



Emission reductions of Air Pollutants from a Heavy-duty Diesel Engine Mixed with Various Amounts of H₂/O₂

Hsin-Kai Wang, Chia-Yu Cheng, Yuan-Chung Lin, Kang-Shin Chen*

Institute of Environmental Engineering, National Sun Yat-Sen University, Kaohsiung 80424, Taiwan

ABSTRACT

This study investigated emission reductions of polycyclic aromatic hydrocarbons (PAHs), hydrocarbons (HCs), carbon monoxide (CO), carbon dioxide (CO₂), particulate matters (PM), and nitrogen oxides (NO_x) from a heavy-duty diesel engine (HDDE) at one low load steady-state condition, 24.5% of the maximum load (40 km/h), using premium diesel fuel (PDF) mixed with various amounts of H₂/O₂. Measurements showed that the mixed fuel of HO60 reduced the brake specific fuel consumption (BSFC) most, by an amount of 12.6%, as compared with PDF. Meanwhile, with HO60, the emission of air pollutant was decreased by 32.3% for PAHs, 9.5% for HCs, 7.2% for CO, 4.4% for CO₂, and 19.3% for PM, but the emission of NO_x was increased by 9.9%.

Keywords: Diesel engine; Hydrogen; Engine Performance; Air Pollutants; Emission.

INTRODUCTION

Due to environmental concerns and the increasing price of traditional fossil fuels, alternative fuels are now receiving more attention than before in many countries. Many developed countries are currently encouraged to find out alternative approaches to promote fuel economy and reduce the environmental impact from internal combustion diesels. Diesel engines are widely used in heavy-duty buses, trucks, construction machines, generators, and so on, as they have greater fuel efficiency and power output than gasoline engines, and lower emissions of harmful materials such as hydrocarbons (HCs), nitrogen oxides (NO_x) and carbon monoxide (CO) (Williams *et al.*, 1989; Schinder, 1992). However, emissions from diesel engines contain carcinogenic components such as polycyclic aromatic hydrocarbons (PAHs), and nitro-PAHs, carbonyl compounds (Grosjean *et al.*, 2001; Kawahara *et al.*, 2001; Ho *et al.*, 2007; Legreid *et al.*, 2007; Wang *et al.*, 2007; Ban-Weiss *et al.*, 2008; Chen *et al.*, 2008; Lin *et al.*, 2008; Chen *et al.*, 2009; Lin *et al.*, 2009; Yuan *et al.*, 2009; Wang *et al.*, 2010a, 2010b; Lin *et al.*, 2011). The sources of PAHs are primarily incomplete fossil-fuel combustions, which take place at steel-making plants, secondary zinc/aluminum sinter plants, diesel trucks and waste incinerators, and, many studies have suggested that mobile sources are the major contributor to PAH concentrations in urban and suburban environments

(Barfknecht, 1983; Lee *et al.*, 1995; Harrison *et al.*, 1996; Yang *et al.*, 1999; Chen *et al.*, 2009). Barfknecht (1983) indicated that PAH emission factors from the exhausts of heavy duty engines (HDDEs) are 10-fold higher than those from gasoline engines. Based on measurements at traffic intersections, Yang *et al.* (1999) found that the contribution of total-PAHs from mobile sources to ambient air was 91.8%, while another study found that the total-PAH concentrations in the ambient air from traffic-sources was approximately 5.3 and 8.3 times higher than mean values in the urban and rural atmosphere, respectively (Lee *et al.*, 1995). The results of principal component analysis (PCA)/absolute principal component scores (APCS) by Chen *et al.* (2009) suggest that the primary pollution sources in Kaohsiung City are vehicle exhausts (gasoline and diesel engines). Over the past 30 years, many studies have suggested that PAHs are environmental immunosuppressive contaminants. Moreover, PAHs, especially benzo(a)pyrene, not only injure the respiratory and immune system, but also cause cell mutation and diseases such as lung and skin cancer (Hecht, 1999; Knize *et al.*, 1999; Laupeze *et al.*, 2002; Page *et al.*, 2002; Grevenynghe *et al.*, 2003).

