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Assessment of the impact of post-injection on exhaust pollutants emitted from a diesel engine fueled with biodiesel

Hao Li, Chonglin Song*, Gang Lv, Huating Pang, Yuehan Qiao

State Key Laboratory of Engines, Tianjin University, Tianjin 300072, China

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ABSTRACT

This paper reports the effect of post-injection on pollutant emissions from a four-cylinder, direct-injection diesel engine fueled with biodiesel. Characteristics of exhaust pollutants were measured and evaluated for different main-post intervals (MPIs) and post-injection rates (PIRs). Measurements included emissions of carbon monoxide (CO), total hydrocarbons (THC), nitrogen oxides (NO_x) and particulate matter (PM), the particle number concentration distribution, and the reactivity and graphitization degree of the soot particles. Increasing the MPI or PIR increased the emissions of CO and THC but decreased those of NO_x. At both low and high MPI values, higher PM emissions and particle number concentrations were observed for the 12 and 20% PIRs. At a PIR of 4%, PM emissions and particle number concentration increased with the increase in MPI. The size distributions of exhaust particulates exhibited a trimodal character under the applied operating conditions. The particle geometric mean diameter decreased with the increase in MPI, probably as a result of an increased yield of soluble organic compounds. Post-injection significantly impacted the reactivity of emitted soot particles, as evidenced by changes in the graphitization degree of soot.

1. Introduction

Biodiesel is a biomass-based, renewable fuel that can be made from vegetable oil, plant oil, or animal fat. Biodiesel has gradually been accepted in diesel engines around the world because of its advantages for the economy, environment and society. As a biomass fuel, biodiesel has a number of desirable properties relative to conventional diesel, such as renewability, low level of sulfur and aromatic content, higher flash point, higher lubricity, higher cetane number and lower toxicity [1–3]. In particular, biodiesel can be used in contemporary diesel engines in pure form or blended form and without engine modification [3]. However, alongside these various benefits of biodiesel, there are also some disadvantages relative to conventional diesel, including higher viscosity, higher pour point, lower calorific value, lower volatility, lower oxidation stability and the corrosivity of some engine components [1,2,4]. Fortunately, the lower calorific value of biodiesel can be partially compensated by its higher density. Moreover, the use of biodiesel shows increased dilution and polymerization of engine sump oil, thus requiring more frequent oil changes [5–7]. With regard to emissions, it is usually reported that using biodiesel or biodiesel/diesel blends in diesel engines substantially reduces unburned total hydrocarbons (THC), smoke, particulate matter (PM) and carbon monoxide (CO) emissions, but results in an increase in nitrogen oxide (NO_x) emissions [8–13]. However, a decrease in NOx emissions was found with the use of biodiesel in several investigations [14–16]. Karabektas [17] attributed this discrepancy to the different engine setting, type of fuel and engine operating condition used in the studies.

In recent decades, driven by increasingly stringent emission regulations, various new techniques such as common-rail injection system, exhaust gas recirculation and after-treatment systems have been widely accepted in diesel engines to reduce the exhaust pollutants. Multiple injections of fuel are an effective and popular technique for controlling diesel engine combustion and emissions [18]. Multiple injection strategies typically include three phases: pilot injection, main injection and post-injection. Post-injection occurs after the main injection and involves the injection of a very small fraction of the fuel, which can increase temperature and generate turbulence in the late combustion phase, and thereby decrease soot exhaust emissions [19,20]. Post-injection also aids the management of exhaust after-treatment for diesel engines by providing additional hydrocarbons in the exhaust for the regeneration of various exhaust after-treatment devices. For example, in the integrated diesel oxidation catalyst (DOC) and diesel particulate filters (DPF) system, the increased exhaust temperature by the oxidation of the additional hydrocarbons on the

* Corresponding author.
E-mail address: songchonglin@tju.edu.cn (C. Song).

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DOC can regenerate the DPF [20]. In the lean NO_x trap (LNT) system, the stored NO_x on LNT catalyst are reduced to N_2 by the additional hydrocarbons, achieving the regeneration of LNT system [21].

