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The Combustion and Exhasut Emission Characteristics on the Low-temperature Combustion of Biodiesel Fuel in a DI Diesel Engine

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Key Words: Low-temperature combustion (LTC), exhaust gas recirculation (EGR), biodisel, direct injection (DI), diesel engine, nitrogen oxides (NO_x), soot

Abstract

The objective of this study is to investigate the effects of low-temperature combustion (LTC) on the correlations of combustion characteristics and reduction of exhaust emissions in a small DI diesel engine with biodiesel fuel. In order to analyze the combustion, exhaust emission characteristics and distribution of nano size particles for biodiesel were investigated. In addition, to evaluate the effect of LTC on the combustion and emission characteristics, 30 and 50% of cooled-EGR rates were investigated. From these results, it revealed that the influence of LTC on the combustion characteristics showed that the ignition delay significantly increased and reduces peak heat release rate of premixed combustion by lowering reaction rate. With 50% EGR and advanced injection timing, soot and NO_x emissions were simultaneously reduced.

1. Introduction

Biodiesel fuel derived from vegetable oils or animal fats and used as substitutes for conventional petroleum fuel in diesel engines has recently received increased attention. This interest is based on a number of properties of biodiesel including its biodegradability and the fact that it is produced from a renewable resource. Biodiesels, as alternative fuels for diesel engines, have the advantages of reducing or eliminating sulfur dioxide (SO_2), CO, and unburned hydrocarbons (UHC) in exhaust emissions[1-2].

These features of biodiesel lead to its greatest advantage, which is its potential for emission reduction. Though the environmental potential for emissions reduction, the vegetable oils have high viscosity and high pour points relative to conventional diesel fuel. The high viscosity of vegetable oils such as biodiesel and its blends tends to alter the injector spray pattern inside the engine, causing fuel impingement on the piston and other combustion chamber surfaces. This leads to the formation of carbon deposits in the engine, eventually resulting in problems such as stuck piston rings in the cylinder and subsequent engine failures, which would not occur otherwise using diesel fuel. The undesirable characteristics of vegetable oils can be substantially mitigated by replacing the triglyceride molecules in them with lighter alcohol molecules such as methanol or ethanol. This reaction is carried out in the presence of a catalyst and produces glycerol in addition to trans-esterfied vegetable oils that are given the generic name of biodiesel[3-4].

The essential merits for using biodiesel are that it is a nontoxic, biodegradable, and renewable fuel. Further advantages over conventional diesel fuel are that is includes a high cetane number, low sulfur, low aromatics, low volatility, and the presence of oxygen atoms in the fuel molecule. The positive effects of biodiesel on diesel engine emissions have been

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proven by a number of previous studies. The regulated and unregulated exhaust emissions from diesel engines with biodiesel and blended fuel were measured by Sharp *et al.*[5]. In their research, it was shown that the measurable HC emissions were generally eliminated, while CO was reduced roughly 40 percent by using a neat biodiesel. However, the NOx emissions increased by 12 percent due to the oxygen content in biodiesel.

For thesse reasons, one way to reduce the temperature during combustion is to use EGR in conventional diesel combustion engines. This results in a reduced local flame temperature during combustion. In low temperature combustion (LTC) regimes where increasing EGR reduces both NO_x and soot emissions[6].

The objective of this study is to investigate the effects of LTC on the correlations of combustion characteristics and reduction of exhaust emissions in a common-rail diesel engine with biodiesel. In order to analyze the combustion, exhaust emission characteristics and distribution of nano size particles for biodiesel were investigated in a common-rail direct injection (DI) diesel engine. In addition, to evaluate the effect of LTC on the combustion and emission characteristics of biodiesel fuel were conducted under the 0, 30 and 50% of cooled-EGR rate conditions.

2. Experimental Apparatus and Procedure

2.1 Experimental Apparatus

The overall setup of the intake-air flow measurement and cooled-EGR system are illustrated schematically in Fig. 1. In order to control and measure the intake air flow rate, an intake air flow meter system (GFM 57, Aalborg) was used, which has a 0 L/min - 200 L/min flow range, accuracy of ±1%, and repeatability of ±0.5% with a given pressure. The principles of operation are like that metered gases are divided into two laminar flow paths, one through the primary flow conduit, and the other through a capillary sensor tube. When gas flow takes place, the resultant temperature differential between two precision temperature windings is linearly proportional to the instantaneous rate of flow. In addition, the compressed intake air (0.18 MPa) was filtered and dried, and pressure of intake air maintained by a pilot-operated pressure regulator. For the exhaust gas recirculation (EGR), water-cooled EGR gas flowed in the intake process and the gas flow was regulated with an EGR control valve. In order to control the EGR rate, the quantity of air flow with EGR and without EGR cases were measured by using an air flow meter system installed in the intake pipe.

