Emissions of Regulated Pollutants and PAHs from Waste-cooking-oil Biodiesel-fuelled Heavy-duty Diesel Engine with Catalyzer

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ABSTRACT

The development of biodiesels is being driven by the need for reducing emissions from diesel engines without modifying engines and for saving energy. The major obstacle to biodiesel commercialization is the high cost of raw materials. Biodiesel from waste cooking oil is an economical source and an effective strategy for reducing the raw material cost. Although biodiesels made from waste cooking oil have been previously investigated, PAH emissions from heavy-duty diesel engines (HDDEs) with catalyzer fueled with biodiesel from waste cooking oil and its blend with ultra-low sulfur diesel (ULSD) for the US-HDD transient cycle have seldom been addressed. Experimental results indicate that ULSD/WCOB (biodiesel made from waste cooking oil) blends had lower PM, HC, and CO emissions but higher CO_2 and NO_x emissions when compared with that of ULSD. Using ULSD/WCOB blends instead of ULSD decreased PAHs by 14.1%–53.3%, PM by 6.80%–15.1%, HC by 6.76%–23.5%, and CO by 0.962%–8.65% but increase CO_2 by 0.318–1.43% and NO_x by 0.384–1.15%. Using WCOB is an economical source and an effective strategy for reducing cost, and solves the problem of waste oil disposal.

Keywords: Waste cooking oil; Biodiesel; PAH; Diesel engine; Ultra-low sulfur diesel.

INTRODUCTION

Emissions from engines contain carcinogenic components such as carbonyl compounds (i.e. formaldehyde), polycyclic aromatic hydrocarbons (PAHs), and nitro-PAHs (Chen *et al.*, 2001; Grosjean *et al.*, 2001; Mi *et al.*, 2001; Lin *et al.*, 2005; Lin *et al.*, 2006; Lin *et al.*, 2006; Lin *et al.*, 2006; Lin *et al.*, 2006; Ho *et al.*, 2007; Legreid *et al.*, 2007; Ban-Weiss *et al.*, 2008; Lin *et al.*, 2008; Lin *et al.*, 2008; Lin *et al.*, 2008; Chien *et al.*, 2009; Lin *et al.*, 2009; Shi *et al.*, 2009; Wu *et al.*, 2009; Shi *et al.*, 2010; Wu *et al.*, 2010; Tsai *et al.*, 2011; Srivastava *et al.*, 2011; Yao *et al.*, 2011; Wang *et al.*, 2012). Therefore, alternative fuel is needed in the future. Biodiesel is considered as one of best alternative fuels. The development of biodiesels is being driven by the need for reducing emissions from diesel engines without modifying engines and for saving energy. Biodiesels used as alternative fuels in diesel engines reduce the emissions of hydrocarbons (HC), carbon monoxide (CO), sulfur oxide (SO_2), and PAHs (Antolin *et al.*, 2002; Beer *et al.*, 2002; Cardone *et al.*, 2002; Durbin *et al.*, 2002; Dorado *et al.*, 2003; Kalam *et al.*, 2003; Kalligeros *et al.*, 2003; Goodrum and Geller, 2005; Hu *et al.*, 2005; Lin *et al.*, 2006; Lin *et al.*, 2006; Legreid *et al.*, 2007; Yuan *et al.*, 2007; Lin *et al.*, 2008; Lin *et al.*, 2008; Chien *et al.*, 2009; Pehan *et al.*, 2009; Yuan *et al.*, 2009; Tsai *et al.*, 2010; Tsai *et al.*, 2011; Tsai *et al.*, 2011). Previous studies and measurements of NO_x emissions from biodiesel showed an increase in NO_x emissions (Scholl and Sorenson, 1993; Graboski *et al.*, 1996; Choi *et al.*, 1997; Graboski and McCormick, 1998; Yoshimoto *et al.*, 1999; McCormick *et al.*, 2001; Grimaldi *et al.*, 2002; Tat and Van Gerpen, 2003; Tat, 2004; Saravanan *et al.*, 2010; Sun *et al.*, 2010). The problem of high NO_x emissions from biodiesel-diesel engines can be mitigated by the use of low-temperature combustion, reformulated biodiesel, selective catalytic reduction, and exhaust gas recirculation (Hess *et al.*, 2007; Tsolakis *et al.*, 2007; Muncrief *et al.*, 2008; Tsolakis *et al.*, 2008). There are mixed results for PM reduction, however, most of results (> 90%) show PM reduction when using biodiesel (Lapuerta *et al.*, 2005; Lapuerta *et al.*, 2008; Cheung *et al.*, 2009; Karavalakis *et al.*, 2010).

