

Effects of Biodiesel Blends on the Performance of Large Diesel Engines

Song-Charng Kong

Department of Mechanical Engineering, Iowa State University

Anne Kimber

Iowa Association of Municipal Utilities

Copyright © 2008 Society of Automotive Engineers, Inc.

ABSTRACT

Particulate matters, nitrogen oxides, and carbon monoxides emissions from large utility generators using diesel/biodiesel blends were measured. Stack measurements were performed on-site in a number of power plants by following the standard procedure of US EPA. The test engines were chosen to represent typical diesel engines used for electricity generation in the state. Tests were performed using the regular diesel fuel (B0), 10%, 20% and 100% biodiesel blends (B10, B20, B100). Test results showed that particulate matters and carbon monoxides decreased significantly as biodiesel content increases, whereas nitrogen oxides increased. Test results are consistent with other studies using mobile engines in the literature. Note that arbitrary changes in fuel or engine operating conditions are prohibited in power generation industry. Results of this study have been used by the state government to allow the use of biodiesel blends in stationary generators.

INTRODUCTION

This study was carried out to provide information for owners of large stationary diesel-fueled generators who are considering using biodiesel blends. There is increasing interest in using higher biodiesel blends in diesel engines for electricity generation, for reasons of economy, a desire to use renewable fuels to decrease dependence on petroleum, higher lubricity of biodiesel compared with the ultra low sulfur fuels now required, and a decrease in PM emissions. There has not been on-site testing of emissions generated by burning biodiesel in large stationary generators in power plants, and this lack of emissions data has been a significant barrier to permitting for biodiesel use.

The use of biodiesel can displace petroleum-based fuels. Biodiesel is renewable and can be produced domestically, reducing dependence on foreign oils. It has the potential to offer lubricity and environmental benefits, as well as other advantage. It is known that biodiesel has a higher cetane number than petro-diesel and the heating value of neat biodiesel (B100) is approximately 12% lower than that of the petro-diesel. Combustion of biodiesel can result in lower particulate matters (PM) and carbon monoxides (CO) emissions but slightly higher nitrogen oxides (NOx) emissions [1–2].

There are extensive data on emissions from mobile engines burning biodiesel, such as laboratory testing of truck engines [3,4], field testing of bus engines [5] and tractor engines [6]. Tests on utility engines are very rare and only limited to laboratory tests on smaller engines (e.g., 276 kW rated power [7]). These data show reductions in particulates, carbon monoxides and hydrocarbons, and an increase in nitrogen oxides emissions with increasing proportions of biodiesel.

The presence of oxygen in mono alkyl esters (biodiesel) molecules enables the reduction of soot emissions in fuel rich regions. Carbon monoxides emissions can also be reduced due to the availability of oxygen for better oxidation. However, biodiesel combustion can result in higher NOx emissions. Several reasons have been suggested that the increase in NOx may be due to the change in injection timing caused by the low compressibility of biodiesel [8] and/or the effects of in-cylinder soot radiation heat transfer [9]. Various NOx reduction strategies have been proposed including retarding the injection timing setting, intake charge cooling, fuel additive and blending, and the use of exhaust gas recirculation (EGR) to lower the combustion temperature [10–12]. It was demonstrated that charge-air cooling (from 90 to 40 C) was very effective at reducing NOx emissions (by 25%) in a utility engine [7].

It is known that the biodiesel can have negative impact on the fuel injector. Both laboratory and field testing with B100 revealed hard, black deposits on the injector tip that interfere with optimum spray pattern in about 1000 hours of operation [13]. Several alternatives to reduce injector tip deposits were tested that included the use of a detergent fuel additive to B100 and the use of a lower biodiesel blend, e.g., B20. The biodiesel quality can also be improved with additive treatment [14].

Despite the extensive study of biodiesel combustion in mobile diesel engines, there have not been comparable amount of data for stationary engines. Operating conditions and test methods differ between mobile and large stationary diesel engines, limiting the use of mobile test data to predict stationary engine emissions.

