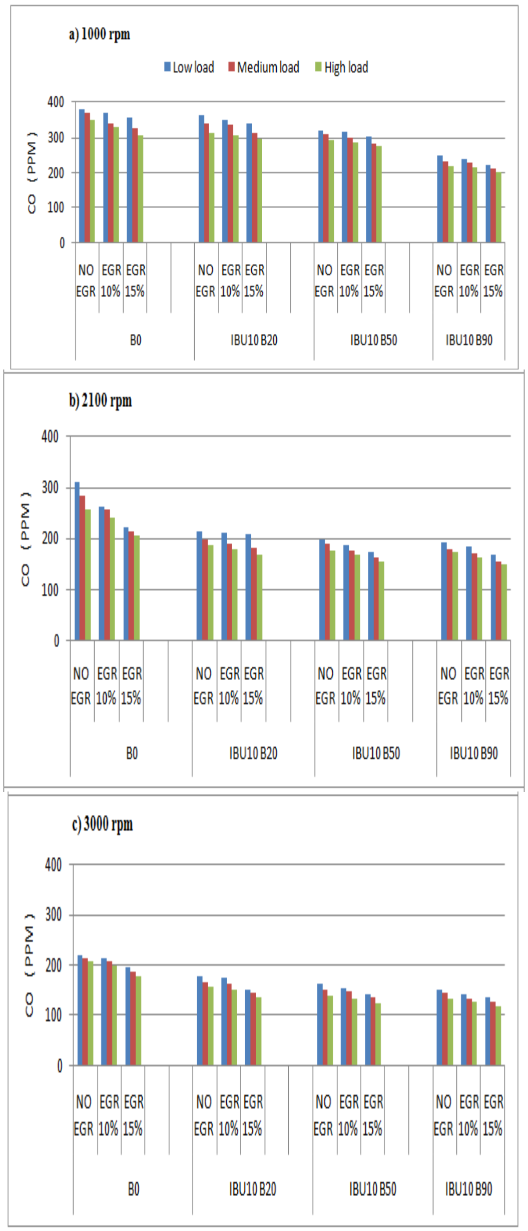

Fig.5: CO emissions of different fuel blends with and without EGR at a) 1000 rpm; b) 2100 rpm; and c) 3000 rpm

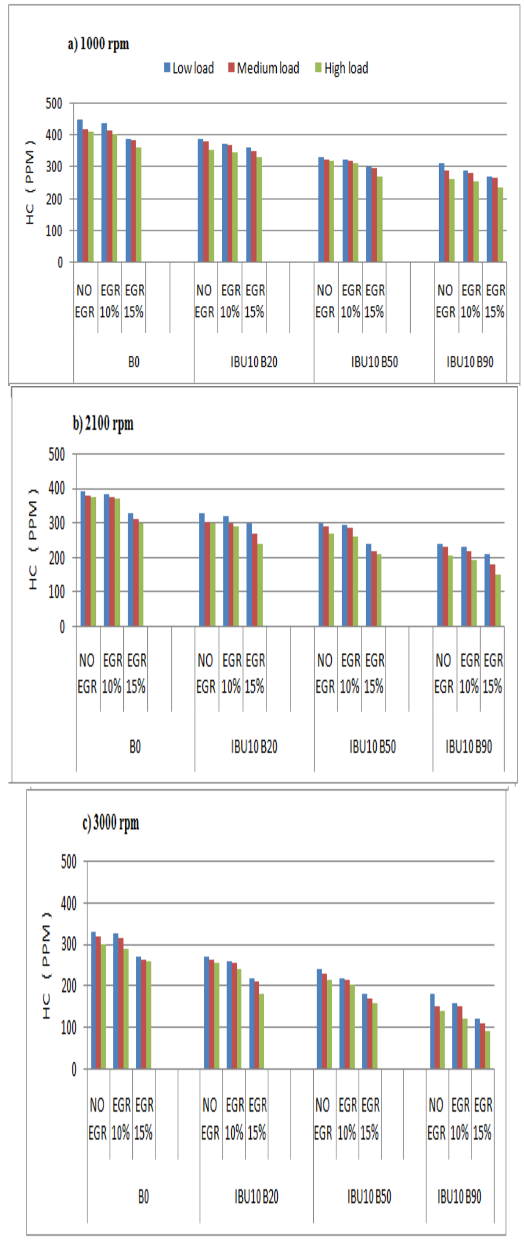

Fig.6: HC emissions of different fuel blends with and without EGR at a) 1000 rpm; b) 2100 rpm; and c) 3000 rpm

