KSME International Journal, Vol. 18 No. 4, pp. 709~717, 2004

Combustion Characteristics of an Agricultural Diesel Engine using Biodiesel Fuel

Kyunghyun Ryu*, Youngtaig Oh
Department of Mechanical Engineering, Chonbuk National University, Duckjin-Dong 1-664-14, Jeonju, Chonbuk 561-756, Korea

Biodiesel has great potential as an alternative fuel for diesel engines that would reduce air pollution. It is a domestically produced, renewable fuel that can be manufactured from fresh or used vegetable oils, or from animal fats. In this study, a biodiesel fuel derived from rice bran oil was tested as an alternative fuel for agricultural diesel engines. The emissions were characterized for both neat and blended biodiesel fuels, and for conventional diesel fuel. Since this biodiesel fuel contained 11% oxygen, it strongly influenced the combustion process. The use of biodiesel fuel resulted in lower carbon monoxide, carbon dioxide, and smoke emissions, without any increase in nitrous oxide emissions. The study demonstrated that biodiesel fuel could be effectively used as a renewable and environmentally innocuous fuel for agricultural diesel engines.

Key Words : Alternative Fuel, Biodiesel Fuel, Smoke, Exhaust Gas Emission, Oxygenated Fuel

1. Introduction

Vegetable oil was used as a diesel fuel as early as 1900 when Rudolf Diesel demonstrated that a diesel engine could run on peanut oil. However, there has been little interest in biodiesel fuels except during times of crisis such as World War II and the energy shortages of the 1970s. Recently, however, as a result of heightened environmental awareness and the exhaustion of conventional petroleum oil sources, biodiesel fuel has been increasingly recognized in Europe and the U.S.A. as a renewable energy source and as an alternative fuel to diesel.

The use of vegetable oils as alternative fuels for diesel engines has been studied by many researchers (Kyle et al., 1993 ; http://www.biodiesel.org). Biodiesel fuels, which are derived from fresh or used vegetable oils or from animal fats, are safe to use in diesel engines and can be used as a substitute for conventional petroleum fuel without any engine modifications. Furthermore, biodiesel fuel can be used in its pure state, or it can be blended with conventional diesel fuel. The American Soybean Association is already trying to legislate biodiesel fuel for commercial business use in the U.S.A. (Howell, 1997).

A diesel engine running on blended diesel fuel produces less smoke than one running on conventional diesel fuel (Ziejewski et al., 1984). Furthermore, reductions in the amount of smoke produced when burning biodiesel fuel derived from soybeans have been reported in related literature (Kyle et al., 1993 ; Schumacher et al., 1992, 1993). Reece et al. (1993) reported that a blend of 20% rapeseed oil and 80% diesel fuel reduced the smoke produced by a diesel engine. Marshall et al. (1993) observed a 1-7% increase in power when burning an animal fat-derived biodiesel fuel in a diesel engine, and Feldman et al. (1992) reported an increase in power when burning biodiesel fuel using controlled fuel

* Corresponding Author,
E-mail : khryu87@hotmail.com
TEL : +82-63-270-2316; **FAX** : +82-63-270-2315
Department of Mechanical Engineering, Chonbuk National University, Duckjin-Dong 1-664-14, Jeonju, Chonbuk 561-756, Korea. (Manuscript **Received** August 29, 2003; **Revised** January 8, 2004)

injection timing in a three cylinder, direct injection (DI) diesel engine. In an indirect injection (IDI) engine, a remarkable reduction was observed in the amounts of smoke produced using both pure biodiesel fuel and blends of biodiesel fuel and diesel fuel (Ryu et al., 2002).

In Korea, studies have shown that used vegetable oils produce less smoke than conventional diesel fuel when burned in a one cylinder DI diesel engine (Oh, 1996) and biodiesel fuel can be utilized effectively as a renewable fuel for an automotive diesel engine (Ryu et al., 2003). However, there are no data available for the combustion characteristics of agricultural diesel engines burning biodiesel fuel derived from rice bran oils that are produced annually 6,000 tons in Korea. Furthermore, the rapid increase in the use of agricultural machinery due to industrialization and the manpower problems of agriculture, has resulted in soil and water contamination from petroleum oil spills, reducing the growth of vegetation. In general, biodiesel fuel is more environmentally friendly ; as it is biodegradable, it will break down quickly, preventing long-term damage to the soil or water sources in the event of a spill. It is necessary, therefore, to study the practicality of using biodiesel fuels in agricultural diesel engines.