TEST FACILITIES

This study was the first testing of its kind for PM, NOx and CO emissions on B10, B20 and B100 in large stationary diesel generators. The goal of this study was to do rigorous testing to produce high quality results that could be widely accepted by utilities and regulators. To this end, Iowa Association of Municipal Utilities (IAMU) worked with the Iowa Department of Natural Resources (IDNR) Air Quality Bureau throughout this project and chose testing methodologies that complied with the IDNR's testing requirements. For NOx, we used EPA Method 7E, 40 CFR, Part 60. For PM, we used EPA Method 5 and 202, 40 CFR, Part 60 and Part 51 [15,16].

EPA methods were used for sampling and analysis as specified by the IDNR. The testing company used in this study was accepted by the IDNR as qualified to test using these EPA methods. Figure 1 shows an example of the setup of the sampling probe in the stack.



Figure 1 An example of the sampling probe setup in the stack on the roof top of a power plant

Nitrogen oxides were analyzed by using a TECO Model 42H NOx analyzer that is based on the chemiluminescence method. Carbon monoxides were measured by a California Analytical 3300 CO analyzer. Carbon dioxides and oxygen were measured by using Horiba PIR 2000 and Ametek 2000, respectively. The schematic of the PM sampling system is shown in Fig. 2. The particulate emission rate was determined following procedures detailed in EPA Methods 5 and 202.

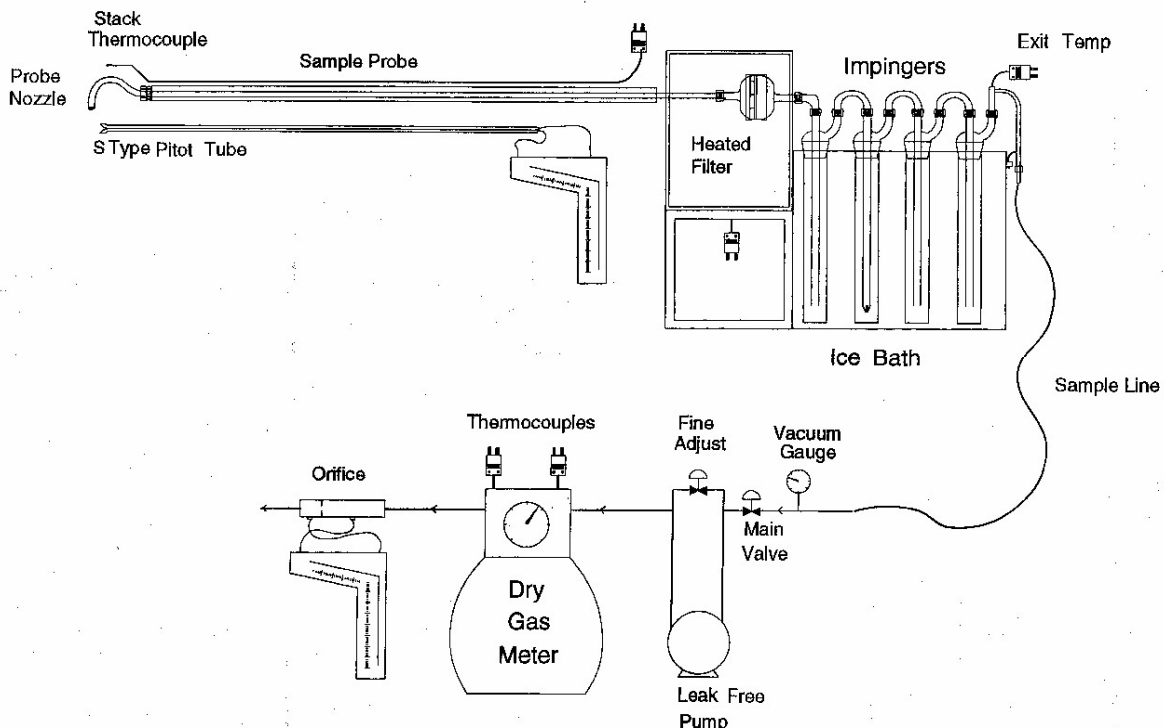


Figure 2 Schematic of the PM sampling system used in this study

Particulate samples collected on Whatman glass fiber filters were analyzed gravimetrically. The probe and nozzles were rinsed with acetone. The rinse was transferred to tarred beakers and evaporated to dryness. The back-half water was collected and separated into organic and in-organic parts. The samples were then transferred to tarred beakers and evaporated to dryness.

