



## Emission Reductions of Carbonyl Compounds in a Heavy-Duty Diesel Engine Supplemented with H<sub>2</sub>/O<sub>2</sub> Fuel

Hsin-Kai Wang<sup>1</sup>, Kang-Shin Chen<sup>2\*</sup>, Yuan-Chung Lin<sup>2</sup>

<sup>1</sup> *Safety Health and Environmental Center, Formosa Plastics Group, Yunlin County 638, Taiwan*

<sup>2</sup> *Institute of Environmental Engineering, National Sun Yat-Sen University, Kaohsiung 80424, Taiwan*

### ABSTRACT

Carbonyl compounds play an important role in atmospheric chemistry, and have adverse effects on human health because they are precursors of ozone and peroxyacyl nitrates. This study investigated the emissions of carbonyl compounds from a heavy-duty diesel engine (HDDE) at one low load steady-state condition (24.5% of the max load at 40 km/h). The experimental results indicate that the emissions of total carbonyl concentrations decreased by 4.7% to 32.3% when 10 to 70 L/min H<sub>2</sub>/O<sub>2</sub> mixture was added to neat diesel fuel. The emissions of nine individual carbonyl species also decreased. Among these, formaldehyde was the major species, accounting for 80.4%–81.5% of the total concentrations in the exhausts of all tested fuels, and its emissions were reduced from 5.1% to 31.7%. Meanwhile, the emission factors of total carbonyl compounds, in mg/L, decreased from 3.6% to 13.0%, and those of total carbonyl compounds, in mg/kWh, decreased from 4.6% to 32.3%. These results indicate that the addition of a H<sub>2</sub>/O<sub>2</sub> mixture to neat diesel fuel can reduce emissions from diesel engines to the atmosphere.

**Keywords:** Hydrogen/Oxygen fuel; Carbonyl compounds; Diesel engine; Dynamometer test.

### INTRODUCTION

Heavy-duty diesel engines (HDDEs) are widely used in buses, trucks, construction machines, and generators due to relatively high fuel efficiency and power output (Williams *et al.*, 1989; Schinder, 1992). However, emissions from diesel engines contain carcinogenic components such as carbonyl compounds, polycyclic aromatic hydrocarbons (PAHs), and nitro-PAHs (Grosjean *et al.*, 2001; Kawahara *et al.*, 2001; Ho *et al.*, 2007; Legreid *et al.*, 2007; Ban-Weiss *et al.*, 2008). Carbonyl compounds are ubiquitous components in atmosphere and play an important role in atmospheric chemistry, which have adverse effects on human health because they are precursors of ozone and peroxyacyl nitrates (Cater *et al.*, 1981, 1995; Hoekman, 1992; Grosjean *et al.*, 1993; Baez *et al.*, 1995; Grosjean *et al.*, 1996). Many studies have found that formaldehyde and acetaldehyde were main species of carbonyl emissions from diesel engines, and their emission factors vary from 2.1 to 38.3 mg/km and 2.4 to 28.0 mg/km, respectively, or 8.0 to 31.0 mg/L (Grosjean *et al.*, 2001; Kean *et al.*, 2001; Schmid *et al.*, 2001; Kristensson *et al.*, 2004; Legreid *et al.*, 2007).

Moreover, formaldehyde and acetaldehyde are toxic contaminants, mutagens, and carcinogens (Goldmacher and Thilly, 1983; Shepson *et al.*, 1986; IARC, 2004). To reduce their emission levels from diesel engines are therefore desirable for human health and environment.

One way to reduce emissions of air pollutants from diesel engines is to use clean fuel. Hydrogen is a widely acknowledged as a renewable, recyclable and clean fuel. Compared to hydrocarbon fuels, hydrogen fuel has wider flammability limits, higher flame speed and faster burning velocity (Verhelst *et al.*, 2005; Bari and Mohammad, 2010), which enable engines running on very lean mixtures (Verhelst and Sierens, 2001; Bari and Mohammad, 2010). Wang *et al.* (2011) found that the engine performance and energy saving were improved when hydrogen/oxygen fuel was injected into the combustion chamber of an HDDE, accompanying with emission reductions of total hydrocarbons, carbon monoxide, carbon dioxide, and nitrogen oxides; emission reductions of particulate matter and PAHs were also reported in Wang *et al.* (2012).

