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Feasibility study of using wood pyrolysis oil–ethanol blended fuel with diesel pilot injection in a diesel engine

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A B S T R A C T

The vast stores of biomass available worldwide have the potential to replace significant amounts of petroleum fuels. Fast pyrolysis of biomass is one of several paths by which biomass can be converted to higher value products. Wood pyrolysis oil (WPO) has been regarded as an alternative to petroleum fuel for use in diesel engines. However, the application of WPO in diesel engines is constrained by the poor fuel properties of WPO, such as low energy density, high acidity, high viscosity, and low cetane number. One possible method by which these shortcomings may be circumvented is to co-fire WPO with other petroleum fuels. WPO has poor miscibility with petroleum fuel oils; the most suitable candidate fuel for direct fuel mixing is ethanol. Early mixing with ethanol has the added benefit of significantly improving the storage and handling properties of WPO. For separate injection co-firing, a WPO–ethanol blended fuel can be fired through diesel pilot injection in a dual-injection diesel engine.

In this study, we examined the performance and emission characteristics of a dual-injection diesel engine fueled with diesel (pilot injection) and WPO–ethanol blended fuel (main injection) experimentally. Results showed that although stable engine operation was possible with dual injection, the indicated fuel conversion efficiency was slightly lower than that of diesel combustion. Regarding exhaust emissions, HC and CO emissions were slightly increased, while NOx and PM emissions were significantly decreased due to the high water content and oxygen content in the WPO–ethanol blended fuel.

1. Introduction

Significant amounts of petroleum fuel, which when burnt produce emissions that are the main cause of global warming, are currently being replaced with biomass-derived fuels. There are many technologies to convert lower energy density biomasses to higher energy density gaseous or liquid fuels. Among these, the fast pyrolysis process is a state-of-the-art technology that converts wood or other biomasses to a liquid fuel called wood pyrolysis oil (WPO) or bio-oil (BO) [1–5]. In countries with an abundance of wood resources, the application of WPO to cogeneration power plants or gas turbines for power generation is being studied [3–5]. Furthermore, some research groups are determining the feasibility of using WPO as a fuel for transportation diesel engines, and are comparing the combustion and exhaust emission characteristics of WPO and diesel [10–16]. It has been reported that WPO mixed with cetane enhancement showed a combustion performance equal to that of diesel, while a WPO–diesel emulsified fuel with a maximum of 30% WPO showed a decreased level of NOx in the exhaust emission in a diesel engine [13,14]. However, the application of WPO to conventional diesel engines is highly constrained by the poor fuel properties of WPO and its tendency to cause wear and corrosion in the fuel supply system within a short period of time [15,16].

Fuel properties of WPO depend strongly on the type of biomass used and the production process; WPO usually contains 18–30% water, and has an oxygen content higher than that of fossil fuel. Due to different physical and chemical characteristics, diesel and WPO have different fuel spray atomization levels, temperatures of ignition, and combustion characteristics, as well as different exhaust emission characteristics. The characteristics of WPO can be summarized as follows [2,4,5,17–20]:

- WPO usually does not produce self-ignition in conventional diesel engines due to a lower cetane number (~5–25). However, for the conditions of a high intake temperature of over 200 °C and a high compression ratio of over 22, combustion of WPO-only is possible in a diesel engine, but abrasion of the fuel supply line still occurs [16]. Clogging also tends to occur.

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Table 1
Fuel properties of petroleum diesel, wood pyrolysis oil, and ethanol.

Fuel	Diesel	Wood pyrolysis oil (WPO)	Ethanol
LHV (kJ/g)	42.6	15.9	26.9
Water (%)	–	33.62	⩽0.3
C (%)	82.0	41.0	52.1
H (%)	12.6	10.1	13.2
O (%)	–	48.8	34.7
Density (kg/m^3)	821.0	1193.5	772.0
Viscosity at 40 °C (cSt)	2.7	9.5	1.07
Cetane number	52.6	N/A	8–10

- Because the oxygen content of WPO is between 42% and 50%, it has a calorific value about 1/3 lower than that of fossil fuels. The viscosity of WPO, which depends on the source material and production process, is between that of heavy fuel oil and conventional light diesel fuel. Its viscosity is highly dependent on the water content and temperature of the fuel. The Sauter mean diameter (SMD) of WPO, which is a spray atomization parameter, is bigger than that of diesel, because WPO is more viscous than diesel [20].
- Due to the high acidity (pH 2–3) and high water content of WPO, long term operation can lead to corrosion in the injection system if conventional materials are used. The tar in WPO can become a gum-like material through polymerization, which occurs even at room temperature over time. Polymers, tar, solid particles, and other substances can accumulate in the injection system and decrease the performance of the system. In addition, WPO 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.