Diesel engine ages and sizes vary widely in the state and it was crucial to select a site that was representative of the overall generator stock. In order to better identify a truly representative generator, we gathered information on the types and ages of generators in each of the 73 municipal utilities. The information includes the start-up years, the size (i.e., generator capacity) and the frequency of use. Based on these results, four engines in three power plants were chosen for testing, as shown in Table 1. The original intent had been to produce emissions data that would allow us to predict the levels of emissions at 2–5% biodiesel, and to improve our capability to predict these emissions. Biodiesel blends such as B10 and B20 would be good data points. On the other hand, due to the increasing interest of using biorenewable fuels, it was also decided to test B100 in two engines to further demonstrate the feasibility and environmental benefits of using pure biodiesel in power plants.

Table 1 also lists the engine data and test conditions. The types of fuel blends and emission species that were tested are based on the availability of the generators, funding, and coordination with the power plants and the local government.

Table 1 Engine data, fuel blends and emissions that were tested in this study

| | Cooper-Besemer 1966 | Cooper-Besemer 1972 | Fairbanks Morse 1972 | Caterpillar 2002 |
|------|---------------------|---------------------|--------------------------|------------------|
| | LS8 GDT | KSV | | 3516 B |
| | 2-stroke | 2-stroke | 2-stroke, Opposed piston | 4-stroke |
| | 1.75 MW | 2.65 MW | 2 MW | 2 MW |
| | 360 rpm | 360 rpm | 720 rpm | 1800 rpm |
| B0 | PM NOx CO | PM NOx | PM NOx CO | PM NOx CO |
| B10 | NOx CO | PM NOx | NOx CO | |
| B20 | PM NOx CO | | PM NOx CO | PM NOx CO |
| B100 | | | PM NOx CO | PM NOx CO |

The fuels used in the tests are provided by West Central Coop. The pure soy biodiesel used for blending meets ASTM D 6751 standards. During the test, a fuel truck with a specific fuel blend was on-site. Fuel samples were drawn from the fuel truck for heating value analysis. The averaged lower heating values for B0, B10, B20 and B100 are 42.7, 42.2, 41.7, 37.9 MJ/k, respectively. In the power plant industry, a higher fuel heating value in English units is usually used for calculating the emissions. The higher heating values for B0, B10, B20 and B100 used in this study were 139,340, 139,540, 138,920 and 126,657 Btu/gal, respectively. The fuel energy data was further used together with the engine power output to determine the brake specific emissions data in lb/MMBTU (mass of pollutant per million BTU fuel energy) per EPA regulations.

RESULTS AND DISCUSSIONS

During the test, the engines were operated at full load conditions. The engines were maintained in operation all time during which fuel blends were switched. Since different fuel blends have different heating values, appropriate fuel flow rates were adjusted to maintain a constant power output for electricity generation. For each fuel blend in a specific engine, three engine tests were performed separately in the same day and each test lasted approximately 65 minutes. Emissions data were acquired and averaged during each test. The resulting emissions data were then averaged over the three engine tests and presented as one data point.

Emissions data were compiled from different engines and shown in Figures 3–5. The unit of exhaust emissions used in power generation industry and government regulation is based on the mass of pollutant per million BTU fuel energy [lb/MMBTU], as shown in the figures. The emissions data are also shown in [g/kg-fuel] for reference. The changes in each emission with respect to the biodiesel content are also shown in Figures 6–8. Overall speaking, the test results showed a decrease in PM and CO emissions, due to the presence of fuel-bound oxygen for better soot oxidation, and an increase in NOx emissions by using biodiesel blends. The trend is similar to that of laboratory tests of diesel engines used for transportation.