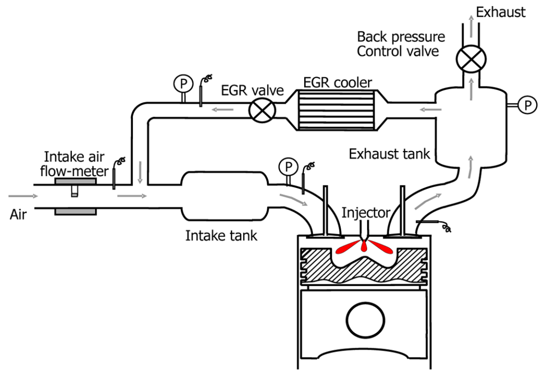


Fig. 1 Schematic diagrams of the intake-air flow and cooled-EGR system

Table 1 Specifications of single-cylinder test engine

Item	Description
Type	DI diesel engine
Bore×Stroke (mm)	75.0 × 84.5
Swept volume (cc)	373.3
Compression ratio	17.8
Combustion chamber type	Re-entrant
Intake system	Naturally aspirated
Number of valve	2-intake + 2-exhaust
Intake ports	1-swirl, 1-tumble
Swirl ratio	1.9
Fuel injection system	Common-rail
Number of nozzle	6 holes
Nozzle diameter (mm)	0.128
Spray angle	156°

Table 2 Experimental test conditions

Item	Description
Test fuel	biodiesel
Engine speed	1200 (rev./min)
Coolant temperature	70±1 (°C)
Oil temperature	70±1 (°C)
Injection pressure	120 (MPa)
Direct injection timing	BTDC 40°~TDC
Injection mass	10.4 (mg)
EGR rate	0, 30%, 50%
Total equivalence ratio	0.43, 0.61, 0.86

Experiments were conducted under a constant engine speed of 1200 rpm. Also, the injection pressure was fixed at a constant pressure of 120 MPa, and the coolant and oil temperatures were maintained at 70±1°C. The experimental investigation was conducted under a steady state condition with injection mass of 10.4 mg (equivalence ratio, Φ=0.43), which is coincident to 10mg of diesel fuel to consider the LHV of each fuel.

In LTC mode with biodiesel fuel, 30% (Φ=0.61) and 50% (Φ=0.86) of EGR were respectively examined, and then the combustion, exhaust emissions, nano-particle characteristics of each cases were measured and compared to without EGR combustion. The injection timing of biodiesel fuel was varied from 40° BTDC to TDC in step of 5° crank angle. In order to reduce the effect of the induction of exhaust gas on the increase of intake air temperature, cooled-EGR was adopted. The detailed experimental test conditions for this study are listed in Table 2.

3. Results and Discussions

3.1 Effects of cooled-EGR rate on combustion characteristics

The combustion pressure and heat release rates of biodiesel fuel for 0%, 30%, and 50% of exhaust gas recirculation (EGR) rates at a injection timing of BTDC 20° is shown in Fig. 2.

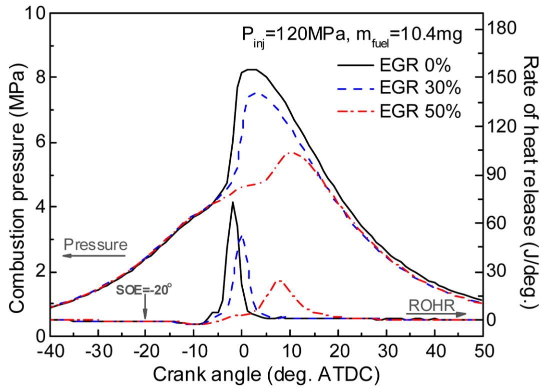


Fig. 2 Effect of LTC on the combustion characteristics (t_{inj})=BTDC 20°

As shown in this figure, combustion with the 30 and 50% of EGR rates show lower combustion pressure and rate of heat release and delayed ignition timing than that of without EGR combustion because of dilution effects. The influence of LTC on the combustion characteristics show that the ignition delay significantly increased and reduces peak heat release rate of premixed combustion by lowering reaction rate.