This study continued our previous work to replace the sampling system to allow collecting carbonyl compounds in an HDDE supplemented with various amounts of H<sub>2</sub>/O<sub>2</sub> fuel. The main goals here were to analyze the emission concentrations and emission reductions of total and nine individual carbonyl species. Emission factors of total and nine carbonyl species were also examined.

\* Corresponding author.

Tel.: +886-7-5254406; Fax: +886-7-5254406  
E-mail address: shin@mail.nsysu.edu.tw

## EXPERIMENTAL PROCEDURES

### Test Engine and Hydrogen/Oxygen Fuel

Table 1 lists the engine specifications used in this work, which was the same as in our previous works (Wang *et al.*, 2011; Wang *et al.*, 2012). The direct-injection, non-catalyst, heavy-duty diesel engine was a Cummins B5.9-160, containing six cylinders with fuel injection sequence 1-5-3-6-2-4. The engine had a bore 102 mm in diameter and a stroke of 120 mm. The total displacement was 5883 mL and the compression ratio was 17.9:1. The maximum horsepower was 118 kW at 2500 rpm, and the maximum torque was 534 Nm at 1600 rpm.

A report from Taiwan's Ministry of Transportation and Communications 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, the engine was tested in a dynamometer (Schenck GS-350 Model) at one low load steady-state condition, corresponding to 24.5 to 28.0% of the maximum load (about 40 km/h). Fig. 1 shows the schematic of the experimental setup.

In this study, an oxy-hydrogen generator machine (Epoch EP-560A Model) was used to electrolyze water to generate hydrogen and oxygen ( $H_2/O_2$ ) mixture. The  $H_2/O_2$  was then directed to the combustion chamber of the test engine as a supplemented fuel. A gas flow meter was used to measure the flow rate of  $H_2/O_2$ . Two flame arrestors were installed in the  $H_2/O_2$  line to suppress explosions before the mixture was transported to the engine via the air inlet manifold. The constituents of  $H_2/O_2$  were not further analyzed here.

Although adding  $H_2/O_2$  can save fuel due to improved combustion efficiency, but it requires additional electricity to electrolyze water to produce hydrogen/oxygen gases. In

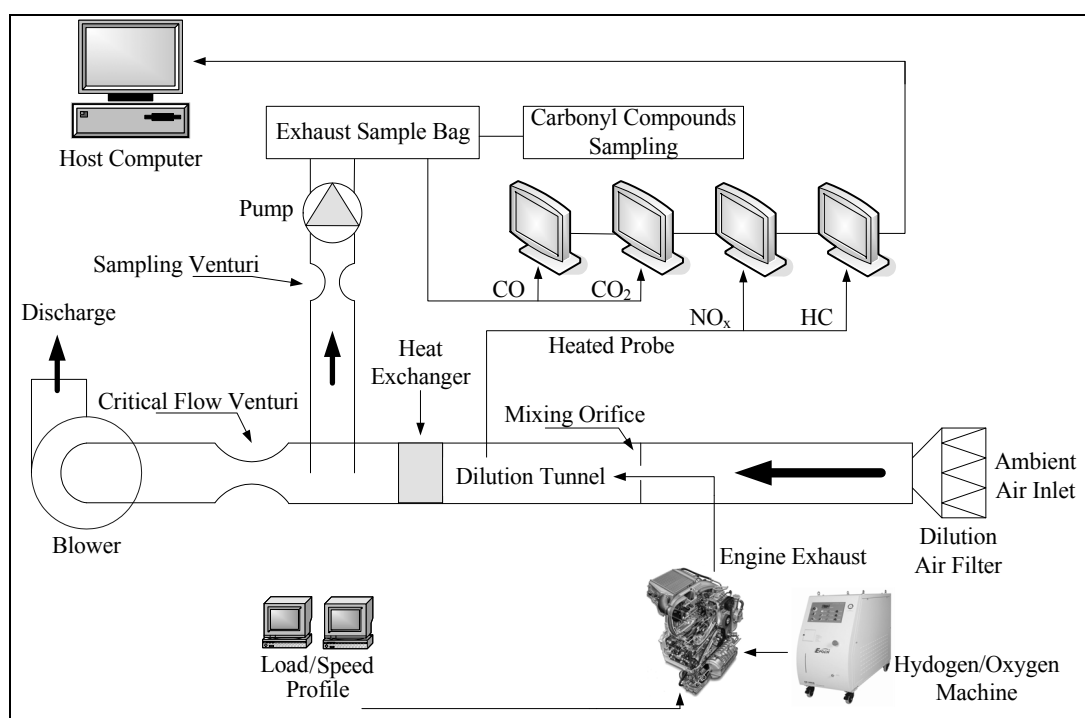
**Table 1.** The diesel engine specifications.