The objective of this paper was to investigate the combustion characteristics of biodiesel fuel derived from rice bran oil when burned in an agricultural diesel engine. A commercial IDI diesel tractor engine was used in this study without modification. The performance and emissions of biodiesel fuel were compared with those of conventional diesel fuel.

2. Experimental Apparatus and Methods

2.1 Test description and fuel

In this study, we considered a water-cooled, 4-cylinder, 4-stroke, commercial IDI agricultural diesel engine with no modifications. The test engine had a swirl chanber with a compression ratio of 21 and a displacement of 1732 cc ; it was started with a starting motor and controlled manually with an eddy current engine dynamometer (HW130). The principal specifications of the test engine are given in Table 1.

Table 1 Specification of test engine

Item	Specification
Engine model	TD1700
Bore×stroke	82×82 (mm)
Displacement	1732 (cm^3)
Compression ratio	21
Combustion chamber type	Swirl chamber
Injection timing	BTDC 25℃A
Coolant temperature	80±2℃

Table 2 Properties of test fuels

Item	Diesel fuel	Biodiesel fuel
Specific gravity (15/4℃)	0.8373	0.8796
Viscosity (50℃, cSt)	3.0	4.2
Flash point (PM, ℃)	74	168
Lower heating value (MJ/kg)	45.88	39.163
Cetane number	51.4	57.9
Sulfur content (wt.%)	0.031	0.008
Carbon content (wt.%)	85.83	76.22
Hydrogen content (wt.%)	13.82	12.38
Nitrogen content (wt.%)	0.16	0.14
Oxygen content (wt.%)	0	11.24

Table 2 shows the properties of the fuels used in this test. The biodiesel fuel was derived from rice bran oil that is produced annually in Korea. It has a lower heating value than diesel fuel, but it is easy to use and store because of the higher cetane number and flash point. In addition, the biodiesel fuel contains 11% oxygen by weight and 10% less carbon than diesel fuel. Furthermore, the biodiesel fuel contains negligible amounts of sulfur, thereby reducing sulfur dioxide emissions that are responsible for acid rain.

2.2 Test method

Five fuels were tested in this study : a neat (100 %) biodiesel fuel, a neat (100%) diesel fuel, and blends of 20, 30, and 50 percent biodiesel fuel by volume in the diesel fuel.

The test engine was operated with cooling water at 80±2℃ under all experimental conditions. After completing each test with a selected fuel, the fuel filter and engine oil were replaced to avoid any possible effect on the subsequent test.

The experiments were conducted at engine speeds of 1200, 1500, 2000, and 2500 rpm, and at engine loads of 0, 25, 50, 75, 90, and 100%. A Bosch smoke meter (HBN-1500) and an exhaust gas analyzer (Green line MK) that used an electrochemical cell detector were installed in the exhaust pipe (300 mm from the exhaust manifold) to measure exhaust emissions. The fuel consumption rate was measured with a 150 cc measuring gauge and a stopwatch.

A piezoelectricity pressure sensor (Kistler 6061B) with a water-cooled adaptor was mounted on the pre-chamber of the fourth cylinder to analyze the combustion characteristics of the diesel engine. The pressure data generated by the sensor were sent to a data acquisition system through a pressure amplifier (Kistler 5011). Figure 1 shows a schematic diagram of the experimental apparatus.

3. Experimental Results and Discussion

3.1 Engine performance with biodiesel fuel

Figure 2 shows the effects of biodiesel fuel on engine performance parameters such as torque, power, and brake-specific energy consumption (BSEC) at a full (100%) load. The torque and power slightly decreased as the biodiesel fuel content increased, except for a slight increase in torque and power with 20% biodiesel/80% diesel fuel. There was a large decrease in torque and power when neat biodiesel fuel was used. The BSEC generally improved when biodiesel was mixed with diesel fuel since combustion with biodiesel fuel was more complete because of the higher oxygen content despite the lower heating value of biodiesel fuel.

To investigate the precise effects of biodiesel fuel in diesel engines, based on the data shown in Fig. 2, the cylinder pressure, pressure rise rate, and rate of heat release for an engine speed of 2500 rpm and a full load are given in Fig. 3. In the premixed period, the pressure and pressure rise rate were reduced when biodiesel fuel was