Furthermore, biodiesel has a relatively high flash point, which makes it less volatile and safer to transport or handle than petroleum diesel (Lin *et al.*, 2006; Lin *et al.*, 2006) and it also enhances lubrication, which can reduce engine wear and extend engine life (Goodrum and Geller, 2005; Hu *et al.*, 2005; Pehan *et al.*, 2009). The major obstacle to

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biodiesel commercialization is the high cost of biodiesel. The cost of biodiesel is approximately 1.5 times higher than that of petroleum diesel fuel due to the cost of vegetable oil (Prokop, 2002; Zhang *et al.*, 2003; Lott, 2005; Hass *et al.*, 2006). Biodiesel made from waste cooking oil is an economical source and an effective strategy for reducing raw material cost (Supple *et al*, 1999; Zhang *et al.*, 2003; Kulkarni and Dalai, 2006; Lapuerta *et al.*, 2008). Using waste cooking oil solves the problem of waste oil disposal. Therefore, biodiesel made from waste cooking oil was used in this study.

Dorado *et al.* (2003) investigated the effect of biodiesel made from waste olive oil for a direct injection diesel engine at several steady-state operating conditions. Results revealed that the use of biodiesel resulted in lower emissions of CO (up to 58.9%), CO_2 (up to 8.6%, except for a case with a 7.4% increase), NO (up to 37.5%), and SO_2 (up to 57.7%), with an increase in emissions of NO_2 (up to 81%, except for a case with a slight reduction). Biodiesel also exhibited a slight increase in BSFC (lower than 8.5%) that may be tolerated due to the exhaust emission benefits. Kulkarni and Dalai (2006) reported that the biodiesel obtained from waste cooking oil gives better engine performance and less emissions, except for NO_x, when tested on commercial diesel engines. Lapuerta *et al.* (2008) tested biodiesel from waste cooking oils in a direct injection diesel commercial engine under a set of engine operating conditions corresponding to typical road conditions. When compared to conventional low sulfur diesel fuel, a sharp decrease was observed in both smoke and particulate matter emissions as the biodiesel concentration was increased. Di *et al.* (2009) investigated a 4-cylinder direct-injection diesel engine using ultra-low sulfur diesel, biodiesel from waste cooking oil, and their blends, to investigate emissions from the engine under five engine loads at an engine speed of 1800 rev/min. They found that HC and CO emissions decreased whereas NO_x and NO_2 emissions increased with increasing biodiesel blends. For unregulated gaseous emissions, generally, the emissions of formaldehyde, 1,3-butadiene, toluene, and xylene decreased with increasing biodiesel blends; however, acetaldehyde and benzene emissions increased. Ozsezen *et al.* (2009) investigated a DI diesel engine fueled with biodiesels from waste cooking oil at a constant engine speed (1500 rpm) under the full load condition of the engine. They also found that biodiesels caused reductions in CO, and HC emissions and smoke opacity, but increased NO_x emissions when compared to petroleum-based diesel fuel.

Emissions from a HDDE (heavy-duty diesel engine) under the US-HDD transient cycle test are representative because the engine is tested over a full range of load and speed conditions, including expressway, congested-urban, and uncongested-urban. Furthermore, further research on the use of biodiesel from waste cooking oil will promote its application to diesel engines. Ultra-low sulfur diesel (ULSD) is becoming increasingly popular for HDDEs. Further research on regulated and unregulated emissions from HDDEs fueled with ULSD/WCOB (waste cooking oil biodiesel) blends is required. Although biodiesels made from waste cooking oil have been previously investigated,

PAH emissions from HDDEs with catalyzer fueled with biodiesel from waste cooking oil and its blend with ULSD for the US-HDD transient cycle have seldom been addressed. This study investigated the brake specific fuel consumption and the feasibility of biodiesel blends was assessed. Emissions of regulated matters and PAHs from HDDEs with catalyzer fueled with waste-cooking-oil biodiesel were calculated and compared.

