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Performance and Emission of a Diesel Engine Fueled by Diesel and Biodiesel Blends with Antioxidant Additives and Their Emulsions

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ABSTRACT
This study is aimed at presenting a new type of antioxidant 2,6-Di-tert-butyl-4-methoxyphenol (DBMP), blended with B20 and B100 and their water emulsions (2.5% and 5%), to produce an emulsified fuel for diesel engines. The antioxidant DBMP is mixed in low proportions (0.1 vol.% and 0.5vol.%) to biodiesel-diesel-emulsion blends. Biodiesel was produced from canola oil through a transesterification process and different fuel blends and emulsions were tested on a modern, small, direct injection (DI) diesel engine at different speeds (1000 rpm, 2100 rpm and 3000 rpm), and at different load conditions (low ≈ 20%, medium ≈ 50% and high > 80%). Brake thermal efficiency (BTE) and brake specific energy consumption (BSEC) were measured as engine performance parameters. In emissions, oxides of nitrogen (NOx), carbon monoxide (CO), hydrocarbon (HC), and smoke were measured.
Keywords- DI diesel engine, biodiesel, antioxidant, emulsion, performance and emissions.

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I. INTRODUCTION

Globally, energy consumption has increased due to lifestyle enhancements and population growth as a result of which fossil fuels are on the verge of depletion. The highest consumers of this energy are the transportation and public sectors, with more needs than ever before. These needs were previously met by fossil fuels (e.g., coal, gasoline and diesel alone). However, increase in combustion of fossil fuels in these sectors has resulted in serious ecological changes, including global warming, changes in rainfall patterns and extreme weather events. To mitigate these problems, huge efforts are being put into action around the world to explore renewable energy sources that can replace fossil fuels. Biomass-based fuels or biodiesel are advantageous over conventional fossil fuels [1]. Biofuels consist of biomethanol, bioethanol, vegetable oils, biodiesel, biogas, biosynthetic gasoline (bio-syngas), bio-char, Fischere-Tropsch drinks, and biohydrogen. However, biodiesel, bioethanol, and biohydrogen are the most widely-studied fuels that have the ability for sustainable [2-4]. Biodiesel is created from fat, edible fat or waste oil, which are often used because they are the basis for a clean substitute for fuel, with no need for modification to diesel engines, boilers or combustion systems.

Previous studies have shown that biodiesel produces considerably less CO, CO_2, particulate material (PM), poly-aromatic hydrocarbons (PAH), nitrated poly-aromatic hydrocarbons (nPAH), sulphur oxides (SOx) and HC emissions than diesel fuel [5,6]. Biodiesel typically contains 10 wt.% of oxygen, and this gives it an advantage in terms of its burning potency, as well as its reduction of PM, CO, and various volatilized pollutants. On the other hand, it produces higher NOx formation, notably in a heat-burning environment and therefore, burning neat biodiesel would result in 10% more NOx than that of petroleum-based diesel, mainly due to the high oxygen content of the neat biodiesel [7,8].

Continuous analytical works have been applied for locating and implementing new techniques in order to reduce NOx emissions, which is achieved by either upgrading the engine style or by modifying the fuel for the present petroleum diesel. NOx emissions are extremely harmful to the atmosphere and can cause problems related to ozone layer depletion and acid precipitation [9]. To reduce NOx emission in internal-combustion engines, water-mixed fuel was experimented to scale back the highest temperature developed within the combustion chamber, thereby reducing NOx emission. With diesel blended with water, a positive result was obtained in terms of NOx reduction as per the expectations, whereas CO and HC emission levels increased considerably compared to diesel [10,11]. One study suggested that emulsion with 15% water content reduced NOx by approximately 30% compared with their base fuels [12].

One other method is through the addition of additives such as antioxidants, which have been used with biodiesel to improve its oxidation stability, engine performance, and emission characteristics, especially in the reduction of NOx in diesel engines [13-19]. A few names of antioxidant additives include butylated chemical group anisole (BHA), butylated chemical group dissolving agent (BHT), pyrogallic acid (PL), diphenylamine (DPA), tert-butyl hydroxyquinone (TBHQ), and propyl-gallate (PG). From the survey, TBHQ, PL and PG are the most popular among all the antioxidants. These additives are mainly employed in biodiesel mixture to induce a higher stabilizing potential [20,21].

In this study, an antioxidant in the group of TBHQ and water-blended canola biodiesel was used to analyze the characteristics of fuel on a DI diesel engine, mainly focusing on the reduction of NOx emission. The engine performance of BSEC and BTE also improved with the addition of the antioxidant and water emulsified biodiesel.

II. MATERIAL AND METHODS

2.1 Material

The materials used for testing and producing biodiesel include: canola oil, purchased from a local dealer; methanol, sodium hydroxide, and 2,6-Di-Tert-Butyl-4-methoxyphenol, obtained from Sigma-Aldrich; and diesel, was purchased from a local dealer.