A number of studies have investigated alternative fuels with regard to their effects on both diesel combustion and emissions. Hydrogen is a generally acknowledged as a renewable, recyclable and non-polluting fuel. The most significant difference between hydrogen and hydrocarbon fuels is the absence of carbon (Kawahara *et al.*, 2001). Additionally, hydrogen has wider flammability limits, higher flame speed and faster burning velocity than diesel fuel (Bari and Mohammad, 2010), which enables engines to run on very lean mixtures (Verhelst and Sierens, 2001;

* Corresponding author. Tel./Fax: +886-7-5254406
E-mail address: shin@mail.nsysu.edu.tw

Mohammadi et al., 2007).

It is known that pollutant emissions from an HDDE 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. However, HDDEs are constantly operating at low load in urban areas, indicating that the related pollution is close to humans. A report from Taiwan's Ministry of Transportation and Communications (MOTC) indicated that the mean speed of vehicles in urban areas ranges from 28.7 to 45.4 km/h, with an average of 38.0 km/h (MOTC, 2008). Therefore, a widely used diesel engine was tested in this study at one low load steady-state condition, 24.5 to 28.0% of the max load (40 km/h), because that is how the engine is generally operating in urban areas.

This work was aimed to study the effects of mixing diesel fuel with various amount of H₂/O₂ fuel on the emissions of PAHs in a diesel engine. The main goal of this study is to find an appropriate H₂/O₂ fuel to reduce emissions of PAHs and other traditional air pollutants, together with the effect on thermal efficiency or fuel consumption, from an HDDE at 24.5% of the maximum load condition (40 km/h).

EXPERIMENTAL PROCEDURES

Test Engine and Hydrogen/Oxygen Fuels

This study used premium diesel fuel (PDF) as the main fuel and added H₂/O₂ as an alternative fuel. The properties of diesel and hydrogen are shown in Table 1 (McCarty and Hord, 1981; Benz et al., 1988). A dilution tunnel and monitoring system were both installed downstream of the diesel engine exhaust and supplied diluted air in a appropriate ratio and for continuous measurement of smoke, suspended particles and gas-phase pollutants. The airflow rate was measured using a Venturi tube downstream of the test section. The HDDE (non-catalyst) used in this work was a Cummins B5.9-160 with the following characteristics: six-cylinders; four strokes; direct injection; fuel injection sequence 1-5-3-6-2-4; bore and stroke of 102 mm (Dia.) × 120 mm; total displacement of 5.88 L; compression ratio of 17.9:1, maximum horsepower of 118 kW at 2500 rpm; and maximum torque of 534 Nm at 1,600 rpm.

An oxy-hydrogen generator machine (EP-560A, Epoch, Kaohsiung, Taiwan) was used to electrolyze water to obtain the mixture of hydrogen and oxygen (H₂/O₂), and then transported H₂/O₂ to the combustion chamber of the test diesel engine. The H₂/O₂ was then passed through a gas flow meter (which measures the flow of H₂/O₂ in terms of

L/min) and two flame arrestors before it was transported to the engine via the air inlet manifold. The constituents of H₂/O₂ were no further analyzed here. A gas flow meter was used to measure the flow rate of H₂/O₂, and two flame arrestors were installed into the H₂/O₂ line to suppress explosions in the experimental procedures.

There were eight test fuels used in this study: premium diesel fuel (PDF), HO10 (PDF + 10 L/min of H₂/O₂ mixture), HO20 (PDF + 20 L/min of H₂/O₂ mixture), HO30 (PDF + 30 L/min of H₂/O₂ mixture), HO40 (PDF + 40 L/min of H₂/O₂ mixture), HO50 (PDF + 50 L/min of H₂/O₂ mixture), HO60 (PDF + 60 L/min of H₂/O₂ mixture), and HO70 (PDF + 70 L/min of H₂/O₂ mixture). Also, the diesel fuel was measured by a digital weighting scale with an accuracy of ± 1 g.

