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Effect of biofuels combustion on the nanoparticle and emission characteristics of a common-rail DI diesel engine

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ABSTRACT

This study was performed to investigate the effect of biogas–biodiesel fuel combustion on the emissions reduction and nanoparticle characteristics in a direct injection (DI) diesel engine. In order to apply the two biofuels, biogas was injected into a premixed chamber during the intake process by using two electronically controlled gas injectors, and biodiesel fuel was directly injected into combustion chamber by a high-pressure injection system. The in-cylinder pressure and rate of heat release (ROHR) were investigated under various fuel conditions for single-fuel (biodiesel) and dual-fuel (biogas–biodiesel) combustions. To evaluate the engine performances and exhaust emissions characteristics, the indicated mean effective pressure (IMEP) and exhaust emissions were also investigated under various test conditions. Furthermore, the particle number concentration and the size distribution of nanoparticles were analyzed by using a scanning mobility particle sizer (SMPS).

In the case of dual-fuels, the peak combustion pressure and ROHR were gradually decreased with the increase of the biogas fraction in the dual-fuels. As the premixed ratios increased, ignition delay and combustion durations were prolonged compared to single-fuel mode. The dual-fuels combustion showed that the IMEP decreased slightly and maintained similar levels up to 20° BTDC due to the retarded combustion phase. The concentrations of NO_x emissions were decreased for all injection timings as the premixed ratio (r_p) increased. The soot emissions in dual-fuel operations were significantly lower than those in the single-fuel mode ($r_p = 0$), and decreased gradually as the premixed ratio increased, regardless of injection timing. A lower nanoparticle size distribution was observed at all premixed ratios for dual-fuel combustion compared to those of the single fuel mode. The number distribution of both nuclei and accumulation modes also decreased with an increase in the biogas fraction. A slight reduction in the total particle number and total volume for all premixed ratios was observed as the injection timing increased from TDC up to 20° BTDC.

1. Introduction

In the transportation sector, the high nitrogen oxides (NO_x) and particulate matter (PM) emissions from the diesel engine are its main problems with respect to air pollution. In this context, the reductions in PM, HC, and CO emissions from the engine can be obtained by use of biodiesel fuel. However, NO_x emissions are slightly increased for the biodiesel blended diesel fuel or undiluted biodiesel fuel [1–3]. Biodiesel is the most attractive alternative fuel for diesel engines because it is obtained from renewable resources and waste materials, and is easily applied to the compression ignition engine without major engine modification. The merits of biodiesel are that it is nontoxic, biodegradable, and renewable. Further advantages over diesel fuel are the potential for reducing emissions or eliminating sulfur dioxide (SO_2), CO, unburned hydrocarbons (UHC), and PM emissions due to the high cetane number, low sulfur content, low aromatics, low volatility, and the presence of oxygen atoms in the fuel molecule [4–6]. The atomization and combustion characteristics of biodiesel blends in a common-rail diesel engine at various operating conditions was investigated by Lee et al. [7], who reported that HC and CO emissions were reduced, whereas the NO_x emissions increased according to the blending ratio. Opat et al. [8] also reported that CO and HC emissions can be reduced through the application of multiple injections and optimal spray targeting in the combustion chamber.

Similarly, biogas is also a representative alternative fuel, and is the easiest to implement into the current refueling infrastructure as a promising clean energy resource because it is made from organic wastes (the anaerobic digestion of sludge, crops, and organic animal wastes) [9]. The principal component of biogas (>65%, vol.) is methane (CH_4), which has lower carbon content than diesel fuel, and has a higher octane number and auto-ignition temperature [10]. It shows that a high anti-knock properties means a high auto-ignition temperature compared to conventional diesel

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Nomenclature

ATDC	after top dead center	FSN	filtered smoke number
BTDC	before top dead center	LHV	lower heating value
CNG	compressed natural gas	NO_x	nitrogen oxides
CO	carbon monoxide	r_p	premixed ratio
COV	coefficient of variation DI direct injection	SMPS	scanning mobility particle sizer
HC	hydrocarbon	SOE	start of energizing
IMEP	indicated mean effective pressure	TDC	top dead center

fuel, and is thus a highly suitable fuel for dual-fuel combustion. In premixed/direct-injection (dual-fuel) combustion, biogas is injected during the intake process to create a homogeneous premixed charge, and direct injection of biodiesel into the cylinder is used to change the concentration and position of local fuel-rich regions to initiate combustion. The earliest concept of premixed/direct-injected combustion was proposed by Suzuki et al. [11]. Accordingly, dual-fuel combustion enables the use of lean or homogeneous mixtures requiring low combustion temperature, and thus leads to reduced NO_x and PM emissions. These results can be found in other investigations of dual-fuel combustion that used various test fuels. Kim and Lee [12] studied the improved emission characteristics of various premixed fuels in the diesel combustion engine. In their results, NO_x and soot emissions were effectively reduced in premixed gasoline as the premixed ratio was increased. Maji et al. [13] investigated the application of compressed natural gas (CNG) to reduce the noise level, specific fuel consumption, and NO_x emissions; however, the UHC increased with the substitution of CNG for 75% of diesel fuel. Badr et al. [14] and Abd Alla et al. [15] reported that increasing the amount of pilot fuel caused an increase in NO_x and a reduction in the thermal efficiency. Until now, many researchers have investigated the combustion and exhaust emissions characteristics of dual-fuel combustion with gaseous-liquid and liquid fuels for various operating parameters, but detailed investigation for the effect of biogas–biodiesel fuel combustion according to the biogas premixed fraction has been little obtained.

