

Impacts of Biodiesel on the Durability of an Advanced After-Treatment Diesel Engine

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ABSTRACT

Due to the rising price of crude oil, biofuel is being considered as a global alternative for fossil fuels to reduce the emission of greenhouse gases. Diesel blended with bio fuel is currently being widely adopted in many countries. The Taiwanese government has been enforcing the adoption of B2 since 2010. However, there have remained consistent concerns about engine durability related to the use of biofuel, especially regarding after-treatment systems. A selective catalytic reduction system (SCR) has been utilized recently to reduce NO_x emission in order to meet the Euro IV and V emission standards. To evaluate the impact of biodiesel on the durability of engines equipped with the SCR system, a long-term testing program was organized for the purposes of this study. The results can be used as a reference for the development of marketing promotion strategies as well as government policies in Taiwan. B8 diesel fuel (8 vol% biodiesel) was employed in a commercial heavy duty common-rail fuel injection engine for testing purposes to determine its influence on the durability of engine components and the SCR system. After a 1000-hour full load test operation, the key components of the engines, including the injector, piston ring, and catalyst were analyzed and characterized through a series of inspections to identify the degree of decay and wear behavior. In addition, the engine performance was evaluated with the SAE J1995 test procedure, and the emissions were measured using the ETC test procedure at each maintenance stage and after the durability test to determine any variations in performance and emissions. Furthermore, non-regulatory emissions, such as $\text{PM}_{2.5}$, PM diameter distributions, and particle numbers, which have been proved to be critically important in terms of causing cancer from diesel engine emissions, were also evaluated in this study. It was found that the standard deviation of performance and emissions varied less than 3% when the diesel engine was fueled with B8 biodiesel. The results also indicated that the SCR system still maintained conversion efficiency at 70~95% after the 1000hr durability tests.

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INTRODUCTION

Biodiesel is being utilized widely all over the world to reduce dependency on fossil fuel and to slow down climate change. The advantages of biodiesel have been extensively discussed and compared with those associated with fossil diesel [1~5]. Biodiesel may reduce toxic engine emissions, including carbon monoxide (CO), hydrocarbons (HC), particulate matter (PM), and polycyclic aromatic hydrocarbons (PAHs), which are closely related to human health, and it also may abate the net production of carbon dioxide (CO_2), which may significantly reduce the impact of the greenhouse effect on the earth [6~8]. However, NO_x emissions have increased with the adoption of biodiesel fuels. Kooter et al. [9] revealed that NO_x increased as higher percentages of biodiesel were used when they compared the emission of B0, B5, B10, B20, B100, PPO (pure plant oil) and B0+DPF. However, the PM showed an opposite trend.

The research of Charles J. Mueller et al. [10] showed that increases in NO_x were not influenced only by a single fuel characteristic, but were also influenced by interaction factors such as injection timing, combustion phasing, radiative heat transfer, adiabatic flame temperature, etc. Furthermore, Wayne A. Eckerle et al. and Janet Yanowitz et al. [11~12] showed that when using B20, which has a lower heating value than fossil fuel, in different engine calibration situations, NO_x increased under an FTP testing procedure. Somnuek Jaroonsathian et al. [13] indicated that the utilization of B20 would decrease torque by approximately 3%, but there was no obvious influence on performance and emissions when an engine was fueled with B5 and B10 after 400hr of durability testing. Jose et al. [14] conducted a study using fossil diesel, B20 and pure biodiesel to compare the emissions by using different after-treatment systems, and the results showed that the EGR/DPF system reduced

the CO and PM emissions more than the SCR system. In contrast to the EGR/DPF system, the SCR system reduced the NO_x and CO_2 emissions more than the EGR/DPF system. The impact on engine emissions equipped with a SCR system was investigated by Lyn McWilliam et al. [15]. They utilized a CAT6.6 engine fueled with B0, B20 and B100 under a NRTC (Non-Road Transient Cycles) testing pattern. Their results showed that NO_x emissions increased only 1% at the exhaust valve outlet, but increased 12.5% at the SCR downstream, and the concentration of NO_x increased 3 ppm when using B20. The trend was similar to that found when using B100; NO_x increased 4.8% at the exhaust valve outlet and increased 105.7% at the SCR downstream, and the concentration increased by 25 ppm. The conversion efficiency of SCR decreased by 1% and 6% when using B20 and B100, respectively. Aaron Williams et al. [16] investigated the impact of B20 on the performance of a selective catalytic reduction (SCR) system. The results showed no change in the NO_x conversion in the SCR system using B20, but the NO_x emission levels were slightly higher for B20 than for ultra-low sulfur diesel. In addition, Aaron Williams et al. [17] developed an accelerated durability test method to determine the potential impact of specific biodiesel impurities. Their study showed that ash, alkali metals, and sodium and potassium can adversely impact the performance of DOC, DPF and SCR systems after long term operation with B20. Jürgen Krahel et al. [18] conducted a 1000hr durability test using different concentrations of phosphorus (9,14.7mg/kg) blended in biodiesel. The results indicated that NO_x emissions exceeded the emission standard after a 1000hr durability test even when using an engine equipped with an SCR system. Therefore, they suggested that the phosphorus content should not exceed 10 mg/kg when using biodiesel.

