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# Effect of Post-Injection and Alternative Fuel on Emission Characteristics and Smoke/Soot Emissions in a Common-Rail DI Diesel Engine

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***Abstract*— *In the current work, the tests were conducted in a direct diesel engine for diesel and alternative fuel under post-injection strategy. The effect of biodiesel and post injection on combustion and engine emissions was studied in this work. The addition of post-injection is reduced the $NO_X$ emissions and increased the carbonaceous emissions (CO and HC) for biodiesel and diesel fuel. The cylinder pressure improved from biodiesel combustion with respect to the diesel fuel. The results showed that the biodiesel can significant reduce the engine emissions than to the diesel fuel. In addition, it is observed that the smoke and soot emissions reduced during the combination of post-injection and biodiesel. The number of soot particles reduced from biodiesel combustion by 25 nm compared to the diesel fuel combustion by 33 nm*.

***Keywords*— *Post-injection, $NO_X$ emissions, CO, HC emissions, smoke, diesel engine*.

## I. Introduction

The problem of global warming and environmental degradation at the present stage caused by the use of fossil fuels has received increasing attention [1, 2]. Many harmful emissions such as $NO_X$, CO, and particulate matter (PM) have raised concerns about environmental pollution and protection [3]. Post injection strategy is one of most potential in-cylinder solutions for emission reduction, a shorter injection following the main fuel injection [4]. The smoke and total hydrocarbon (THC) reduction were examined by Hotta et al. [5] with present effect of post injection timing in a small high speed direct injection diesel engine. They found that effectively reduce smoke and THC emissions from suitable post injection timing for promoting atmosphere temperature and increasing air circulation. Fayad et al. [6] observed that the particulate matter improved from using biodiesel and poat-injection strategy. Difficult problems needed to solve such as reduce $NO_X$ emissions in natural gas engine under high compression ratio [7-10]. The soot and THC emissions could be reduced with employed the strategy of post-injection by increasing exhaust gas temperature and air circulation [6]. Early and small post-injection was stated in many prior works that effective to reduce smoke emissions due to the final-stage combustion acceleration phenomenon [11]. Using a suitable post-injection strategy in condition of single main injection was more effectively in reducing CO and THC emissions as well as $NO_X$ emissions [10, 12].

Due to increasing the oil depletion, environmental pollution, the use of alternative fuels is consider the good solution for these concerns [13]. The good properties of biodiesel encouraged the researchers to use pure diesel or blended with diesel fuel to use in diesel engines. The both feedstock of biodiesel (edible or non-edible) can offer good alternative conventional diesel fuel in internal combustion (IC) engines [14, 15]. Most of studies reported that biodiesel improve exhaust gas temperature and engine out emissions [6, 16-18]. In addition, the effective reduction in engine emissions and improve engine performance as well as combustion process can be occurred with using biofuel. It is reported that carbon monoxide, hydrocarbon, and PM reduced with a marginal increase in $NO_X$ emissions from biodiesel combustion usage in compression ignition engines. Furthermore, another reason for increase $NO_X$ emissions is due to the presence of fuel bound oxygen, which can improve the combustion of biodiesel [11, 19]. It is observed early occurrence of peak heat release rate and higher peak pressure at lower to medium load conditions during biodiesel combustion in comparison with diesel [20, 21]. The smoke and soot emissions reduced when engine using biodiesel fuel [3, 22-26]. Previous work stated that smoke emissions reduced when retarded fuel injection in the combustion process [17, 27]. In order to reduce the pollution emissions in diesel engine to the atmosphere, the international emission regulations are more and more stringent. Subsequently, various advanced emission reduction technologies, including in-cylinder purification [6, 20, 28]. There are numerous investigations on post injection strategy, but how post injection affects exhaust emissions is still unclear. Therefore, the purpose of this study is to investigate the influences of strategy of post-injection and alternative fuel on emissions characteristics and smoke/soot emissions.

