Increase in Ozone due to the Use of Biodiesel Fuel Rather than Diesel Fuel

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Abstract

The consumption of fuel by vehicles emits nitrogen oxides (NO_x) and non-methane hydrocarbons (NMHCs) into the atmosphere, which are important ozone precursors. Ozone is formed as a secondary pollutant via photochemical processes and is not emitted directly into the

atmosphere. In this paper, the ozone increase resulting from the use of biodiesel and diesel fuels was investigated, and the different ozone formation trends were experimentally evaluated. Known amounts of exhaust gas from a power generator operated using biodiesel and diesel fuels were added to ambient air. The quality of the ambient air, such as the initial NMHC and NO_x concentrations, and the irradiation intensity have an effect on the ozone levels. When 30 cm³ of biodiesel fuel exhaust gas (BFEG) or diesel fuel exhausted gas (DFEG) was added to 18 dm³ of ambient air, the highest ratios of ozone increase from BFEG compared with DFEG in Japan and Vietnam were 31.2 and 42.8 %, respectively, and the maximum ozone increases resulting from DFEG and BFEG compared with the ambient air in Japan were 17.4 and 26.4 ppb, respectively. The ozone increase resulting from the use of BFEG was large and significant compared to that from DFEG under all experimental conditions. The ozone concentration increased as the amount of added exhaust gas increased. The ozone increase from the *Jatropha*-BFEG was slightly higher than that from waste cooking oil-BFEG.

Capsule “The first ozone increment in the use of biodiesel fuel was experimentally evaluated, and compared the ozone increment between biodiesel and petroleum diesel fuel”.

Highlights

+ *Ozone increment with the use of biodiesel fuel rather than diesel fuel*

+ *Ozone increment was evaluated by direct experimental measurement*

+ *The ozone concentration was increased with increasing amount of exhausted gas addition*

+ *Due to different ambient air composition, the trend of ozone increment between Vietnam and Japan are different*

Introduction

The ozone layer in the stratosphere plays an important protective role; however, tropospheric ozone is a photochemical oxidant. Ozone is a secondary pollutant that is produced from volatile organic compounds (VOCs) and NO_x under sunlight (Orlando et al., 2010). It reacts with some gases, such as NO, NO_2 and alkenes, as well as with some surfaces, leaves, and biological membranes. These reactions can damage living cells and human lungs. Exposure to ozone has been associated with several adverse health effects and decreased lung function (Hadavi, 2013). Ozone pollution at the ground level is an environmental concern in the US, Brazil, China, Japan, and other countries.

Understanding the increases in ozone production will help improve predictability and reduce ozone pollution by controlling NO_x and VOCs emissions. A considerable number of studies on the ozone increases resulting from emissions from vehicles, engines and generators operating using various fuels have been conducted; however, most of these studies were conducted using modeling, computer simulations or direct tailpipe measurements (Mellouki et al., 2015; Shin et al., 2016). To assess the ozone formation potential in the atmosphere and the importance of NMHC precursors, the maximum incremental reactivity (MIR), also known as the maximum ozone incremental reactivity (MOIR) was proposed by Carter in the late 1980s (Carter and Atkinson, 1987, 1989). The values for quantifying the relative ground-level ozone impacts of VOCs and associated uncertainty classifications have been updated (Carter, 1994; Carter, 2010; Carter et al., 1995), and these values have been used to describe the maximum ability of a certain hydrocarbon to produce ozone under specific atmospheric conditions.