Sample Collection

PAH samples of both the 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 h before sampling to remove any organic compounds that might be present, and then put in an isothermal box for cooling and weighing. After sampling, the filters were brought back to the laboratory and put in a desiccator for 8 h to remove moisture, and were weighed again to determine the net mass of particles collected. Gas-phase PAHs were collected on three stage glass cartridge containing polyurethane foam (PUF) plugs and 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 sampling and extraction processes. After 8 h of adherence, the PUF/resin cartridge was cleaned up by Soxhlet extracting for one day each with distilled water, methanol, dichloromethane, and n-hexane, over a total of 4 days, then placed in a vacuum oven at 60°C for 2 h to dry and evaporate the residual solvent. 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 sample collected (including particulate and gaseous PAH samples) was extracted in a Soxhlet extractor with a

Table 1. Properties of diesel and hydrogen.

Properties	Hydrogen ^{a, b}	Diesel	Analytic method
Sulfur content, ppmw (parts per million by weight)	0	31	ASTM ^c D2622
Polyaromatic content, wt%	0	0.4	ASTM D6591
Cetane number	–	55.2	ASTM D613
Boiling point, °C	–252.8	363	ASTM D86
Density, kg/L	0.084	0.834	ASTM D4052
Calorific value, kJ/kg	119,930	42,490	ASTM D3286

Notes: ^a McCarty et al. (1981), ^b Benz et al. (1988), ^c American Society for Testing and Materials.

mixed solvent (n-hexane and dichloromethane; vol/vol, 1:1; 500 mL each) for 24 h. 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) (Agilent Technologies 6890N, Santa Clara, CA, USA), a mass selective detector (MSD) (Agilent Technologies 5973), and a computer workstation (Aspire 3935; Acer, Taipei, Taiwan). This GC/MSD was equipped with a capillary column (Ultra 2 19091B–015, 50 m × 0.32 mm × 0.17 mm) and an automatic sampler (Agilent Technologies 7683) and operated under the following conditions: injection volume of 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 min. 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 are as follows: naphthalene (Nap) for 2-ring; acenaphthylene (AcPy), acenaphthene (Acp), fluorine (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 (BaP), perylene (PER), dibenzo(a,h)anthracene (DBA), benzo(b)chrysene (BbC) for 5-ring; indeno(1,2,3-c-d)pyrene (IND), benzo(g,h,i)perylene (BghiP) for 6-ring; and, coronene (COR) for 7-ring. According to the molecular weight, these 21 individual PAHs are divided into three categories: low molecular weights (LMW–PAHs containing two- and three-ringed PAHs); middle molecular weights (MMW–PAHs containing four-ringed PAHs); and high molecular weights (HMW–PAHs containing five to seven ringed PAHs).

The total-PAH data for the HDDE exhausts are the summation of 21 individual PAHs. The GC/MSD was calibrated with a diluted standard solution of 16 PAH compounds (PAH mixture; Supelco, Bellefonte, PA, USA) plus five additional individual PAHs obtained from Dr. Ehrenstorfer (Augsburg, Germany). Analysis of serial dilutions of PAH standards showed the detection limit (DL) for GC/MSD were between 26 pg and 308 pg for the 21 PAH compounds. The limit of quantification (LOQ) is defined as DL divided by the sampling volume or sampling time. The LOQ for individual PAHs was between 24 pg/m³ and 276 pg/m³, while values for sampling time were between 75 pg/h and 950 pg/h. Ten consecutive injections of a PAH 610-M standard yielded an average relative standard deviation of the GC/MSD integrated area of 6.82%, within a range of 4.23% to 9.69%. 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 of 0.830 to 1.179. 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).

Data Analysis

The total-PAH concentration was the sum of the concentrations for the 21 PAH compounds in each collected sample. To assess PAH homologue distribution for each collected sample, total-PAHs were further classified into three categories of the LMW–PAHs, MMW–PAHs, and HMW–PAHs. Moreover, considering that several PAH compounds are known human carcinogens, the carcinogenic potencies of PAH emissions from each emission source were also determined. In principle, the carcinogenic potency of a given PAH compound is assessed on the basis of its benzo(a)pyrene equivalent concentration (BaP_{eq}). Calculation of the BaP_{eq} concentration for a given PAH compound uses its toxic equivalent factor (TEF), which represents the relative carcinogenic potency of the given PAH compound, using benzo[a]pyrene as a reference compound to adjust its original concentration. Only a few related proposals for TEFs are available, and this study applied those presented by Nisbet and LaGoy (1992) to assess the carcinogenic potency of total-PAHs (i.e., total-BaP_{eq}), using the sum of the BaP_{eq} concentrations estimated for each PAH compound with a TEF in the total PAHs.

