Development of an Automated Diesel Engine Test Stand for Evaluating Combustion and Exhaust Emission Characteristics of Nanoemulsion Biofuels

Final Report for GNC09-109

Project Type: Graduate Student
Funds awarded in 2009: $9,942.00
Projected End Date: 12/31/2011
Grant Recipient: University of Missouri
Region: North Central
State: Missouri

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Project Information

Summary:

Using biodiesel in diesel engines has several positive effects on reducing the exhaust emissions. However, biodiesel containing fuel blends tend to increase the NOx emissions from diesel engines compared to petroleum diesel. The objective of this study was to determine the effects of biodiesel and surfactant concentrations of a water-biodiesel-diesel nanoemulsion fuel on engine performance and exhaust emissions of a 4-cylinder diesel engine. Biodiesel nanoemulsions were prepared based on statistical experimental design methodology. An instrumented 4-cylinder diesel engine test stand was developed and used for the engine performance and exhaust emissions of the biodiesel nanoemulsions. The results showed that biodiesel nanoemulsions reduced the NOx emissions compared to biodiesel-diesel blends at the same biodiesel concentrations. Increasing the surfactant concentration at constant water and biodiesel concentrations produced higher engine powers. Emulsified biodiesel reduced the NOx emissions and exhaust temperature but increased the brake specific fuel consumption and CO emissions.

Project Objectives:

The objective of this study was to evaluate the performance and exhaust emissions (NOx, CO, CO?, soot opacity) of a 4-cylinder diesel engine fueled with water-biodiesel-diesel emulsions at various biodiesel and surfactant concentrations.

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Research

Materials and methods:

An on-site 4-cylinder diesel engine test stand was developed (Figures 1 and 2). A Cummins 60 kW (80 HP), 3.3 liter diesel engine equipped with a direct injection fuel system was mounted on a metal frame anchored to the ground. The engine test system had three fuel tanks. One fuel tank was used for the base fuel (certified # 2 diesel), the second tank was used for the experimental fuel and the third tank was used to flush the fuel line between the experimental and base fuels during the tests. Manual valves were used to control the direction of the fuel supply and return lines between the fuel tanks and the engine fuel system during the tests. A fuel stand, as shown in Figure 3, was set up to hold the fuel tanks. A load cell (SSM-AJ-50, MFG, Arizona, USA) was mounted on the fuel stand to measure the fuel consumption gravimetrically in real time. A cooling tower was used to control the engine temperature. The temperature of the cooling tower was controlled with a thermostatic valve. Eight thermocouples were mounted on the engine to monitor the temperatures of the inlet air, fuel, turbocharger, engine cylinder, cooling water, and engine oil. A control box was built to house the engine ignition key, throttle control valve and the data acquisition terminal box (Figure 4). An AW 400 Dynamometer (AW Dynamometer, INC, Illinois, USA) was coupled with the engine to supply the engine load. The dynamometer was directly connected to the engine flywheel using a high-speed driveline (AW Dynamometer, INC, Illinois, USA). The dynamometer was equipped with a load cell for engine torque measurement and a magnetic pick-up sensor for the measurement of the shaft speed. The frequency readings from the magnetic pick up sensor was monitored using a digital indicator (Shimpo, Itasca, IL). The indicator displayed the engine speed (rpm) and converted the frequency to voltage for real-time data recording. A hydraulic pump driven by the engine shaft and two hydraulic valves for coarse and fine control were used to control the engine load by changing the water flow rate to the dynamometer.

Exhaust emission analyzer: An exhaust emission analyzer (TESTO 350 XL, Flanders, NJ) monitored the exhaust emissions of NOx, NO, NO?, CO, CO2, O?, and exhaust temperature (Figure 5a). The emission analyzer probe was mounted on the exhaust pipe and the analyzer was connected to a computer via serial connection. Exhaust emission measurements can be captured at various intervals. The emission analyzer was set to warm up for 20 minutes at ambient conditions before the measurements. An opacity meter (6500, Wager, Inc, NC) mounted on the exhaust pipe measured the smoke opacity in real time (Figure 5b). The emitter and receiver of the opacity sensor temperatures were kept constant with supplying circulating water around the sensor. The meter measures the smoke opacity based on the light transmission method. Therefore, pressured air was supplied around the emitter and receiver lenses to keep them clean.