The production, emissions, and benefits of biodiesel fuel (BDF) have been the focus of studies for several decades. Currently, the benefits of using biodiesel fuel include its ability to mitigate emissions that cause global warming; its ability to minimize CO, SO_2 and particulate emissions

(Basha et al., 2009; Basha and Raja G., 2012; Guarieiro et al., 2009; Zhu et al., 2010); and its use as an alternative to fossil fuels, which are continuously being depleted. Previous studies have shown some negative aspects related to the use of biodiesel, such as increased emissions of low-molecular-weight methyl esters (Thang et al., 2014, 2016) and carbonyl compounds (Chai et al., 2013; Dong et al., 2014; Guarieiro et al., 2009; Schröder, 1999), increased ozone formation potential (OFP) (Chai et al., 2013; Gentner et al., 2013; Li et al., 2011) and increased NO_x concentration compared to conventional diesel fuel emission (Dorado et al., 2003; Fernando et al., 2005; Guarieiro et al., 2009; Lin et al., 2006; Ribeiro et al., 2016; Xue et al., 2011). The majority of published reports examine biodiesel production, engine performance and biodiesel emissions. Biodiesel emissions have also been considered when BDFs were used rather than diesel fuel. Scientists are interested in clarifying the characteristic emissions from the use of BDFs, therefore, studies have been conducted on the use of B100 (100 % BDFs), various blend ratios, different types of engines and operating modes (Basha et al., 2009; Fontaras et al., 2009; Lopes et al., 2014; Schröder et al., 2013a).

BFEG has been demonstrated to increase NO_x and carbonyl compounds, which are important ozone precursors. The highest emission of carbonyl compounds was found from B100(Chai et al., 2013), and this result was consistent with those of other reports (Cardone et al., 2002; Fontaras et al., 2009; He et al., 2009; Lin et al., 2009). These studies also indicated that formaldehyde, acetaldehyde and acrolein were the most abundant carbonyl compounds under all test conditions. The MIR method was applied to several models to estimate the ozone increase associated with the use of BDFs (Chai et al., 2013; Gentner et al., 2013; Hadavi, 2013; Schröder, 1999). However, reports on the ozone increase determined experimentally using biodiesel exhaust gas and a diesel fuel engine are not available. An achievement of this study was

providing a better understanding of ozone as a secondary pollutant. We focused on the increase in ozone when BDF was used as a substitute for conventional diesel fuel. Sunlight and test chamber experiments were conducted and compared using ambient air and ambient air plus exhaust gas. The impacts of NO_x, NMHC, irradiation intensity and quality of the regional ambient air between Hanoi, Vietnam and Osaka, Japan were evaluated.

Experimental

An electric power generator (Yanmar YDG 250 VS with 2.5 kVA, four cylinders and direct injection) was used for the emission test. CO, CO₂, hydrocarbon (HC), and NO_x emissions from biodiesel and diesel fuel were analyzed using a Horiba MEXA 584L. Commercial diesel fuel and *Jatropha* and waste cooking oil (WCO) biodiesel fuels were used for testing. The *Jatropha* and WCO biodiesel fuels and their qualities were reported in our previous study (Thanh et al., 2013). Emission gases were collected in a 1-dm³ glass vacuum bottle. Known volumes of exhaust were then removed and injected into 18-dm³ Teflon bags using a MS - CANX00 gastight syringe with a volume of 30-cm³. The Teflon bags were filled with 18-dm³ of ambient air that was homogenized before the experiment. The ambient air was collected in a 100-dm³ Teflon bag prior to homogenization, and the ambient air was then divided into three or four 18-dm³ Teflon bags. The flow rate was controlled using a mass flow controller (KOFLOC, Model 3660). The 18-dm³ Teflon bags were purchased from GL Sciences Co. Ltd. The transmittance of the Teflon bags is shown in Figure 1 of the supporting information. The same volume of exhaust gas was collected from the power generator while using biodiesel or diesel fuel during idle mode and injected into two or three 18-dm³ Teflon bags. One 18-dm³ bag was filled with ambient air only. The experiments were conducted under two irradiation conditions: one experiment was conducted using natural sunlight on the roof of the B5 building, Nakamozu campus, Osaka