Parameters	Specifications
General details	Direct injection type 6 cylinders, constant speed, water cooled
Bore	102 mm
Stroke	120 mm
Displacement	5883 mL
Compression ratio	17.9:1
Maximum horsepower	118 kW at 2500 rpm
Maximum torque	534 Nm at 1600 rpm

our previous work (Wang *et al.*, 2012a), the electricity needed to electrolyze water to produce  $H_2/O_2$  was converted to diesel-fuel equivalent, and total fuel consumption, i.e., the brake specific fuel consumption (BSFC), is the sum of diesel fuel and diesel-fuel equivalent. Wang *et al.* (2012a) found that for 10 to 40 L/min of  $H_2/O_2$  mixture addition, the BSFC was higher than that of neat diesel. However, for 50, 60 and 70 L/min of  $H_2/O_2$  mixture addition, the BSFC was lower than that of neat diesel by about 3.2%, 9.9% and 10.5%, respectively; hence, both fuel and energy saving can be achieved.

### Sampling

The engine exhausts were sampled through a critical flow Venturi-type (CFV) wind tunnel, 350 mm in diameter (Wang *et al.*, 2011; Wang *et al.*, 2012). After passing through the tunnel, the exhausts were diluted with air simultaneously drawn into the tunnel, and then mixed completely by a Spencer blower. All exhausts were introduced into the dilution system through a solid insulated pipe, 10 cm in diameter and 7.5 m in length.



**Fig. 1.** The schematic of experimental setup, including wind tunnel, diesel engine, dynamometer, and sampling system.

The exhaust streams were collected in a 10 L Tedlar bag (SKC-10L) placed inside a vacuum sampling box (SKC-40L) according to US EPA Method 18. Air was pumped out of the vacuum box, thus causing the exhausts to be sucked into the Tedlar bag. The total sampling time for each run lasted more than 10 min. After sampling, all Tedlar bags were stored in black opaque plastic bags to keep them away from sunlight. The samples collected in Tedlar bags were immediately pumped through a 2,4-DNPH-coated cartridge (Sep-Pak cartridge, Supelco) at a flow rate of 200 mL/min for 10 min. All carbonyl compounds captured in the cartridge were subsequently converted to corresponding hydrazone derivatives. Cartridges were then eluted with acetonitrile. The eluted solutions were analyzed using a high performance liquid chromatograph (Hewlett Packard 1100 series HPLC) with an ultraviolet-visible detector at  $\lambda = 360$  nm. Filters with active carbons were used to clean the ambient dilution air. Clean ambient air was used to dilute and lower the temperature of the original exhausts. The sampling time was 20 min per test run.

### Analysis

The sampling method described above allowed analyses of carbonyl compounds within 1–2 h. Nine carbonyl compounds, including formaldehyde, acetaldehyde, acrolein, acetone, propionaldehyde, crotonaldehyde, butyraldehyde, valeraldehyde, and benzaldehyde, were identified and quantified with an Agilent HP 1100 HLPC/UV. These nine carbonyl compounds were chosen since they were the dominant carbonyl species associated with diesel engine emissions (Kean *et al.*, 2001; Kristensson *et al.*, 2004; Legreid *et al.*, 2007). The standard solutions of the nine carbonyl compounds were purchased from Rescek. A column C<sub>18</sub> (5  $\mu$ m in film thickness, 4.6 mm i.d., and 250 mm in length; Zarbox, USA) was used to separate the nine compounds. Solvent A (water/acetonitrile/tetrahydrofuran mixture at 60:30:10 by volume) and/or solvent B (water/acetonitrile mixture at 40:60 by volume) were used as the mobile phase. The flow rate was maintained at 1.5 mL/min and the injection volume was 20 mL. The concentration gradients of solvents A and B in the mobile phase were varied linearly from 100% solvent A at the beginning to 100% solvent B after 10 min. For the blank tests, ultra-pure nitrogen was introduced into a Tedlar bag. The content of the bag was then analyzed for carbonyl compounds in the same procedures described earlier. The amounts of formaldehyde and acetaldehyde measured from the blank test accounted for 0.50% and 0.92% of a typical sample, respectively. Field blank tests show that the amounts of formaldehyde and acetaldehyde per cartridge were 0.035 and 0.05  $\mu$ g, respectively.