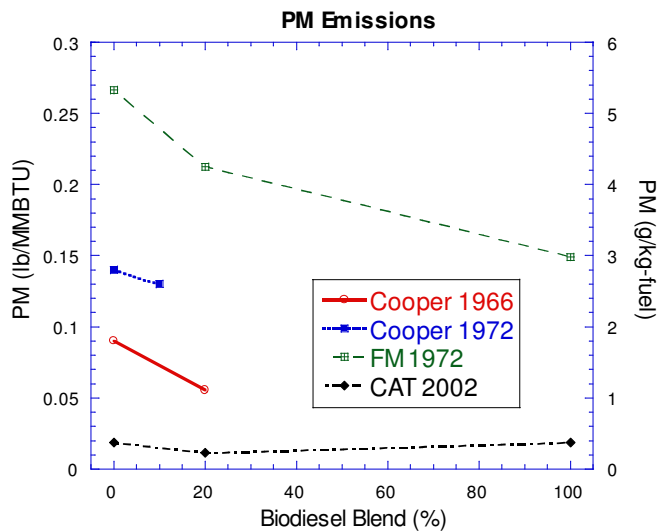


Figure 3 PM emissions of various biodiesel blends

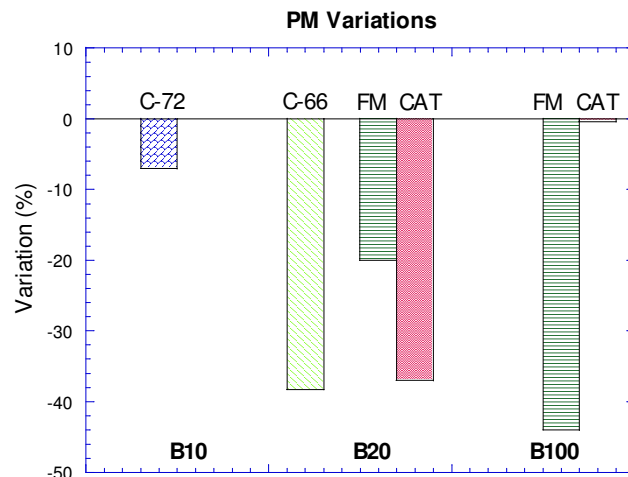


Figure 6 Variations in PM emissions for various biodiesel blends (C-66 Cooper 1966; C-72: Cooper 1972; FM: FM 1972; CAT: CAT 2002)

