*International Journal of Scientific Engineering and Applied Science (IJSEAS) – Volume-7, Issue-6, June 2021*
*ISSN: 2395-3470*
*www.ijseas.com*

# Performance and Emissions of a Biodiesel Fueled Engine Equipped with Intake Non-thermal Plasma Charger

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## Abstract

Diesel engines today are widely used for transportation and various off-road applications due to their beneficial efficiency among hindrances on some emitted pollutants. Innumerable techniques have been established and applied to reduce these emissions covering renewable fuel such as biodiesel. A non-thermal plasma (NTP) technology is promising by generating plasma field in thermodynamic inequilibrium state between electrodes. This research study aims to preliminary investigate the performance and emissions from a four-cylinder diesel engine equipped with a high voltage generator into the engine's intake manifold for fresh air becoming NTP state. The study was experimentally accomplished on the engine fueled with biodiesel and diesel fuels for comparison at 1,500 rpm, 50% pedal position load condition. The engine equipped with intake NTP device resulted in improved fuel consumption and thermal efficiency. The NTP enhanced combustion process resulting in increasing nitric oxide but lowering carbon monoxide and smoke emissions, prominently for biodiesel combustion.

***Keywords:*** *Biodiesel, Diesel, Emission, Intake, Non-thermal Plasma, Performance.*

## 1. Introduction

Land transportation in present plays a vital role for local economics especially on road where rail system cannot be easily accessible. Conventional vehicles that run on fossil gasoline or diesel fuels have been unceasingly developed in terms of fuel economy and fuel conversion efficiency. Meanwhile, conventional fossil fuels are globally fluctuated in price [1]. Diesel engines today are in widespread use due to their high thermal efficiency but higher amounts of particulate matter (PM) and black smoke than gasoline engines [2]. Some incomplete combustion gases are harmful to human respiratory system and cause air pollution issues [3]. In general, diesel exhaust emissions are associated to particulate matter in conjunction with nitrogen oxides ($NO_x$) as the well-known trade-off emissions that require simultaneously mitigation [4]. Various techniques have been established and applied to combustion engines to reduce these emissions.

Among various applications, both plasma and non-thermal plasma (NTP) technologies are techniques to reduce pollutants from combustion [5-6]. By generating thermodynamic inequilibrium plasma field, an NTP device creates a dielectric barrier discharge (DBD) between cathode and anode electrodes with electrical insulator in between, commonly recognized as to produce ozone [7].

The NTP charger has been frequently reported as an aftertreatment of diesel engines mainly to remove PM pollutant [8]. Moon *et al*. (2000) [9] explored their findings on the reduction of $NO_x$ using ozone catalytic oxidation and electron-produced heating coils. The NTP technique was also employed to lessen volatile organic compounds as a result of hydrocarbon fuel combustion [10]. Okumoto *et al*. (2005) [11] used double rectangular electrode in plate shape for NTP charger, in co-flow direction of the emitted combustion gas. This equipment at 480-W power can reduce PM up to 58% from burning diesel fuel. At low temperature, Okubo *et al*. (2007) [12] combined the NTP device and a diesel particulate filter (DPF) to efficiently oxidize PM. In addition, the $NO_x$ reduction comparison between temperature swinging adsorption and NTP technique were explored by Yoshida (2013) [13]. Thitipatanapong *et al*. (2015) [14] characterized particulate matter from the combustion of biodiesel blended fuel in a diesel engine equipped with exhaust NTP charger using thermo-gravimetric analysis. At 2,500 rpm, PM reduction by 40% at low to medium engine loads was obtained during NTP activation. Furthermore, the exhaust NTP also reduced smoke opacity and nitric oxide (NO) emissions, respectively by 44% and 14% at low load. Wang *et al*. (2015) [15] studied and analyzed the micro-structural scale of PM from diesel engines with NTP equipped, using GC-MS, SEM, EDX, and TGA. The main findings associated to the reduction of soluble organic fraction (SOF) of PM after NTP treatment by 24.36%. The maximum SOF removal efficiency of 21.7% was achieved. After NTP was enabled, the degree of agglomeration was declined and the PM was smaller in diameter.

NTP technology was also adopted to utilize in the intake system of diesel engine. Kumhin *et al*. (2015) studied the combustion characteristics of a multi-cylinder diesel engine equipped with NTP at the intake manifold. The engine ran at 2,500 rpm speed with 25% and 50% loads. The experimental data have shown that the engine started combustion earlier and ignition delay was shortened. Meanwhile, Thitipatanapong *et al*. (2016) commissioned on a single-cylinder agricultural diesel engine with intake NTP charger installed without complex modification requirement.