For analysis of the particulate matters (PM), each filter sample was weighed again using an electronic analytical balance with fully automatic calibration technology (AT200, Mettler, Switzerland) to determine the net mass of the collected PM. For hydrocarbon (HC) analysis, each sample was analyzed using a flame ionization detector (FID) (model 404, Rosemount, UK). For carbon monoxide (CO)/carbon dioxide (CO₂) analysis, each sample was analyzed using a non-dispersive infrared detector (NDIR) (model 880A, Rosemount, UK). For nitrogen oxides (NO_x) analysis, each sample was analyzed using a chemiluminescent detection (CLD) (model 955, Rosemount, UK). An anon-touch type HBM torque meter was used to measure engine speed and engine load simultaneously. Finally, a K-Type thermal couple was used to measure exhaust temperature.

RESULTS AND DISCUSSION

Brake Thermal Efficiency and Brake Specific Fuel Consumption

The brake thermal efficiency of the HDDE fueled with various H₂/O₂ flow rate is shown in Fig. 1. The thermal efficiency of an engine can be improved by optimizing the combustion system or fuel properties, and it is important in evaluating an engine's economic and overall performance (Ji and Wang, 2009). The flame speed of hydrogen is faster than that of diesel (Kumar et al., 2003), and, thus burning diesel in the presence of hydrogen will result in over all faster and more complete combustion (Bari and Mohammad, 2010). As shown in Fig. 1, the brake thermal efficiency in PDF, HO10, HO20, HO30, HO40, HO50, HO60, and HO70 were 33.0%, 33.3%, 33.6%, 34.3%, 35.1%, 37.9%, 41.8%, and 42.3%, respectively. The brake thermal efficiency increased with increasing amounts of H₂/O₂. Compared with PDF, the increasing fractions of brake thermal efficiencies were 0.9%, 1.8%, 3.9%, 6.4%, 14.8%, 26.7%, and 28.2% for HO10, HO20, HO30, HO40, HO50, HO60, and HO70,

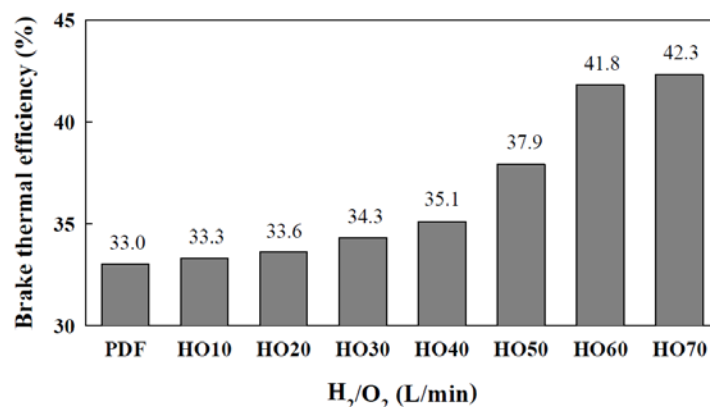


Fig. 1. The brake thermal efficiency of the HDDE fueled with various H₂/O₂ flow rates.

respectively. The results indicate that higher brake thermal efficiency can be attributed to better mixing of H₂/O₂ with air, which results in better combustion. Similar results for the brake thermal efficiency of the hydrogen blends have also been found in earlier studies (Saravanan *et al.*, 2007, 2008; Bose and Maji, 2009) that used diesel as the main fuel and pure hydrogen as an additive injected into the air intake port during the intake stroke. Saravanan *et al.* (2007) found that brake thermal efficiency increased from 23.6% to 29.4% when running a diesel engine at 1500 rpm with 10 L/min hydrogen for intake port injection timing of 5° after top dead centre (ATDC) with an injection duration of 90° crank angle (CA), compared to diesel. Saravanan *et al.* (2008) also found that brake thermal efficiency was increased from 21.8% to 23.2% while running a diesel engine at 1500 rpm with 20 L/min hydrogen. Bose and Maji (2009) found that brake thermal efficiency for hydrogen with diesel as the ignition source was 34.1% at 80% load with a hydrogen flow rate of 0.15 kg/h, whereas that of baseline diesel fuel was 30.2%. Similar results were found by Bari and Mohammad (2010), who used H₂/O₂ mixture as an additive, with the brake thermal efficiency increasing from 32.9% to 35.8% when running a diesel engine at 22 kW with 6.0% induction of H₂/O₂ mixture (Bari and Mohammad, 2010). All these studies including the present work indicate that the mixing of hydrogen with the diesel fuel can improve the thermal efficiency of a diesel engine.