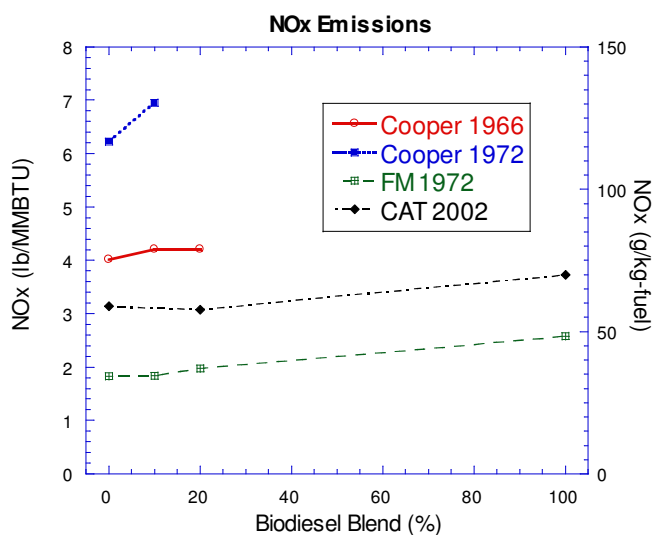


Figure 4 NOx emissions of various biodiesel blends

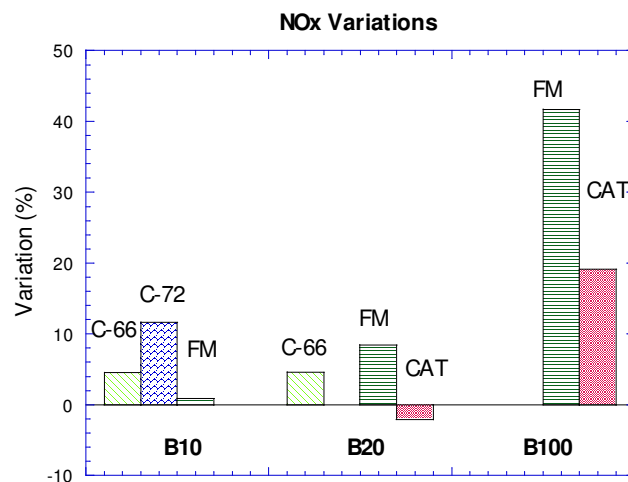


Figure 7 Variations in NOx emissions for various biodiesel blends

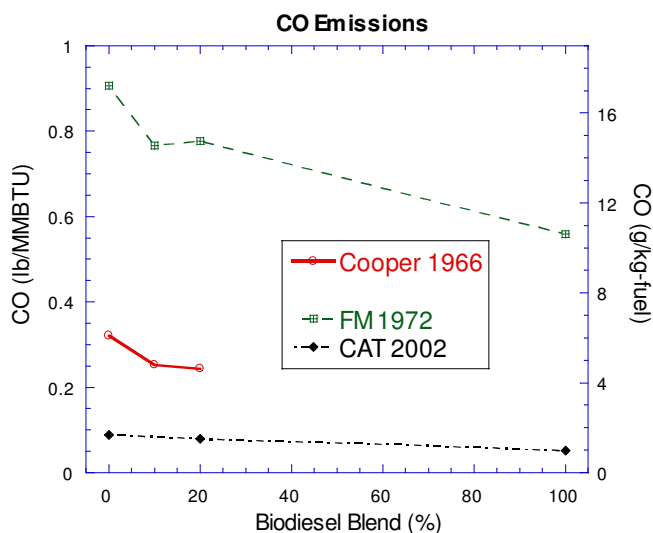


Figure 5 CO emissions of various biodiesel blends

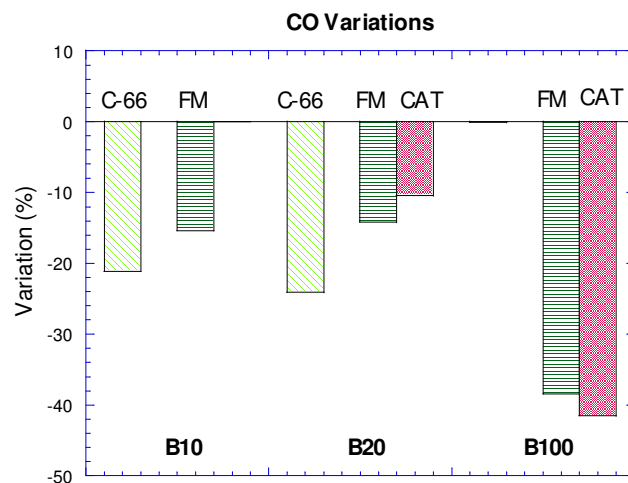


Figure 8 Variations in CO emissions for various biodiesel blends

Notice that effects of using biodiesel blends on exhaust emissions may be different in different engines due to different operating conditions and fuel systems. The three old engines (Cooper 1966, Cooper 1972 and Fairbanks Morse 1972) exhibited the expected behaviors in the emissions with respect to the biodiesel content. PM and CO were both reduced by approximately 40% when B100 was used in the Fairbanks Morse engine, whereas NO_x was increased by 40% under the same conditions. On the other hand, PM and NO_x data from the Caterpillar 2002 engine did not show a clear trend as the biodiesel content increased. It is thought that the electronic control unit or the fuel system of the engine may play a role in such emissions behaviors. A newer engine, such as the present Caterpillar 2002 engine, may respond to the subtle change in the fuel such that certain operating conditions (e.g., injection parameters) are altered automatically. However, detailed information was not available in this study. Nonetheless, such information may be useful for evaluating using biodiesel blends for utility generators.