Data Acquisition: An NI-PXI platform and NI-USB 6009 DAQ card (National Instruments, Austin, TX) were used to capture the sensor readings. The engine temperatures were measured at eight locations using K-type thermocouples. Engine speed, torque and fuel consumption were measured via the USB DAQ card. NI-PXI platform was connected to a laptop using an express card (NI Express card-8360). The signals from the torque and fuel consumption sensors were conditioned using load cell bridge amplifiers (OMEGA, DMD-465). A program written in Labview controlled the data acquisition system. The system captured the digital signals from the sensors, calculated, displayed, and recorded the engine performance parameters on the computer. The schematic diagram showing the major components of the diesel engine test stand is shown in Figure 6.

Preparation of Nanoemulsions: The surfactant was obtained from CYTEC (Georgia, USA). Biodiesel was obtained from Global Fuels LLC. (Missouri, USA) and certified #2 diesel fuel was purchased from Brownfield Oil Company, Inc. (Moberly, MO). De-ionized water was used to prepare the biodiesel emulsions. The physical properties of the biodiesel and diesel fuels are shown in Table 1.

Nanoemulsion fuel samples were prepared using a three-step procedure. The first step was adding biodiesel to the surfactant solution. The ratio of solution was adjusted to 30% surfactant and 70% biodiesel volumetrically to enhance the surfactant solubility. The concentrations of the fuel emulsions used for this study are shown in Table 2. Surfactant and biodiesel mixture was stirred for 30 min to homogenize the solution. The mixing was carried out at room temperature. Biodiesel in the emulsions was considered as part of the oil phase (continues phase), whereas surfactant was part of the dispersed phase (water phase). The second step was carried out by adding constant amount of water (10%) to the surfactant-biodiesel solution based on the experimental design. Next, the solution was stirred for 30 min at room temperature. The final step of the emulsion preparation was adding the water-biodiesel solution to diesel fuel. All the emulsions were homogenized by applying high intensity ultrasound for 10 min in each trial.

Engine tests: The tests were performed under different engine loads at five engine speeds. Biodiesel fuels of B7, B12.25 and B17.5 were compared to the emulsion fuels at the same volume of biodiesel and 10% water. The results were analyzed by using SAS statistical analysis software (SAS Institute Inc., Cary, NC, USA) with F-test to determine the significant effect of biodiesel emulsions at ($P<0.05$) on engine performance and exhaust emissions compared to biodiesel.

The droplet size distributions of water in fuel emulsions were measured using a Dyna Pro 99 molecular size Dynamic Light Scattering System. Helium-Neon laser wavelength was set to (836 nm) and scattering angle was 90?. The system was operated at 20 ?C. The samples of emulsions were put inside a cuvette and each sample was observed for 200 s. The hydrodynamic radius (Rh) of the nanoemulsion particles was computed using a software program (Dynamics V.5.26.38). The viscosity and refractive index of each sample was determined and set before running the system. The viscosity of biodiesel-nanoemulsion was performed by using a HAAKE Viscometer (VT 550, Thermo Scientific, Inc, Germany). For viscosity measurements, 75 ml of emulsion samples were used. The speed of the spindle was adjusted to 227 rpm and the temperature was set at 40 ?C by using a constant-temperature refrigerated circulating liquid bath (JulaboFP50-MC, Inc, USA). A standard density measurement procedure was used to determine the density of the samples. A glass hydrometer with specific gravity range of 800–900 kg/m^3 was used.

To collect density-dependent data, a 100 ml graduated cylinder containing the nanoemulsion sample was placed in a temperature controlled water bath. The water bath temperature was set at 25 °C. The measurements were repeated twice and the average values were taken.

Research results and discussion:

The properties of biodiesel emulsions are shown in Table 3. Increasing the biodiesel concentration increased the density and viscosity of biodiesel nanoemulsions. The average droplet size of emulsions reduced from 110 nm to 10.5 nm when biodiesel concentration was increased from 7% to 17.5% at the same volume of water and surfactant concentrations. These results confirm that increasing biodiesel concentration in the emulsion can reduce the droplet size of water and enhance stability of the emulsions. This effect may be due to the high solubility of biodiesel compared to the other fuels. The droplet size distribution of water in biodiesel nanoemulsions are shown in Figure 7. Biodiesel nanoemulsions with 17.5% and 12.25% produced low ploydipersity compared to 7% biodiesel at the same water concentration. Low polydispersity refers to high level of homogeneity of the water droplets which form stable emulsions at room temperature without changing the appearance of the emulsions significantly (Leong, Wooster et al. 2009).

The effects of different biodiesel nanoemulsions on engine performance and exhaust emissions are shown in Table 4. The results show that the effects of biodiesel nanoemulsions on engine power, torque, BSFC, NOx, CO, CO2 and exhaust temperature at $P<0.05$ level are significant for all the biodiesel concentrations. While the effects of biodiesel nanoemulsions on soot opacity at $P<0.05$ level was not significant when 12.25% and B17.5% biodiesel were used.