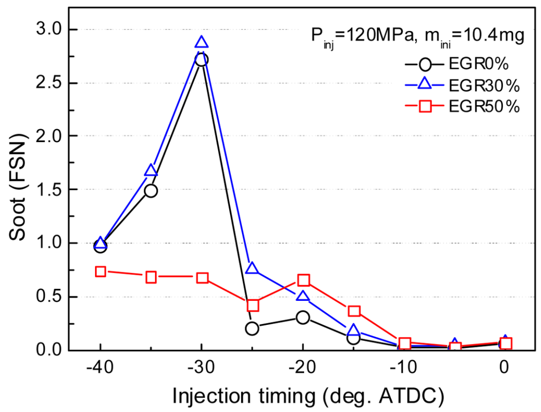
In general, the combustion performance of diesel fuel revealed a nearly miss-fire phenomenon with up to 50% EGR rate, so it is hard for the inducing of 50% EGR gas to achieve a stable mixture and combustion performance because the induce of EGR are dilute the oxidizer content and lower combustion temperatures. However, combustion in the engine fueled with biodiesel occurred more actively in this study even though the high rate of 50 % EGR was applied.

3.2 Effects of high EGR rate on exhaust emission characteristics

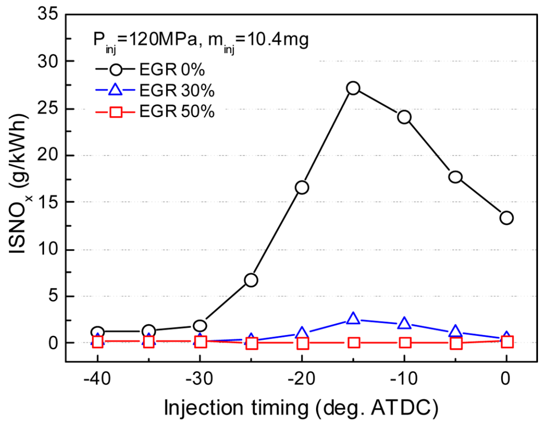
Figure 3(a) and (b) show the LTC and injection timing on the exhaust emission of soot and $ISNO_x$ characteristics, respectively.

In conventional diesel fuel combustion, diesel fuel generally emits larger amounts of soot because the mixture of oxygen concentration is decreased by EGR in the combustion phase. However, in this results, regardless of EGR rate, biodiesel combustion indicated generally low level of soot emissions at all injection timing ranges due to the high oxygen content, the absence of soot precursors and the short diffusion combustion phase suppressed soot formation a shown in Fig. 3(a). With LTC regime (high EGR rate), the increase of EGR slows down the reactions kinetically and gives the system more time to transfer heat to cooler regions during the combustion process. Moreover, the addition reactions are also hindered and therefore the accumulation mode for soot begins to slow down and this reduces soot with increase in EGR(7).

In Fig. 3(b), 50 and 30% EGR combustions indicated very low ISNO$_x$ levels. The ISNOx emission of biodiesel with the 50% EGR rate shows a trend of very low levels, which is nearly 40% of cases without EGR. Inducing of cooled-EGR is a very effective and simple method to reduce NOx emission. It can be suspected that the high rates of EGR result in a temperature drop in the burning-zone due to a dilution effect, thermal and chemical effects. The EGR dilutes the oxygen concentration of the intake fluid. Concurrently, the EGR increases the specific heat capacity of the working fluid thereby reducing the flame temperature. Furthermore, the endothermic dissociation of the EGR constituents such as H_2O may contribute to the reduction in flame temperatures.(8) In addition, increased ignition delay caused by dilution effect provides time for fuel evaporation and reduces inhomogeneities in the reactant mixture, thus reducing NO$_x$ formation from locally high tem-