Fig. 2 shows the variation in brake specific fuel consumption (BSFC) of the HDDE fueled with various H₂/O₂ flow rates. This study used PDF with H₂/O₂ as an additive, and so fuel consumption is the sum of the diesel and diesel equivalent hydrogen flow rate. As it is seen in Fig. 2, the BSFC of PDF was 190.0 g/BHP-hr, and was 190.9 g/BHP-hr, 191.8 g/BHP-hr, 190.8 g/BHP-hr, 189.5 g/BHP-hr, 178.7 g/BHP-hr, 166.1 g/BHP-hr, and 166.9 g/BHP-hr for HO10, HO20, HO30, HO40, HO50, HO60, and HO70, respectively. With HO10 to HO40, there was no significant gain in engine BSFC, and the average value was 190.6 ± 0.9 g/BHP-hr. For HO40 to HO70, the BSFC reduction fractions compared with PDF were 0.3%, 6.0%, 12.6%, and 12.2%, respectively, and this is due not only to the greater uniformity in hydrogen mixture formation with air, resulting in better combustion, but also because hydrogen has a higher flame speed than

diesel, which leads to more complete combustion. Notably, this result indicates that the best way to reduce the BSFC of diesel engines is to use HO60.

Air-fuel Ratio

Fig. 3 shows the air-fuel ratio (A/F ratio) of the HDDE fueled with various H₂/O₂ flow rates. It can be observed that the A/F ratio of PDF was 46.39, and A/F ratio increased from 46.85 for HO10 to 61.08 for HO70. In addition, the A/F ratio increased with increasing H₂/O₂ mixture, because the increasing amount of H₂/O₂ in the intake displaces more air. The increased fractions compared with PDF were 1.0%, 2.0%, 4.0%, 6.4%, 15.1%, 26.9%, and 31.7% for HO10, HO20, HO30, HO40, HO50, HO60, and HO70, respectively. These results support those of Bari and Mohammad (2010), in which the A/F ratio increased from 92.6 to 103.7 when running a diesel engine at 22 kW with 29.8 L/min of H₂/O₂ mixture.

Emissions of Air Pollutants

The emission factors of air pollutants from the HDDE are listed in Table 2. Adding H₂/O₂ had lower HC, CO, CO₂, and PM emissions when compared with those of neat diesel. The emissions of HC, CO and CO₂ with the addition of H₂/O₂ were lower than those for PDF. The percentage reductions of air pollutants from the HDDE are shown in Table 3. The reductions of HC were 2.6%, 5.2%, 7.2%, 8.6%, 9.2%, 9.5%, and 9.7% for HO10, HO20, HO30, HO40, HO50, HO60, and HO70, respectively, compared with neat diesel (PDF = 0.349 g/BHP-hr). The reductions of CO were 1.5%, 3.6%, 4.4%, 6.6%, 6.9%, 7.2%, and 7.6% for HO10, HO20, HO30, HO40, HO50, HO60, and HO70, respectively, compared with PDF (PDF = 1.701 g/BHP-hr). The reductions of CO₂ were 0.1%, 0.6%, 1.5%, 3.5%, 4.3%, 4.4%, and 4.8% for HO10, HO20, HO30, HO40, HO50, HO60, and HO70, respectively, compared with PDF (PDF = 813 g/BHP-hr). The reductions of PM were 0.9%, 3.5%, 7.0%, 9.9%, 12.6%, 19.3%, and 21.5% for HO10, HO20, HO30, HO40, HO50, HO60, and HO70, respectively, compared with PDF (PDF = 0.256 g/BHP-hr). The above results indicate that the addition of H₂/O₂ form an alternative fuel can increase combustion efficiency and reduce emissions of HC, CO, CO₂, and PM from HDDE. Since the