To determine the detection limit (DL) of carbonyl compounds, seven measurements were made on a sample whose concentration was at or near the detection limit. The standard deviation and variance were calculated for the data set and used to calculate the DL at the 99% confidence level. The DLs of the nine carbonyl compounds were determined as between 0.112 and 0.283  $\mu$ g. Some researchers (Tejada, 1986; Possanzini and Dipalo, 1995; Risner, 1995;

Mohammadi *et al.*, 2007) reported that several dimmers form when acrolein and crotonaldehyde are absorbed onto 2,4-DNPH cartridges. In this study, the recovery efficiencies for carbonyl compounds were determined using the same procedures for the blank tests as described earlier, except that the bag was spiked with a known amount of each individual aldehyde. The results show that the recovery efficiency of carbonyl compounds varied from 97.4% to 106.1%, with an average of 102.6%. The mean relative standard deviation in recovery efficiencies was below 14.2%. The breakthrough test was conducted by pumping the exhaust collected in the Tedlar bags out and through two 2,4-DNPH cartridges connected in series. The measured carbonyl compounds in the front cartridge were greater than 95%, while those for the back cartridge were less than 5%. To cope with the wide concentration ranges of carbonyl compounds emitted from the diesel engine exhaust, calibration curves for both high and low concentrations of carbonyl compounds were prepared during each sampling day.

## RESULTS and DISCUSSION

### Carbonyl Concentrations in the Exhausts of HDDE

Table 2 lists the measured concentrations of nine carbonyls from the engine exhausts. Total concentration of carbonyl compounds using neat diesel was 3218  $\mu$ g/m<sup>3</sup>. These were 3068, 3006, 2823, 2707, 2501, 2217, and 2178  $\mu$ g/m<sup>3</sup> for neat diesel fuel supplemented with 10 to 70 L/min, at intervals of 10 L/min of H<sub>2</sub>/O<sub>2</sub> mixture, corresponding to emission reductions of 4.7%, 6.6%, 12.3%, 15.9%, 22.3%, 31.1%, and 32.3%, respectively, when 10 to 70 L/min H<sub>2</sub>/O<sub>2</sub> mixtures were added to the neat diesel. That is, total carbonyl emissions from the diesel engine decreased with increasing H<sub>2</sub>/O<sub>2</sub> mixtures.

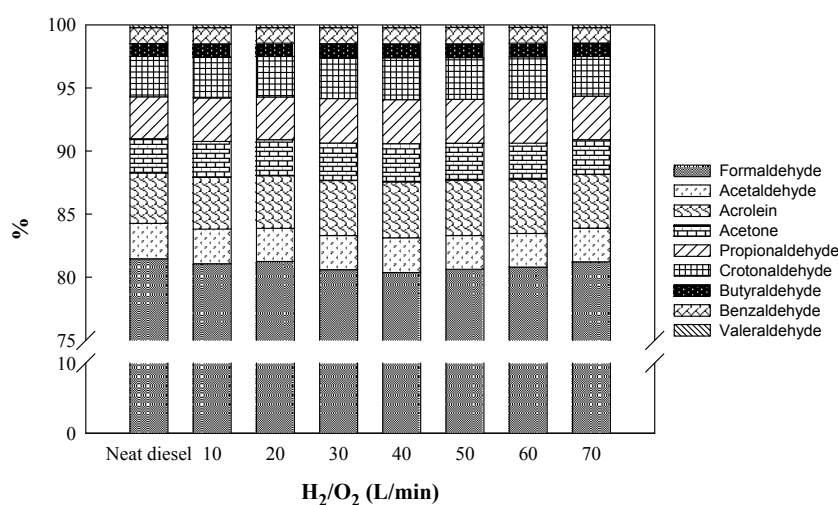
Table 2 also shows that the addition of a H<sub>2</sub>/O<sub>2</sub> mixture to neat diesel significantly decreased the emissions of all individual carbonyl species. For example, for neat diesel, the five predominant species were formaldehyde (2621  $\mu$ g/m<sup>3</sup>), acrolein (129  $\mu$ g/m<sup>3</sup>), propionaldehyde (107  $\mu$ g/m<sup>3</sup>), crotonaldehyde (103  $\mu$ g/m<sup>3</sup>), and acetaldehyde (90  $\mu$ g/m<sup>3</sup>). As compared to those of neat diesel, the emission reductions for 10 to 70 L/min, at intervals of 10 L/min of H<sub>2</sub>/O<sub>2</sub> mixture were 5.1%, 6.8%, 13.2%, 17.0%, 23.1%, 31.7%, and 32.5% for formaldehyde; were 1.3%, 2.5%, 4.3%, 6.9%, 14.6%, 26.2%, and 28.0% for acrolein; were 1.1%, 4.7%, 7.3%, 11.4%, 18.8%, 27.3%, and 30.1% for propionaldehyde; were 3.4%, 6.0%, 10.3%, 12.6%, 19.6%, 28.0%, and 33.2% for crotonaldehyde; were 6.8%, 12.2%, 15.1%, 17.2%, 26.0%, 34.3%, and 35.6% for acetaldehyde. These reductions in carbonyl compounds are mainly due to the absence of carbon element in hydrogen/oxygen fuel and improved combustion efficiency (Wang *et al.*, 2011).