Most studies have used NTP technology as an aftertreatment device for single or multi-cylinder diesel engine. Meanwhile, limited work has been done on the application of NTP for the intake side of diesel engine. Additionally, other renewable fuels such as biodiesel may be used as partial substitution or pure [18-19]. Besides, there is less available information for performance and emissions from this application. In subsequence, some other facets have not yet been discovered regarding these issues.

The main objective of this work is to examine the performance and emissions of the four-cylinder diesel engine running on biodiesel, and diesel fuel in comparison, with NTP device installed in the intake manifold. The engine was commissioned at a steady state condition of 1,500 rpm, 50% pedal position load as representative for the application frequently used. The engine performance in terms of brake specific fuel consumption and thermal efficiency will be presented. The exhaust emissions: NO, HC and smoke will be explored and discussed.

## 2. Experimental Apparatus and Procedure

### 2.1 Test Cell and Instrumentation

The experimental study was carried out using an in-line, single overhead camshaft, water cooled diesel engine (Mitsubishi, Model 4D56) installed on an eddy current type dynamometer (DYNOmite, Model 012-200-1K) to control and load the engine. The engine specifications are concisely shown in Table 1. A digital weight scale (CST, Model CDR-3) with ±0.05 g accuracy was employed to measure the fuel consumption in each test, while the flow meter (Testo, Model 435) with accuracy in the range of ± 0.3% of reading was used to measure the air flow rate. In addition, the temperatures of ambient, fuel, coolant, and intake and exhaust ports were measured by K-type thermocouple and recorded by in-house developed based LabVIEW data acquisition system (National Instruments, Model NI USB-6218). The fuel temperature was control at 40±l°C.

Table 1: Engine specifications

| Parameter | Specification |
|---|---|
| Number of cylinders | 4 |
| Bore × stroke | 91.1 mm × 95.0 mm |
| Maximum torque | 142 Nm at 2,500 rpm |
| Maximum power | 55 kW at 4,200 rpm |
| Compression ratio | 21:1 |

## 2.2 Exhaust Emission Measurement

An emission analyzer (Horiba, Model MEXA-584L) was used to measure the total unburned hydrocarbon (HC), nitric oxide (NO), and carbon monoxide (CO) on a dry basis. The working principle of the analyzer is based on a non-dispersive infrared (NDIR) measurement. The black smoke of exhaust gas in opacity percentage was measured by a smoke meter (Horiba, Model MEXA-600S) at the tail pipe, based on the light absorption. The measurement range and accuracy of the exhaust gas analyzer and smoke meter are congregated in Table 2.

Table 2: Exhaust emission measurement range and accuracy

| Component | Measurement range | Accuracy |
|---|---|---|
| NO | 0-4,000 ppm vol. | 4% of reading |
| CO | 0-10 % vol. | 0.01 % vol. |
| HC | 0-10,000 ppm vol. | 3.3 ppm vol. |
| Smoke | 0-99.9 % opacity | ± 0.5 % opacity |

## 2.3 Fuel

There are two types of fuel used in this study: diesel and biodiesel and their main properties are listed in Table 3. It is to note that the diesel fuel contains a trace of fatty acid methyl ester (FAME) by local regulation.

Table 3: Fuel properties

| Analysis | Unit | Method | Diesel | Biodiesel |
|---|---|---|---|---|
| Flash Point | $^{o}$C | ASTM D93 | 60.0 | 131 |
| Density at 15 $^{o}$C | g/cm$^3$ | ASTM D4052 | 0.8255 | 0.8752 |
| Kinematic Viscosity at 40 $^{o}$C | cSt | ASTM D445 | 2.9 | 4.5 |
| Lower Calorific Value | MJ/kg | ASTM D240 | 42.5 | 38.3 |
| Sulfur Content | % wt. | ASTM D2622 | 0.0037 | - |
|  | % wt. | ASTM D5453 | - | 0.0002 |
| Ester Content | % vol. | EN 14078 | 4.7 | - |
|  | % wt. | EN 14103 | - | 98.08 |

## 2.4 Performance Parameter Calculation

The brake specific fuel consumption (bsfc) is calculated based on measured fuel mass consumption rate ($\dot{m}_{\mathrm{f}}$) divided by brake power ($P_{\mathrm{b}}$) absorbed by the dynamometer, as

$$\mathrm{bsfc} = \frac{\dot{m}_{\mathrm{f}}}{P_{\mathrm{b}}} \quad (1)$$

The brake thermal efficiency ($\eta_{\mathrm{th}}$) is calculated by brake power produced from fuel chemical energy input, as

$$\eta_{\mathrm{th}} = \frac{P_{\mathrm{b}}}{\dot{m}_{\mathrm{f}} Q_{\mathrm{LCV}}} \quad (2)$$

where $Q_{\mathrm{LCV}}$ is lower calorific value of fuel.