In Taiwan, the use of biodiesel has been ongoing since 1992. In 2008, the Taiwanese government mandated a 1% biodiesel policy and increased the percentage to 2% in 2010. A new policy to increase the percentage up to 5% in the forthcoming year has been announced, and in the meantime, an even higher percentage biodiesel such as 8% will be promoted to fleets. However, fleet owners are concerned about the durability issue when the use of high percentage biodiesel is enforced. There are not much local data to persuade vehicle users. Therefore, the purpose of this study is to evaluate the performance of and emission variations in engines equipped with SCR systems after a durability test when fueled with 8% biodiesel.

EXPERIMENTAL METHODS

Figure 1 illustrates the engine laboratory equipment and the exhaust sampling system used in this study. The SCHENCK MP-DYNAS 335 AC motor engine dynamometer was used for engine test. Its maximum capacity is 800N-m, and its maximum speed is 8000rpm. The reaction rate from positive torque to negative torque is less than one second. It can effectively conduct EU ETC as well as EU ESC test cycles. Exhaust analysis was carried out with the HORIBA CVS 9400T sampling system and the HORIBA MEXA 9200D analyzer. In addition, the HORIBA MEXA 7500D direct sampling system was used for evaluation of SCR catalyst performance.

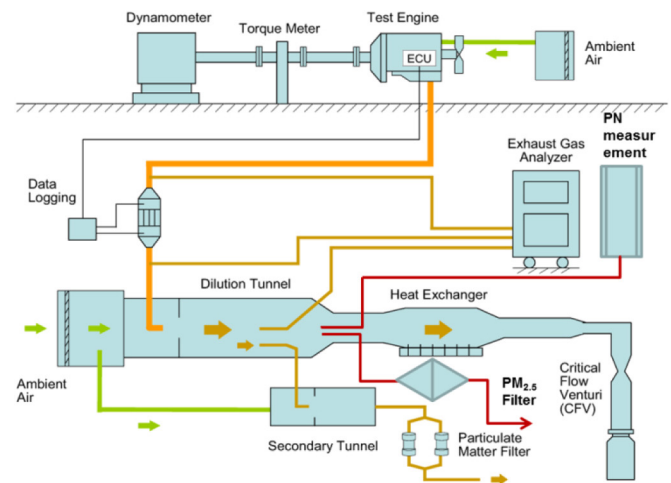


Figure 1. Engine Test Lab Equipment and the Engine Exhaust Sampling System

Figure 1 also shows the equipment for measuring $\text{PM}_{2.5}$ concentration and particle number (PN). A sampling tube is inserted into the dilution tunnel to extract exhaust gas to the analyzers. The exhaust gas was then bifurcated to two identical samplings. To ensure reliable measurements, two sampling systems were used in this study. The flow rate of each sampling unit was 10 liter/min. In each sampling system, there was a cyclone used to separate the $\text{PM}_{2.5}$ from the exhaust stream. The particles were collected on a crystal filter, and the weight of the filter was measured with a high precision microbalance before and after the test to determine the amount of particulates that was collected. The mass concentration of $\text{PM}_{2.5}$ could then be obtained.

A Sequential Mobility Particle Sizer (SMPS+C) was connected to another sampling tube downstream of the dilution tunnel, as shown in Figure 1. This system is used to measure the number concentration and diameter distribution of particulates. The SMPS+C system is composed of two parts: a Differential Mobility Analyzer (DMA), which is used to set the measurement range, which is from 0.005 to 1 μm in this study, and a Condensation Particle Counter (CPC), which is used to count the number of particles, with a limitation of measurement of $10^7 \text{ \#}/\text{cm}^3$. An electric heating element is required to keep the sampling system at 300 $^\circ\text{C}$ to avoid vapor condensation and to remove volatile content such that only the non-volatile and solid particle matters can be collected.

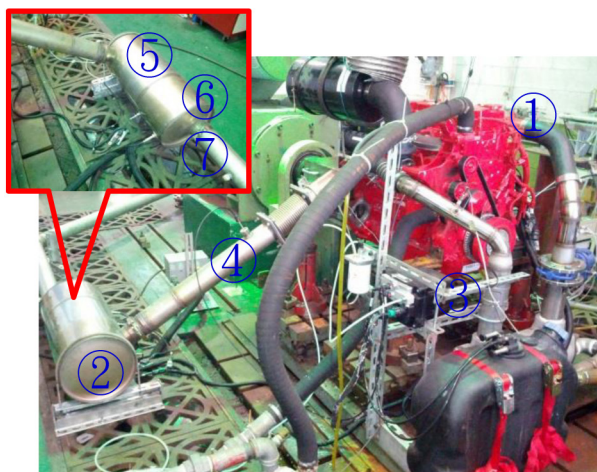
A diesel engine equipped with an SCR system was used for the durability tests in this study. It was a 4462 c.c. Cummins diesel engine equipped with a common rail fuel injection system. This engine is widely used as a commercial truck engine and complies with the regulations issued by the Taiwan EPA in 2012, which are equivalent to those of the Euro IV standard. The basic specifications of the test engine are shown in Table 1.