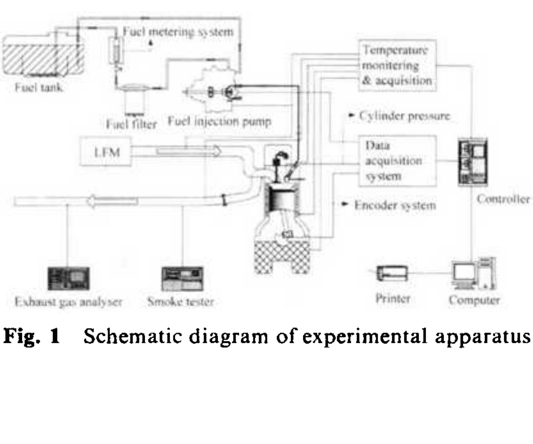

Fig. 1 Schematic diagram of experimental apparatus

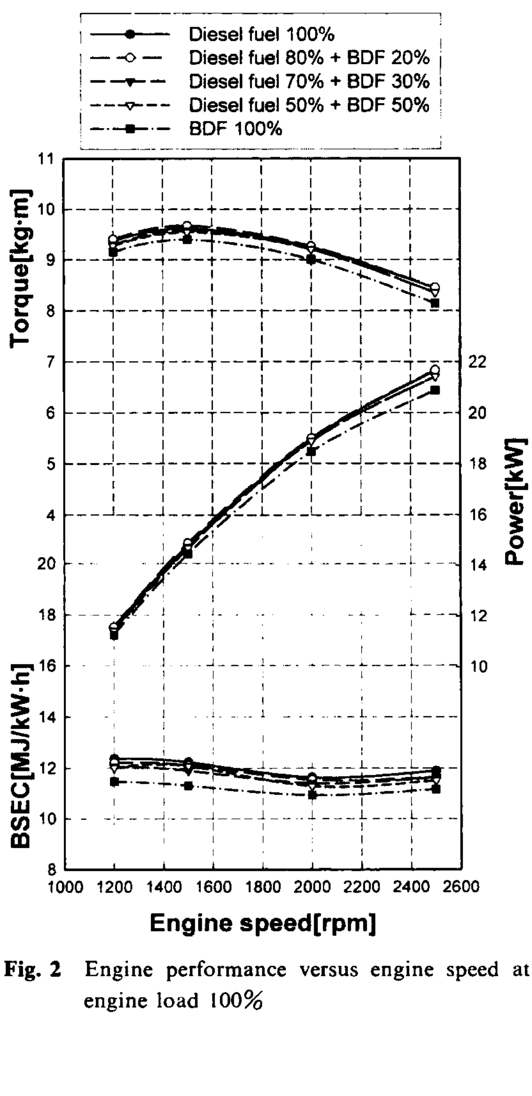

Fig. 2 Engine performance versus engine speed at engine load 100%

used because of the reduction in premixed combustion, which was due to the higher cetane number of biodiesel. As the biodiesel content of the diesel fuel increased, the first peak value of the heat release rate decreased due to the higher cetane number of biodiesel. However the auto-ignition delay period of the premixed mixture was not shortened in the plots of pressure and heat release rate, while the heat released during the late combustion period greatly increased with the biodiesel content. This means that the oxygen content of the biodiesel fuel accelerated more complete combustion and that the biodiesel fuel burned more easily during the late combustion period when it is generally difficult to combine fuel with oxygen components. Also, the heat release rate showed that the combustion process ended sooner with increasing biodiesel content; i.e., the total combustion period with biodiesel fuel was shortened. Thus biodiesel would be very effective in the suppression of smoke production during the late combustion stage.

Figure 4 shows the BSEC versus the engine load at various engine speeds. The BSEC improved for biodiesel fuel, as compared to diesel fuel. The BSEC was also reduced by increasing the biodiesel content of the diesel fuel under all

