

Performance and Emission Characteristics of a Diesel Engine Fueled with Pyrolysis Oil-Ethanol Blend with Diesel and Biodiesel Pilot Injection

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ABSTRACT

The vast stores of biomass available worldwide have the potential to displace significant amounts of petroleum fuels. Fast pyrolysis of biomass is one of several possible paths by which we can convert biomass to higher value products. Pyrolysis oil (PO) derived from wood has been regarded as an alternative fuel to be used in diesel engines. However, the use of PO in a diesel engine requires engine modifications due to the low energy density, high acidity, high viscosity, and low cetane number of PO. Therefore, PO should be blended or emulsified with other fuels that have a high cetane number or used through pilot injection.

PO has poor miscibility with light petroleum fuel oils; the most suitable candidate fuels for direct fuel mixing are alcohol fuels. Early mixing with alcohol fuels has the added benefit of significantly improving the storage and handling properties of the PO. For separate injection co-firing, a PO-ethanol blend can be fired through diesel or biodiesel pilot injection in a dual-injection diesel engine. In this study, the performance and emission characteristics of a dual-injection diesel engine fueled with diesel & biodiesel (pilot injection) and PO-ethanol blend (main injection) were experimentally investigated. Results showed that although stable engine operation was possible with dual injection, the fuel conversion efficiency was slightly decreased compared to that of diesel and biodiesel combustion. Regarding the exhaust emissions, THC & CO emissions were slightly increased and NO_x & soot emissions were significantly decreased due to the high water content and oxygen content in the PO-ethanol blend.

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INTRODUCTION

To replace fossil fuel, which is the main cause of global warming, renewable energies have recently become the center of attention; among them, there are technologies that use wood and various sources of biomass to produce liquid, solid, and gaseous fuels [1, 2]. In nations with plenty of lumber resources, cogeneration power plants that use PO are being built, and technologies that produce power with gas turbines [3, 4] and diesel engines are being studied [5]. Furthermore, some researchers are trying to use PO as fuel for transportation diesel engines [6]. As a part of this research, the combustion characteristics, namely the exhaust

emission characteristics of PO and diesel, were compared [7]. It has been reported that PO mixed with a cetane enhancer showed a combustion performance equal to that of diesel [8], while a PO-diesel emulsified fuel with a maximum of 30 % PO showed a decreased level of NO_x in the exhaust emission in a diesel engine [9]. PO, however, has fuel properties that are not suitable for diesel engines. Although PO is also capable of combustion, it causes wear and corrosion in fuel supply systems [10].

Fuel properties of PO highly depends on the type of biomass used and the production process and usually contains 18-30% water, as well as oxygen content higher than that of fossil fuel. Due to these differences in properties, diesel and

PO have different fuel spray atomization levels, temperature of ignition, and combustion characteristics, as well as having different emission characteristics of exhaust. The characteristics of PO are summarized as follows [11]:

- Due to a low cetane number of PO, PO usually does not produce self-ignition in conventional diesel engines. Therefore, PO should be blended or emulsified with other fuels that have a high cetane number or should be used through diesel pilot injection. However, for the conditions of a high intake temperature of over 200°C and a high compression ratio of 22, combustion of only PO is possible in a diesel engine, but abrasions in the fuel supply line still occur. Reports of clogging have also been prominent [12].
- Since the oxygen content of PO is between 42-50%, it has a calorific value about 1/3 lower than that of fossil fuels.
- The viscosity of PO, which depends on the source material and production process, is between that of heavy fuel oil and conventional light diesel fuel. The viscosity is highly dependent on the water content and the temperature of the fuel. The spray atomization characteristic, which could be defined as the SMD (Sauter mean diameter), of PO is poorer than that of diesel, because it has a higher viscosity [13].
- Due to the high acidity (pH 2-3) and high water content of PO, long term operation could lead to corrosion in the injection system, if conventional materials are used.
- The tar in PO can become a gum-like material through polymerization, which occurs even at room temperature over time. Polymer, tar, solid particles and other substances can accumulate in the injection system and decrease the performance of the system. In addition, PO combustion can create carbonaceous deposits that accumulate in the injection system, combustion chamber, exhaust valve, and piston, among other places, which can decrease the performance of the engine components [14].