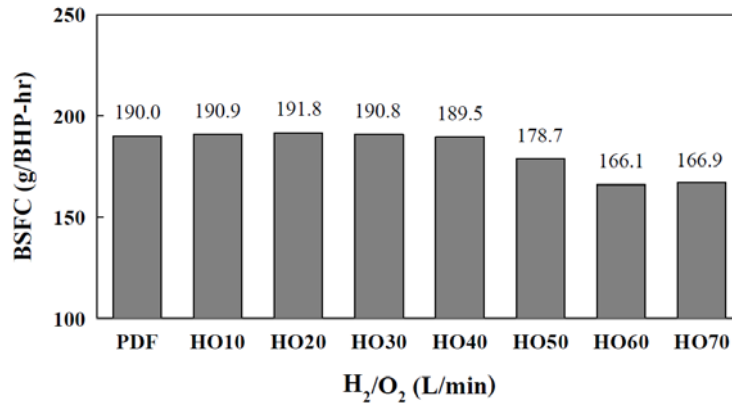


Fig. 2. The brake specific fuel consumption of the HDDE fueled with various H₂/O₂ flow rates.

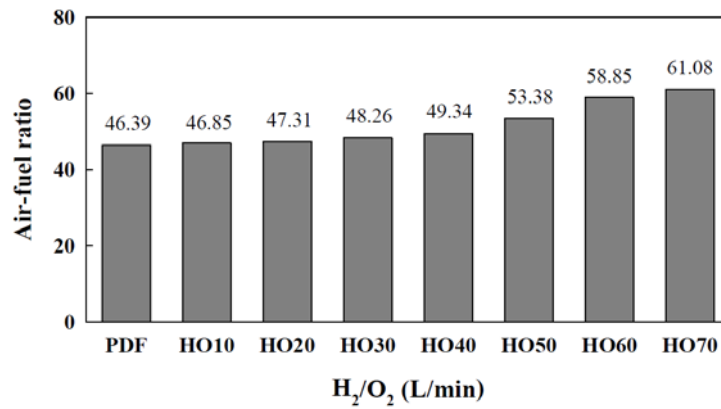


Fig. 3. The air-fuel ratio of the HDDE fueled with various H₂/O₂ flow rates.

Table 2. Emission factors of air pollutants from the HDDE (unit: g/BHP-h).

Tested fuels	THC	CO	CO ₂	NO _x	PM
PDF	0.349	1.70	813	6.45	0.256
HO10	0.340	1.68	812	6.51	0.254
HO20	0.331	1.64	808	6.62	0.247
HO30	0.324	1.63	801	6.73	0.238
HO40	0.319	1.59	784	6.80	0.231
HO50	0.317	1.58	778	6.85	0.224
HO60	0.316	1.58	777	7.09	0.207
HO70	0.315	1.57	774	7.23	0.201

Table 3. The percentage reduction of air pollutants from the HDDE (unit: %).

Tested fuels	THC	CO	CO ₂	NO _x	PM
HO10	2.6	1.5	0.1	-0.8	0.9
HO20	5.2	3.6	0.6	-2.6	3.5
HO30	7.2	4.4	1.5	-4.3	7.0
HO40	8.6	6.6	3.5	-5.3	9.9
HO50	9.2	6.9	4.3	-6.2	12.6
HO60	9.5	7.2	4.4	-9.9	19.3
HO70	9.7	7.6	4.8	-12.0	21.5

experiments were only conducted at one low-load condition, the emission factor (= emission concentration per load) and emission concentration (not shown) exhibit the same trend.

Additionally, the higher flame speed of hydrogen compared

to diesel leads to more complete combustion and the absence of carbon atoms in the hydrogen flame (Stebar and Parks, 1974; Swain, 1996; Kawahara *et al.*, 2001). In addition, the HC, CO, CO₂, and PM, the NO_x emissions increased 0.8%,

2.6%, 4.3%, 5.3%, 6.2%, 9.9%, and 12.0% for HO10, HO20, HO30, HO40, HO50, HO60, and HO70, respectively, compared with those of PDF (PDF = 6.45 g/BHP-hr). The higher temperature and more available oxygen in the formed mixture might have caused a rise in the NO_x emissions (Heywood, 1988; Saravanan *et al.*, 2008). Notably, higher NO_x emissions were seen with the higher A/F ratios, due to both the higher A/F ratio and better combustion. Similar results have been found in earlier studies (Saravanan *et al.*, 2007, 2008; Bose and Maji, 2009; Bari and Mohammad, 2010), the results of which indicated that the emissions of HC, CO, CO₂, PM decreased, whereas those of NO_x increased.