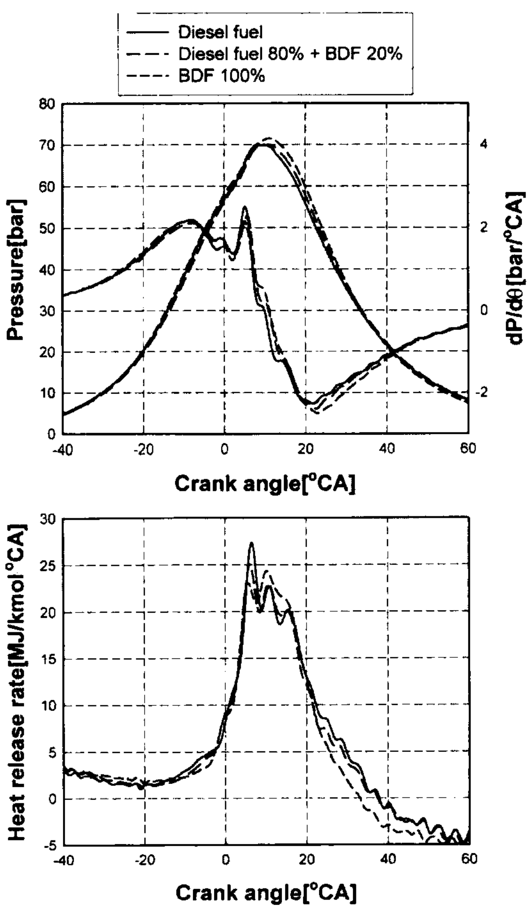

Fig. 3 Pressure, DP/Dθ, and dQ/dθ at engine speed 2500 rpm and load 100%

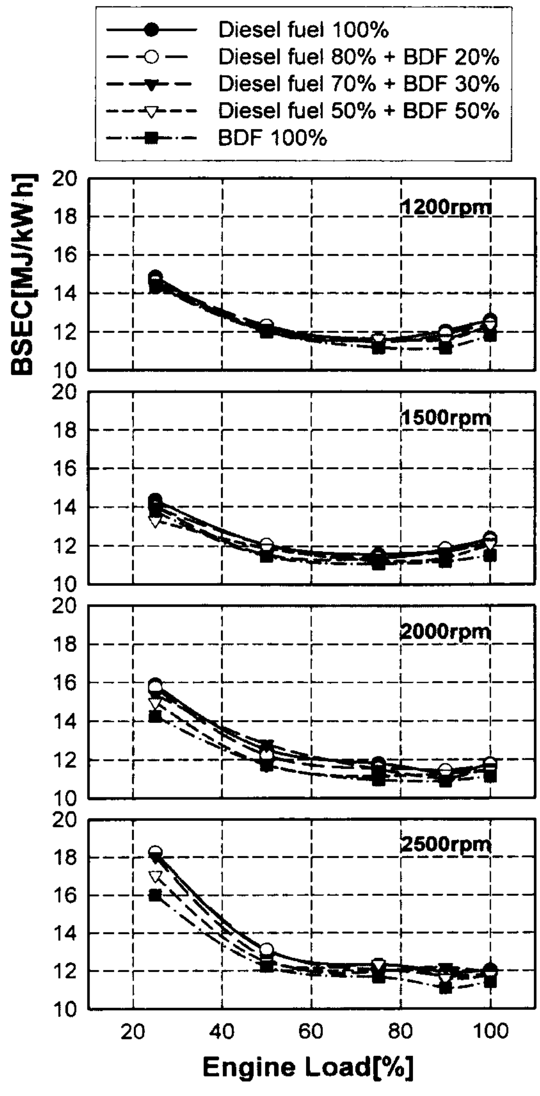

Fig. 4 BSEC versus engine load at various engine speeds

conditions. This can also be attributed to the fact that the oxygen content of the biodiesel fuel caused more complete combustion.

3.2 Exhaust emissions with biodiesel fuel

Figure 5 shows the effect of biodiesel fuel on smoke emission at various engine loads and speeds. Under all conditions, the smoke concentration increased with the engine load. However, the smoke emissions for biodiesel fuel were less than those for diesel fuel, and could be reduced up to 46% at a full load by increasing the biodiesel content of the diesel fuel. This was because of the shortened total combustion process and the more complete combustion due to the extra oxygen in the fuel, as suggested by the heat release rates shown in Fig. 3.

Figure 6 shows the effect of the biodiesel fuel on NOx emissions at various engine loads and speeds. For all fuels, NOx emissions increased with engine load, but there were no remarkable