Polymerization of PO can be prevented by diluting PO in alcohol fuels like ethanol or methanol. Early mixing with alcohol fuels has the added benefit of significantly improving the storage and handling properties of PO [15, 16]. For separate injection co-firing, a PO-ethanol blend can be fired through a diesel or biodiesel pilot injection in a dual-injection diesel engine.

In this study, the performance and emission characteristics of a dual-injection diesel engine fueled with diesel & biodiesel (pilot injection) and PO-ethanol blend (main injection) were experimentally investigated. Effects of pilot injection fuels and PO-ethanol blend on particle number concentrations and number size distributions of the dual-injection diesel engine are also investigated using a Fast Mobility Particle Sizer (FMPS).

EXPERIMENTAL METHODOLOGY

Test Fuel

The PO used in this study was produced from sawdust through fast pyrolysis process [17]. The produced PO was dark brown in color, had fuel properties similar to those reported for pyrolysis oil [11], and had a pungent odor. PO normally contains approximately 33% of water content, has a heating value that is approximately 1/3 that of conventional light diesel and an oxygen content of about 50%. Due to its low heating value and acidic characteristics, as well as its high density and viscosity compared to that of light diesel, PO can damage the fuel supply system in a short period of time when 100% PO is used in diesel engines. In order to use 100% PO in a diesel engine, corrosion-resistant materials including stainless steel, cobalt materials, and various polymers should be used for all surface in contact with PO; a larger injector hole and other modifications are also needed [14]. Therefore, using PO-diesel or PO-biodiesel emulsion is the easiest way to utilize a conventional fuel supply system without further modifications [18]. Carbon-based fuels from crude oils tend to mix with each other easily; however, PO forms layers when mixed with fossil fuel due to the different polarity. Thus, a proper surfactant has to be added in order to completely mix PO and fossil fuel [19]. This study rectifies this issue by using dual injectors to supply two independent sources of fuel into the diesel engine. Diesel or biodiesel fuel was used for the pilot injection and PO was used for the main injection. To prevent polymerization and lowering of the viscosity of PO, the PO was mixed with 70% ethanol by mass.

Table 1. Fuel properties of petroleum diesel, biodiesel from soybean, pyrolysis oil, and ethanol.

Fuel	Diesel	Biodiesel (Soybean)	Pyrolysis Oil	Ethanol
LHV (kJ/g)	45.8	39.8	15.9	26.9
Water (%)	-	0.14	33.62	≤0.3
C (%)	82.0	77.4	41.0	52.1
H (%)	12.6	12.1	10.1	13.2
O (%)	-	10.1	48.8	34.7
Density (kg/m ³)	827.7	898.2	1193.5	772.0
Viscosity at 40°C (cSt)	2.6	4.4	9.5	1.07
Cetane number	54.8	51.8	5-25 ^{a)}	8-10

a) Cetane number of PO was estimated by Suppes et al. [20].

The fuel properties of diesel, biodiesel (Soybean), PO, and ethanol are provided in Table 1. Through the data acquired, it can be seen that PO possesses a lower heating value (LHV) corresponding to 1/3 that of diesel, signifying that the energy density of PO is only 1/3 that of diesel. Additionally, due to 33% water content in PO, it is unsuitable

for independent use as a fuel. However, the high oxygen contents of PO and ethanol compared to that of diesel mean that during co-firing, an increase in combustion stability and a decrease in soot may be expected.