Emissions of PAHs

The PAH emission factors (mg/BHP-hr) from the HDDE are listed in Table 4. As shown in the sequence of the magnitude of emission factors of total PAHs and total BaP_{eq} (denoted EF_{total-PAH} and EF_{total-BaP_{eq}}), the results showed that PDF > HO10 > HO20 > HO30 > HO40 > HO50 > HO60 > HO70, and the reductions of EF_{total-PAH} from the HDDE were 4.5%, 10.7%, 17.0%, 19.5%, 25.0%, 32.3%, and 37.0% for HO10, HO20, HO30, HO40, HO50, HO60, and HO70, respectively, compared with PDF (PDF = 6.006 mg/BHP-hr). As for EF_{total-BaP_{eq}}, the reductions of total BaP_{eq} from the HDDE were 1.6%, 2.4%, 4.5%, 5.5%, 9.6%, 14.1%, and 16.3% for HO10, HO20, HO30, HO40, HO50, HO60, and HO70, respectively, compared with PDF (PDF = 0.0514

mg/BHP-hr).

Output/Input Mass (O/I) Ratio of PAHs for the Diesel Engine

The output/input mass (O/I) ratio is be a useful tool to explain the fate of PAHs during the combustion process in a diesel engine. An O/I ratio greater than 1.0 implies that PAHs are generated during the combustion process. In contrasts, an O/I ratio less than 1.0 means that PAHs are depleted during the combustion process, due to the complexity of PAH formation mechanisms and the difficulty in predicting the combustion products of PAHs. For the test fuels, the O/I ratios of most individual PAHs were lower than 1.0. The O/I ratio of total PAHs in neat diesel was 10.95%, or 4.5, 10.7, 17.0, 19.5, 25.0, 32.3, and 37.0 times higher than in HO10, HO20, HO30, HO40, HO50, HO60, and HO70, respectively. The O/I ratio of total BaP_{eq} in PDF was 8.70%, or 1.6, 2.4, 4.5, 5.5, 9.6, 14.1, and 16.3 times higher than in HO10, HO20, HO30, HO40, HO50, HO60, and HO70, respectively (Fig. 4). These results indicate that when H₂/O₂ is added to diesel greater depletion efficiency is obtained than with PDF.

CONCLUSIONS

The results of the experiments indicated that PDF blends mixed with H₂/O₂ had higher brake thermal efficiency and lower HC, CO, CO₂, and PM emissions when compared with PDF. On adding H₂/O₂ into PDF, brake thermal efficiency

Table 4. Emission factors of PAHs from the HDDE (unit: mg/BHP-h).

