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Influence of injection timing and split injection strategies on performance, emissions, and combustion characteristics of diesel engine fueled with biodiesel blended fuels

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ABSTRACT

Biodiesel can be used as alternative to replace fossil diesel. However, usage of biodiesel in an unmodified diesel engine can cause higher in nitrogen oxides (NOx) emission. In order to reduce the harmful emission, certain injection strategies can be carried out. In this paper, the effects of biodiesel blends, fuel injection timing and split injection schemes on the engine performance, emissions and combustion characteristics of a medium-duty diesel engine are investigated. Parametric studies relating with start of injection timing variation and multiple injection schemes using B20 and B50 biodiesel blends were performed and benchmarked with petroleum diesel fuel as baseline. A remarkably lower NOx level below 100 ppm can be obtained by retard start of injection (SOI) timing for both of the B20 and B50 fuel operations and with triple injection scheme. It was found that with the use of B50, simultaneous NOx and smoke suppression from the levels of petroleum diesel fuel is attainable in parallel with the implementation of late SOI timing and triple injection scheme in a diesel engine. In conclusion, multiple split injections is a practical strategies to simultaneously decrease NOx and smoke emissions when the SOI timing is fine-tuned and is an ideal alternative to operate with biodiesel fuel.

1. Introduction

The widespread use of diesel engine has caused air pollution problems. This is due to their higher exhaust discharges of nitrogen oxides (NO_x), particulate matter (PM) and smoke in comparison with that of a gasoline engine [1]. The air pollutants jeopardize human health in different ways, necessitating the needs to curb this problem [2–4]. To minimize this impact, research effort are being focused on injection strategies such as variable injection timing, split injection, variable injection pressure, variable nozzle configuration, and others [5,6]. Injection timing optimization can be performed in order to produce a suitable ignition delay as well as to reduce the amount of exhaust emission in diesel engine. For instance, advancing the injection timing reduces the amount of carbon monoxide (CO), hydrocarbon (HC) and smoke while increases the amount of NO_x emitted [5]. More time is available for oxidation when injection is advanced, thus reducing the amount of CO, HC and smoke, but with higher amount of NO_x emitted. In order to reduce amount of NO_x emitted, the injection can be carried out later to lessen the air temperature even though at the expense of increasing the amount of CO, HC and smoke emitted due to incomplete combustion.

Another strategy can be implemented to diesel engines to attain lower emission limit is by split injection. It can be carried out to reduce engine noise and amount of NO_x emitted. Furthermore, accurately performed split injection schemes can be favorable in reducing combustion noise, waste emissions and diesel consumption and therefore, they are effective tools [7]. Besides, particulate emissions can be reduced substantially without a great increase in NO_x emissions [8,9]. This is because high heat release rate (HRR) can be prevented at the beginning of combustion, hence decrease the flame temperature and permit better fuel and air mixing to enhance in-cylinder charge homogeneity. Besides, energy demands of the world are increasing nowadays. Depletion of fossil diesel fuel can be slowed by adopting renewable source of energy such as biodiesel. Biodiesel can be made from vegetable oil, animal fat or waste materials such as spent coffee grounds [10]. Also, it is nontoxic, renewable and biodegradable

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compared to conventional diesel [11]. Generally, CO, smoke and particulate matter concentration emitted when biodiesel is used are lower compared to conventional diesel [12,13]. However, NO_x emission of biodiesel can be higher or lower for different types of biodiesel and operating condition [12,14]. Biodiesel has cetane number which is higher than ordinary petroleum diesel, which implies that it has a better ignition properties and higher combustion efficiency [12,15,16]. Biodiesel evaporates, atomizes and breaks up slower because it has a higher kinematic viscosity and surface tension. Hence, it is important to apply a suitable injection strategies to overcome this problem.