EXPERIMENTAL SECTION

Test Engine and Fuels

The experimental setup is shown in Fig. 1. The tested HDDE with catalyzer used in this study was a Cummins B5.9-160. Testing was conducted according to Code of Federal Regulations (CFR) 40 Part 86 Subpart N (the US-HDD transient cycle), with related mild engine loaded conditions, which represents typical urban and freeway driving conditions (Code of Federal Regulations). Cold start and hot start emissions were measured and a complex emission index was calculated by multiplying weighting factors (1/7 × cold start + 6/7 × hot start). Operation conditions of test engine varied with time under US-HDD transient cycle test. Therefore, the air/fuel ratio was not constant. In this study, the air/fuel ratio ranged from 29 to 33. The specifications of the test HDDE with catalyzer is listed in Table 1. A Schenck GS-350 dynamometer was used. A dilution tunnel and a monitoring system were installed downstream of the exhaust to supply dilute air and to facilitate continuous measurement of suspended particles (PM and particulate-phase PAHs). Gas-phase pollutants (THC, CO, CO_2, NO_x, and gas-phase PAHs) were also collected and measured. In order to decrease the temperature of the original exhaust, clean ambient air was used to dilute the original exhaust. The appropriate dilution ratio is approximately 18 fold. In this study, ultra-low sulfur diesel (ULSD) was purchased from CPC Corporation in Taiwan and the biodiesel made from waste cooking oil (WCOB) was purchased from Great Green Renewable Energy Technology Corporation in Taiwan. The following five test fuels were selected for this study: ultra-low sulfur diesel (ULSD), WCOB5 (5 vol% biodiesel made from waste cooking oil + 95 vol% ULSD), WCOB10 (10 vol% biodiesel made from waste cooking oil + 90 vol% ULSD), WCOB20 (20 vol% biodiesel made from waste cooking oil + 80 vol% ULSD), and WCOB30 (30 vol% biodiesel made from waste cooking oil + 70 vol% ULSD).

Sample Collection

PAH samples of both particulate-phase and gas-phase were collected by using a PAH sampling system at a temperature below 52°C. Particulate-phase PAHs were collected on a glass-fiber filter. Filters were placed in an oven at 450°C for 8 hrs before sampling to burn off any organic compounds that might be present. The cleaned filters were stored in a desiccator for at least 8 hrs to achieve moisture equilibrium before weighing. After sampling, the filters were brought back to the laboratory and put in a desiccator for 8 hrs to remove moisture, and were weighed again to determine the net mass of particles collected. Gas-phase PAHs were
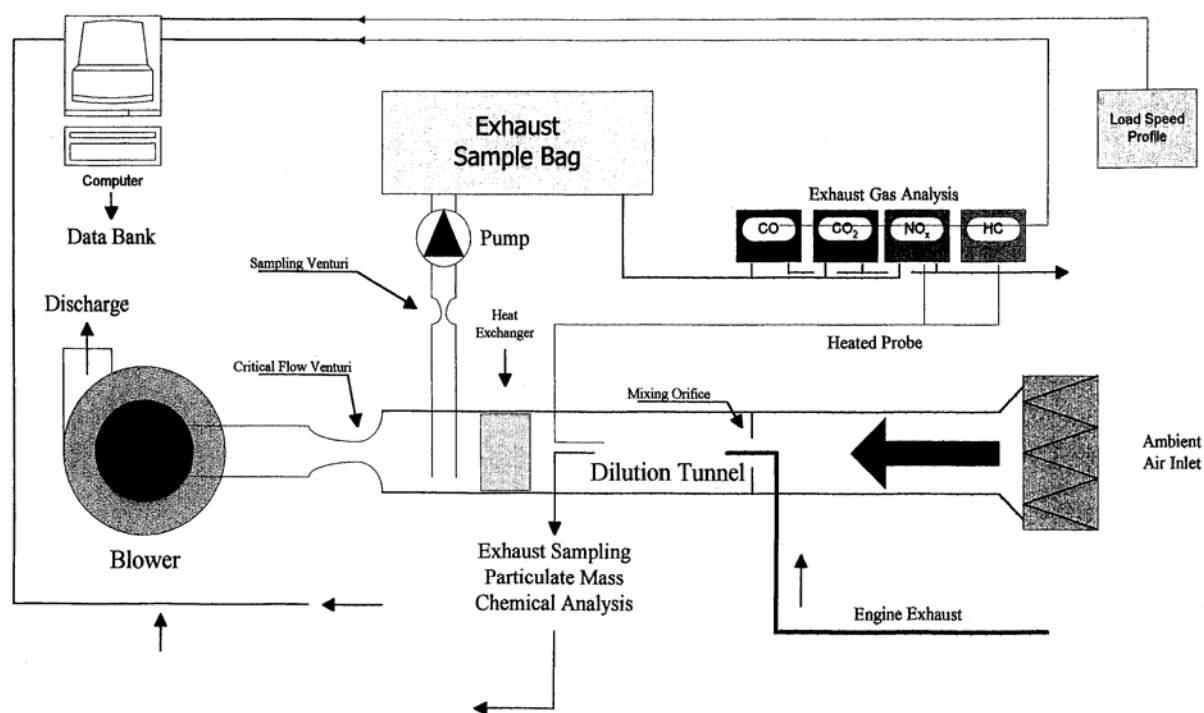
Fig. 1. Experiment setup.