110 Prefecture University, and the other experiment was conducted using four UV lamps in a test
111 chamber. In the first experiment, three Teflon bags were exposed to sunlight for 6 to 8 hours
112 after being filled with ambient air and with ambient air plus BFEG and DFEG. The
113 concentrations of ozone and NO_x were analyzed after every two hours of irradiation. In the
114 second experiment, three Teflon bags (the same ones as above) were placed in the test chamber,
115 which had a cubic shape with dimensions of 110 (height) x 91 x 91 cm for the measurements in
116 Osaka, Japan and dimensions of 105 x 105 x 105 cm for the measurements in Vietnam. The
117 interior walls of both test chambers were covered with aluminum tape for effective reflection.
118 Four IZ-SLH UV black lights lamp with wavelengths of 315 $\sim$ 400 nm and powers of 21 W
119 were used as the UV source. Ozone and NO_x were detected using a Thermo Fisher Scientific
120 model 49 ozone analyzer and a 42i NO_x analyzer, respectively. The irradiation intensity and
121 meteorology factors in the test chamber were detected using a YK-35UV UV light meter
122 purchased from Lutron Electronic Enterprise Co., Ltd. Three bags were placed on a round
123 wooden plate with a diameter of 40.6 cm that could be rotated 360°. After varying the irradiation
124 time, the concentrations of NO_x and O_3 in the Teflon bag were analyzed. The solar intensity in
125 the summer (August and September) ranged from 2 to 4 mW cm^{-2} , whereas the UV light
126 intensity in the test chamber was only $0.2 \pm 0.02 \text{ mW cm}^{-2}$. The photochemical reaction under
127 natural sunlight occurred very fast and reached its maximum within 2 hours; inside the test
128 chamber, the reaction required 24 - 30 hours and 12 hours for the Osaka and Hanoi experiments,
129 respectively.

130 To investigate and explain why the NO_x concentration decreased in the air after the
131 photochemical reaction, two Teflon bags containing ambient air were used: One was placed in
132 the dark, and the other was exposed to UV light. To observe the decrease in NO_x after irradiation,

a known concentration of standard NO gas was spiked into both bags. After 36 hours, all air samples were filtered using an ADVENTEC glass fiber filter, 90608702 (47 mm i.d. and 0.6 μ m pore size) before introduction into the NO_x analyzer. The filter was extracted with 5 cm³ of Millipore water (resistivity $\geq$ 18.2 M Ω cm) by shaking for 10 min. The extracted solution was then filtered using a 0.5- μ m filter, and the nitrate and nitrite concentrations were analyzed using a Dionex ICS-1500 ion chromatograph (IC) (the eluent was a 9 mM Na₂CO₃ solution with a 1-cm³ / min flow rate). To wash the interior wall of the bag, 10 cm³ of pure water was added to the bag before the air was added. The concentrations of NO₂⁻ and NO₃⁻ in the solution were analyzed using IC and the same method mentioned above.

Results and Discussion

Primary emission of biodiesel and diesel fuels, ozone formation impacts

Biodiesel fuel is known to reduce HC emissions but increase NO_x emissions. The primary emissions from this study are shown in Figure 1 and are consistent with those of many previous studies. Much of the literature reports that the use of pure BDFs increases NO_x emissions (Basha et al., 2009; Randazzo and Sodré, 2011; Xue et al., 2011). The use of BDFs reduces HC emissions when compared to diesel; however, more carbonyl compounds are produced. These compounds are the main cause of the photochemical reactions that form ozone in the troposphere. Based on model calculations, William PL Carter proposed the MIR, which revealed that carbonyl compounds have the greatest impact on ozone formation (Carter, 2010). Biodiesel fuel emissions have high MIR and NO_x concentrations, which is predictive of an increase in ozone.