### Carbonyl Compound Profiles

Fig. 2 shows the profiles of nine carbonyl compounds. For neat diesel, the top five species were formaldehyde (81.5%), acrolein (4.0%), propionaldehyde (3.3%), and crotonaldehyde (3.2%), and acetaldehyde (2.8). When neat diesel was mixed with 10 to 70 L/min H<sub>2</sub>/O<sub>2</sub> mixture, the

**Table 2.** Carbonyl compound concentrations in the exhausts of the HDDE mixed with various H<sub>2</sub>/O<sub>2</sub> flow rates (unit: µg/m<sup>3</sup>).

Carbonyl compounds	Neat diesel	H <sub>2</sub> /O <sub>2</sub> (L/min)						
		10	20	30	40	50	60	70
Formaldehyde	2621.39	2487.34	2442.45	2275.17	2175.64	2016.14	1791.26	1769.37
Acetaldehyde	90.22	84.05	79.17	76.58	74.68	66.75	59.29	58.09
Acrolein	128.73	127.07	125.51	123.23	119.88	109.95	94.97	92.66
Acetone	87.37	86.26	85.49	83.79	81.71	73.32	63.49	60.13
Propionaldehyde	107.11	105.93	102.06	99.32	94.90	86.99	77.89	74.91
Crotonaldehyde	102.81	99.35	96.62	92.24	89.84	82.68	74.02	68.70
Butyraldehyde	32.97	32.06	31.61	30.97	29.83	27.48	23.84	23.07
Valeraldehyde	40.17	39.21	36.87	35.77	34.71	32.01	27.47	26.76
Benzaldehyde	7.26	7.00	6.62	6.03	5.87	5.23	4.64	4.58
Total	3218.03	3068.27	3006.40	2823.10	2707.06	2500.55	2216.87	2178.27

**Fig. 2.** Carbonyl compound profiles in the exhausts of the HDDE mixed with various H<sub>2</sub>/O<sub>2</sub> flow rates.

five predominant species were similar, being formaldehyde (80.4%–81.2%), acrolein (4.1%–4.4%), propionaldehyde (3.4%–3.5%), crotonaldehyde (3.2%–3.3%), and acetaldehyde (2.6%–2.8%). Hence, formaldehyde was the major carbonyl species in diesel engine exhaust, accounting for 80.4%–81.5% of total carbonyl concentrations for all test fuels, followed by acrolein (4.0%–4.4%). Acetaldehyde, acetone, and crotonaldehyde were found to be in the same order of magnitude; each accounted for 2.6%–3.5% of total carbonyls. Other carbonyls (butyraldehyde, benzaldehyde, and valeraldehyde) were minor, accounted for less than 1.3% of total carbonyls.