2.2 Biodiesel Production

Biodiesel is produced through a process called transesterification or alcoholysis, which is the most commonly-applied methodology for biodiesel production. The transesterification of canola oil when mixed with a mixture of sodium hydroxide and methanol produced biodiesel. Biodiesel was produced when canola oil (1000 ml) was heated to 64°C and blended with a mixture containing methanol (200 ml) and sodium hydroxide (3.5 g); it was then continuously stirred in a mechanical magnetic stirrer for about 45 minutes. This mixture was subsequently kept for 12 hours so that the separation of methyl ester and glycerol could take place. The methyl ester that separated from the glycerol was washed with water to remove fat and glycerin. In the final process, water was used in quantities of 500 ml for the first wash and 300 ml for second wash. Finally, the washed fuel was heated to 105°C, which resulted in the evaporation of the remaining water, giving us pure biodiesel.

2.3 Fuel and Antioxidant Properties

Density was determined by measuring the mass of a certain volume (100 ml) of samples, using the formula: density=mass/volume. Viscosity was checked according to the standards followed by ASTM and measured by using an Ostwald viscometer and a water bath at a constant temperature of 40°C. The heating value of the fuels was determined by using bomb calorimeter (Parr 6200 calorimeter) with a handling system (Parr 6510 water handling system). The data of these measurements are listed in Table 1.

2.4 Antioxidant Dissolved in Biodiesel

2,6-Di-tert-butyl-4-methoxyphenol is an alkylated hydroquinone antioxidant, which is part of the phenolic group [22]. Phenols are used in the food packaging industry to protect cosmetics and drugs from oxidative degradation [23]. The phenolic antioxidant was used in quantities of 0.1 vol%, and 0.5 vol% with B20 and B100, along with their emulsion of 2.5% and 5% water. The alkylated hydroquinone was mixed with biodiesel-in-diesel and stirred on a magnetic stirrer while heating it to 30°C for about 20 minutes until the antioxidant was completely dissolved. This mixture was cooled, and the emulsion fuels were prepared by gradually pouring water and the surfactant into the mixture while stirring continuously for about 45 minutes on the magnetic stirrer.

2.5 Emulsified Fuel

The blends were achieved by mixing the fuel with a suitable surfactant: polysorbate 80 (TWEEN 80) and sorbitane monooleate (SPAN 80) in proper quantities. This quantity was calculated using the formula given below.

HLB = [(% surfactant A × HLB of A) + (% surfactant B × HLB of B)]/(HLB of A + HLB of B)

An HLB value of 10.58 was achieved. The HLB value of Tween 80 is 15.6, and that of Span 80 is 4.6. Tween 80 and span 80 were mixed in proportions of 60% by 40%. The quantity of surfactant needed for achieving a stable emulsification was 1% and 1.5%. The biodiesel-diesel-additive-water blend showed a stability of approximately 22 to 24 hours, whereas biodiesel-diesel-additive blends showed a stability of about 50 to 60 days.

2.6 Engine Test Procedure

An air-cooled, 2-cylinder, 4-stroke diesel engine with a direct injection system was used, and its specifications are highlighted in Table 2. The light-duty engine was tested at three different speeds (1000 rpm, 2100 rpm, 3000 rpm) at three load

Table 1: Fuel properties

Fuels/additives	Fuel Composition	H.V (MJ/kg)	Density (kg/m^3)	Viscosity (cSt)
Diesel/B0	100% diesel	45.395	835	3.123
Biodiesel/B100	100% biodiesel	38.026	881	4.200
DBMP	2,6-Di-tert-butyl-4-methoxyphenol	45.093	996	3.470
B20DBMP0.1	20% biodiesel in diesel with DBMP 0.1vol.%	44.375	843	3.144
B20DBMP0.5	20% biodiesel in diesel with DBMP 0.5vol.%	44.121	844	3.230
B20DBMP0.1W2.5%	B20DBMP0.1 emulsion with 2.5% water	43.606	857	3.124
B20DBMP0.5W2.5%	B20DBMP0.5 emulsion with 2.5% water	43.276	859	3.126
B20DBMP0.1W5%	B20DBMP0.1 emulsion with 5% water	42.583	871	3.120
B20DBMP0.5W5%	B20DBMP0.5 emulsion with 5% water	42.037	873	3.160
B100DBMP0.1	100% biodiesel with DBMP 0.1vol%	37.389	883	3.230
B100DBMP0.5	100% biodiesel with DBMP 0.5vol%	37.071	886	3.661
B100DBMP0.1W2.5%	B100DBMP0.1 emulsion with 2.5% water	36.349	892	3.125
B100DBMP0.5W2.5%	B100DBMP0.5 emulsion with 2.5% water	36.021	895	3.136
B100DBMP0.1W5%	B100DBMP0.1 emulsion with 5% water	35.212	908	3.128
B100DBMP0.5W5%	B100DBMP0.5 emulsion with 5% water	34.654	911	3.156

conditions of low, medium and high. The engine was mounted on an engine test bed and vented outside through the roof of the engine room. The exhaust values for emissions testing were installed on the exhaust system. The engine was fitted with a water brake dynamometer and a servo controller was installed for water load release to control the engine load. Before starting the experiment, the engine was run for about 10 minutes to heat up in order to achieve the constant reading of emissions. The smoke emission was recorded using an opacimeter. The data was recorded using data acquisition software installed on laptop provided by the equipment manufacturer. Figure 1 shows the schematic diagram of the engine experiment.