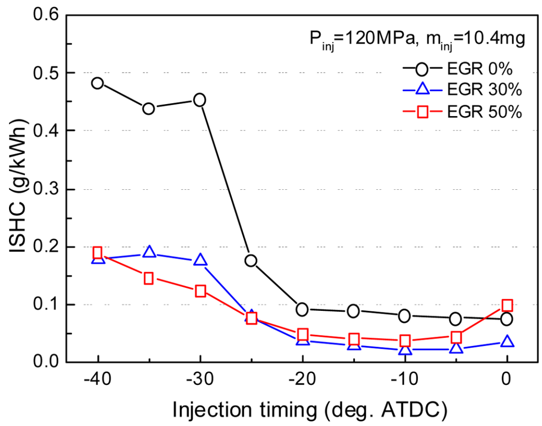


(a) Soot emission

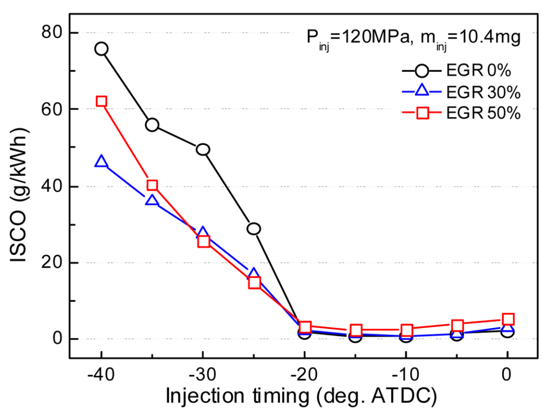


(b) NO$_x$ emission

Fig. 3 Effect of LTC on the exhaust emissions of soot and NOx



(a) HC emission

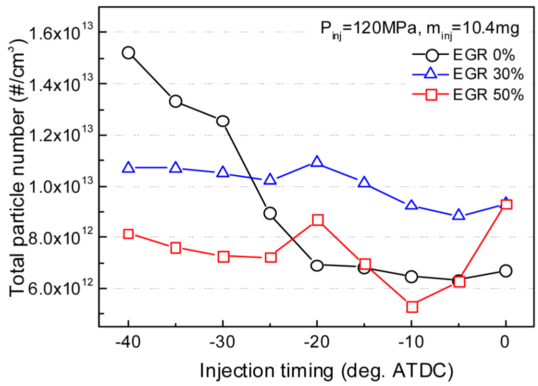


(b) CO emission

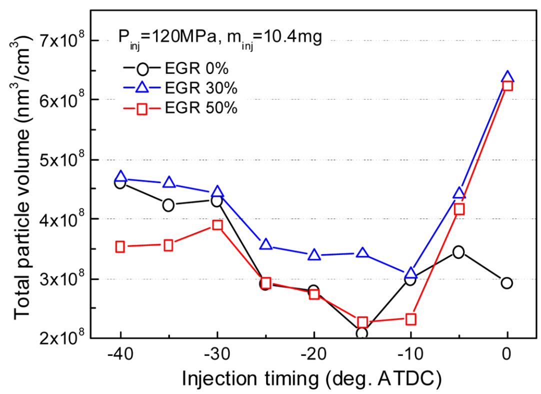
Fig. 4 Effect of LTC on the exhaust emissions of HC and CO perature region and soot formation from locally rich mixtures.

Figure 4 showed the LTC of EGR rate on the exhaust emissions of HC and CO. In these results, the ISHC and ISCO emissions(g/kWh) with 30% and 50% of EGR are relatively lower than those of without EGR. These results are mainly due to the lower combustion performances as shown in combustion pressure results (Fig. 2), which leads to reduce IS emissions.

At advanced injection timing (BTDC 25°~40°), the portion of fuel spray injected toward the piston head and bowl lip edge, then entering the squish area of the combustion chamber, in the investigation of the piston and crank angle geometry. Consequently, fuel spray in the squish region produced larger amounts of unburned emissions (CO and HC) with regardless of EGR rate.



(a) Total particle number



(b) Total particle volume

Fig. 5 Effect of EGR rate on the nano-particle emissions characteristics

3.3 Effects of LTC on the nano-particle emission characteristics

Figure 5(a) and (b) showed the effect of LTC and injection timing on the total particle number and particle volume characteristics. As shown in this figure, total particle number and volume of 50% EGR combustion indicated relatively lower than other cases with test injection timings. In the case of particle volume resutls (Fig. 5(b)), 30% EGR combustion indicated relatively higher than other cases with test injection timings. However, a close correlation between the total particle volume and the injection strategy with EGR rates were not found in these results.

5. Summary

In order to achieve the simultaneous reduction of soot and NO_x emissions fueled with biodiesel fuel, the effects of LTC on combustion characteristics, performance, exhaust emissions, and nano-particle characteristics were investigated.

(1) The influence of LTC on the combustion characteristics show that the ignition delay significantly increased and reduces peak heat release rate of premixed combustion by lowering reaction rate.

(2) Biodiesel combustion with LTC regime indicated generally low level of soot emissions at all injection timing ranges. In the case of NOx emission, ISNOx emission of biodiesel with the 50 % EGR rate shows a trend of very low levels, which is nearly 40% of cases without EGR.

(3) The ISHC and ISCO emissions (g/kWh) with 30% and 50% of EGR are relatively lower than those of without EGR. At advanced injection timing (BTDC 25°~40°), larger amounts of unburned emissions (CO and HC) emitted with regardless of EGR rate.

(4) Total particle number and volume of 50% EGR combustion indicated relatively lower than other cases with test injection timings. In addition, 30% EGR combustion indicated relatively higher than other cases with test injection timings.

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