PAHs	PDF	HO10	HO20	HO30	HO40	HO50	HO60	HO70	TEF ^a
Nap	3.881	3.836	3.628	3.347	3.280	3.056	2.752	2.545	0.001
AcPy	0.417	0.368	0.341	0.333	0.326	0.316	0.282	0.261	0.001
Acp	0.152	0.133	0.123	0.112	0.108	0.099	0.093	0.086	0.001
Flu	0.277	0.267	0.218	0.193	0.177	0.153	0.134	0.129	0.001
PA	0.849	0.727	0.671	0.629	0.586	0.530	0.474	0.447	0.001
Ant	0.047	0.036	0.035	0.034	0.033	0.031	0.031	0.023	0.01
FL	0.084	0.077	0.077	0.071	0.066	0.063	0.059	0.056	0.001
Pyr	0.120	0.113	0.096	0.092	0.088	0.056	0.081	0.079	0.001
CYC	0.013	0.013	0.013	0.013	0.013	0.013	0.012	0.012	<i>b</i>
BaA	0.009	0.009	0.009	0.009	0.009	0.008	0.008	0.008	0.1
CHR	0.013	0.013	0.013	0.013	0.012	0.012	0.012	0.012	0.01
BbF	0.019	0.019	0.018	0.018	0.018	0.017	0.016	0.016	0.1
BkF	0.017	0.017	0.017	0.011	0.017	0.016	0.015	0.015	0.1
BeP	0.015	0.015	0.015	0.014	0.014	0.014	0.013	0.012	<i>b</i>
BaP	0.026	0.026	0.026	0.025	0.025	0.023	0.022	0.021	1
PER	0.011	0.011	0.011	0.011	0.011	0.010	0.010	0.010	<i>b</i>
IND	0.013	0.013	0.013	0.013	0.013	0.012	0.012	0.012	0.1
DBA	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	1
BbC	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	<i>b</i>
BghiP	0.012	0.012	0.011	0.011	0.011	0.011	0.011	0.011	0.01
COR	0.011	0.011	0.011	0.011	0.011	0.011	0.010	0.010	<i>b</i>
LMW-PAHs	5.624	5.367	5.016	4.649	4.509	4.186	3.765	3.491	
MMW-PAHs	0.225	0.212	0.194	0.184	0.175	0.105	0.160	0.154	
HMW-PAHs	0.157	0.155	0.155	0.098	0.147	0.152	0.142	0.139	
Total PAHs	6.006	5.734	5.364	4.986	4.836	2.983	4.068	3.785	
Total BaP _{eq}	0.0514	0.0505	0.0501	0.0491	0.0485	0.0464	0.0441	0.0430	

Notes: ^a Benz *et al.* (1988), ^b No TEF has been suggested.

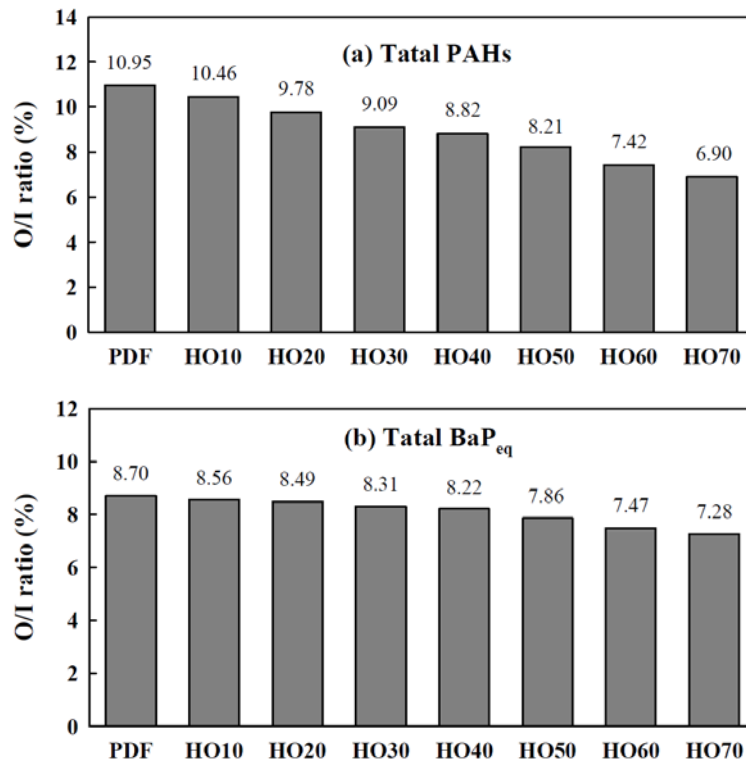


Fig. 4. The output/Input (O/I) ratio of (a) total-PAHs and (b) total-BaP_{eq} from the exhaust of HDDE fueled with various H₂/O₂ flow rates.

was increased by 0.9%–28.2%, and air pollutants were decreased by 4.5%–37.0% for PAHs, 2.6%–9.7% for HCs, 1.5%–7.2% for CO, 0.1%–4.4% for CO₂, and 0.9%–21.5% for PM. However, the emissions of NO_x were increased by 1.8%–12.0% due to the higher temperature and more oxygen available in the fuel. The BSFC decreased from 254.74 g/BHP-hr for PDF to 166.1 g/BHP-hr for HO60, but the further addition of H₂/O₂ resulted in an increased BSFC (HO70 = 166.9 g/BHP-hr). These results indicated that the best way to reduce the BSFC of diesel engines is to use HO60

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