#### Carbonyl Emission Factors and Reductions from the HDDE

Tables 3 and 4 present total carbonyl emission factors (denoted EF<sub>total-carbonyls</sub>) in mg/L (= emission concentration per fuel) and in mg/kWh (= emission concentration per load) for various H<sub>2</sub>/O<sub>2</sub> mixtures, respectively. Total carbonyl emission factors were 793.77, 764.55, 755.15, 719.97, 707.36, 704.40, 694.27, and 690.47 mg/L for neat diesel and for neat diesel mixed with 10 to 70 L/min, at intervals of 10 L/min of H<sub>2</sub>/O<sub>2</sub> fuel, respectively. As compared to neat diesel, the reductions were 3.6%, 4.9%, 9.3%, 10.9%, 11.3%, 12.5%, and 13.0% when mixed with 10 to 70 L/min, at intervals of

10 L/min of H<sub>2</sub>/O<sub>2</sub> mixture, respectively. A similar trend was also identified for EF<sub>total-carbonyls</sub> in mg/kWh, in which the corresponding total carbonyl emission factors were 242.46, 231.36, 226.18, 211.41, 203.14, 186.98, 167.17, and 164.23 mg/kWh, respectively. Hence, the corresponding emission reductions were 4.6%, 6.7%, 12.8%, 16.2%, 22.9%, 31.1%, and 32.3%, respectively.

The results also show that the reductions of emission factors in mg/L were 4.1%–13.3% for formaldehyde, 0.2%–7.5% for acrolein, 0.1%–10.1% for propionaldehyde, 2.3%–14.1% for crotonaldehyde, and 5.8%–17.3% for acetaldehyde for neat diesel adding 10 to 70 L/min, at intervals of 10 L/min of H<sub>2</sub>/O<sub>2</sub> mixture, respectively. Meanwhile, the reductions of emission factors in mg/kWh were 5.0%–32.5% for formaldehyde, 1.2%–28.0% for acrolein, 1.0%–30.0% for propionaldehyde, 3.3%–33.1% for crotonaldehyde, and 6.8%–35.6% for neat diesel mixed with 10 to 70 L/min, at intervals of 10 L/min of H<sub>2</sub>/O<sub>2</sub> mixture were, respectively.

Notably, previous study by Wang *et al.* (2012a) indicated that brake thermal efficiency was increased from 31.1% for neat diesel to 39.9% for 70 L/min of H<sub>2</sub>/O<sub>2</sub> mixture. Additionally, the emission concentrations of air pollutant, including THC, CO, and CO<sub>2</sub>, were reduced due to improved combustion and the absence of carbon element in H<sub>2</sub>/O<sub>2</sub> auxiliary fuel.

**Table 3.** Carbonyl compound emission factors in mg/L in the exhaust of the HDDE fueled with various H<sub>2</sub>/O<sub>2</sub> flow rates.

Carbonyl compounds	Neat diesel	H <sub>2</sub> /O <sub>2</sub> (L/min)						
		10	20	30	40	50	60	70
Formaldehyde	646.60	620.12	613.50	580.23	568.50	567.94	560.98	560.86
Acetaldehyde	22.25	20.95	19.89	19.53	19.51	18.80	18.57	18.41
Acrolein	31.75	31.68	31.53	31.43	31.32	30.97	29.74	29.37
Acetone	21.55	21.51	21.47	21.37	21.35	20.65	19.88	19.06
Propionaldehyde	26.42	26.41	25.64	25.33	24.80	24.50	24.39	23.75
Crotonaldehyde	25.36	24.77	24.27	23.52	23.48	23.29	23.18	21.78
Butyraldehyde	8.13	7.99	7.94	7.90	7.79	7.74	7.47	7.31
Valeraldehyde	9.91	9.78	9.26	9.12	9.07	9.02	8.60	8.48
Benzaldehyde	1.79	1.75	1.66	1.54	1.53	1.47	1.45	1.45
Total	793.77	764.95	755.15	719.97	707.36	704.40	694.27	690.47

**Table 4.** Carbonyl compound emission factors in mg/kWh in the exhaust of the HDDE fueled with various H<sub>2</sub>/O<sub>2</sub> flow rates.

Carbonyl compounds	Neat diesel	H <sub>2</sub> /O <sub>2</sub> (L/min)						
		10	20	30	40	50	60	70
Formaldehyde	197.50	187.56	183.75	170.38	163.26	150.76	135.08	133.40
Acetaldehyde	6.80	6.34	5.96	5.73	5.60	4.99	4.47	4.38
Acrolein	9.70	9.58	9.44	9.23	9.00	8.22	7.16	6.99
Acetone	6.58	6.50	6.43	6.27	6.13	5.48	4.79	4.53
Propionaldehyde	8.07	7.99	7.68	7.44	7.12	6.50	5.87	5.65
Crotonaldehyde	7.75	7.49	7.27	6.91	6.74	6.18	5.58	5.18
Butyraldehyde	2.48	2.42	2.38	2.32	2.24	2.05	1.80	1.74
Valeraldehyde	3.03	2.96	2.77	2.68	2.60	2.39	2.07	2.02
Benzaldehyde	0.55	0.53	0.50	0.45	0.44	0.39	0.35	0.35
Total	242.46	231.36	226.18	211.41	203.14	186.98	167.17	164.23