Table 1. The specifications of the test HDDE with catalyzer.

Parameters	Test HDDE
Engine Model	Cummins
Engine Type	B5.9-160
Aspiration	Turbocharged
Intercooler	Water Cooler
Injection Type	Direct Injection
Bore × Stroke	102 mm × 120 mm
Displacement	5880 cc
Injection Sequence	1-5-3-6-2-4
Injection Timing	12.3° BTDC[a]
Compression Ratio	17.9:1
Idle Speed	810 rpm
Max. Power	118 kW (at 2400 rpm)
Max. Torque	534 Nm (at 1600 rpm)

[a] BTDC = Before Top Dead Center

collected on a three-stage glass cartridge containing a polyurethane foam (PUF) plug XAD-16 resin. The glass cartridge was packed with 5.0 cm of XAD-16 resin sandwiched between 2.5 cm top and bottom PUF plugs. Silicone glue was used to seal and hold these two pieces of PUF to prevent resin from leaking out during the sampling and extraction processes. After 8 hrs of adherence, the newly PUF/resin cartridge was cleaned up by Soxhlet extraction for one day each with distilled water, methanol, dichloromethane, and n-hexane for a total of 4 days, then placed in a vacuum oven at 60°C for 2 hrs to dry and evaporate the residual solvent in them. After drying, each PUF/resin cartridge was individually wrapped in hexane-washed aluminum foil and stored in a refrigerator at 4°C and transported in clean screw-capped jars with Teflon cap liners before sampling. Each

glass fiber filter was transported to and from the field in a glass box, which was also wrapped with aluminum foil.

Analysis

Each collected sample (including particulate and gaseous PAH samples) was extracted in a Soxhlet extractor with a mixed solvent (n-hexane and dichloromethane; vol/vol, 1:1; 500 mL each) for 24 hrs. The extract was then concentrated, cleaned up, and reconcentrated to exactly 1.0 mL. The PAH contents were determined by a Hewlett-Packard (HP) gas chromatograph (GC) (HP 5890A; Hewlett-Packard, Wilmington, DE, USA), a mass selective detector (MSD) (HP 5972), and a computer workstation (Aspire C500; Acer, Taipei, Taiwan). This GC/MSD was equipped with a capillary column (HP Ultra 2, 50 m × 0.32 mm × 0.17 μm) and an automatic sampler (HP-7673A), and operated under the following conditions: the injection volume of the GC/MSD was 1 μL; the splitless injection temperature was 310°C; the ion source temperature was 310°C; the oven was heated from 50°C to 100°C at 20 °C/min, 100°C to 290°C at 3 °C/min, then held at 290°C for 40 minutes. The mass of primary and secondary PAH ions was determined by using the scan mode for pure PAH standards. The PAHs were qualified by using the selected ion monitoring (SIM) mode. The PAH homologues grouped by the number of rings were as follows: naphthalene(Nap) for 2-ring; acenaphthylene (AcPy), acenaphthene (Acp), fluorene (Flu), phenanthrene (PA) and anthracene (Ant) for 3-ring; fluoranthene (FL), pyrene (Pyr), benzo[a]anthracene (BaA) and chrysene (CHR) for 4-ring; cyclopenta[c,d]pyrene (CYC), benzo[b]fluoranthene (BbF), benzo[k]fluoranthene (BkF), benzo[e]pyrene (BeP), benzo(a)pyrene (B[a]P), perylene (PER), dibenzo[a,h]anthracene (DBA) and

benzo[b]chrycene (BbC) for 5-ring; indeno[1,2,3,-cd]pyrene (IND), benzo[ghi]perylene (Bghip) for 6-ring; and, coronene (COR) for 7-ring. The total-PAHs data for the HDDE exhaust is given by the sum of the 21 individual PAHs. The GC/MSD was calibrated with a diluted standard solution of 16 PAH compounds (PAH mixture-610M; Supelco, Bellefonte, PA, USA) plus five additional individual PAHs obtained from Merck (Darmstadt, Germany). Analysis of serial dilutions of PAHs standards showed that the detection limit (DL) for GC/MSD was between 26 pg and 308 pg for the 21 PAH compounds. The limit of quantification (LOQ) is defined as the DL divided by the sampling volume or sampling time. The LOQ for individual PAHs was between 24 pg/m^3 and 277 pg/m^3, while values for sampling time were between 75 pg/hr and 952 pg/hr. Ten consecutive injections of a PAH 610-M standard yielded an average relative standard deviation of the GC/MSD integration area of 6.71%, within a range of 4.18% to 9.63%. Following the same experimental procedures used for sample treatment, recovery efficiencies were determined by processing a solution containing known PAH concentrations. The experimental results showed the recovery efficiencies for the 21 PAH compounds ranged from 0.835 to 1.08, with an average value of 0.942. Analyses of field blanks, including aluminum foil, glass-fiber filters and PUF/XAD-16 cartridges, revealed no significant contamination (GC/MSD integrated area < detection limit).