Table 2: 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

2.7 Emission Measurement

A multi-gas analyzer (NOVA Model 7466 PK) and CO analyzer (Dwyer 1205A) was used to measure CO, NO, NO_2, HC, CO_2, and O_2 of the exhaust gases. Smoke emission was recorded using an opacimeter (SMART 1500). The specifications of the gas analyzer and opacimeter are provided in Table 3. The regulated emissions of NOx, CO, HC and smoke are presented.

A: Engine block, B: Dynamometer, C: Graduated cylinder, D: Opacimeter, E: Gas analyser, F: Data acquisition unit, G: Exhaust pipe

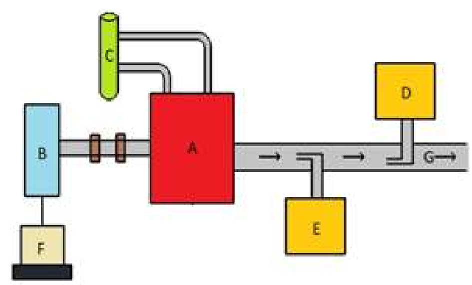


Fig. 1: Schematic diagram of engine experiment

III. RESULTS AND DISCUSSION

3.1 Brake Specific Energy Consumption (BSEC)

BSEC is defined as the amount of energy consumed by an engine to develop one kilowatt of power per hour. The BSEC for different blends at speeds of 1000 rpm, 2100 rpm and 3000 rpm are shown in Fig 2. It was observed that BSEC for all fuels decreased with an increasing load and speed.

BSEC further decreased with the addition of DBMP. The lowest BSEC was observed at 3000 rpm with the B20 and B100 non-emulsified fuels with 0.1 vol% DBMP, which is approximately 15% lower than that of diesel. These can be attributed to

Table 3: Emission analyzers' specifications

Method of Detection	Species	Measured Unit	Range	Resolution	Accuracy
NovaGas 7466 PK					
Electrochemical/ Infrared detector	CO	%	0-10%	0.10%	±1%
Infrared detector	CO_2	%	0-20%	0.10%	±1%
Electrochemical	NO	ppm	0-2000 ppm	1 ppm	±2%
Electrochemical	NO_2	ppm	0-800 ppm	1 ppm	±2%
Electrochemical	O_2	%	0-25%	0.10%	±1%
Infrared detector	HC	ppm x 10	0-20000 ppm	10 ppm	±1%
Dwyer 1205A Electrochemical	CO	ppm	0-2000	1 ppm	±5%
ExTech EA10	Temp.	0.1°C	(-)200°C-1360 °C	0.1°C	±0.3%
Smart 1500	Opacity	%	0-100%	0.1%	±2%

the fact that the cylinder temperature rises at higher engine loads and speeds due to which combustion is improved, therefore resulting in lower BSEC. While the higher heating value of the antioxidant helped the fuel burn better.

3.2 Brake Thermal Efficiency (BTE)

The BTE for the biodiesel-diesel-additive-water blends are shown in Fig. 3 for two different amounts of additives at three different engine rpm (1000, 2100 and 3000). BTE, in simple terms, indicates how much the heat energy is converting to mechanical work. It is found that BTE increased with the increase in loads and speeds as well with the increase in biodiesel percentage. It further increased with the addition of DBMP and emulsified fuels. The maximum BTE obtained is approximately 40% for B100 with DBMP0.5 vol% for 5% emulsion, which is about 20% higher than that of diesel. One reason for this increase in BTE with emulsion could be because of the micro-explosion of emulsion fuel and the vaporization of water during combustion, which enhanced air fuel mixing, which greatly improved combustion efficiency. A similar results were presented in [24].

3.3 Exhaust Emission

3.3.1 NOx Emission

Biodiesel has high NOx emissions because of its high combustion temperature and high oxygen content. Thus, base fuels (B20 and B100) showed higher NOx emissions than diesel (Fig. 4). The fuel blends with antioxidant and emulsions showed a considerable reduction in NOx emission, while the lowest was noted for B20DBMP0.5W5 at 3000 rpm, which was more than 25% lower than biodiesel and 20% lower than diesel. This was due to excess air, and reduced availability of nitrogen molecule in fuels. Also, one other reason for reduced NOx emission is because of emulsification leading to lower combustion temperature. Furthermore, the antioxidant contains no nitrogen molecule, and higher carbon and hydrogen atoms, thus resulting in reduced NOx emission.