## CONCLUSIONS

The experimental results indicate that the emissions of total carbonyl concentrations were decreased by 4.7% to 32.3% when supplemented 10 to 70 L/min H<sub>2</sub>/O<sub>2</sub> mixture with neat diesel fuel. The emissions of nine individual carbonyl species were also decreased. Among these, formaldehyde was the major species, accounting for 80.4%–81.5% of total concentrations in the exhausts for all tested fuels, and its emissions were reduced from 5.1% to 31.7%. Meanwhile, the emission factors of total carbonyl compounds, EF<sub>total-carbonyls</sub> in mg/L, were decreased from 3.6% to 13.0%, and EF<sub>total-carbonyls</sub> in mg/kWh were decreased from 4.6% to 32.3%. These results indicate that neat diesel fuel supplemented with H<sub>2</sub>/O<sub>2</sub> mixture can reduce air pollutant emissions from diesel engines to the atmosphere.

## ACKNOWLEDGEMENTS

This work was supported in part by National Science Council in Taiwan under NSC 98-2221-E-110-015. The authors also thank Dr. C.B. Chen and Mr. S.H. Gua at the Chinese Petroleum Corporation for their help in the dynamometer testing of heavy-duty diesel engine.

## REFERENCES

- Baez, A.P., Belmont, R. and Padilla, H. (1995). Measurements of Formaldehyde and Acetaldehyde in the Atmosphere of Mexico City. *Environ. Pollut.* 89: 163–167.
- Ban-Weiss, G.A., McLaughlin, J.P., Harley, R.A., Kean, A.J., Grosjean, E. and Grosjean, D. (2008). Carbonyl and Nitrogen dioxide Emissions from Gasoline and Diesel Powered Motor Vehicles. *Environ. Sci. Technol.* 42: 3944–3950.
- Bari, S. and Mohammad, E.M. (2010). Effect of H<sub>2</sub>/O<sub>2</sub> Addition in Increasing the Thermal Efficiency of a Diesel Engine. *Fuel* 89: 378–383.
- Carter, W.P.L., Winer, A.M. and Pitts, J.N. (1981). Effect of Peroxyacetyl Nitrate on the Initiation of Photochemical Smog. *Environ. Sci. Technol.* 15: 831–837.
- Carter, W.P.L. (1995). Computer Modeling of Environmental Chamber Measurements of Maximum Incremental Reactivities of Volatile Organic Compounds. *Atmos. Environ.* 29: 2513–2527.
- Goldmacher, V.S. and Thilly, W.G. (1983). Formaldehyde is Mutagenic for Cultured Human Cells. *Mutat. Res.* 116: 417–422.
- Grosjean, D., Grojean, E. and Seinfeld, J.H. (1996). Atmospheric Chemistry of 1-Octene, 1-Decene, and Cyclohexene Gas-Phase Carbonyl and Peroxyacyl Nitrate Products. *Environ. Sci. Technol.* 30: 1038–1047.
- Grosjean, D., Grosjean, E. and Gertler, A.W. (2001). On-road Emissions of Carbonyls from Light-Duty and Heavy-Duty Vehicles. *Environ. Sci. Technol.* 35: 45–53.
- Grosjean, E., Williams, II. and Grosjean, D. (1993). Ambient Levels of Formaldehyde and Acetaldehyde in