For particulate matter (PM) analysis, each filter sample was weighed again using an electronic analytical balance with fully automatic calibration technology (AT200, Mettler, Switzerland with accuracy of 0.001 mg) to determine the net mass of collected PM. For total hydrocarbon analysis, each sample was analyzed using a flame ionization detector (FID) (model 404, Rosemount, UK with precision of 0.5%). For carbon monoxide/carbon dioxide analysis, each sample was analyzed using a non-dispersive infrared detector (NDIR) (model 880A, Rosemount, UK with precision of 1%). For nitrogen oxides analysis, each sample was analyzed using a chemiluminescent detection (CLD) (model 404, Rosemount, UK with precision of 0.5%). Anon-touch type HBM torque meter was used to measure engine speed and engine load simultaneously. K-Type thermal couple was used to measure exhaust temperature.

RESULTS AND DISCUSSION

Fuel Specifications

In this study, test fuels were analyzed according to the American Society for Testing and Materials (ASTM), which is one of the most frequently used methods in the US. Fuel specifications are shown in Table 2. The mean total poly-aromatic content of ULSD was 0.4 wt%, but that of WCOB was less than the detection limit (0.1 wt%). The mean sulfur content of ULSD and WCOB were 36.4 and 6.2 ppmw (parts per million by weight). Analytical results reveal that using WCOB instead of ULSD can reduce emissions of SO$_x$ and PAHs. Previous studies indicate that the viscosity, flash points and pour points of biodiesel is higher than that of diesel (Lin *et al.*, 2006; Lin *et al.*, 2006; Legreid *et al.*, 2007; Lin *et al.*, 2008; Lin *et al.*, 2008; Lin *et al.*, 2009). High viscosity is good for the lubrication of engines, but it causes poor nebulization, resulting in poor combustion. The boiling point is important for air-fuel mixing. A high boiling point may lead to long penetration, resulting in increased fuel impingement and poor combustion (Dec *et al.*, 1998). Although biodiesels have higher flash point, previous studies indicated that biodiesel was not suitable to be used in cold weather conditions because of its higher viscosity, cetane number, iodine value, and minor constituents such as saturated monoacylglycerols or free steryl glucosides (Dunn, 2009; Eevera *et al.*, 2009; Tesfa *et al.*, 2010) which may influence pipeline transportation and induce fuel system flushing and power loss. Therefore, biodiesels were not suitable to be used in cold weather conditions unless additive or heating system was used (Chiu *et al.*, 2004; Tate *et al.*, 2006).

Brake Specific Fuel Consumption

The brake specific fuel consumptions (BSFC) of ULSD, WCOB5, WCOB10, WCOB20, and WCOB30 were shown in Table 3. BSFC increased with increasing WCOB blends at cold start and hot start. The mean BSFC (1/7 cold start + 6/7 hot start) of ULSD, WCOB5, WCOB10, WCOB20, and WCOB30 were 198, 199, 199, 200, and 201 g/BHP-hr, respectively. The mean increases of BSFC were 0.505%, 0.505%, 1.01%, and 1.52% for WCOB5, WCOB10, WCOB20, and WCOB30, respectively, when compared with the BSFC for ULSD. These increases are due to the gross heat value (GHV) of WCOB (41.2 kJ/g) being lower than that of ULSD (45.2 kJ/g) (Table 2). The results indicate that BSFC was higher for biodiesel blends as a consequence of biodiesel having a lower heating value. However, this increase was compensated by higher density

Table 2. Specifications of the test fuel.

Fuel parameter	ULSD[a]	WCOB[b]	Analytic method
Sulfur content, ppmw (parts per million by weight)	36.4	6.2	ASTM[c] D2622
Poly-aromatic content, wt%	0.4	ND[d]	ASTM D6591
Gross heating value (kJ/g)	45.2	41.2	ASTM D3286
Cetane number	57.9	54.1	ASTM D613
Density , g/mL at 15°C	0.839	0.880	ASTM D4052
Viscosity , mm^2/s at 40°C	3.11	4.31	ASTM D445
Flash point, °C	80	169	ASTM D93

[a] Ultra-low sulfur diesel, [b] Waste cooking oil biodiesel, [c] American Society for Testing and Materials, [d] Not Detected.