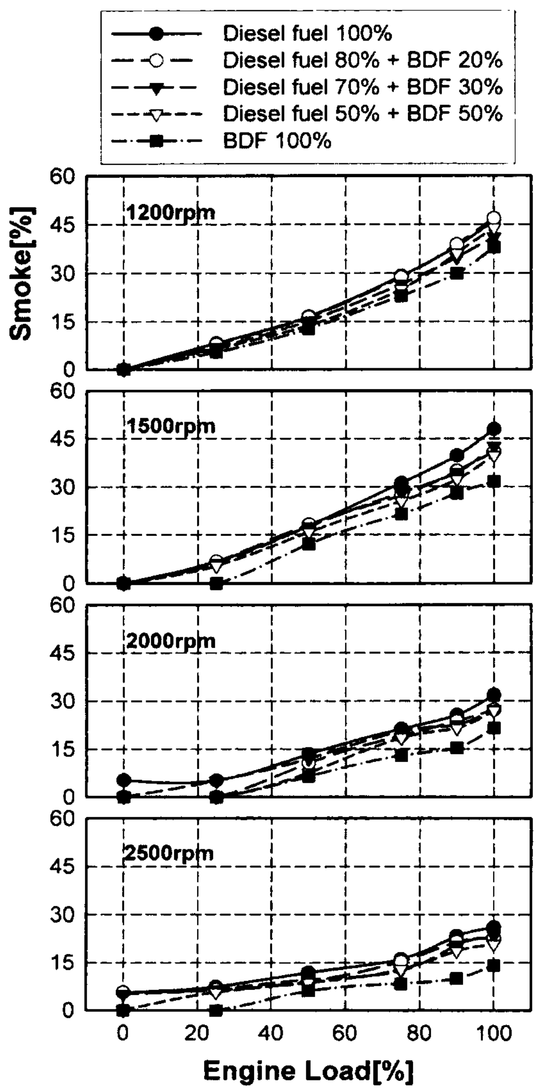

Fig. 5 Smoke emissions versus engine load at various engine speeds

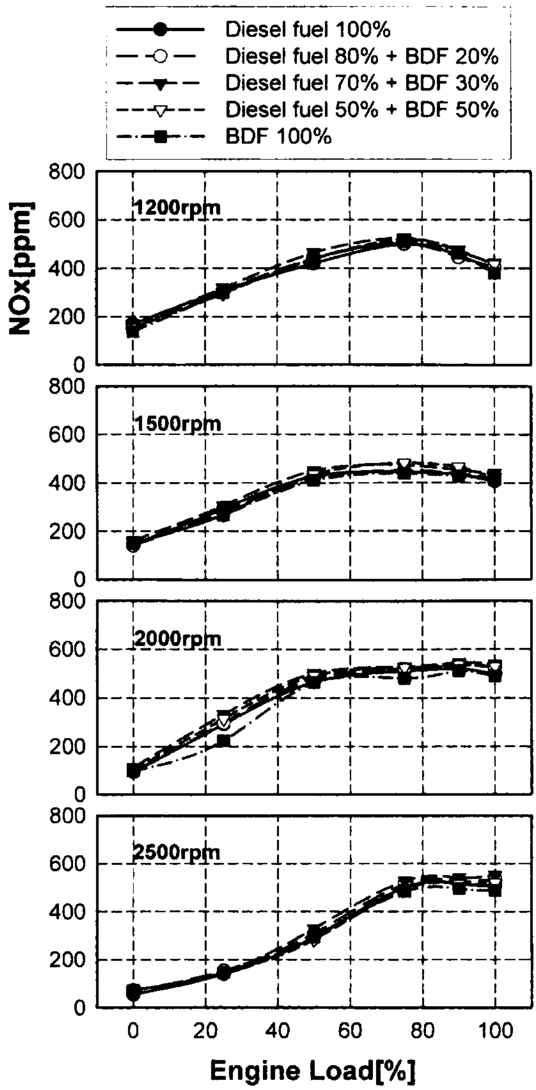

Fig. 6 NOx emissions versus engine load at various engine speeds

trends as the biodiesel content varied ; the NOx emissions produced using blended biodiesel fuel were similar to those produced using diesel fuel. However, the NOx emissions obtained using neat biodiesel fuel were less than those obtained using neat diesel fuel. Usually, NOx emissions have a trade-off relationship with smoke emissions, but this trend was not observed for the IDI agricultural diesel engine used in this study.

Figure 7 shows the carbon monoxide (CO) emissions for the biodiesel and diesel fuels under all test conditions. At low engine speeds (1200 and 1500 rpm), CO emissions in the exhaust were higher at the lowest and highest loads than at medium loads, for all fuels. The CO emissions were especially high for a full load and an engine speed of 1200 rpm. At engine speeds of 2000 rpm and more, however, the CO emissions decreased as the engine load increased for all fuels. The CO emissions were sensitive to the biodiesel content of the diesel fuel. The CO emissions decreased as the biodiesel content increased,