3.3.2 CO Emission

Figure 5 shows CO emissions for different fuel blends at various engine conditions. In the combustion stage within the diesel engine, CO is created when air is deficient and/or with lower flame temperature [25]. This is reflected with higher CO emissions at lower engine speeds, where the flame temperature is lower. Higher loads improved CO emissions because of higher in-cylinder temperatures. Biodiesel in the blends also helped to lower the CO emissions because of its oxygen content. Furthermore, addition of DBMP reduced CO significantly. However, addition of water deteriorated CO emissions due to a lower combustion temperature. The minimum average CO obtained is about 220 ppm at 3000 rpm for B20 with DBMP0.1 without emulsion, which is approximately 20% and 25% lower than B20 and B0, respectively.

3.3.3 HC Emission

The two main reasons for HC emission in diesel engines are (1) mixing of fuel, which is leaner than the lean combustion limit during the delay period; and (2) low velocity due to the time lag between mixing the fuel, and the fuel leaving the injector nozzle during the combustion process [1]. HC emission followed a similar trend throughout the experiment, appearing to decrease as the load increased, and to decrease with the increase in speed (Fig. 6). From the observations, diesel showed the highest HC emission at all engine rpm. Base fuels (B20 and B100) showed considerably higher emissions compared to their blends with antioxidant and emulsions. The minimum HC (350 ppm) was observed in

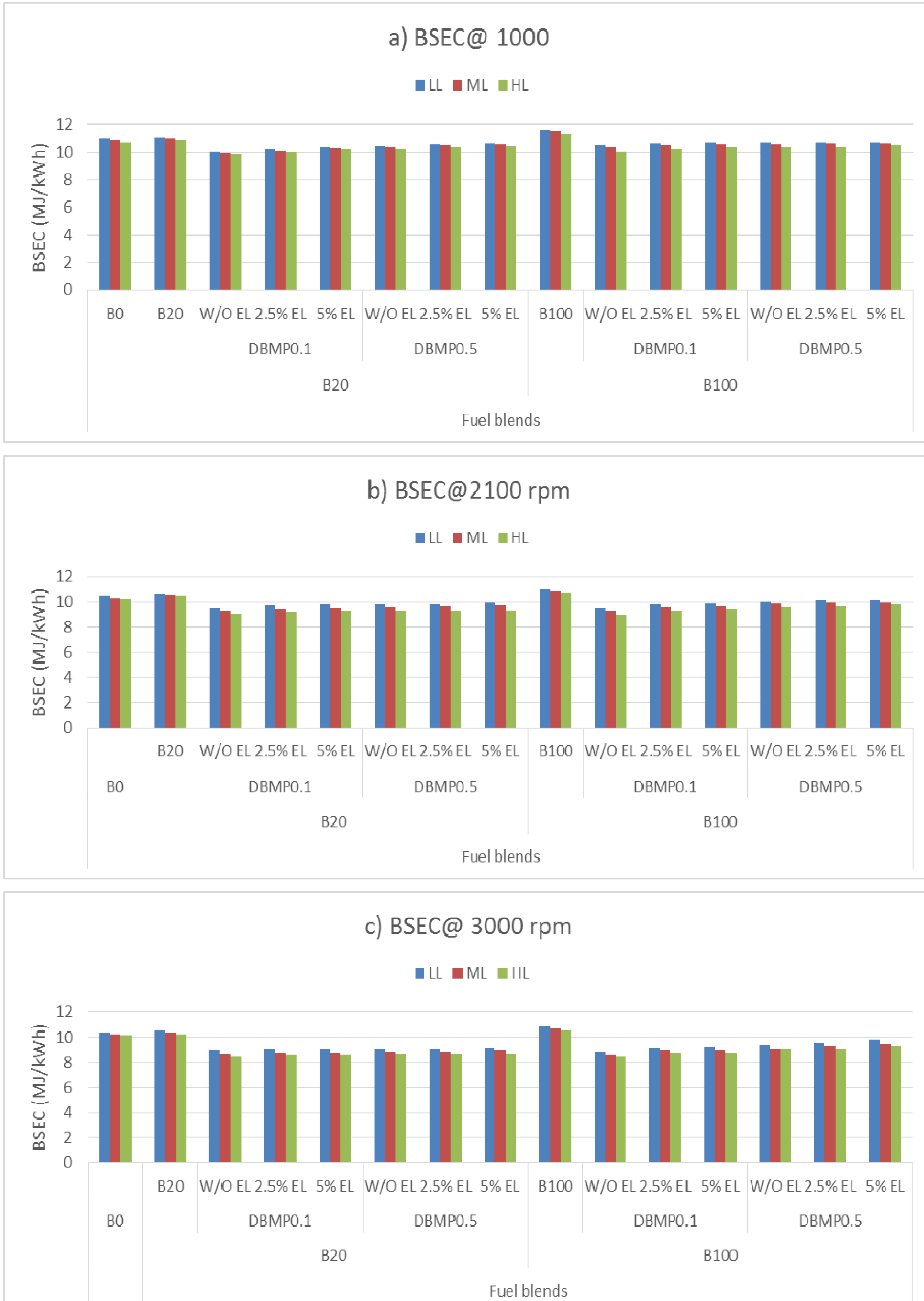
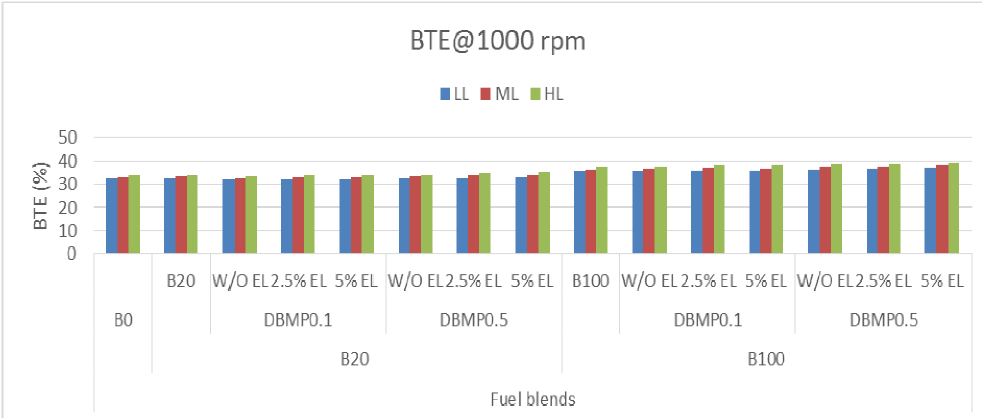
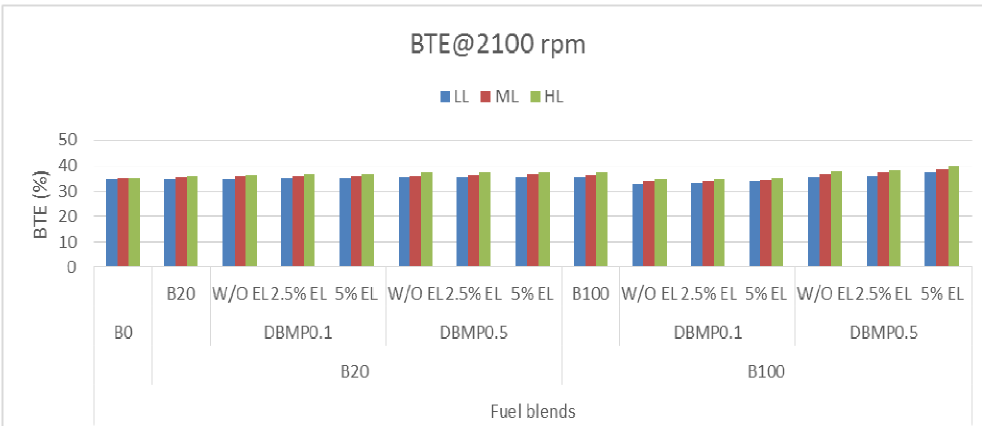