Ozone increase due to the use of biodiesel and diesel fuels

VOCs and NO_x are important well-known O₃ precursors. Many studies have been conducted on the important relationships between NO_x, VOCs and meteorological conditions as well as

their roles in ozone formation (Atkinson, 2000; Itano et al., 2007; Li et al., 2013; Ling and Guo, 2014; Shao et al., 2009; Wang et al., 2008). VOCs include hundreds of organic compounds, and the reactivity of each VOC is different. The contributions of individual VOCs with the highest activities for ozone formation were calculated and reported, and it was found that NMHCs have the highest activities (Borbon et al., 2002; Carter et al., 1995; Chai et al., 2013; Westphal et al., 2013; Xiao and Zhu, 2003). Ozone isopleth plots based on the simulation of the photochemical reactions between NO_x , NMHCs and VOCs were reported by (Jenkin and Clemitshaw, 2000; Seinfeld. and Pandis., 2006; Sillman, 1999; Xiao and Zhu, 2003). These simulated results have shown that the maximum O_3 concentration depends on the initial concentrations of NO_x and NMHC, with a high NMHC/ NO_x ratio corresponding to NO_x sensitivity and a low NMHC/ NO_x ratio corresponding to NMHC sensitivity.

Our study tested both real sunlight and chamber conditions. In the sunlight experiments, the irradiation of sunlight was performed over three months from August to October 2013. From 1 to 10 cm^3 of exhaust gas was added to 21 set samples (the set sample has consists of three bags: one bag with ambient air, one bag with ambient air plus *Jatropha* BFEG and another with ambient air plus DFEG), and each set sample was collected on different days. The original data are shown in the supporting information (Figure 2). The data showed different results, indicating that the ozone increase from the BFEG addition is higher than that from the DFEG on most days.

The results obtained under sunlight irradiation were evaluated using two methods: First, the increase in the ozone concentration was calculated using the ratio between BFEG and DFEG versus ambient air ($\Delta[\text{O}_3]_{\text{Biodiesel}}/\Delta[\text{O}_3]_{\text{Ambient air}}$ and $\Delta[\text{O}_3]_{\text{diesel}}/\Delta[\text{O}_3]_{\text{ambient air}}$), where $\Delta[\text{O}_3]$ is the difference between the ozone concentration before and after irradiation. Figure 2 (a) presents the correlation ratio. The larger number of points above the red line indicates an abundant and

significant increase in ozone due to the use of biodiesel. Second, the increase in the ozone concentration was calculated from the difference between BFEG and DFEG versus ambient air ($[O_3]_{\text{Biodiesel}} - [O_3]_{\text{Ambient air}}$ and $[O_3]_{\text{Diesel}} - [O_3]_{\text{Ambient air}}$). The initial ozone concentration was almost identical in all the three conditions because the dilution factor reached nearly 1000, and the initial state had no photochemical reactions. Figure 2 (b) shows this correlation and indicates that the ozone increase resulting from BFEG was higher than that resulting from DFEG. The results in Figure 2 were obtained from 83 measurements under the sunlight condition. The t -test values were also examined to confirm the difference in the ozone increase between *Jatropha*-BFEG and DFEG when compared with ambient air. The ratio and difference were 2.95 and 3.64, respectively. In the evaluated methods, the ozone increase resulting from BFEG was higher than that resulting from DFEG, with a confidence level greater than 99.9 %.

In the test chamber, 7.5, 15 and 30 cm³ of *Jatropha*-BFEG and DFEG were injected into 18-dm³ air bags filled with ambient air. Figure 3 shows that differing amounts of exhaust gas result in different O₃ formation trends. In Figure 3 (a), which corresponds to the addition of 7.5 cm³ of exhaust gas, the ozone from *Jatropha*-BFEG was always higher than the ozone from DFEG and the ambient air. However, in Figures 3 (b) and (c), which correspond to the additions of 15 cm³ and 30 cm³ of exhaust gas, respectively, the ozone in DFEG was higher than the ozone in *Jatropha*-BFEG after 12 hours of irradiation. More information is provided in Figures 3, 4, and 5 in the supporting information. This phenomenon will be explained in the next section, which presents a comparison of the ozone formation trends in Japan and Vietnam. The maximum ozone increases for each volume addition were also calculated and are shown in Figure 4. After 24 and 36 hours of irradiation using UV light, the ozone in *Jatropha*-BFEG and DFEG significantly increased when compared with ambient air without added exhausted gas. The black and blue

