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Evaluation of regulated and unregulated emissions from a diesel powered vehicle fueled with diesel/biodiesel blends in Korea

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The emission characteristics of diesel powered vehicles using conventional diesel fuel and six different biodiesel blends at proportions of 1% (B1), 3% (B3), 5% (B5), and 20% (B20) by volume were investigated. The emission tests were performed following the NEDC (New European Driving Cycle) and regulated and unregulated emissions were measured for two vehicles – one equipped with a DOC (diesel oxidation catalyst) and the other equipped with a DPF (diesel particulate filter). Emissions of THC (total hydrocarbon), CO, and PM (particulate matter) generally decreased with increasing biodiesel content in the fuel, while NO_x emissions increased slightly in both vehicles. CO_2 emissions were virtually identical. The extent of PM reduction in the DPF-equipped vehicle was almost 40 times higher than in the DOC-equipped vehicle. PAH (polycyclic aromatic hydrocarbon) emissions decreased with increasing biodiesel content in the fuel, with average reduction rates of the six biodiesels for particle-phase PAHs compared to the base diesel fuel in the range of 18.2–27.2% and 48.9–79.7% for the DOC- and DPF-equipped vehicles, respectively. Nanoparticle emissions from the DOC- and DPF-equipped vehicles were predominantly in the size range of 25.5–191.1 nm and <25.5 nm, respectively.

1. Introduction

Given that biodiesel is a promising alternative to conventional diesel fuel, the demand for it has been growing rapidly [1]. Biodiesel is a product of the transesterification of vegetable oils, waste cooking oils, and animal fats with methanol, using an acid or basic catalyst [2]. Biodiesel offers many technical advantages; it is non-toxic, biodegradable and renewable with a high cetane number, and contains no aromatics and almost no sulfur [3]. In most EU countries, conventional diesel fuel has been substituted by biodiesels in passenger vehicles [2,4].

Numerous studies have been conducted regarding emissions from vehicles using biodiesels. Wu et al. studied the emission characteristics of regulated pollutants using five methyl ester biodiesels by changing the BMEP (brake mean effective pressure) [5]. Many studies have considered regulated and unregulated emissions from diesel engines fueled with different biodiesel blends [2,4,6–10]. Studies have also investigated the performance and emissions of diesel engines fueled by various types of biodiesel blends, such as biodiesel–diesel, biodiesel–diesel-additive and kerosene–biodiesel blends [11], and sewage sludge oil and biodiesel blends [12]. Various studies have furthermore been conducted to determine exhaust emissions using soybean biodiesel fuel [3,13,14] and jatropha biodiesel blends [1,15–17]. Liu et al. investigated the emissions of *n*-butanol/biodiesel dual-fuel injection on a diesel engine and found that the same 50% burn point (CA50) can be achieved by early or late-injection of biodiesel [18]. Fattah et al. studied the effect of adding stabilizer antioxidants to palm biodiesel blends on engine performance and emission characteristics [19]. Di et al. tested an ultra-low sulfur diesel fuel blended with biodiesel from waste cooking oil and found that the biodiesel blends reduced emissions of HC, CO, PM (particulate

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Nomenclature

B1, B3, B5, B20	biodiesel blends at proportions of 1%, 3%, 5%, 20% by volume
BMEP	brake mean effective pressure
BTEX	benzene, toluene, ethylbenzene, xylene
CLD	chemiluminescent detector
CN	cetane number
CO	carbon monoxide
CO_2	carbon dioxide
CVS	constant volume sampler
DCU	dyno control unit
DOC	diesel oxidation catalyst
DPF	diesel particulate filter
DT	dilution tunnel
EEPS	engine exhaust particle sizer
EU	European Union
EUDC	extra urban driving cycle
FAMEs	fatty acid methyl esters
HBD	hydrotreated biodiesel
HC	hydrocarbon
HFID	heated flame ionization detector
JO, PO, RO, SO	jatropha oil, palm oil, rapeseed oil, soybean oil
NDIR	non dispersive infrared
NEDC	New European Driving Cycle
NO_x	nitrogen oxides
PAHs	polycyclic aromatic hydrocarbons
PBDD/Fs	polybrominated dibenzo-p-dioxins/furans
PCBs	polychlorinated biphenyls
PCDD/Fs	polychlorinated dibenzo-p-dioxins/furans
PEU	power exchange unit
PM	particulate matter
THC	total hydrocarbon
TPM	total particulate matter
UDC	urban driving cycle
ULSD	ultra-low sulfur diesel
VOCs	volatile organic compounds
WCO	waste cooking oil

matter), formaldehyde, toluene, and xylene, but increased emissions of NO_x, acetaldehyde, and benzene [7]. Yasin et al. measured emissions when using a biodiesel blend with a methanol additive, and observed that NO_x emissions increased, while emissions of CO/CO_2 were reduced when the diesel engine was operated with the B20 and B20 M5 blends [20].