Engine Test Procedure

All engine bench experiments were performed on a single cylinder, four-stroke, direct injection diesel engine equipped with an electronic control high-pressure common-rail fuel system. A schematic diagram of the experimental setup and summary of engine features are provided in Fig. 1 and Table 2, respectively. To supply pilot injection fuel (diesel or biodiesel) and main injection fuel (PO-ethanol blend) independently, two common-rail injectors connected to each fuel supply system were attached to the engine head. A 100 kW DC dynamometer was used to control the engine speed and load. To analyze the combustion characteristics, a pressure transducer (Kistler, 6052C) and an adapter (Kistler, 6542Q27) were attached to the cylinder glow plug and set to measure the cylinder pressure at every 1 degree of crank angle by synchronizing the signal from the encoder. A flow meter (Meriam Inst. Co.) was installed on the upper side of the intake reservoir to measure the amount of air sucked in. The air/fuel ratio was measured using a lambda meter (ETAS, LA4) connected to a wide-band O₂ sensor. The amount of fuel was gauged with a balance. For the analysis of gaseous emission, an exhaust gas analyzer (AVL, AMA i-60) was used to measure THC (detection limit: 5,000 ppm), CO (detection limit: 50,000 ppm), and NO_x (detection limit: 5,000 ppm) emissions; an aerosol monitor (TSI, Dusttrak DRX 8533) was used to measure the mass of particulate matter (PM).

The particle number concentrations and number size distributions of engine particle emissions were measured using a Fast Mobility Particle Sizer (FMPS) by TSI Inc. The FMPS is based on the development of the electric aerosol spectrometer, and measures particle size from 5.6 to 560 nm with a sizing resolution of 32 channels. The FMPS can measure particle size distribution at a frequency of 1 Hz.

The experiments were conducted at an engine speed of 1,000 rpm and under changing load (IMEP 0.2 ~ 0.8 MPa). The injection pressure was set to 120 MPa for the pilot injection of diesel or biodiesel and to 90 MPa for the main injection of PO-ethanol blend. To protect the fuel supply system from damage, the engine was first started using only the diesel fuel for 10 minutes; after the experiment, only ethanol was solely introduced, in order to dissolve and rinse out solidified materials left inside the fuel supply system.

Table 2. Engine specifications.

Cycle	4-stroke
Displaced volume	1858 cc
Stroke	140 mm
Bore	130 mm
Cylinders	1
Compression ratio	17.1:1
Number of Valves	2
Injection system	Common Rail Injector, Direct Injection
Nozzle dimension	8 × ϕ 0.124 mm

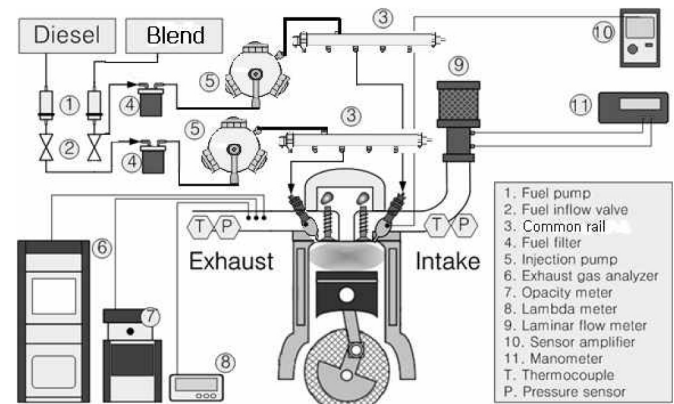


Figure 1. Schematic diagram of experimental setup.

RESULTS AND DISCUSSION

Optimal Injection Timings of Pilot Injection and Main Injection

A pilot and main injection timing sweep test was performed to find the maximum Indicated Mean Effective Pressure (IMEP) and minimum Coefficient of Variance (COV) in IMEP (which is calculated from the average IMEP). Engine speed was fixed at 1000 rpm, and 0.43 mg/inj of diesel fuel for pilot injection and 4.85 mg/inj of PO-ethanol blend (30% of PO by mass) for main injection were supplied independently.

Figures 2 and 3 show the changes in IMEP and combustion stability in terms of COV according to PO-ethanol blend injection timings at pilot diesel injection timings of Before Top-Dead Center (BTDC) 8, 12, 16°CA. The optimal engine performance was seen at PO-ethanol blend injection timings of BTDC 16 ~ 4°CA at diesel pilot injection timings of 12, 16°CA. For the main injections made before BTDC 20°CA or after top-dead center (ATDC) conditions, the combustion stability and IMEP were seen to deteriorate. In the case of BTDC 8°CA for diesel pilot injection timing, there was stable engine combustion in the very narrow region of BTDC 8 ~ ATDC 4°CA. However,