## II. Materials and Materials

The test was conducted on four-cylinder, direct injection (DI) diesel engine. Figure 1 demonstrated the arrangement of the experimental setup and tools. A GW160 electric dynamometer (PowerLink) and FC3000 dynamometer controller (PowerLink) that was coupled with the engine were used to control and measure the state parameters such as engine torque and speed. The biodiesel and alcohol were employed as alternative fuel and tested as a pure fuel and blended with diesel fuel. The biodiesel used in the current study was produced from sunflower oil, which is collected for biodiesel production. Further, the main properties of diesel and biodiesel are listed in Table 1.

TABLE 1. Specification of tested fuels

| Properties | Diesel | Biodiesel |
|---|---|---|
| Chemical formula | $C_{16}H_{34}$ | $C_{19}H_{36}O_2$ |
| Derived cetane number | 51.8 | 62 |
| Latent heat of vaporization (kJ/kg) | 242 | 216 |
| bulk modulus (MPa) | 1410 | 1554 |
| density at 15 °C (kg/m$^3$) | 844.3 | 896.1 |
| Calorific value (MJ/kg) | 45.80 | 38.90 |
| Falsh & Fire point (°C) | 65-70 | 157-162 |
| Water content by coulometric KF (mg/kg) | 40 | 170 |
| kinematic viscosity at 40 °C (cSt) | 2.77 | 5.0 |
| Stoichiometric air fuel ratio | 14.4 | - |
| lubricity at 60 °C(μm) | 312 | 205 |

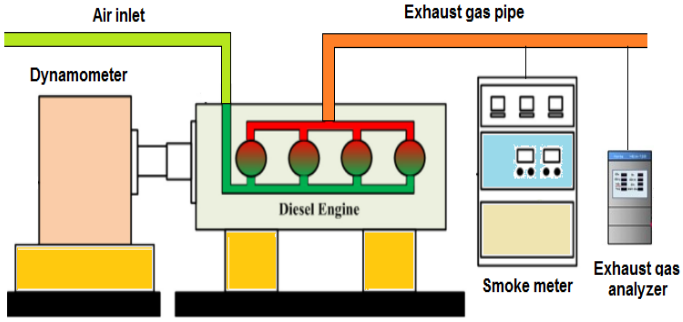


Figure 1: Engine setup and tools.

## III. RESULTS AND DISCUSSION

### *3.1 Combustion Performance*

Figure 2 showed the effect of the post-injection timing on the combustion phase and rate of heat release (ROHR) using alternative fuel. It was possible that the more effective combustion due to higher in cylinder temperature and greater oxygen utilization with the early post-injection. It was observed that more oxygen was consumed by the combustion of the main injection and the in-cylinder temperatures decrease as the post-injection delaying due to cylinder expansion and heat transfer [29]. It was found that the the increase of the amount of post-injection leads to gradually decreases in-cylinder temperature of main combustion. The cylinder pressure and rate of heat release (ROHR) profile increased from biodiesel combustion with multiple injection compared to the diesel (Figure 2). This is due to the fuel bound oxygen present in biodiesel, which enhances the local air/fuel ratio to promote premixed combustion [6, 17]. Another reason, this change is majorly attributed to the rise in premixed combustion with higher injection pressure.

### *3.2 Exhaust Gas Emissions*

Figure 3 shows the effect of multiple injection and alternative fuel on exhaust gas emissions such as carbon monoxide (CO), nitrogen oxide ($NO_X$), and total hydrocarbons (THC). The level of CO and THC reduced from alternative fuel than to the diesel. The two functions of oxygen content and absence aromatic compounds in the fuel properties (biodiesel) help in reduction the gaseous emissions [20, 30].