lines show that the O₃ value increased by adding DFEG and *Jatropha*-BFEG, respectively, which increased from 7.2 to 17.4 ppb for DFEG and from 22.2 to 26.4 for *Jatropha*-BFEG. In both sunlight and test chamber conditions, the ozone increase resulting from the use of BFEG was always higher than that resulting from the use of DFEG. The result of this study is another negative feature of biodiesel fuel in addition to the higher emissions of NO_x, carbonyl compounds and LMW-ME, even though multiple benefits of BDFs have been recognized. To the best of our knowledge, there were differences in the ozone increase between several of the BFEGs and DFEGs, which were investigated and are shown in Table 1 (except for reference 16 gasoline/diesel). Our study used direct measurements of real samples, and the results were consistent with the trend of the MIR method based on modeling (Hadavi, 2013; Schröder, 1999; Schröder et al., 2013b).

Difference in ozone formation trends between Japan and Vietnam

Different ambient air qualities will create different ozone formation trends. In Osaka, the annual mean concentrations of NO_x and NMHCs in 2013 were 15.2 ppbv and 198.3 ppbC, respectively (these data were obtained from the Kanaoka continuous monitoring station, Osaka). However, in Hanoi, the annual mean concentration of NO_x in 2013 was 21.1 ppbv, and the average concentration of NMHCs over five months in late 2013 was 445.7 ppbC (these data were obtained from the Vietnam Academy of Science and Technology continuous monitoring station, Hanoi). Total hydrocarbon (THC) includes methane (CH₄) and NMHCs. CH₄ is an abundant compound, but NMHCs are the main contributors to ozone formation (Itano et al., 2007; Xiao and Zhu, 2003).

As shown in Figures 5 and 6, the ozone formation trends in Osaka and Hanoi were different. NMHCs and NO_x are important ozone precursors, and the primary emission of the power

generator contained 10.1 ± 2.7 ppm HC and 84.7 ± 8.0 NO (means of eight samples $\pm$ one standard deviation). When 30 cm³ of exhaust gas was added to an 18-dm³ Teflon bag filled with ambient air from Osaka, Japan, and Hanoi, Vietnam, the spiked NMHC concentration was small compared to the NMHC in ambient air, whereas the NO_x concentration was significantly affected. The maximum increases were 66 and 19 ppb for Japan and Vietnam (see NO_x graph in Figures 5 and 6), respectively. The addition of exhaust gas to the air bags in this experiment is similar to the emissions from vehicles to the atmosphere. In our previous study, we observed the air quality at Osaka Prefecture road number 29 at the cross-sector in Izumiotsu, Osaka, in December 2001 to investigate the contribution of NO_x to ambient air from on-road vehicles and its transportation by wind. The average wind speed in the daytime is 2.95 m s⁻¹, and the wind direction is WNW (west–north–west). To distinguish between upwind and downwind sources of NO_x, the NO_x concentration was monitored. The average concentrations of NO_x were 420.7 and 86.1 ppbv for upwind and downwind, respectively. Consequently, the upwind area was 4.9 times more contaminated than the downwind area. This ratio would be further diluted by air mass transportation. As with the above result, from 1 to 30 cm³ of biodiesel and diesel fuel exhaust gas was spiked into 18-dm³ of ambient air in this study. The dilution factors corresponded to 1,800 and 600 times, and the dilution ratio in our experiment was not far from the actual atmospheric environments around the selected areas.