Figure 2 shows the engine/SCR system experimental device layout used in this study. The engine is controlled with a standard ECU. The exhaust gas after-treatment system is a Cummins SCR-kit device, consisting of a 300mm (diameter)*1000mm (D) catalyst housing, dosing unit, a nozzle, a urea tank, an NO_x sensor, a catalyst inlet and

an outlet temperature sensor and pipes. The air-assisted urea dosing pump is driven by a 2-phase stepping motor. A CAN bus (SAE J1939) signal controller is implemented via the engine ECU (CM2150E type) environment.

Table 1. Test Engine Specifications

Item	Specification
Displacement	4462 c.c.
Rated Power	112.3 kW/2500rpm
Rated Torque	588 N.m/1100rpm
Cylinders	In-line 4 Cylinder/4 Stroke
Compression Ratio	17.3:1
Fuel System	Common Rail (Direct Injection)
Injection Pressure	1800 bar max.
Nozzle	Hole
Air Intake System	Turbocharged with intercooler
Emission Control System	SCR, OBD



①	CUMMINS ISB4.5E5160 Diesel Engine
②	SCR Catalyst ($V_2O_5/WO_3/TiO_2$)
③	Urea Dosing Unit (Air-Assisted Type)
④	Urea Nozzle
⑤	Catalyst inlet Temperature Sensor (Thermistor)
⑥	Catalyst outlet Temperature Sensor (Thermistor)
⑦	NO_x Sensor (Downstream)

Figure 2. The engine/SCR system experiment layout

The test fuel was B8 biodiesel blended with 8 vol% biodiesel (B100) and 92 vol% fossil diesel. The biodiesel (B100) was made from waste cooking oils by local manufacturers in Taiwan and complied with biodiesel standard CNS 15072, which is equivalent to EN 14214.

Table 2 shows the properties of the B8 test fuel as well as the fossil diesel for comparison. The properties of biodiesel are not much different from those of fossil diesel fuel. The cetane index of B8 is slightly higher than that of fossil diesel. The heating values are about the same. Thus, little difference in engine performance can be expected. However, the kinematic viscosity of B8 is higher than that of fossil fuel, and there is a major difference in lubricity, which is

represented by a corrected wear scar diameter. It can be seen that B8 has a much lower lubricity value than fossil diesel, indicating that the lubrication of engine parts could be improved with adequate amounts of biodiesel. The oxygen content of B8 is 1.03%. The oxygen content in fuel may enhance the oxidation of unburned carbon during the combustion process, resulting in lower particulate levels.

Table 2. Fuel Properties of Blend with 8% Biodiesel

Test item	D100(B0)	B100	B8	Unit
Cetane index	52	61	54	—
Density, 15°C	0.834	0.881	0.840	g/mL
Copper strip corrosion (3hr at 50°C)	1a	1a	1a	rating
Flash point	76.0	174.0	76.5	°C
Kinematic viscosity, 40°C	3.125	4.286	3.287	cSt
Carbon residue (on 10% distillation residue)	<0.1	0.1	<0.1	% (m/m)
Distillation, T95	349.6	348.0	353.1	°C
Ash	<0.001	0.004	<0.001	% (m/m)
Sulfur content	8.5	3.1	7.0	ppm
Polyaromatics content	5.00	----	5.58	% (m/m)
Lubricity, corrected wear scar diameter (1.4 wsd, 60°C)	425	----	225	μ m
Water and sediment	0.00	----	0.01	% (v/v)
Water content	135	354	183	ppm
Total contaminant	0.3	6.3	6.2	ppm
Pour point	-6	----	-5	°C
Cold filtration plug point (CFPP)	-3	-1	-3	°C
Group I metals (Na + K)	----	0.27	----	ppm
Group II metals (Ca + Mg)	----	0.13	----	ppm
Phosphorous	----	0.30	----	ppm

A full-load operation was performed for the durability test in this study. The whole process was 1000 hours, representing 160,000 km of operation in the real world. Every 125 hours, the operation was stopped temporarily for engine maintenance and examination. Every 250 hours, engine performance, regulatory and non-regulatory emissions were measured. The engine performance was determined using the SAE J1995 test method. The emission measurements were conducted according to the EU ETC cycle. As for the conversion efficiency of the SCR system, the ESC cycle was adopted.

To conduct a detailed inspection of the wear of engine components, the 3D Coordinate Measuring Machine (CMM), profile meter and other measurement rigs were used to measure the size of specific parts and calculate the size variations in each component before and after the durability tests. After the tests, the engine components were cut into appropriate sizes and examined with a Field-Emission Scanning Electron Microscope (FESEM) to determine the wear characteristics of each part of the components.