The most widely used method to improve the fuel qualities of WPO to the extent that satisfies the fuel standard for stable combustion in a conventional diesel engine is blending of WPO with other hydrocarbon fuels with a higher cetane number. However, WPO and fossil fuels are not usually blended because of the difference in polarity of WPO and fossil fuels, and high probability of phase separation. Hence, a cumbersome process called emulsification with proper surfactants is needed to mix WPO and fossil fuels. The emulsification process needs additional time and money, and clogging and polymerization problems in the fuel supply system still occur because of the polymer, tar, and solid particle components present in WPO–fossil fuel emulsions [21–26].

Polymerization of WPO can be prevented by diluting WPO in alcohol fuels such as ethanol or butanol. Early mixing with alcohol fuels has the added benefit of significantly improving the storage and handling properties of WPO [27,28]. Among various alcohol fuels, ethanol, with a viscosity of 1.07 cSt, can effectively lower the viscosity of blended fuel to the proper level for direct application in conventional diesel engines. Furthermore, as an organic solvent, ethanol dissolves solid particles present in the WPO and also suppresses the polymerization of tar in the WPO. Additionally, WPO can be easily blended with ethanol, and no phase separation occurs in the blended fuel. However, WPO–ethanol blended fuel still does not meet fuel property standards, especially the self-ignition property; additional cetane should be added to the blended fuel or an additional flame source is needed to initiate combustion from the blended fuel. The second approach could be realized with a dual-injection strategy [29].

Our research group has designed a dual injection system using an engine head modified to install two fuel injectors separately to facilitate the use of WPO in automotive applications. In this system, a pilot fuel with a high cetane number, such as diesel or bio-diesel, is injected first to develop conditions in the combustion chamber so that the main WPO–ethanol blended fuel is stably combusted.

In this study, we investigated the combustion performance and emission characteristics of a dual-injection diesel engine fueled with diesel (pilot injection) and WPO–ethanol blended fuel with a maximum WPO content of 40 wt% (main injection) experimentally. Effects of the WPO content in the WPO–ethanol blended fuel on particle number concentrations and number size distributions of the dual-injection diesel engine were also investigated using a fast mobility particle sizer (FMPS).

2. Experimental apparatus

2.1. Test fuel

The wood pyrolysis oil used in this study was produced from sawdust through the fast pyrolysis process [30]. The produced WPO was dark brown, had similar fuel properties to those of reported pyrolysis oils [2,4,5,18,22], and a pungent odor. WPO normally contains approximately 33% water, 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, acidic characteristics, as well as high density and viscosity compared to light diesel, WPO can damage the fuel supply system in a short period of time when 100% WPO is used in diesel engines. To use 100% WPO in a diesel engine, corrosion-resistant materials including stainless steel, cobalt materials, and various polymers should be used for all surfaces in contact with WPO. Furthermore, a larger injector hole than used for other fuels, in addition to other modifications, are needed. Therefore, using WPO and a diesel or biodiesel emulsion is the easiest way to utilize a conventional fuel supply system without further modifications [23–26]. Carbon-based fuels from crude oils tend to mix easily with each other; however, WPO forms layers when mixed with fossil fuel due to differences in the polarity of WPO and fossil fuels. Thus, a surfactant has to be added to facilitate complete mixing of the WPO and fossil fuel. We used dual injectors to supply two independent sources of fuel into the diesel engine. Diesel fuel was used for the pilot injection and WPO was used for the main injection. To prevent polymerization and lowering of the viscosity of WPO, 20–40% WPO was blended with ethanol by mass. 500 ppm of lubricant (Lubrizol corp.) was also added to the blended fuel to avoid mechanical wear in the fuel supply system.

The fuel properties of diesel, WPO, and ethanol determined by the Korea Petroleum Quality & Distribution Authority are provided in Table 1. WPO has a lower heating value (LHV) 1/3 lower than that of diesel, signifying that the energy density of WPO is only 1/3 that of diesel. Additionally, due to the water content of WPO (33%), it is unsuitable for independent use as a fuel for conventional engines. However, the high oxygen content of WPO and ethanol compared to that of diesel means that during co-firing, an increase in combustion stability and a decrease in particulate matter (PM) can be expected.

2.2. 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 a summary of engine features are provided in Fig. 1 and Table 2, respectively. To supply pilot injection fuel (diesel) and main injection fuel (WPO–ethanol blended fuel) independently, two common-rail injectors connected to each fuel supply system were mounted to the engine head. A