Engine performance: The effects of biodiesel nanoemulsions and biodiesel fuel blends on engine brake power are shown in Figure 8. The results show that nanoemulsion fuel at 7% biodiesel level produced the minimum output power compared to biodiesel-diesel fuel blends (B7) at the same biodiesel concentration. The effects of nanoemulsion were higher at high engine speed (2000 rpm), which is 3.7% and 11.8% less than 7% biodiesel and diesel fuel, respectively. Figure 8(b) shows that nanoemulsion fuel containing 12.25% biodiesel produced 2.5% and 8% less engine brake power than B12.25 fuel and diesel fuel at high engine speed (2000 rpm). Whereas, biodiesel nanoemulsions with 17.5% biodiesel (Figure 8c) shows higher engine output power than B17.5 fuel over all engine speed levels. This result may be due to the enhanced solubility of emulsion with increasing biodiesel concentration at constant water concentration (10%), which produced stable and uniform nanoemulsions. However, heating value of biodiesel is 10% less than diesel fuel on weight basis which reduced the engine brake power compared to diesel fuel (Agarwal 2007). Increasing the biodiesel and surfactant concentrations at constant water amount in nanoemulsions can improve the output power compared to biodiesel-diesel blends.

The effects of biodiesel nanoemulsions and biodiesel fuel on engine torque is shown in Figure 9. The results show that biodiesel nanoemulsion with 7% biodiesel (Figure 9a) produced the lowest engine torque compared to B7 and diesel fuel. The maximum torque was observed at 1800 rpm for all fuel compositions. Figure 9(b) shows that biodiesel nanoemulsion with 12.25% biodiesel which produced 2.4% higher engine torque than B12.25 at 1800 rpm. As it is observed in Figure 9(c), biodiesel nanoemulsion with 17.5% biodiesel produced 3.3% higher engine torque than B17.5 at 1800 rpm. In general, increasing biodiesel and surfactant concentrations in B12.25 and B17.5 nanoemulsions produced higher torque than biodiesel blend. These results maybe due to the effect of increasing surfactant concentration at constant water level (10%), which produced uniform and homogenized biodiesel nanoemulsions compared to lower surfactant concentrations, which increased engine combustion efficiency and the diesel engine torque.

The effects of biodiesel nanoemulsions and biodiesel-diesel blends on brake specific fuel consumption (BSFC) is shown in Figure 10. These results indicate that biodiesel nanoemulsions with 7% biodiesel produced higher BSFC than B7 and diesel fuel (Figure 10(a)). However, BSFC for B7 was higher than diesel fuel. More biodiesel nanoemulsion fuel was consumed to produce as much engine power as diesel fuel (Kannan and Anand 2011). In addition, Figure 10(b) shows that biodiesel emulsions with 12.25% biodiesel produced higher BSFC than B12.25 and diesel fuel. Biodiesel nanoemulsion at 17.5% biodiesel obtained 16% and 17% higher BSFC than B17.5 and diesel fuel at 2000 rpm as shown in Figure 10(c). In general, biodiesel nanoemulsions with a specific biodiesel concentration produced higher BSFC under all engine load conditions at the same biodiesel concentration in a biodiesel blend and diesel fuel.

Exhaust emissions

Oxides of nitrogen (NOx): The effects of biodiesel nanoemulsion and biodiesel fuel on NOx emissions can be seen in Figure 11. The result shows that biodiesel nanoemulsion with 7% biodiesel obtained NOx emission of 970 ppm at full engine load (1200 rpm), which was 0.1% less than those measured for B7 (Figure 11(a)). However, diesel fuel produced 8.5% less NOx emissions than biodiesel nanoemulsions. Figure 11(b) shows that biodiesel nanoemulsion with 12.25% biodiesel produced 2.3% less NOx emissions than B12.25 blend (Figure 11(c)). The biodiesel nanoemulsion at B17.5 reduced NOx emissions by about 4.7% compared to B17.5 blend. These results indicate that biodiesel nanoemulsion reduced NOx emissions significantly at varying biodiesel and surfactant concentrations. This is due to the effect of vaporization and the sensible heat of water which reduces the local adiabatic flame temperature (Alahmer, Yamin et al. 2010). At constant water concentration, increasing the surfactant concentration in the fuel emulsion reduced the amount of NOx emissions slightly. This observation is due to the high water dispersion with increased surfactant concentration at constant water level.