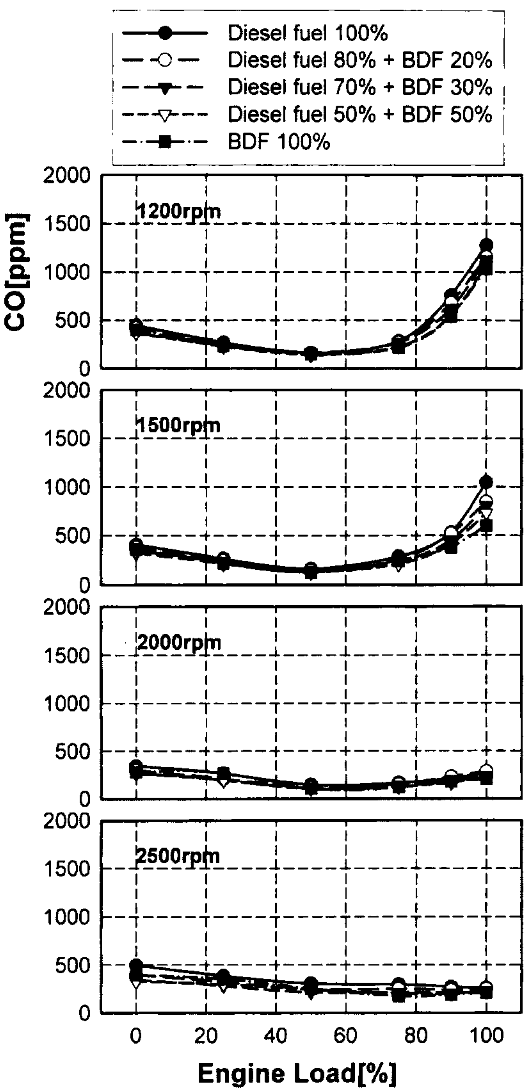

Fig. 7 CO emissions versus engine load at various engine speeds

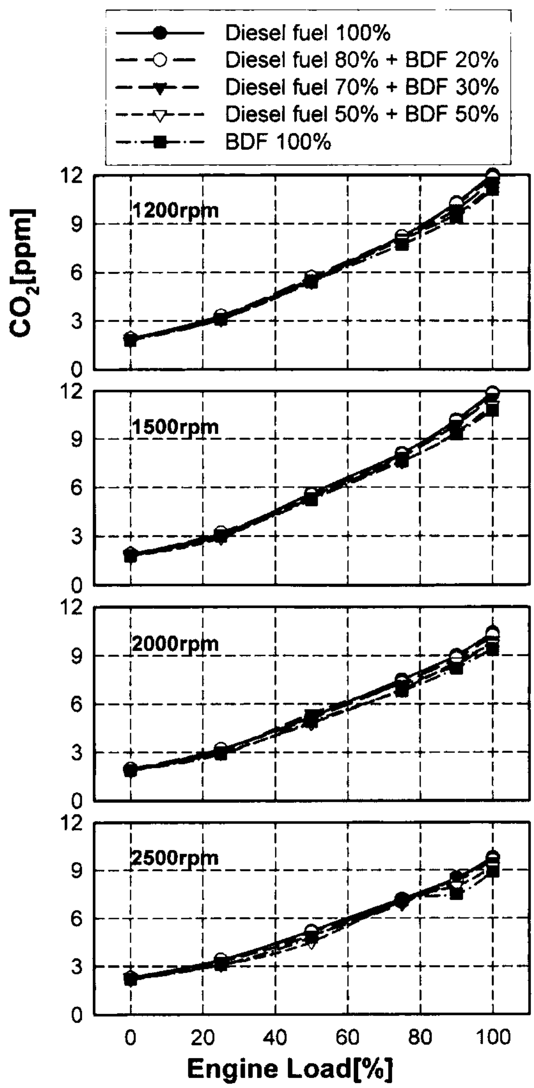

Fig. 8 CO_2 emissions versus engine load at various engine speeds

especially for high loads and engine speeds of 1200 and 1500 rpm.

Figure 8 shows the carbon dioxide (CO_2) emissions for the biodiesel and diesel fuels under all test conditions. In general, CO_2 emissions increased with engine load for all fuels, and CO_2 emissions decreased as the biodiesel content increased. CO_2 emissions can be reduced by using biodiesel fuel since it has less carbon than diesel fuel, as shown in Table 2. This result is important because CO_e is the primary greenhouse gas contributing to global warming.

Figure 9 shows the effects of biodiesel fuel on the smoke and NOx emissions in relation to the oxygen content of the fuel under all test conditions. The figure shows that the amount of smoke produced was sensitive to the oxygen content of the fuel. The peak smoke concentration was reduced by increasing the oxygen content.