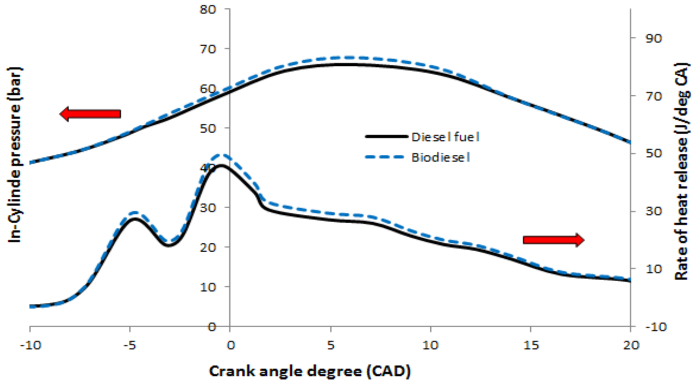


Figure 2: Effect of post-injection timing and alternative fuel on in-cylinder pressure and ROHR.

The THC emissions increase slowly with the retarded injection timing because the in-cylinder temperature is slightly lower. More complete combustion process consists of the following events including vaporization, atomization, self-ignition, mixing, and combustion. It is stated that alternative fuels produces lower exhaust emissions than to the diesel fuel [17, 22, 31]. The fuel can be relatively completely combusted producing a small quantity of THC emissions, since post injection is activated close to the main injection. [8] The engine-out CO emissions increased relatively with post-injection timing in the early injection timing range, reached the peak values around 70 crake angle degree (CAD) after top dead centre (ATDC) as presented in Figure 3. Less engine-out CO emissions can be occurred with earlier injection timing [17] in this range can lead to more complete combustion [17]. The engine-out $NO_X$ concentrations decreased for biodiesel mainly because the thermal $NO_X$ formation is inhibited due to the sharp reductions of in-cylinder temperatures (Figure 3) [32]. On the other hand, it is documented in some work that $NO_X$ emissions increased from alternative fuels than to the diesel [33, 34]. They found that the high temperature and oxygen enrichment are the conditions which promote the formation of $NO_X$ emissions.

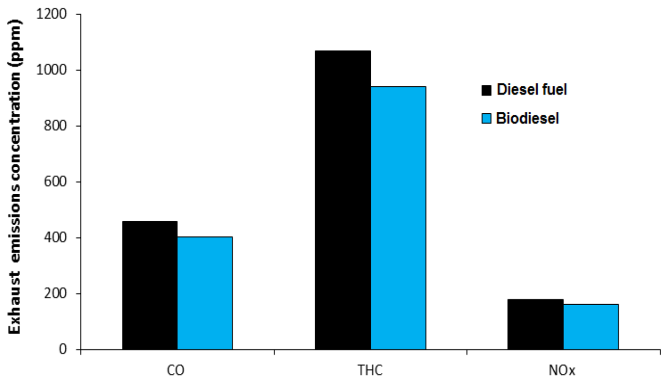


Figure 3: Different exhaust gas concentrations under post-injection and alternative fuels.



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*3.3 Smoke Emissions*

The influence of post-injection on smoke opacity for diesel and biodiesel is presented in Figure 4. It can be noticed that smoke opacity were reduced with biodiesel due to high levels of premixing for all the tested blends with respect to the diesel fuel [6]. The availability of time required for premixing and oxygen content, which enabled the reduction of the emitted smoke [8, 35]. The exhaust smoke concentration was lower existence of fuel bound oxygen increases the soot oxidation (Figure 4). This could be attributed to the reduced diffusion combustion phase for biodiesel achieved with the help of fuel bound oxygen, which enhances the combustion rate and smoke emissions. The use of biodiesel reduced the smoke emissions by 23.5% with post-injection than to the diesel fuel Figure 4). The post-injection has a more beneficial impact on smoke reduction for biodiesel.