Fig. 2: BSEC for different fuel blends at various engine conditions





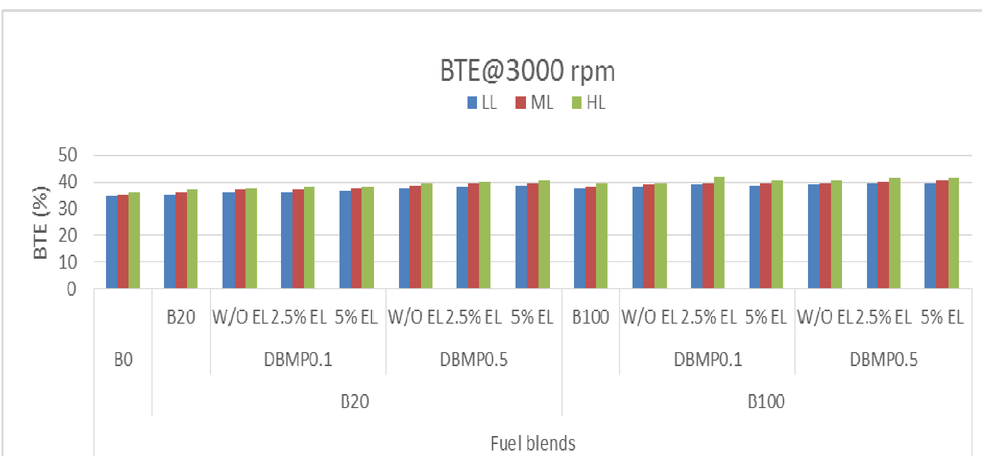


Fig. 3: BTE for different fuel blends at various engine conditions

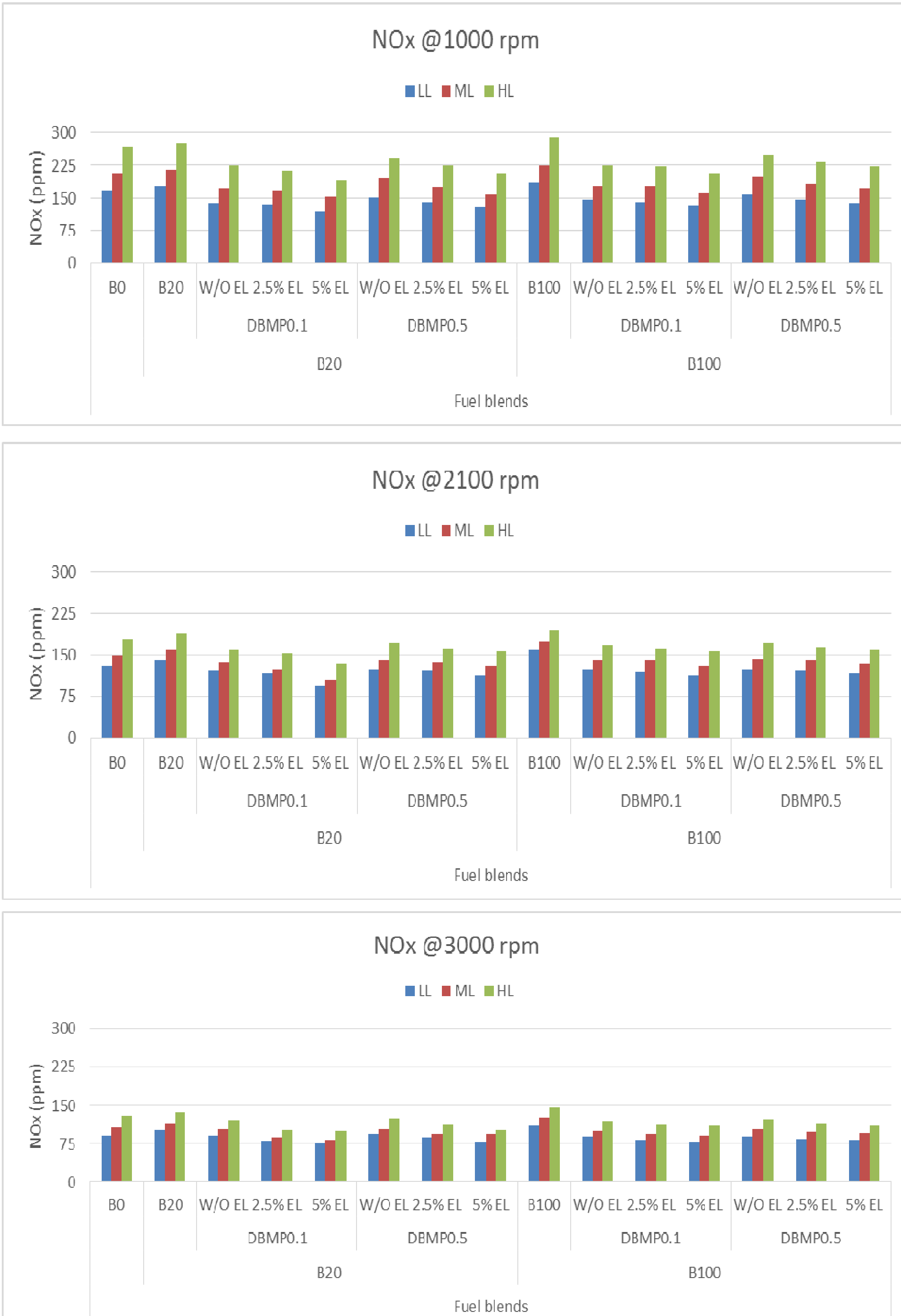


Fig. 4: NOx emissions for different fuel blends at various engine conditions

Fig. 5: CO emissions for different fuel blends at various engine conditions

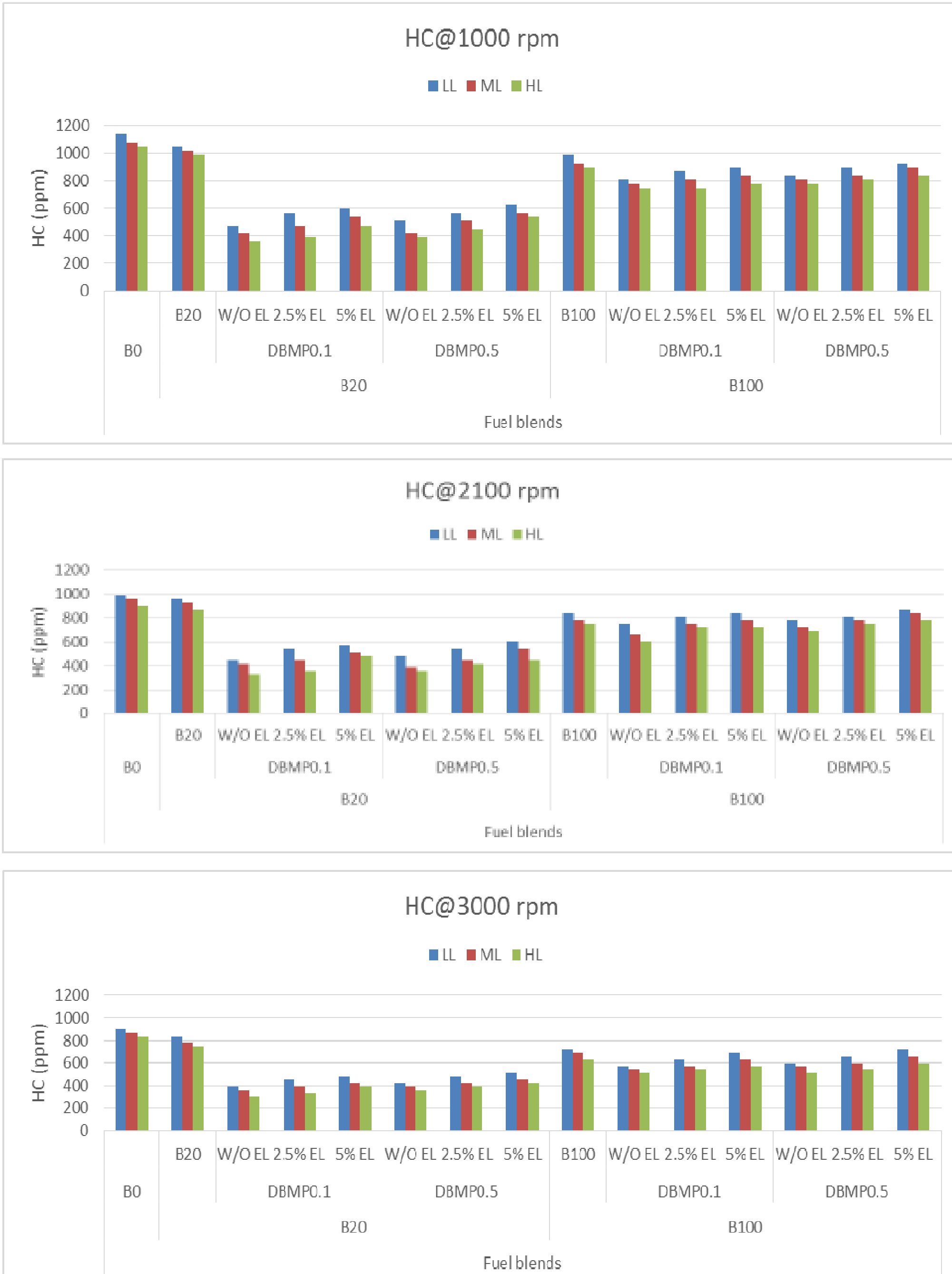


Fig. 6: HC emissions for different fuel blends at various engine conditions

B20DBMP0.1 at 3000 rpm and high load condition, which was 64% lower than diesel. Usually, due to high oxygen content of the biodiesel, its advantages over diesel (post flame oxidization, higher flame during air fuel interaction, especially in fuel-rich regions), increased the oxidization of unburned HC and therefore, considerably reduced HC [26].

3.3.4 Smoke Emission

Biodiesel usually emits less particulate matter (PM), as the amount of biodiesel increases in diesel [27,28]; this is because of the higher oxygen content in fuel, helping to achieve complete combustion. However, in our small diesel engine, smoke emission increased with the increase in biodiesel (B20 and B100) (Fig. 7). This may be due

