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Effect of injection parameters on the combustion and emission characteristics in a common-rail direct injection diesel engine fueled with waste cooking oil biodiesel

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ABSTRACT

The objective of this paper was to study the effects of the injection pressure and injection timing on the combustion and emission characteristics in a single-cylinder common-rail direct injection (CRDI) diesel engine fueled with waste cooking oil (WCO) biodiesel and commercial diesel fuel. The fuel property including fatty acid composition for the biodiesel were measured and compared with those of the conventional diesel fuel. The engine tests were conducted at two injection pressures (80 and 160 MPa) and different injection timings from −25 to 0 crank angle degree (CAD) after top dead center (aTDC) under two different engine loads. The results showed that the indicated specific fuel consumption (ISFC) with respect to the injection timings of the biodiesel was higher than that of the diesel fuel under all experimental conditions. The peak cylinder pressure and the peak heat release rate of the biodiesel were slightly lower, while the ignition delay was slightly longer under all operating conditions. In terms of emissions, the biodiesel had benefits in reduction of smoke, carbon monoxide (CO), hydrocarbon (HC) emissions especially with high fuel injection pressure. The nitrogen oxide (NO_x) emissions of the biodiesel were relatively higher than those of the diesel under all experimental conditions.

1. Introduction

In the last 3 decades, the search for alternative and renewable fuels has gained importance because of the increasing environmental concerns and depletion of petroleum resources. Biodiesel is derived from vegetable oil or animal fats by transesterification with alcohols such as methanol and ethanol. It is recommended for substitution of petroleum based diesel fuel because biodiesel is an oxygenated, renewable, biodegradable and environment-friendly fuel. However the high costs of biodiesel are a major barrier to its commercialization. The use of low-cost feedstock such as WCO makes biodiesel competitive in price with petroleum diesel fuel. This opens an opportunity for the use of WCO as production feedstock [1–3]. Reusing of WCO can not only reduce the costs of disposing the waste and treating the oily wastewater, but also lower the production costs of biodiesel significantly.

A lot of researchers have reported that using WCO biodiesel instead of diesel fuel decreases harmful exhaust emissions with equivalent engine performance [4,5]. Lapuerta et al. [6] studied two different WCO biodiesel–diesel blends with a reference diesel fuel in a DI diesel commercial engine. The results showed that the brake thermal efficiency was not significantly affected, but the fuel consumption of biodiesel was increased. A sharp decrease was observed in smoke emissions as the biodiesel concentration was increased. Lin et al. [7] investigated the emissions of polycyclic aromatic hydrocarbons (PAHs), carcinogenic potencies and regulated matters of a heavy-duty diesel engine under the US-HDD transient cycle. The engine was fueled with ultra-low sulfur diesel (ULSD) and WCO biodiesel-ULSD blends. Experimental results showed that the use of the biodiesel blends decreased PAHs by 7.53%–37.5%, particulate matter by 5.29%–8.32%, HC by 10.5%–36.0% and CO by 3.33%–13.1% compared to using ULSD. Muralidharan et al. [8] evaluated the performance, emission and combustion characteristics of a single cylinder DI diesel engine fueled with WCO biodiesel and its 20%, 40%, 60% and 80% by volume blends with diesel fuel. The results indicated longer ignition delay, higher maximum rate of pressure rise, lower heat release rate and higher mass fraction burnt for the WCO biodiesel compared to those of diesel fuel. At the same time, several studies have shown that the injection timing affects the injection and combustion characteristics, engine performance and exhaust emissions of diesel engines when using biodiesel [9]. Bari et al. [10] examined the influence of advanced

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Abbreviations

aTDC	after top dead center
BSFC	brake specific fuel consumption
CAD	crank angle degree
CO	carbon monoxide
CO_2	carbon dioxide
CRDI	common-rail direct injection
DI	direct injection
EGR	exhaust gas recirculation
HC	hydrocarbon
ISFC	indicated specific fuel consumption
LHV	lower heating value
NO	nitric oxide
NO_x	nitrogen oxide
PAHs	polycyclic aromatic hydrocarbons
ULSD	ultra-low sulfur diesel
WCO	waste cooking oil

injection timing on the CO and NO_x emissions of a DI diesel engine using diesel and WCO biodiesel. The results indicated that the CO emissions were reduced, but the NO_x emissions increased when the injection timing was advanced. Qi et al. [11] studied the effect of injection timing and exhaust gas recirculation (EGR) rate on the combustion and emissions of a Ford Lion V6 DI diesel engine by using neat biodiesel produced from soybean oil. The results showed that the brake specific fuel consumption (BSFC) was slightly increased when the main injection timing was retarded. NO_x emissions were decreased and soot emissions hardly varied. Kannan et al. [12] investigated the effect of injection pressure and injection timing on a single cylinder DI diesel engine fueled with WCO biodiesel. The results showed that the combined effect of higher injection pressure and advanced injection timing improved the brake thermal efficiency significantly. Reduction in nitric oxide (NO) and smoke emissions were also observed. Gumus et al. [13] experimentally investigated the influence of injection timing on the engine performance, exhaust emissions and combustion characteristics of a diesel engine. The experimental test results showed that maximum cylinder pressure, heat release rate, combustion efficiency, NO_x and carbon dioxide (CO_2) emissions decreased when injection timing was retarded. The smoke number and HC and CO emissions increased at all test conditions.