In Japan, the initial NMHCs concentration was approximately 200 ppbv in ambient air, and the initial NO_x concentration after adding 30 cm³ of exhaust gas ranged from 115 to 125 ppbv. The ozone isopleth plot (Jenkin and Clemitshaw, 2000; Seinfeld. and Pandis., 2006; Sillman, 1999; Xiao and Zhu, 2003) can explain why the ozone concentration of BFEG was lower than that of DFEG after twelve hours of irradiation. However, after twelve hours, when the initial NO_x

concentration is less than 80 ppbv, the ozone concentration would primarily be affected by NO_x, which means that the final ozone formation resulting from BFEG would be higher than that of DFEG and ambient air. Therefore, NO_x was the dominant factor controlling the photochemical ozone under the condition of a high NMHC/NO_x ratio. Figure 6 shows the trend of the ozone increase in Vietnam. The photochemical reaction in Vietnam was faster than that in Japan, and the ozone increase resulting from BFEG was always the highest because the concentration of NMHCs in Hanoi is approximately 450 ppbv. In this case, the NO_x concentration is higher, and more ozone will be produced. This result was also consistent with the ozone isopleth plot, which was reported in previous studies, as mentioned above. The ozone increase depends on the type of fuel, two types of biodiesel fuels (*Jatropha* and waste cooking oil) were used in Vietnam, and the ozone increase resulting from the use of *Jatropha*–BFEG was slightly higher than that resulting from the use of waste cooking oil–BFEG. With the same UV intensity, amount of added exhaust gas and irradiation time, however, the largest ozone increases due to the use of biodiesel instead of diesel in Japan and Vietnam were 31.2 and 42.8 %, respectively. This result indicates that if the NMHC/NO_x ratio in ambient air is high, the addition of exhaust gas would significantly affect the ozone increase.

Decrease in the NO_x concentration during the photochemical reaction

The concentration of NO_x was a sensitive factor in ozone formation, which involves a NO-to-NO₂ conversion reaction to form O₃ in the presence of NMHC, M (the third body) and light with a wavelength shorter than 420 nm, according to the following reactions:

However, the concentration of NO_x decreased during both experiments under sunlight and chamber conditions. For example, with *Jatropha* BFEG, the average NO_x concentration decreases were 44.1 and 72.3 % after 8 hours under sunlight in Osaka and after 48 hours of irradiation in the chamber, respectively. Figure 7 illustrates the decrease in the NO_x concentration and products with and without irradiation, as well as in ambient air and ambient air with added standard NO gas. Due to the low NO_x concentration in the ambient air, it is difficult to observe the decrease in the concentration of NO_x in the air bag. Therefore, NO standard gas was added to increase the initial NO_x concentration for better observation. Most of the NO_x became HNO_3 in the ambient air and deposited on the interior of the bag after thirty-six hours of radiation. However, in the ambient air plus NO with added sample, NO_x remained; the NO_3^- concentration was also not equal to the initial NO_x concentration. NO_3^- in the particulate phase was lower than the limit of detection in both the ambient air and spiked samples. Therefore, it is concluded that NO_3^- was not absorbed by the particulate phase. In contrast, the concentration of NO_x did not decrease for thirty-six hours without irradiation, indicating that NO_3^- was not formed if the photochemical reaction did not occur. The ratios of formed NO_3^- / initial NO_x in the ambient air and ambient air plus NO standard were 69.8 and 15.7 %, respectively. OH radicals were formed in the photochemical cycle, followed by reaction with NO_2 to become HNO_3 (Atkinson, 2000). This reaction causes some loss of NO_x during the daytime. For example, the *Jatropha*-BFEG line from the Osaka chamber experiment shows that, at higher O_3 and OH radical concentrations, the NO_x concentration is lower than in the DFEG and ambient air (Figure 5).

We hypothesized that NO_x react with OH radicals and VOCs to form unknown organic nitrates in addition to HNO_3 . The yields of the unknown organic compounds depend on the initial NO_x

concentrations. The formation of the unknown organic nitrate due to the use of biodiesel and diesel fuels will be investigated in future work.