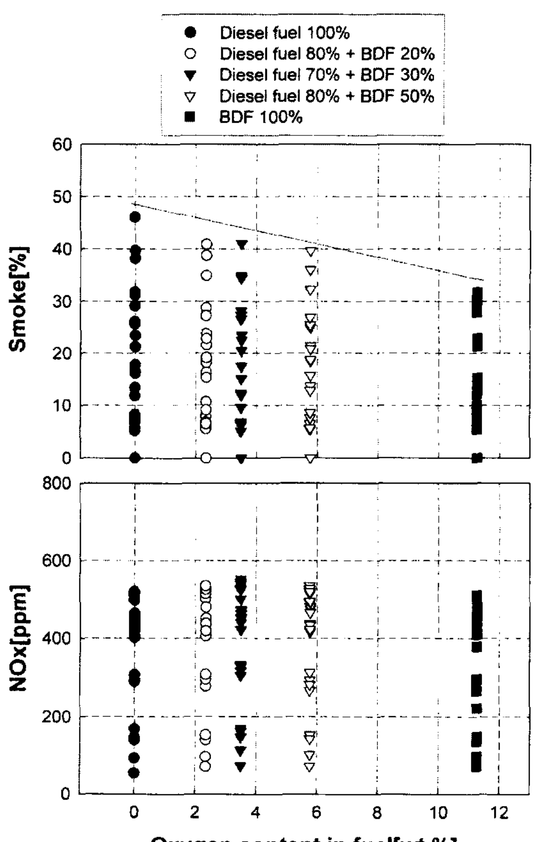

Fig. 9 Smoke and NOx versus oxygen content in fuel

However, the NOx emissions were not sensitive to the oxygen content of the fuel and no specific trends were apparent in the NOx data, possibly because NOx is more affected by the flame temperature and the amount of premixed combustion (indicated by the cetane number of the fuel) than it is by the oxygen content.

The agricultural IDI diesel engine tested in this study did not exhibit the expected trade-off relationship between smoke and NOx emissions that generally appears in automotive IDI diesel engines (Ryu et al., 2003), and this was unaffected by the oxygen content. A possible reason for this is that the fuel injection timing of the injection pump for an agricultural IDI diesel engine is not advanced by increasing the engine speed unlike the fuel injection pump for an automotive diesel engine. Another reason is that the smoke and NOx are usually produced respectively in the mixing-controlled combustion and in the premixed combustion, but the smoke and NOx emissions with biodiesel fuel are respectively constrained by the cetane number of biodiesel fuel in the mixing-controlled combustion and by the oxygen content of biodiesel fuel in the premixed combustion. Smoke is usually produced in the mixing-controlled combustion process due to the lack of oxygen to combine the fuel and oxygen while NOx is mainly formed in the premixed combustion region by the higher temperature. However, NOx is not increased by the oxygen content in biodiesel fuel because the oxygen in biodiesel fuel is mainly decomposed and combined in the late combustion process and because the cetane number of biodiesel fuel reduces NOx emission.

Figure 10 shows the unburned hydrocarbon (UHC) emissions for diesel fuel, a 20% blend of biodiesel fuel, and neat biodiesel fuel under all test conditions, which were measured by gas chromatography. For all fuels, the total peak area of the UHC emissions increased when the engine load was 75% or greater. The peak area of the UHC emissions also increased with engine speed, but was reduced by increasing the biodiesel content of the diesel fuel. An especially large reduction in the peak area occurred for a full load at

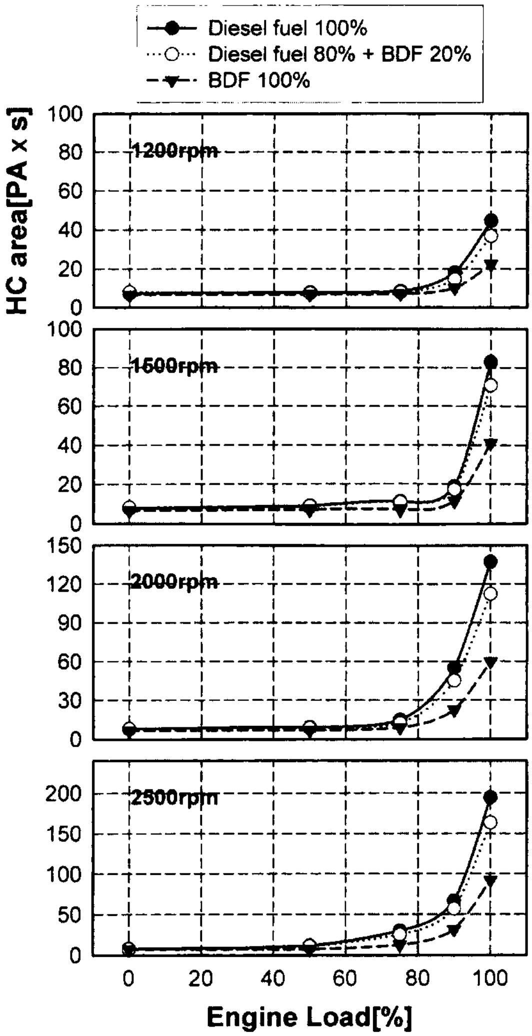

Fig. 10 Total area of hydrocarbon versus engine load at various engine speeds

high engine speeds. These results show that biodiesel fuel effectively reduces the UHC content of diesel engine emissions because the fuel is composed of 11% oxygen.