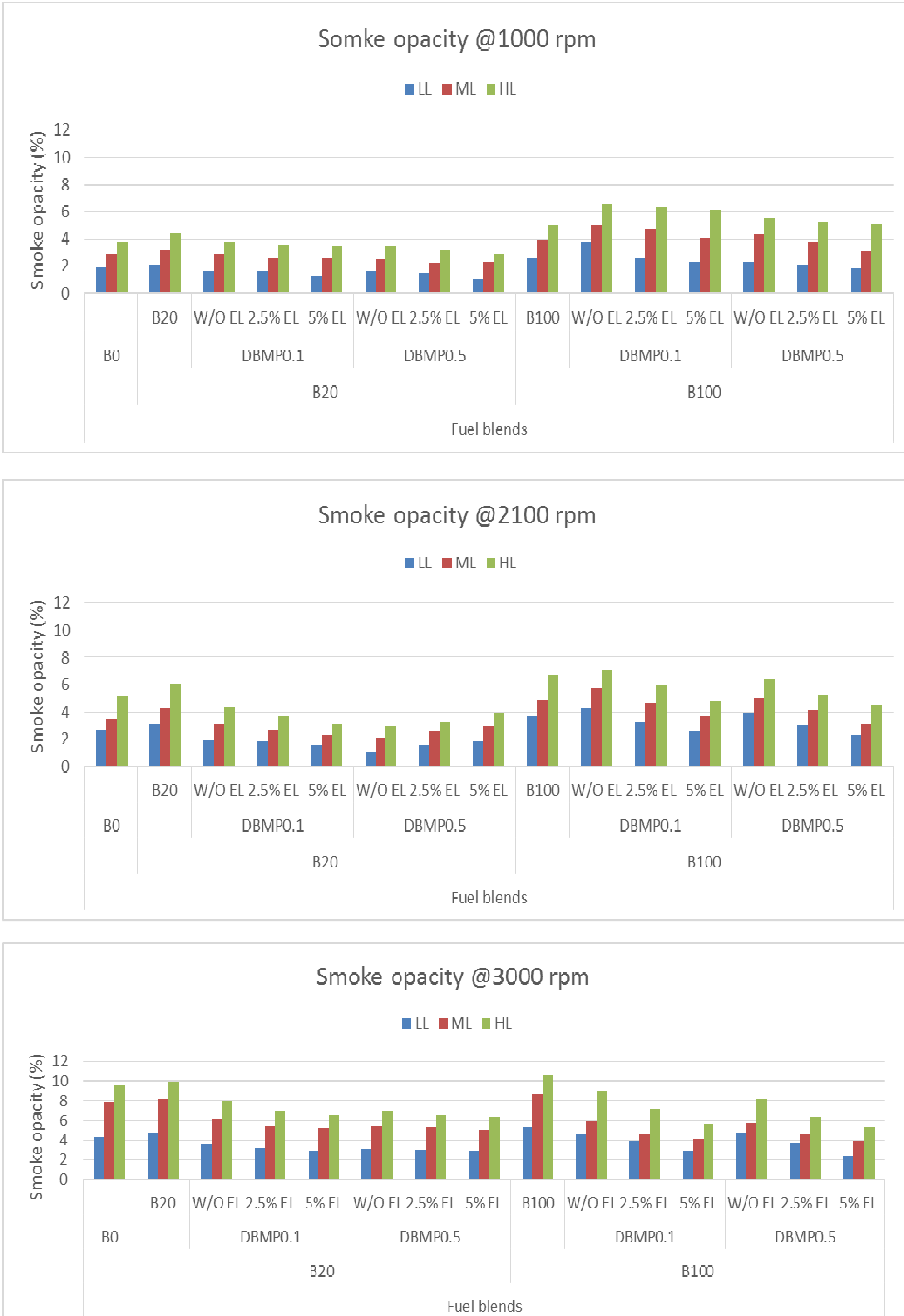


Fig. 7: Smoke emissions for different fuel blends at various engine conditions

to heavier molecules and the higher viscosity of biodiesel that slowed down the combustion process, which increased smoke emission in this small DI diesel engine. The low percentage DBMP (up to 0.5vol%) and its water emulsions showed a very significant smoke reductions. With B20DBMP0.1 and B20DBMP0.5 for 2.5% and 5% water emulsions, the smoke is approximately 25-50% reduced at all rpm conditions. Reduction in smoke with higher water concentration was observed probably due to micro-explosion of emulsion fuel and better fuel mixing and vaporization in the combustion chamber.

IV. CONCLUSIONS

This study investigated the effects of phenolic alkylated hydroquinone 2,6-Di-tert-butyl-4-methoxyphenol, and the emulsions on emission and performance of a diesel engine fueled by diesel-biodiesel blends. From the results obtained from the study, the following conclusions can be made:

1) The viscosity of fuel blends with biodiesel and antioxidant is less than ASTM limit of 6 cSt thus proving to be a pretty good alternative to diesel. Its density and heating values are pretty much like biodiesel.

2) The lowest BSEC obtained is with B20 and B100 non-emulsified fuels with 0.1 vol% DBMP. The maximum BTE obtained is for B100 with DBMP0.5 vol% for 5% water emulsion, which is about 20% higher than that of diesel.

3) The fuel blends with antioxidant and emulsions showed a considerable reduction in NOx emission, and the lowest was noted for B20DBMP0.5 with 5% water at 3000 rpm, which is more than 25% lower than biodiesel and 20% lower than diesel.

4) The average CO emissions at the highest engine speed for B20 with DBMP0.1 without emulsion is approximately 20% and 25% lower than B20 and diesel, respectively. The minimum HC is observed in B20DBMP0.1 at 3000 rpm and high load condition, which is 64% lower than diesel.

5) The low percentage DBMP and its water emulsions showed very significant smoke reductions. For all fuel blends with DBMP and emulsions, the smoke is approximately 25-50% reduced at all rpm conditions.

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