- Atlanta, Georgia. *J. Air Waste Manage. Assoc.* 43: 469–474.
- Ho, K.F., Ho, S.S.H., Cheng, Y., Lee, S.C. and Yu, J.Z. (2007). Real-World Emission Factors of Fifteen Carbonyl Compounds Measured in a Hong Kong Tunnel. *Atmos. Environ.* 41: 1747–1758.
- Hoekman, S.K. (1992). Speciated Measurements and Calculated Reactivities of Vehicle Exhaust Emissions from Conventional and Reformulated Gasoline. *Environ. Sci. Technol.* 26: 1206–1216.
- Kawahara, E.T.N., Piao, Z. and Fujita, S. (2001). Hydrogen Combustion and Exhaust Emissions Ignited with Diesel Oil in a Dual Fuel Engine. *SAE Paper* 2001-01-3503.
- Kean, A.J., Grosjean, E., Grosjean, D. and Harley, R.A. (2001). On-Road Measurement of Carbonyls in California Light-Duty Vehicle Emissions. *Environ. Sci. Technol.* 35: 4198–4204.
- Kristensson, A., Johansson, C., Westerholm, R., Swietlicki, E., Gidhagen, L., Wideqvist, U. and Vesely, V. (2004). Real-World Traffic Emission Factors of Gases and Particles Measured in a Road Tunnel in Stockholm, Sweden. *Atmos. Environ.* 38: 657–673.
- IARC (2004). International Agency for Research on Cancer, Press Release n# 154 from 15 June 2004. Available from: [www.iarc.fr/ENG/Press\\_Releases/archives/pr153a.html](http://www.iarc.fr/ENG/Press_Releases/archives/pr153a.html).
- Legreid, G., Reimann, S., Steinbacher, M., Staehelin, J., Young, D. and Stemmler, K. (2007). Measurements of OVOCs and NMHCs in a Swiss Highway Tunnel for Estimation of Road Transport Emissions. *Environ. Sci. Technol.* 41: 7060–7066.
- Ministry of Transportation and Communications, Taiwan, (2008). MOTC-IOT-97-85-5321/ISBN: 978-986-01-4539-7.
- Mohammadi, A., Shioji, M., Nakai, Y., Ishikura, W. and Tabo, E. (2007). Performance and Combustion Characteristics of a Direct Injection SI Hydrogen Engine. *Int. J. Hydrogen Energy* 32: 296–304.
- Possanzini, M. and Dipalo, V. (1995). Determination of Olefinic Aldehydes and other Volatile Carbonyls in Air Samples by DNPH-Coated Cartridges and HPLC. *Chromatographia* 40: 134–138.
- Risner, C.H. (1995). High-Performance Liquid Chromatographic Determination of Major Carbonyl Compounds from Various Sources in Ambient Air. *J. Chromatogr. Sci.* 33: 168–175.
- Schinder, K.P. (1992). Integrated Diesel European Action (IDEA): Study of Diesel Combustion. *SAE Paper* 920591.
- Schmid, H., Pucher, E., Ellinger, R., Biebl, P. and Puxbaum, H. (2001). Decadal Reductions of Traffic Emissions on a Transit Route in Austria – Results of the Tauerntunnel experiment 1997. *Atmos. Environ.* 35: 3585–3593.
- Shepson, P.B., Kleindienst, T.E., Edney, E.O. and Nero, C.M. (1986). Acetaldehyde the Mutagenic Activity of Its Photooxidation Products. *Environ. Sci. Technol.* 20: 1008–1013.
- Tejada, S.B. (1986). Evaluation of Silica Gel Cartridges Coated in Situ with Acidified 2,4-Dinitrophenylhydrazine for Sampling Aldehydes and ketones in Air. *Int. J. Environ. Anal. Chem.* 34: 167–185.
- Verhelst, S. and Sierens, R. (2001). Aspects Concerning the Optimisation of a Hydrogen Fueled Engine. *Int. J. Hydrogen Energy* 26: 981–985.
- Verhelst, S., Woolley, R., Lawes, M. and Sierens, R. (2005). Laminar and Unstable Burning Velocities and Markstein Lengths of Hydrogen–Air Mixtures at Engine-Like Conditions. *Proc. Combust. Inst.* 30: 209–216.
- Wang, H.K., Cheng, C.Y., Chen, K.S., Lin, Y.C. and Chen, C.B. (2012a). Effect of Regulated Harmful Matters from a Heavy-Duty Diesel Engine by H<sub>2</sub>/O<sub>2</sub> Addition to the Combustion Chamber. *Fuel* 93: 524–527.
- Wang, H.K., Cheng, C.Y., Lin, Y.C. and Chen, K.S. (2012b). Emission Reductions of Air Pollutants from a Heavy-Duty Diesel Engine Mixed with Various Amounts of H<sub>2</sub>/O<sub>2</sub>. *Aerosol Air Qual. Res.* 12: 133–140.
- Williams, P.T. Abbass, M.K. and Andrews, G.E. (1989). Diesel Particulate Emission: the Role of Unburned Fuel. *Combust. Flame* 75: 1–24.

Received for review, January 3, 2013

Accepted, March 31, 2013