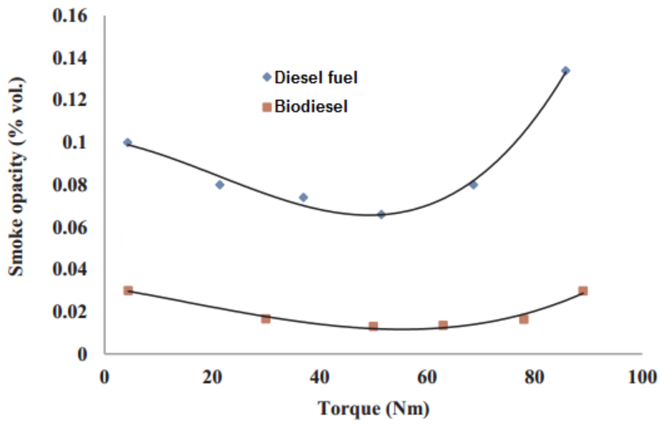

Figure 4: Effect of post-injection and alternative fuels on smoke opacity for diesel and biodiesel.

*3.4 Soot Emissions*

The variations of soot emissions under post-injection conditions and alternative fuel are shown in Figure 5. According to the results, it can be seen that the soot emissions are significantly with biodiesel compared to the diesel. The generation of soot under post-injection condition reduced for both fuels. This could be likely that part of the post-injection fuel is sucked into the main combustion product, resulting in the combustion of the post-injection fuel in the oxygen-depleted region [36, 37]. Further, the level of soot emissions reduced with biodiesel than to the diesel fuel fir the same post-injection condition (Figure 5). The soot emissions reduced from the injection of post fuel compared to a single injection condition [38, 39]. Additional turbulent energy enhanced the Soot oxidation and combustion exothermic provided by the post-injection. For the same post injection fuel quantity, the level of soot emission is relatively high at early post injection timing [11, 40]. Biodiesel combustion produces smaller soot particles by 25 nm than to the diesel fuel combustion by 33 nm.

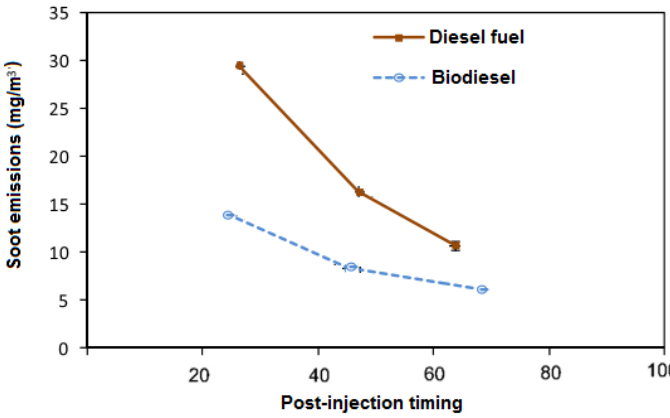

Figure 5: Effect of post-injection and alternative fuels on soot level for diesel and biodiesel.

## IV. Conclusions

The impact of multiple injections on engine performance, exhaust gas emissions, smoke and soot emissions was studied. The results show that the presence of oxygen in biodiesel used in this study is enough to alleviate the exhaust gas emissions and improve the combustion process. It was found that the CO and HC concentrations increased with presented post-injection for diesel and biodiesel. It is concluded that CO, $NO_X$, and THC reduced when using biodiesel fuel compared with diesel duel. Lower smoke opacity can be achieved when biodiesel fuel was used. This can be achieved with relative enhancement in thermal efficiency. It was found that the smaller soot particles produced from biodiesel combustion by 25 nm than to the diesel fuel combustion by 33 nm. The interaction of biodiesel with strategy of post-injection has been shown to be a feasible for emissions reduction. The presence of the hydroxyl group has been shown to be beneficial in terms of engine performance and engine-out emissions.

## Abbreviations

ATDC = after top dead centre

CI = compression ignition

CO = carbon monoxide

CAD = crake angle degree

DI = direct injection

HCs = hydrocarbons

IMEP = indicated mean effective pressure

$NO_X$ = nitrogen oxides

PM = particulate matter

ROHR = rate of heat release

THC = total hydrocarbons

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