Table 3. The brake specific fuel consumptions (g/BHP-hr).

	Tested fuel				
	ULSD	WCOB5	WCOB10	WCOB20	WCOB30
Cold start	202	201	202	203	204
Hot start	198	199	199	200	201
1/7 Cold start + 6/7 Hot start	198	199	199	200	201

of biodiesel in the volumetric injection system. Thus, differences in volumetric consumption between diesel and biodiesel would become smaller. According to the report by Ozsezen *et al*. (2009), the above results may be due to the fuel injection pump being controlled by the test HDDE and the engine load being controlled by the fuel injection volume. For the same volume, more biodiesel fuel, based on mass, was injected into the combustion chamber than ULSD due to the higher density of biodiesel blends. Moreover, fuel properties such as higher density and kinematic viscosity influence the atomization ratio, slowing down the fuel–air mixing rates (Ozsezen *et al*., 2009).

Reductions of PM, HC, and CO Emissions

The emission factor of PM, HC, and CO emissions in the exhaust is listed in Fig. 2. The biodiesel blends had lower PM, HC, and CO emissions when compared with those of ULSD. PM emissions from engines have three major components: soot formed during combustion, heavy hydrocarbon condensed or absorbed on the soot, and sulfates. On the whole, PM emission levels generally decreased with increasing WCOB blends from 0% to 20% palm-biodiesel blends, and increased with increasing WCOB blends from 20% to 30% WCOB blends. The mean reductions of PM (ULSD = 0.103 g/BHP-hr) were 6.80%, 8.74%, 15.5%, and 12.0% for WCOB5, WCOB10, WCOB20, and WCOB30, respectively, when compared with the PM value for ULSD. The above result may be attributed to lower soot formation and soluble organic fraction (Akasaka *et al*., 1997; Kimura *et al*., 1999; Kimura *et al*., 2001; Fang *et al*., 2008). Although biodiesel is better than diesel fuel, the HDDE is not designed for biodiesel. Adding an excess of biodiesel to
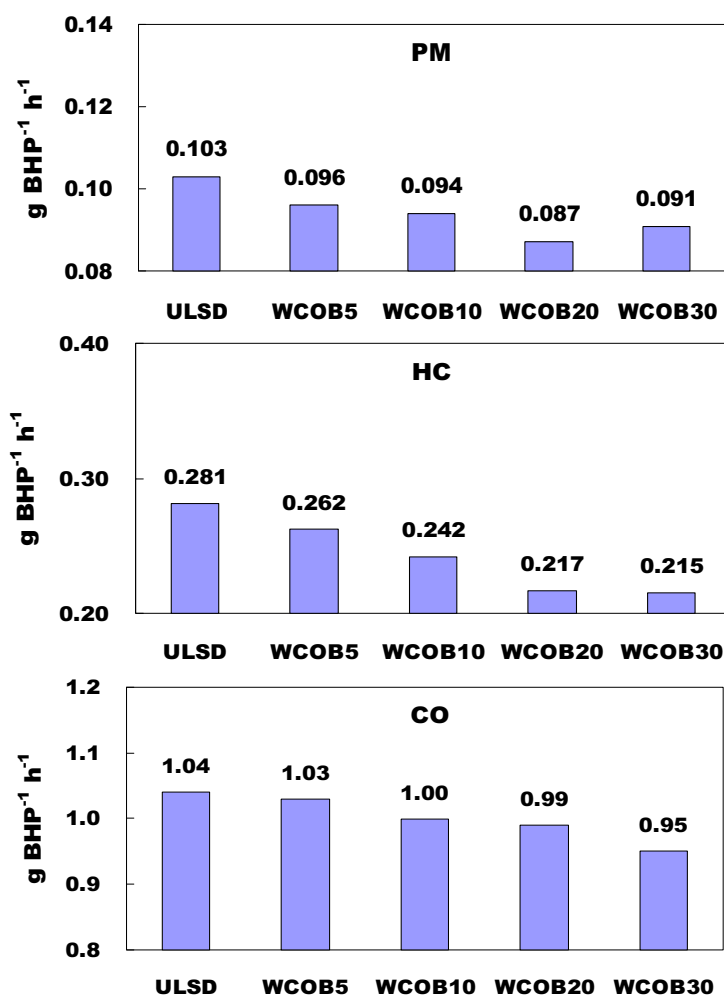