4. Conclusions

Experiments were performed using an agricultural IDI diesel engine to investigate the combustion characteristics of biodiesel fuel derived from rice bran oil. The following conclusions were obtained.

(1) The torque and power slightly increased when 20% biodiesel fuel was used, as compared to neat diesel fuel. Otherwise, the torque and power remained similar as the biodiesel content of the diesel fuel increased, except when using neat biodiesel fuel. The BSEC decreased with the biodiesel content of the diesel fuel.

(2) As the biodiesel content of the diesel fuel increased, the smoke emissions decreased up to 46%. The biodiesel fuel was very effective for reducing the smoke emissions at high engine speeds and full loads. The smoke emissions were also sensitive to the oxygen content of the fuel. The CO and CO_2 emissions decreased as the biodiesel content of the diesel fuel increased.

(3) NOx emissions were not very sensitive to the biodiesel content of the diesel fuel; the emissions were similar to those measured using neat diesel fuel.

Based on these results, we conclude that biodiesel fuel can be utilized effectively as a renewable and low-pollution alternative fuel for agricultural IDI diesel engines. Furthermore, biodiesel fuel can significantly reduce smoke emission without increasing NOx emission.

Acknowledgment

This study was supported by Technology Development Program for Agriculture and Forestry, Ministry of Agriculture and Forestry, Republic of Korea.

References

Feldman, M. E. and Peterson, C. L., 1992, "Fuel Injector Timing and Pressure Optimization on a DI Diesel Engine for Operation on Biodiesel," *Liquid Fuels From Renewable Resources-Proceedings of an Alternative Energy Conference*.

Howell, S., 1997, "Biodiesel Fuel Standard Making Progress," *ASTM Standardization News*, Vol. 25, No. 4, pp. 16~19.

http://www.biodiesel.org/default2.htm

Lue, Y.-F., Yeh, Y.-Y. and Wu, C.-H., 2001, "The Emission Characteristics of a Small D.I. Diesel Engine Using Biodiesel Blended Fuels," *Journal of Environmental Science and Health, Part A*, Vol. 36, No. 5, pp. 845~859.

Marshall, W. F., 1993, "Effects of Methyl Esters of Tallow and Grease on Exhaust Emissions and Performance of a Cummins L10 Engine," *Itt Research Institute, National Institute for Petroleum and Energy Research.*

Oh, Y. T., 1998, "A Study on the Usability of Used Vegetable Oil as a Diesel Substitute in Diesel Engine," *KSME in Korea*, Vol. 22, No. 4, pp. 481~488.

Reece, D. L. and Peterson, C. L., 1993, "A Report on the Idaho on-road Vehicle Test with RME and Neat Rapeseed Oil as an Alternative to Diesel Fuel," *ASAE paper*, No. 93-5018.

Ryu, K. H. and Oh, Y. T. 2003, "A Study on the Usability of Biodiesel Fuel Derived from Rice Bran Oil as an Alternative Fuel for IDI Diesel Engine," *KSME International Journal*, Vol. 17, No. 2, pp. 310~317.

Ryu, K. H., Yun, Y. J. and Oh, Y. T., 2002, "An Experimental Study on the Usability of Biodiesel fuel as an Alternative Fuel for Diesel Engine," *KSME 2002th Conference in Korea*, pp. 2025~2030.

Scholl, K. W. and Sorenson, S. C., 1993, "Combustion of Soybean Oil Methyl Ester in a Direct Injection Diesel Engine," *SAE paper*, No. 930934.

Schumacher, L. G., Borgelt, S. C. and Hires, W. G. 1993, "Soydiesel/Biodiesel Blend Research," *ASAE paper*, No. 93-6523.

Schumacher, L. G., Hires, W. G. and Borgelt, S. C., 1992, "Fueling a Diesel Engine with Methylester Soybean Oil," *Liquid Fuels From Renewable Resources-Proceedings of an Alternative Energy Conference.*

Ziejewski, M., Kaufman, K. R., Schwab, A. W. and Pryde, E. H., 1984, "Diesel Engine Evaluation of an Nonionic Sunflower Oil-Aqueous Ethanol Microemulsion," *Journal of the American Oil Chemists Society*, Vol. 61, No. 10, pp. 1620~1626.