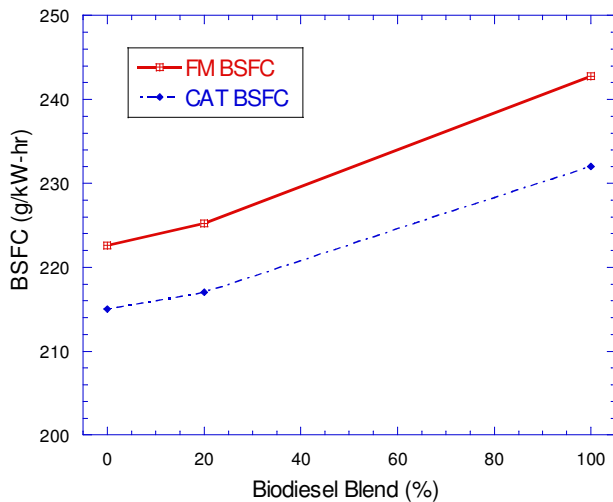


Figure 9 Variations in BSFC with respect to biodiesel blend percentage.

Figure 9 shows the variations in the brake specific fuel consumption (BSFC) when different biodiesel blends were used for the two engines that were tested using B100. The fuel consumption in the unit of [g/kW-hr] increases as the content of biodiesel increases due to the lower energy content of biodiesel.

It should be noted that usually laboratory tests of using biodiesel blends were performed under controlled conditions in terms of injection parameters and surrounding temperature. The present tests on utility generators were performed on-site without any external engine adjustments in operating conditions. The emissions trade-offs presented in this paper might not be representative of the "best possible trade-offs. The present results will be useful since they are the first hand data that were obtained during regular power generation.

Note that the on-site engine emissions testing in a power plant is a large scale endeavor due to the size of the engine, fuel consumption and the number of staff involved. The personnel included the power plant operators, stack testing technicians, fuel suppliers, and data analysts. Careful coordination is also required regarding the electricity generated during the testing. Therefore, only a limited number of designated operating points were tested. Nonetheless, the data are valuable and can also be used for legislative purposes in regulating the fuels used in power plants.

It should be noted that arbitrary changes in fuel or engine operating conditions are prohibited in power generation industry. After the initial testing, results were provided to the state's Department of Natural Resources who has considered several approaches including using the lb/MMBTU emissions data to calculate new emissions factors for biodiesel blends. The utilities would be able to use the factors to determine the number of hours per year they could burn biodiesel to comply with their air permit requirements. As a result, the power plant is allowed to burn B2 (2% biodiesel) with no modifications required for existing air permits due partly to the availability of B2 on the market [17].

SUMMARY

A selected number of large, stationary diesel engines used for electricity generation were tested using petrodiesel, 10%, 20% and 100% biodiesel blends. On-site emissions data, including PM, NO_x and CO were collected from the stack using EPA standardized methods. The test engines include three older engines that were in service in 1966 and 1972, and a newer engine, in service in 2002.

The three older engines exhibited the expected behaviors in the emissions as the biodiesel content was increased, namely decrease in PM and CO and increase in NO_x. When B100 was used, PM and CO can be reduced by approximately 40% while NO_x was increased by 40%. On the other hand, PM and NO_x data from the 2002 model engine did not show a linear trend corresponding to the biodiesel content. However, overall speaking, reductions in PM and CO with increases in NO_x emissions were also observed by burning biodiesel.

This study provided regulators and utilities the information that was needed to enable greater use of biodiesel. The rigorous testing methods used for this project should enable the results to be widely applicable and enhance the use of biorenewable energy for power generation.