In efforts to achieve the reduction of engine emissions and fuel consumption while keeping other engine performances at an acceptable level, the fuel injection parameters play an important role. The most important injection parameters are injection timing, injection duration and injection pressure. From the literature review, the combined effects of fuel injection pressure and injection timing on the combustion and emission characteristics of a CRDI diesel engine have not been clearly studied with using WCO biodiesel. In this study, therefore, the effects of injection pressure and injection timing on the combustion and emission characteristics of WCO biodiesel were experimentally studied.

2. Experimental setup and procedure

2.1. Biodiesel production, composition and properties

The biodiesel fuel used in this study was produced from WCO by transesterification technology with methanol (CH_3OH) catalyzed by sodium methoxide ($NaOCH_3$). A titration was performed to determine the amount of $NaOCH_3$ needed to neutralize the free fatty acids in WCO. For the transesterification, 220 g of CH_3OH and 18 g of $NaOCH_3$ were added for 1 kg of WCO at 343 K. The mixture separated into crude glycerin and biodiesel in this process. The separated crude biodiesel was washed with mildly acidic water to remove the neutralized catalysts, water soluble glycerin and soaps.

The fatty acid composition of the biodiesel was measured as shown in Table 1. In the WCO biodiesel, approximately 35% of the fatty acids were found to be mono-unsaturated. Poly-unsaturated fatty acids were found to be approximately 44%. Only approximately 17% fatty acids were saturated. Linoleic acid and oleic acid were the major fatty acids in the WCO biodiesel.

The major fuel properties of the biodiesel were measured according to ASTM standards and compared with those of diesel fuel, as shown in Table 2. It is obvious that the viscosity of the biodiesel is higher than that of diesel fuel. The density of the biodiesel is approximately 6.6% higher than that of diesel fuel. The LHV is approximately 9.6% lower than that of diesel fuel. Therefore, it is necessary to increase the fuel amount to be injected into the combustion chamber to retain same LHV. The sulfur content of the biodiesel is 1.0 mg/kg which is evidently lower than that of diesel fuel. The cetane number of the biodiesel is slightly higher than that of diesel fuel.

2.2. Experimental apparatus and conditions

The test engine was a single cylinder DI diesel engine with a bore of 100 mm, a stroke of 125 mm, displacement of 980 cc and compression ratio of 17.4. It was equipped with a high pressure common-rail injection system. The main specifications of engine are summarized in Table 3. The injection pressure, injection timing and injection quantity were controlled by a common-rail engine controller (Zenobalti, ZB-9013). An eight-hole solenoid type injector (Bosch) with a hole diameter of 0.131 mm and an injection angle of 150° was used. Engine speed was controlled constantly by a DC dynamometer (82 kW). A rotary encoder (Autonics, E40S) was mounted on the crankshaft. A smoke meter (AVL, 415S) was used to measure the engine-out smoke emissions. The NO_x, HC and CO emissions were measured using an exhaust gas analyzer (Horiba, MEXA 1500D). In-cylinder pressure was recorded at every 0.2 CAD by a piezoelectric pressure transducer (Kistler, 6052C) coupled with a charge amplifier (Kistler, 5011). The in-cylinder pressures of 100 engine cycles were averaged to calculate the heat release rate. Fig. 1 shows a schematic diagram of the experimental apparatus used in this study.

The engine was operated at an engine speed of 1400 rpm and the coolant temperature was set to 353 K. EGR was not used during the investigation. Injection pressures of 80 and 160 MPa of the common-rail injection system were adopted to verify the effect of the injection pressure. Injection timings were varied from −25 to 0 CAD aTDC by 5 CAD. Injection quantities of each fuel were set to 20 and 40 mg/stroke for diesel fuel as well as 22.1 and 44.3 mg/

Table 1
Fatty acid composition of waste cooking oil biodiesel.

Type of fatty acid	Carbon chain	% (By mass)
Myristic	C14:0	0.24
Palmitic	C16:0	13.12
Palmitoleic	C16:1	0.82
Stearic	C18:0	3.23
Oleic	C18:1	33.4
Linoleic	C18:2	39.2
Linolenic	C18:3	4.33
Arachidic	C20:0	0.39
Eicosenic	C20:1	0.47
Behenic	C22:0	0.2
Unknown components		4.6
Total		100