## 2.5 Non-thermal Plasma Charger

The high voltage non-thermal plasma (NTP) charger was installed into the intake manifold of the test engine on a modified non-conductive air tube approx. 50 cm from intake valve. It can generate a voltage of 18 kV. There was a terminal copper electrode located in the middle of the air tube with 6.2-cm diameter, approx.30 cm apart from the other electrode. The NTP device consumed input power from an ordinary 12 VDC battery, recharged by a regular alternator of the engine electrical system. The schematic diagram of the NTP charger installation is depicted in Fig. 1.

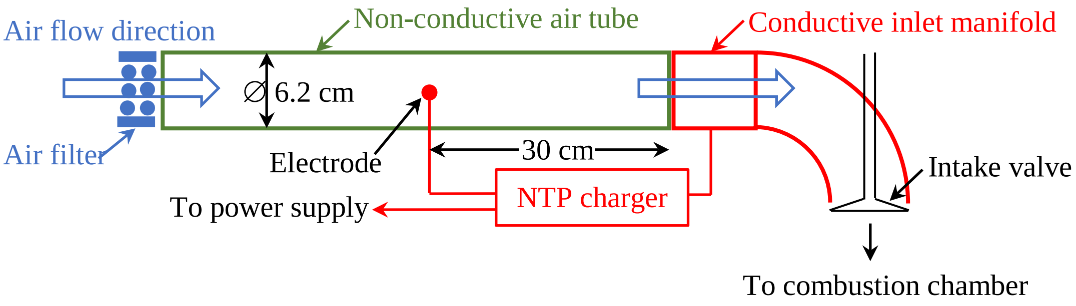

Fig. 1 The NTP charger installation arrangement.

2.6 Test Procedure

The study was experimentally accomplished on the stock engine with the two fuels previously mentioned with and without the use of NTP charger. The engine ran at a constant 1,500 rpm speed, 50% pedal position load. The constant engine speed and load chosen were by the frequent use of laden application. The engine was first warmed up to the normal operating temperature of approx. 82 °C. When stabilized, all concerned engine operating parameters were collected and analyzed. Each test conditions were tested for three times and average values are representatively shown.

## 3. Results and Discussion

### 3.1 Fuel Consumption and Efficiency

The engine performances in terms of brake specific fuel consumption and brake thermal efficiency are shown in Fig. 2 when running the engine at steady state condition of 1,500 rpm, 50% pedal position load using diesel and biodiesel fuels while the NTP device was in use. It can be obviously seen in Fig. 2 that the bsfc values of biodiesel were higher than that of diesel fuel. The use of NTP device reduced the bsfc values for both fuels.

Generally, the engine running on biodiesel consumed more fuel due to its lower calorific value (see Table 3 for comparison) and thus, lowered brake thermal efficiency compared to diesel fueling. After NTP charger activation, the engine consumed lesser fuels for both biodiesel and diesel but prominently seen its effects on biodiesel combustion: bsfc reductions by 6.3% for biodiesel and 2.0% for diesel. This yields the brake thermal efficiency of both fuels increasing while operating the NTP device. When the NTP was enable, the brake thermal efficiencies increased by 6.7% for biodiesel and 2.0% for diesel. These improved performances are associated to the combustion of fuel-air mixture [16], that were stimulated by NTP which can be observed by exhaust emission concentrations discussed in the next section.