ACKNOWLEDGEMENTS

This work was sponsored by Iowa Energy Center and the American Public Power Association DEED program. West Central Coop is acknowledged for providing biodiesel for testing. We also thank Erin Peiffer of IAMU

and all the staff in Sumner, Winterset and Story City facilities, Iowa, for their assistance.

REFERENCES

1. EPA, Research Triangle Park, North Carolina, EPA420-P-02-001. A comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions. EPA420-P-02-001. 126 pp, 2002.
2. US EPA Publication, <http://www.epa.gov/otaq/models/analysis/biodsl/p02001.pdf>
3. Sharp, C.A., Howell, S.A. and Jobe, J. "The Effects of Biodiesel Fuels on Transient Emissions from Modern Diesel Engines, Part I Regulated Emissions and Performance," SAE 2000-01-1967, 2000.
4. Alam, M., Song, J., Acharya, R., Boehman, A. and Miller, K. "Combustion and Emissions Performance of Low Sulfur, Ultra Low Sulfur and Biodiesel Blends in a DI Diesel Engine," SAE 2004-01-3024, 2004.
5. Souigny, M., Graham, L., Rideout, G. and Hosatte, P. "Heavy-Duty Diesel Engine Performance and Comparative Emission Measurements for Different Biodiesel Blends Used in the Montreal BIOBUS Project," SAE 2004-01-1861, 2004.
6. Bouche, T., Hinz, M., Pittermann, R. and Hermann, M. "Optimizing Tractor CI Engines for Biodiesel Operation," SAE 2000-01-1969, 2000.
7. Zarling, D.D., Bickel, K.L., Waytulonis, R.W. and Sweeney, J.R. "Improving Air Quality by Using Biodiesel in Generators," SAE 2004-01-3032, 2004.
8. Szybist, J.P. and A. L. Boehman "Behavior of a Diesel Injection System with Biodiesel Fuel," SAE 2003-01-1039, 2003.
9. Cheng, A., Upatnieks, A. and Mueller, C. "Investigation of the impact of biodiesel fuelling on NO_x emissions using an optical direct injection diesel engine," Int. J. Engine Research, Vol. 7, No. 4, pp.297-318, 2006.
10. McCormick, R.L., Alvarez, J.R., Graboski, M.S., Tyson, K.S. and Vertin, K. "Fuel Additive and Blending Approaches to Reducing NO_x Emissions from Biodiesel," SAE 2002-01-1658, 2002.
11. Yoshimoto, Y. and Tamaki, H. "Reduction of NO_x and Smoke Emissions in a Diesel Engine Fueled by Biodiesel Emulsion Combined with EGR," SAE 2001-01-0649, 2001.
12. Szybist, J.P., Simmons, J., Druckenmiller, M., Al-Qurashi, K., Boehman, A.L. and Scaroni, A. "Potential Methods for NO_x Reduction from Biodiesel," SAE 2003-01-3205, 2003.
13. Sem, T.R. "Investigation of Injector Tip Deposits on Transport Refrigeration Units Running on Biodiesel Fuel," SAE 2004-01-0091, 2004.
14. Quigley, R. and Barbour, R.H. "Biodiesel Quality Improvement with Additive Treatment," SAE 2004-01-1859, 2004.
15. EPA, Research Triangle Park, North Carolina, Compilation of Air Pollutant Emissions Factors, AP-42 Fifth edition, Volume 1, stationary point and and

area sources, January 2005. Website:

<http://www.epa.gov/ttn/chief/ap42/index.html>

16. Federal Register Vol 65, No. 201, Environmental Protection Agency. 40CFR Part 60, 61 and 63. Amendments for Testing and Monitoring Provisions. October 17, 2000.
17. Iowa Administrative Code, Section 567, Chapters 20-32. Iowa Administrative Rules for Air Quality, 2005.

CONTACT

Song-Charng Kong (kong@iastate.edu)
Department of Mechanical Engineering
Iowa State University