There have been extensive studies concerning the effects of post-injection on the pollutant emissions from diesel engines fueled with diesel [19,22–25]. To my knowledge, however, only Chen et al. [20] focused on fueling with biodiesel. They reported that when using biodiesel fuel on an eight-cylinder direct injection diesel engine, the engine-out THC emissions at late post-injection timings were significantly higher than that at early post-injection timings, while the engine-out CO emissions reached the peak values in mid phase of power strokes and the engine-out NOx emissions could be reduced with a late post-injection. Post-injection rate was found to be the dominant factor influencing the exhaust emissions at fixed post start of injection timings. For early post-injections with a high fuel rate, biodiesel produced higher engine-out THC and CO emissions, and lower engine-out NOx emissions than diesel. For early post-injections with a small quantity of fuel and late post-injections, biodiesel was observed to produce significantly lower engine-out THC and CO emissions than diesel. Compared with diesel, biodiesel has different physicochemical properties of the liquid fuels, including lubricity, cetane number, aromatic content and fuel composition. These differences in fuel properties inevitably affect combustion and may lead to different emission characteristics of diesel engines. Boehman et al. [26] reported that the soluble organic friction (SOF) content of the particulates produced from biodiesel/diesel blend was higher than that from pure diesel. At the same time, biodiesel addition altered the nanostructure and oxidation reactivity of the primary soot particles, yielding a more amorphous soot structure, which enhanced the rate of soot oxidation. Ess et al. [27] determined increase in soot reactivity when increasing biodiesel content as well as for increasing boost and injection pressure. However, the soot nanostructure was found to be similar for all soot samples of different engine operation parameters and biodiesel blends. They stated that the soot oxidation reactivity was a product of many factors such as soot nanostructure, agglomerate size and ash content and not only determined by one soot property. In the study of Rodríguez-Fernández et al. [28], the soot generated from oxygenated biofuels were also more reactive than the soot from fossil diesel. Moreover, it was revealed that small advances/delays of the injection timing and/or the presence of a fuel post-injection did not significantly alter the reactivity of soot. Based on a comparison of complete oxidation behavior and burning mode, Song et al. [29] claimed that the oxidation mechanism of neat biodiesel soot was substantially different from those of diesel and Fischer–Tropsch fuel soots. The crucial mechanism by which biodiesel soot enhanced oxidation was a significant structural change of the outer band and a subsequent hollowing out during the early stage of oxidation.

For the widespread acceptance of biodiesel in diesel engines, it is therefore necessary to understand how post-injection affects the emission characteristics of diesel engines with the use of biodiesel. In this study, we aimed to assess the impact of post-injection on the exhaust pollutants emitted from a four-cylinder, four-stroke diesel engine using biodiesel. For different post-injection rates (PIRs) and main-post intervals (MPIs), exhaust pollutants (including CO, THC, NO_x and PM) were characterized and discussed in detail. In addition, the reactivity and graphitization degree of exhaust soot particles were analyzed using thermogravimetric analysis (TGA) and Raman spectroscopy.

2. Materials and methods

2.1. Diesel engine and test procedure

Tests were performed on a direct-injection, light-duty diesel engine that was not fitted with after-treatment and EGR systems. Specifications of the engine used are given in Table 1. The engine was coupled with an eddy-current dynamometer (AVL ALPHA350AF), and a PUMA control system was used to adjust the engine speed and torque. During testing, the temperature of the coolant and the oil were automatically controlled at 80–85 °C and 85–90 °C, respectively. The test engine was fueled with neat soybean oil methyl ester, which fulfilled the Chinese standard of GB/T 20828-2007. The properties of the used biodiesel fuel are listed in Table 2. Engine operating speeds were set at 1300, 1800 and 2300 rpm, and total injection fuel mass was fixed at 58 mg/cyc. The average indicated mean effective pressure (IMEP) was 10.6 bar when measured on a single-injection case.

The common rail fuel injection system was controlled by a PC-linked, electronic control unit (EDC 17CV54, Bosch). An ETAS ES590 calibration device and INCA 6.2 software were used to control the fuel injection mass and timing. As shown in Fig. 1, we employed a two-stage injection strategy: a single-shot main injection and a single-shot post-injection with injection pressure of 130 MPa. To avoid an unacceptable maximum pressure rise ratio, the main injection was timed to occur at a crank angle (CA) of $-1°$ after the compression top dead center (ATDC). The PIR was defined as the ratio of the mass of fuel post-injected against the total mass of fuel used per cycle. The PIRs used in the present study were 4, 12 and 20%, and the corresponding post-injection fuel mass is 2.3, 7.0 and 11.6 mg/cyc, respectively. The MPI was defined as the CA from the end of main injection to the start of post-injection. Because of the deterioration of thermal efficiency and unstable combustion for large MPI values, the MPI values investigated were 8, 12, 16 and 20° CA. Since the combustion efficiency was modified when varying MPI and PIR, different engine powers could be obtained using the same fuel mass for the applied tests. Fortunately, no significant difference was found in the engine power, and the relative errors between the experimental data and the average values were all below 3.9% for engine power. The in-cylinder pressure traces were measured with a pressure transducer (Kistler 6052C31). The pressure trace voltages from the pressure transducer were amplified by an amplifiers (Kistler 5010B) connected with the pressure transducer. The cylinder pressure was recorded in 0.5° CA increments, triggered by an optical shaft encoder (Kistler 2614A4). At each operating point, 50 consecutive pressure cycles were recorded and stored. The in-cylinder pressure data along with other engine operating parameters were analyzed to obtain the apparent heat release rate and gas mean temperature. Fig. 2 showed the typical in-cylinder pressures, gas mean temperatures and heat release rates.

2.2. Measurement of exhaust pollutants

The exhaust gas was measured using a HORIBA MEXA-7100DEGR exhaust analyzer with a resolution of 1 ppm. The THC, NO_x and CO concentrations were measured by a flame ionization detector, a chemiluminescent detector, and a non-dispersive

Table 1
Specifications of the diesel engine.

No. of cylinders, configuration	Four, in-line
Bore × stroke (mm)	102 × 118
Engine displacement (cm^3)	3856
Compression ratio	17.5:1
Valves per cylinder	4
Fuel injection type	Common rail system
Intake system	Turbocharged, intercooled
Rated power (kW)	100@2800 rpm
Maximum torque (Nm)	420@1500–1700 rpm