Chang et al. investigated emissions of toxic organic pollutants (PAHs, PCDD/Fs, PCBs, and PBDD/Fs) from a diesel engine fueled with WCO (waste cooking oil)-based biodiesel, and concluded that the use of WCO-based biodiesel not only solves the problem of waste oil disposal, but also reduces emissions of toxic organic pollutants from diesel engines [21]. Many studies also measured two classes of unregulated emissions, PAHs [6,21–23] and aldehyde [6,24,25], from a diesel engine fueled with biodiesel blends. Bermudez et al. undertook a comparative study of regulated and unregulated emissions in a light-duty diesel engine fueled with Fischer–Tropsch and biodiesel fuels during the NEDC (New European Driving Cycle). They found that Fischer–Tropsch fuel generated less regulated and unregulated emissions and also lowered fuel consumption compared to the use of conventional diesel fuel [10]. Ferreira et al. investigated the effect of ethanol additions on emissions from a diesel engine fueled with a blend of diesel-biodiesel, and demonstrated that the addition of ethanol can reduce NO_x emissions and fuel consumption [26]. The effects of antioxidant additives on diesel engine performance and exhaust emissions were investigated by Ileri et al., with results showing that the addition of antioxidants can improve the CN (cetane number) and also reduce NO_x emissions when using the B20 blend [27]. Imtenan et al. investigated the impact of oxygenated additives to palm and jatropha biodiesel blends and found the use of ethanol as an additive reduced CO emissions by up to 40%, while use of diethyl ether as an additive reduced NO_x emissions by up to 13% [28].

Durbin et al. conducted a comprehensive study of biodiesel fuels in both on- and off-road applications, and reported that blends with a higher biodiesel content had a tendency to increase THC (total hydrocarbon) and CO emissions but reduce PM emissions. It was also noted that the use of JP-8 biodiesel resulted in an increase in THC and CO compared to the use of ULSD (ultra-low sulfur diesel) [29]. Kousoulidou et al. measured emissions from passenger cars using saturated and unsaturated biodiesel fuels and investigated the impact of biodiesel in terms of fuel properties, blending ratios, and vehicle technology. They found that the use of neat biodiesel (B100) led to an average increase in NO_x emissions of 16% and a decrease in PM emissions of the order of 70%. The use of unsaturated fuels generally led to higher NO_x emissions [30].

Biofuels were supplied to some metropolitan areas in Korea from 2001 to 2005 and have been supplied to the whole country from 2006. The biodiesel content in diesel fuel was 3.0% in 2012, with a scheduled increase of up to 5.0% in 0.5% annual increments. While rapeseed oil is the most popular biodiesel raw material in the world, soybean oil (75%) and waste cooking oil (20%) are the most commonly used raw materials in Korea. Because most biodiesel raw materials are imported from abroad, Korea has also considered use of new rapeseed fuels and the production of biodiesels using marine algae [31–33].

The main focus of this study was to investigate the effect of diesel/biodiesel blends on regulated (CO, NO_x, HC, and PM) and unregulated emissions (VOCs, aldehydes, and PAHs) for two types of diesel vehicle – one equipped with a diesel oxidation catalyst (DOC) and the other equipped with a diesel particulate filter (DPF) – over the NEDC. These vehicles were selected because they are widely used in urban areas of Korea. Six biodiesels, which are either currently used in Korea (soybean oil, waste cooking oil, and palm oil), or which have the greatest possibility to be used in future (jatropha oil, rapeseed oil, and HBD (hydrotreated biodiesel)), were selected and their emission characteristics were investigated using different blending ratios (1%, 3%, 5%, and 20%). Measurements of regulated and unregulated emissions, and of particle size distribution and particle number concentrations for nanoparticles were conducted and the results were compared with those for conventional diesel fuel.

2. Experimental

2.1. Test vehicles and driving cycle

Two recreational vehicles (Hyundai Santafe, 2006 and 2007 model year) were used in this study; these have the highest number of registrations of all vehicles in Korea and meet the Euro 4 emission standards. To compare the effect of different exhaust after-treatment devices on emissions, one vehicle selected was equipped with a DOC (diesel oxidation catalyst) and the other with a DPF (diesel particulate filter). The technical specifications of the two test vehicles are listed in Table 1.

The NEDC was used as the driving cycle; this is currently used for emission certification of light duty diesel vehicles in Europe and

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