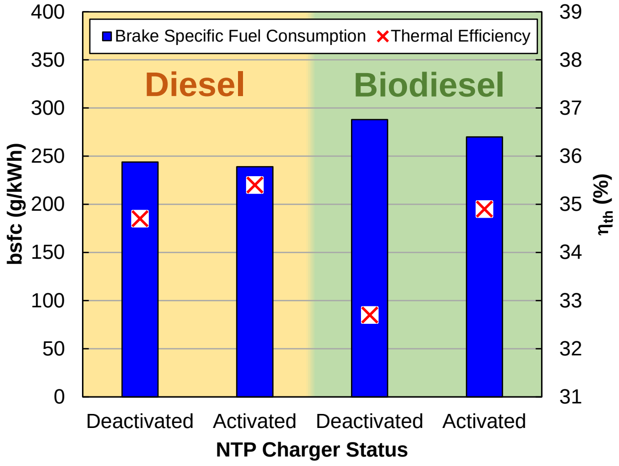

Fig. 2 Engine performances (a) brake specific fuel consumption and (b) brake thermal efficiency.

### 3.2 Exhaust Emissions

The exhaust emissions from the combustion of both fuels such as nitric oxide (NO), hydrocarbon (HC), and black smoke in terms of opacity percentage are shown in Fig. 3. Meanwhile, CO emissions were insignificantly changed; the values were approx. 0.02 %vol. and, therefore, they are not shown here as their values changed were within the accuracy range of the measurement device. It can be apparently seen in Fig. 3 that the exhaust concentrations of NO and HC as well as smoke opacity from biodiesel combustion were lower than that of diesel fuel. The use of NTP device elevated the NO emissions for both fuels but lowering HC and smoke opacity.

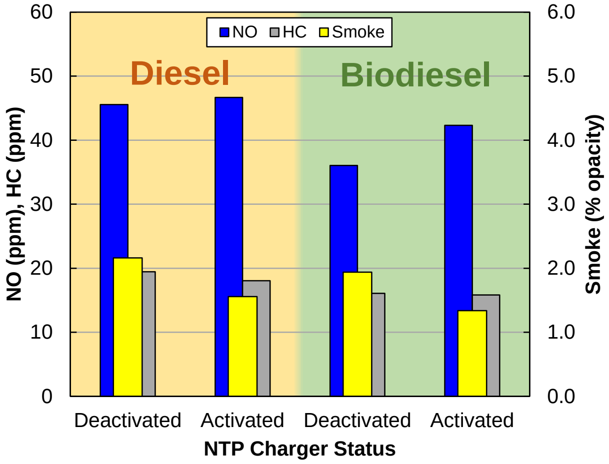

Fig. 3 Exhaust emissions of nitric oxide, hydrocarbon, and smoke opacity.

For the set engine test condition in regardless of NTP activation, biodiesel was burned in richer mixture of fuel and air as it can be seen by the increased bsfc as previously discussed (see Fig. 2). As a result, the NO and HC concentrations as well as smoke opacity from biodiesel combustion were lower than that of diesel fuel. During NTP activation, the engine running on both fuels was likely to promote more complete combustion observed by the increased NO and the reduced HC and black smoke. When the NTP was enable, NO emissions were increased by 17.5% for biodiesel and 2.4% for diesel while HC concentrations were reduced by 1.6% for biodiesel and 7.2% for diesel and smoke opacities were improved by 30.9% for biodiesel and 28.0% for diesel, respectively.

## 4. Conclusions

This research study examines the effects of using high voltage generating device to keep the intake charge in NTP state for the four-cylinder biodiesel-fueled engine on performance and emissions at 1,500 rpm speed, 50 % pedal position load condition. The conclusions are as follows.

1. In general, the biodiesel fueled engine consumed greater fuel mass and thus, lowered brake thermal efficiency than diesel fueling. During NTP charger activated, the bsfc values were reduced by 6.3% for biodiesel and 2.0% for diesel. This yields the thermal efficiency of both fuels increasing by 6.7% for biodiesel and 2.0% for diesel.
2. For the set engine test condition in regardless of NTP activation, the exhaust concentrations of NO and HC as well as smoke opacity from biodiesel combustion were lower than that of diesel due to richer fuel and air mixture. However, CO emissions were insignificantly changed. After NTP activation that enhances the combustion process, NO emissions were increased by 17.5% for biodiesel and 2.4% for diesel while HC concentrations were reduced by 1.6% for biodiesel and 7.2% for diesel and smoke opacities were improved by 30.9% for biodiesel and 28.0% for diesel, respectively. The intake NTP evidently shown to affect on NO and black smoke for biodiesel combustion rather than diesel fuel.

## Acknowledgments

The authors thank Thailand Research Fund (TRF) through Research and Researcher for Industry (RRI) Project and Saveplus Limited Partnership for financial support (Contract No.: PHD57I0077).

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