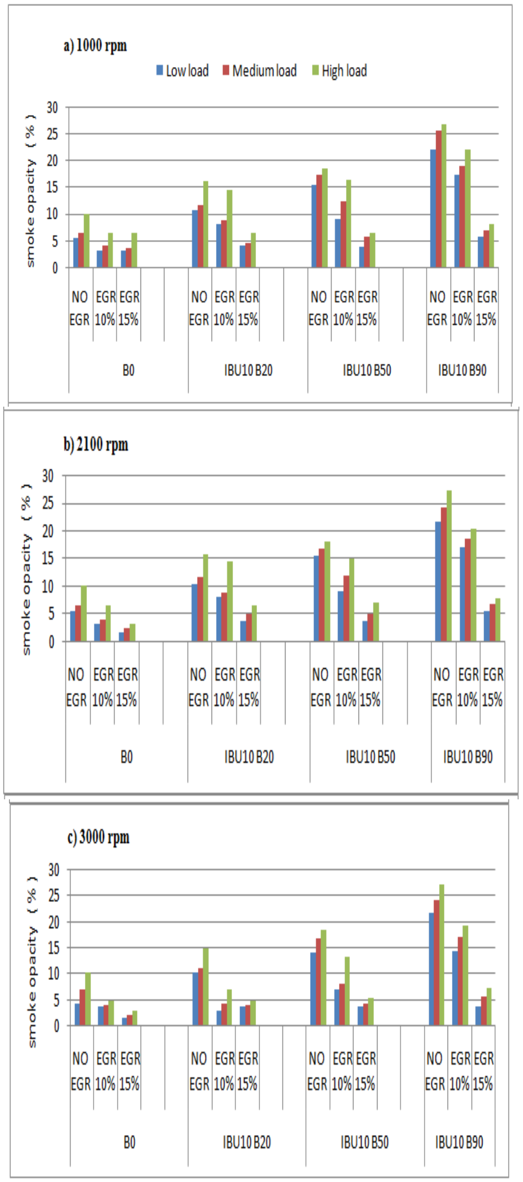

Fig.7: Smoke opacity of different fuel blends with and without EGR at a) 1000 rpm; b) 2100 rpm; and c) 3000 rpm

IV. CONCLUSION

In this paper, ternary blends of diesel, biodiesel and 10% iso-butanol were investigated for their characteristics and performance and emissions in a modern small unmodified DI diesel engine at different load and speed conditions. The most important conclusion of this investigation is that blend IBU10B90, which contains 90% biodiesel and 10% iso-butanol, can effectively be used in a diesel engine with much improved engine performance and emissions than pure diesel.

The following are further conclusions drawn from the experimental results:

1. The values of BSEC indicate that the BSEC decreases slightly with an increase of biodiesel in the blends compared to diesel fuel. Using EGR helps to further reduce BSEC values approximately 1.4% for 10% EGR and 1.6% for 15% EGR.
2. Increased biodiesel content in the blends tend to improve the BTE than neat diesel. BTE with the EGR is also increased. The result of using IBU10 B90wasthat BTE slightly increased by approximately 1% at 10% EGR condition, and by2% at 15% EGR condition; both were at high load.
3. Using iso-butanol as a fuel additive helps to decrease NO_x emissions. IBU10 B90 is found as the best blend to reduce NO_x emissions. Maximum reduction achieved with this blend is 20% compared to diesel.
4. The CO emissions are decreased without EGR, as well as with EGR. In both conditions of EGR (10%and15%), the CO emissions for IBU10 B90 at high load declined by approximately6% and 12%, respectively, compared to that of diesel with no-EGR.
5. HC emissions decreased with an increase in biodiesel proportion in blends. In addition, the reduction increased with EGR conditions.More than 60% average HC reduction is achieved for IBU10 B90 with 15% EGR condition than diesel with no-EGR condition.
6. The smoke emission increased significantly in the blends with high biodiesel content at various engine operating conditions. However, EGR reduces smoke emissions, and there is no significant change in smoke emissions with engine speeds.

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