The purpose of the present study is to experimentally investigate and analyze the effects of dual-fuel combustion with various premixed ratios of biogas–biodiesel on the characteristics of combustion performance and the reduction of exhaust emissions. In order to investigate the nanoparticle emissions according to biogas–biodiesel fuel, the characteristics of particle size distribution and number concentrations are studied in a direct injection (DI) diesel engine equipped with a high-pressure injection system.

2. Experimental setup and procedure

2.1. Test fuels and experimental setup

In this study, biodiesel is 100% methyl ester derived from soybean oil, which injected into the combustion chamber as an ignition source (pilot injection), and it satisfies the ASTM D6751 specification. Table 1 shows the properties of the test fuels and test engine used in this experiment. In comparison with petroleum diesel fuel, biodiesel has different physical properties, such as higher density, viscosity, cetane number (CN), and a lower C–H ratio. The biogas used in this study was composed of methane (CH_4) (>70% by vol.), CO_2, H_2S, N_2, H_2, and O_2.

The engine used in this work is a four-stroke cycle single cylinder natural aspirated direct-injection diesel engine with 373.3 cc of displacement volume (bore 75 mm, stroke 84.5 mm) and 17.8 of compression ratio. The injection system is composed of a high-pressure electronically controlled injector with a six holes nozzle and 156 deg of spray angle. The power output of test engine was measured by a dynamometer (55 kW DC at 3500 rpm), and the combustion pressure was measured by a pressure transducer (6052B1, Kistler) and a charge amplifier (5011B, Kistler). The combustion pressure data were measured over 500 cycles and acquired by a data acquisition board (DAQ board, PCI-MIO-16E-1, NI) with a sampling interval of 1° crank angle (CA). The injection pressure, injection timing, and fuel injection quantity were precisely controlled using an injection pressure controller (TDA-1100, TEMS) and an injector driver (TDA-3300, TEMS). The exhaust emissions from the engine was measured with a NO_x analyzer (BCL-511, Yanco), a HC–CO emissions analyzer (Mexa-554JK, Horiba), and a smoke meter (415S, AVL). The size distribution and number concentration of particle emissions were measured using a rotating disk thermo-diluter (MD19-E, Matter Engineering), a condensation particle counters (CPC), and a scanning mobility particle sizer (SMPS, Model 3936, TSI). The premixed fuel system consisted of a premixing chamber, a premixed fuel injector, an injector controller, a fuel supply system, a biogas flow meter (GFM 57, Aalborg) and a fuel temperature control system as shown in Fig. 1.

Table 1
Properties of test biofuels and diesel fuel.

Properties	Biodiesel	Biogas	Diesel
Density (kg/m^3)	881	0.915	826
Viscosity (cSt 40 °C)	4.75	–	3.11
Carbon content (wt%)	78	75	87
Hydrogen content (wt%)	11	25	13
Oxygen content (wt%)	11	<2	–
Boiling point (°C)	315–350	−162	180–330
Cetane number	57–58	–	52–53
Octane number	–	130	–
Auto-ignition temperature (°C)	<200	632	220–360
A/F ratio (by vol.)	14.1	17.23	14.6
Lower heating value (MJ/kg)	38.0	26.17	42.5

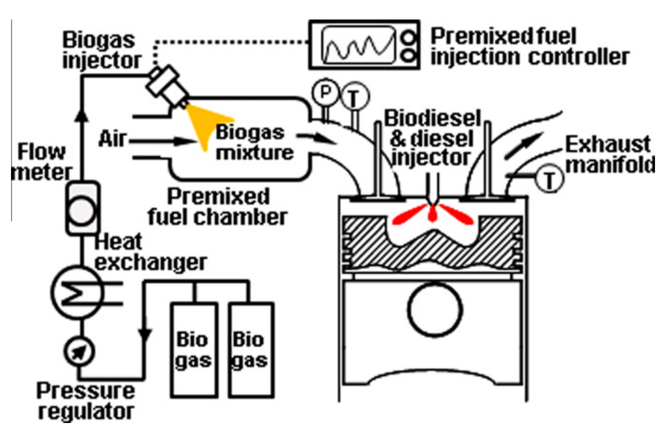

Fig. 1. Schematic diagram of the biodiesel and biogas injection system.