Fig. 2. Emission factor of PM, HC, and CO from the HDDE with catalyzer under US-HDD transient cycle.

diesel leaded to incomplete combustion in the HDDE and inhibited the release of energy in the fuel (Lin *et al.*, 2006). This phenomenon probably resulted from incomplete the increases of cetane number and viscosity after adding a significant amount of biodiesel (Tsai *et al.*, 2010). These combustion of fuel in the combustion chamber when the nebulization efficiency of nozzle was insufficient due to results displayed useful information for the direction of future design for the high additional fraction of WCOB in the HDDE. The emissions of HC and CO for biodiesel blends were lower than those for ULSD. The mean reductions of HC (ULSD = 0.281 g/BHP-hr) were 6.76%, 13.9%, 22.8%, and 23.5% for WCOB5, WCOB10, WCOB20, and WCOB30, respectively, when compared with the HC value for ULSD. The mean reductions of CO (ULSD = 1.04 g/BHP-hr) were 0.962%, 3.85%, 4.81%, and 8.65% for WCOB5, WCOB10, WCOB20, and WCOB30, respectively, when compared with the CO value for ULSD. The above results indicate that WCOB, an oxygenated fuel, can increase combustion efficiency and reduce PM, HC, and CO emissions from HDDEs. In this study, it was found that more PM generated but less HC and CO emitted under incomplete combustion. The above result might be attributed to unburned PM expected to be burned and to generate HC and CO emission. Similar results have been published (Dorado *et al.*, 2003; Kulkarni and Dalai, 2006; Legreid *et al.*, 2007; Di *et al.*, 2009; Ozsezen *et al.*, 2009). The difference in reductions may be attributed to the different operation conditions and the products formed during frying, such as free fatty acids and some polymerized triglycerides, which affect the transesterification reaction and lead to various biodiesel properties.

Increases of CO_2 and NO_x Emissions

The emission factor of CO_2 and NO_x emissions in the exhaust is listed in Fig. 3. The biodiesel blends had higher CO_2 and NO_x emissions when compared with those of ULSD. The mean increases of CO_2 (ULSD = 628 g/BHP-hr) were 0.318%, 0.318%, 0.955%, and 1.43% for WCOB5, WCOB10, WCOB20, and WCOB30, respectively, when compared with the CO_2 value for ULSD. This is because WCOB, an oxygenated fuel, increase combustion efficiency causing higher CO_2 emission. The mean increases of NO_x (ULSD = 5.21 g/BHP-hr) were 0.384%, 0.960%, 0.960%, and 1.15% for WCOB5, WCOB10, WCOB20, and WCOB30, respectively, when compared with the NO_x value for ULSD. The problem of high NO_x emissions from biodiesel-diesel engines can be mitigated by the use of low-temperature combustion or selective catalytic reduction (He and Yu, 2005; Kelly *et al.*, 2006; Ciardelli *et al.*, 2007; Dong *et al.*, 2008; Fang *et al.*, 2008; Grossale *et al.*, 2008).