Conclusion

The results of this study are confirmed that the ozone was increased by the use of biodiesel and diesel fuel. The direct measurement method was applied to evaluate the different trend of ozone formation: The ozone increment from BFEG is abundant and significant compared to DFEG under all experimental conditions, and the ozone concentration was increased with increasing amount of exhausted gas addition, which is available for considering BDFs as an alternative fuel. Due to different ambient air composition, the trend of ozone increment between Vietnam and Japan are different: 1) ozone increment in Vietnam was higher and faster than Japan. 2) The ozone increment resulting from the use of BFEG in Vietnam was high compared to that from DFEG under all experimental conditions, but in Japan the opposite results were observed. The ozone increment by *Jatropha*-BFEG was slightly higher than that by waste cooking oil-BFEG. The ozone increment depends on radiation intensity, quality of ambient air and NMHCs/NO_x ratio.

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Table 1: Comparison of the ozone increase due to different fuels, engines and calculation methods.

No	Type of fuel	Type of engine	Maximum ozone increase (%)	Calculation method	Reference
1	Vegetable BDF/ diesel	Passenger car	284	MIR method	(Hadavi, 2013)
2	Soybean and waste vegetable BDF/ diesel	Non-road generator	34.7	MIR method	(Chai et al., 2013)
3	Rapeseed BDF/diesel	One cylinder and four cylinder Farymann	30	MIR method	(Schröder, 1999)
4	Gasoline/diesel	Motor vehicles	45.5	MIR method	(Gentner et al., 2013)
5	Waste cooking oil BDF/ Kerosene	The premixed gas turbine combustor test rig	50	MIR method	(Li et al., 2011)
6	<i>Jatropha</i> -BDF and WCO-BDF/diesel	Power generator	31.2 – 42.8	Direct measurement	This study

Figure captions

Figure 1. Primary emissions from the three types of fuels and a power engine generator:

The CO, HC, and NO_x concentrations are in ppm (vol), and the CO₂ is in % (vol). Brown column: DFEG; Blue column: *Jatropha*-BFEG; Green column: Waste cooking oil-BFEG. The columns present the average of eight samples, and the error bars show the standard deviations.

Figure 2. Correlation between the ozone increases due to *Jatropha*-BFEG and DFEG versus ambient air under sunlight.

Figure 2 (a) shows the ratio, and Figure 2 (b) shows the difference. The red line indicates a 1:1 ratio; please refer to the text for more detail.

Figure 3. Different volumes of exhaust gas were added to Teflon bags with ambient air from Osaka, Japan under a UV lamp in the following test chamber conditions:

Blue: 18 dm³ ambient air; red: 18 dm³ ambient air plus DFEG; green: 18-dm³ ambient air plus *Jatropha*-BFEG. Figure 3-(a) 7.5 cm³ added, Figure 3-(b) 15 cm³ added and Figure 3- (c) 30 cm³ added.

Figure 4. Maximum ozone increases due to the addition of different volumes of exhaust gas with a UV lamp in the test chamber.

The columns are different ozone concentrations, and the lines are the maximum increases in the ozone values.

Figure 5. The trends of the ozone increase and NO_x decrease under UV irradiation in Japan after adding 30-cm³ of exhaust gas under the following test chamber conditions:

Blue: 18-dm³ ambient air; red: 18-dm³ ambient air plus DFEG; green: 18-dm³ ambient air plus *Jatropha*-BFEG.

Figure 6. The trends of the ozone increase and NO_x decrease in Vietnam after the addition of 30 cm³ of exhaust gas.

Blue: 18-dm³ ambient air; red: 18-dm³ ambient air plus diesel exhausted gas; green: 18-dm³ ambient air plus *Jatropha*-BFEG; Black: 18-dm³ ambient plus WCO-BFEG.

Figure 7. Decrease in the NO_x concentration in ambient air and ambient air spiked with the NO standard due to the photochemical processes.

Columns are the averages of six samples, and the error bars show the standard deviation.

Figure 1 Thang P.Q. et al.

Figure 2 Thang P.Q. et al.

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● Ambient air ■ Ambient air + Diesel ▲ Ambient air + Biodiesel

Figure 3 Thang P.Q. et al.

Figure 4 Thang P.Q. et al.

Figure 5 Thang P.Q. et al.

Figure 6 Thang P.Q. et al.

Figure 7 Thang P.Q. et al.

Graphical abstract