The increasing of world population has rapidly increasing the energy demand from non-renewable resources [17]. Biodiesel fuels have gained increasing attention worldwide as blending components or direct substitution for diesel engines [18]. However, the utilization of biodiesel in diesel engines has usually produced higher NOx and brake specific fuel consumption [19–21]. Using alternative fuels and optimization of fuel injection parameters in diesel engine can be reliable methods to solving this problem. According to Shivakumar et al. [22] in the research of effects of biodiesel and injection timing on single-cylinder diesel engine performance, NOx emission of waste cooking oil blended fuel is relatively higher than that of baseline diesel. It is found that the NOx emission will be lower at retarded injection timing for baseline diesel and biodiesel. The smoke emission of biodiesel is less than baseline diesel and the advanced injection timing will reduce the smoke reduction of both kinds of diesel. Qi et al. [23] showed that NOx emission always decreases with the retarding injection timing when using biodiesel produced from soybean as energy source in six-cylinder diesel engine. Sayin et al. [24] and Ganapathy et al. [25] also obtained the same results as Shivakumar et al. [22] when Jatropha biodiesel are used correspondingly in their researches by using single-cylinder diesel engine. Recently, modern engines are trending toward multiple fuel injection events as a means to decrease emissions and improve engine performance [26,27]. In the investigation of effects of split injection on the emissions of biodiesel, Fang et al. [28] found that NOx emission of biodiesel can be 34% lower than baseline diesel under certain injection scheme at specific condition in single-cylinder diesel engine. The injection strategies used in their study included double injection of a small first injection with an early pre-TDC (top dead center) timing and followed by a main injection at or after TDC. Joonho Jeon et al. [29] discovered that retardation of pilot injection timing will cause increasing amount of NOx emission when soybean biodiesel is used in single-cylinder diesel engine. Kuen Yehliu et al. [30] showed that under single injection scheme in four-cylinder diesel engine, the amount of emission of NOx is higher for biodiesel compared to baseline diesel. However, when split (pilot and main with non-equal fuel quantity) injection scheme is carried out, the NOx emission is the lowest for biodiesel. The drawback is that there will be an increase in particulate matter emitted when biodiesel and baseline diesel are used when split injection scheme is carried out. Su Han Park et al. [31] studied about the relationship of injection timing and split injection (with up to two injections per combustion cycle) with the performance of biodiesel by using a single-cylinder diesel engine. They found that NOx emission increases with advanced injection timing. Multiple injection scheme cause less soot to be emitted compared to single injection scheme except at highly advanced injection timing. The retardation of pilot injection timing reduces the amount of soot emitted. Besides, multiple injection strategy has been proposed as an effective way to reduce unburned emissions and noise [32,33].

From the previous works, it is evident that most of the studies have been focused on experimental research of biodiesels in which few experiments were conducted with injection timing variation and split injection, specifically dealing with two or more fuel injections of equal quantities per combustion cycle. Besides, although the above mentioned literature reported the studies of split injection engine combustion, but most of them have been performed on single-cylinder research engine, which is not practical representative of the production engine adopted in commercial vehicles. Thus a research gap remains in these fields which are addressed in this research study. The outcome due to changes in biodiesel blends, injection timing and split (with up to three injections of equal fuel quantity) injection schemes on a four-cylinder medium-duty diesel engine will be investigated in the present study. From the results, the effect of each of the injection strategy will be determined to enhance the research in developing biodiesel to overcome the air pollution and fossil fuels depletion issues.

2. Experimental apparatus and procedure

2.1. Apparatus setup

The experimental study was implemented using three types of fuel sample. The samples consist of diesel, B20 (in a volume fraction of 20% biodiesel blends and 80% diesel) and B50 (in a volume fraction of 50% biodiesel blends and 50% diesel) of coconut oil biodiesel (COB) blends. A four-cylinder diesel engine with Delphi common-rail fuel injection system and turbocharger set up was utilized in the research. Variation of speeds and loads was controlled using eddy current engine dynamometer with rating of 150 kW. Measurement of engine fuel consumption was done by employing Kobold fuel flow meter. Temperatures of surrounding air, engine lubricant oil, exhaust gas emitted and engine coolant were obtained by using K-type thermocouples. Table 1 shows the specifications and information of test engine.

Commercially available microcontroller was used as the engine control module (ECM). The microcontroller employed three interrupt service routines in order to receive the signals from incremental encoder and engine camshaft. Besides, a C programming language was used in programming coding. The codes were uploaded to microcontroller through serial communication with personal computer. A graphic user interface (GUI) program was created using LabVIEW to manipulate and examine the engine parameters including start of injection (SOI) timing, engine speed, opening pulse-width (PW) and number of injections (single, double and triple injection) and closed-loop engine speed control mode selection. Quantity of diesel injected was regulated by a dedicated engine speed controller to maintain engine rpm to within ± 10 rpm (revolution per minute) from the set point. This engine speed controller comprised a fine-tuned proportional-integral (PI) control loop. By deploying this approach, the speed controller could reject a huge amount of disturbance and minor steady-state error spanning the whole engine operating range. In addition, programmable peak and hold pulse-width-modulation (PWM) was incorporated in engine controller to control the solenoid injectors for common-rail direct injection efficiently. Engine parameters could be fully controlled by this specifically designed control unit.

To execute the combustion process analysis, the gas pressure in cylinder was obtained with a Kistler 6058A piezoelectric sensor and high speed data acquisition system was used to record its signal. Glow plug adapter was utilized so that pressure sensor could be fixed in the first cylinder's head. DAQ-Charge-B charge amplifier was employed to enlarge the signal from pressure sensor. Incremental encoder with the

Table 1
Specifications and information of the test engine.

Type of Engine	Diesel, 4-stroke, turbocharged direct injection engine
Fuel injection supply system	Diesel common-rail with rail pressure 140 MPa max.
Cylinder	4
Valve per each cylinder	2
Bore x stroke	76.0 mm × 80.5 mm
Connecting rod length	135 mm
Displacement	1461 cm^3
Compression ratio	18.25–1
Maximum power & torque	48 kW at 4000 rpm & 160 Nm at 2000 rpm

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