PAH Emissions

PAH concentrations of biodiesel blends are listed in Fig. 4. Total PAH emission concentrations from the HDDE decreased with increasing biodiesel blends. The mean reductions of total PAH concentration from the HDDE were 13.5%, 23.3%, 32.0%, and 37.7% for WCOB5, WCOB10, WCOB20, and WCOB30, respectively, when compared with the total PAH concentration for ULSD. These findings are a result of PAH content in WCOB being close to zero. Therefore, a high fraction of biodiesel blends resulted in lower PAH emissions. Similar results have been published (Hori *et al.*, 1997; Bagley *et al.*, 1998; Durbin *et al.*, 2000; Sidhu *et al.*, 2001; Cardone *et al.*, 2002; Lin *et al.*, 2006; Lin *et al.*, 2006; Yuan *et al.*, 2009). PAH emission factor (μg/BHP-hr) for total PAHs (denoted by $EF_{total-PAH}$) was calculated and listed in Fig. 5. As shown in sequence for
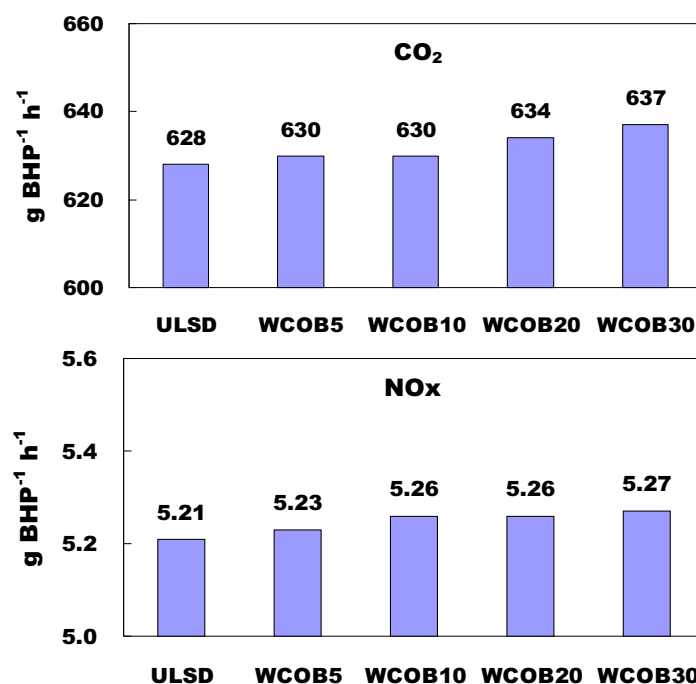
Fig. 3. Emission factor of CO_2 and NO_x from the HDDE with catalyzer under US-HDD transient cycle.
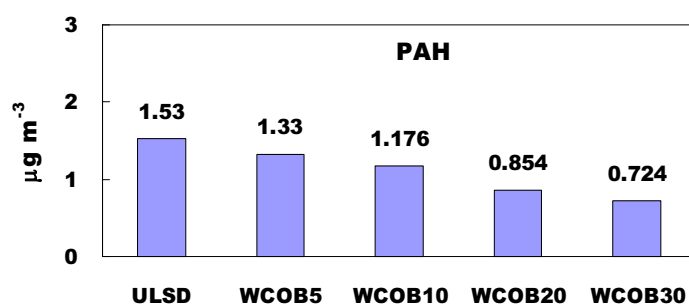
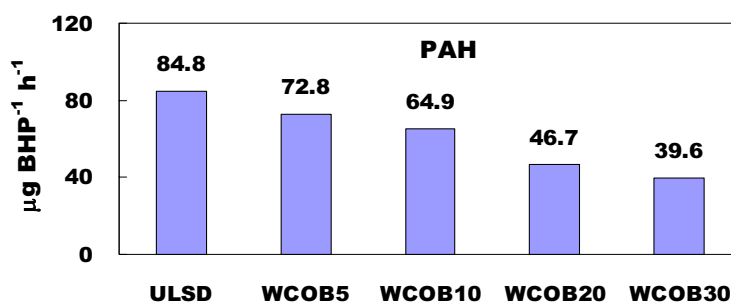**Fig. 4.** PAH concentration from the HDDE with catalyzer under US-HDD transient cycle.

Fig. 5. PAH emission factor from the HDDE with catalyzer under US-HDD transient cycle.

magnitudes of $EF_{total\text{-}PAH}$, analysis identified ULSD > WCOB5 > WCOB10 > WCOB20 > WCOB30. When compared with the total PAH emission factor for ULSD (ULSD = 84.8 µg/BHP-hr), the mean reductions of total PAH emission factor from the HDDE were 14.1%, 23.5%, 44.9%, and 53.3% for WCOB5, WCOB10, WCOB20, and WCOB30, respectively.

CONCLUSION

Although biodiesels made from waste cooking oil have been previously investigated, PAH emissions from HDDEs with catalyzer fueled with biodiesel from waste cooking oil and its blend with ULSD for the US-HDD transient cycle have seldom been addressed. This study investigated the brake specific fuel consumption and the feasibility of biodiesel blends was assessed. Emissions of regulated matters and PAHs from HDDEs with catalyzer fueled with waste-cooking-oil biodiesel were calculated and compared. Experimental results indicate that ULSD/WCOB blends had lower PM, HC, and CO emissions but higher CO_2 and NO_x emissions when compared with that of ULSD. Using ULSD/WCOB blends instead of ULSD decreased PAHs by 14.1%–53.3%, PM by 6.80%–15.1%, HC by 6.76%–23.5%, and CO by 0.962%–8.65% but increase CO_2 by 0.318–1.43% and NO_x by 0.384–1.15%. The above results indicate that WCOB can increase combustion efficiency and reduce PM, HC, and CO emissions. A high fraction of biodiesel blends resulted in lower PAH emissions due to no PAH in WCOB. BSFC was higher for biodiesel blends as a consequence of biodiesel having a lower heating value. Furthermore, using WCOB is an economical source and an effective strategy for reducing cost, and solves the problem of waste oil disposal.

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