Carbon monoxide (CO) emissions: The effects of biodiesel emulsions on CO emissions are shown in Figure 12. The result shows that biodiesel nanoemulsion with 7biodiesel produced 2% higher CO emissions than B7 blend under full engine load as it is shown in Figure 12(a). In addition, CO emissions for diesel fuel were 3% and 5% higher than B7 blend and diesel fuel. Biodiesel nanoemulsions with 12.25% biodiesel increased the CO emissions by 2.2% compared to B12.25 as shown in Figure 12(b). Biodiesel nanoemulsions increased the amount of CO emissions about 5% at 17.5% biodiesel compared to biodiesel fuel at the same concentration under full engine load (1200 rpm) shown in Figure 12(c). In general, nanoemulsion fuels increased the CO emissions more than biodiesel fuel at varying biodiesel and surfactant concentrations. This result is due to the capability of water content at biodiesel fuel on absorbed heat of vaporization, which shortened the oxygenation time for the CO gas (Lif and Holmberg 2006). The formula for calculation of CO oxygenation (KCO) is: CO + OH ? CO? + H (Lin and Wang 2004). According to this formula, when the temperature of engine rises, the CO oxygenation rises as well. Presence of water in biodiesel nanoemulsion reduces the engine temperature, which increase the CO emissions compared to biodiesel blend. However, diesel fuel produced higher CO emissions than biodiesel nanoemulsion and biodiesel fuel.

Carbon dioxide (CO2) emissions: The variation of CO2 emissions at various engine speeds for different biodiesel nanoemulsions and biodiesel blends are shown in Figure 13. These results show that biodiesel nanoemulsion with 7% biodiesel increased the CO_2 emissions significantly in comparison to B7 as shown in Figure 13(a). This result may be due to increased amount of oxygen in nanoemulsions (Kass, Lewis et al. 2009). The amount of CO_2 emissions increased with increasing engine loads and reached a peak value at 1600 rpm. Beyond this level, the emissions were decreased with increasing engine load. In addition, biodiesel nanoemulsions with 12.25% biodiesel produced 1% higher CO_2 emissions than B12.25 blend as shown in Figure 13(b). Compared to B17.5 blend, biodiesel nanoemulsions at 17.5% biodiesel increased the CO_2 emissions significantly (Figure 13(c)). One can observe from these results that increasing the surfactant concentration reduced the CO_2 emissions of biodiesel nanoemulsion. Increasing surfactant amount reduce the average water droplet size of biodiesel nanoemulsion.

Soot opacity: The effect of biodiesel nanoemulsion and biodiesel fuel on soot opacity can be seen in Figure 14. Biodiesel nanoemulsions with 7% biodiesel reduced the soot opacity significantly, which is 46% less than the soot opacity measured for B7 blend (Figure 14(a)). This result could be due to the volatility differences between the water and fuel which enhanced the fuel-air mixing in the combustion chamber and reduced the formation of soot (Kannan and Anand 2011). Diesel fuel produced the highest soot opacity compared to the biodiesel nanoemulsion and biodiesel blend. The effects of biodiesel nanoemulsions on soot opacity at 12.25% and 17.5% biodiesel levels were insignificant compared to B12.25 and B17.5 blends as shown in Figure 14(b) and (c). However, biodiesel nanoemulsions reduced the soot opacity at varying biodiesel and surfactant concentrations.

Conclusions

The results of this study indicate that biodiesel nanoemulsions at 7%, 12.25% and 17.5% biodiesel levels reduced the NOx emissions significantly in comparison to B7, B12.25 and B17.5 when fueling the 4-cylinder diesel engine. Increasing biodiesel and surfactant concentrations biodiesel nanoemulsions further decreased the NOx emissions. However, the NOx emissions of biodiesel nanoemulsions were still higher than the certified #2 diesel fuel. Engine torque measured for biodiesel nanoemulsions at 17.5% biodiesel obtained higher torque values than B17.5 blend. Biodiesel nanoemulsions produced higher brake specific fuel consumption (BSFC) than biodiesel fuel. The analysis of CO emissions showed that biodiesel nanoemulsion increased the CO emissions slightly compared to the biodiesel fuel. At 2000 rpm engine speed, increasing the surfactant concentration reduced the CO emissions for the biodiesel nanoemulsions. Biodiesel nanoemulsions reduced the exhaust temperature significantly compared to biodiesel blend. At the same biodiesel concentration levels, biodiesel nanoemulsions reduced the soot opacity significantly. Biodiesel nanoemulsions with high biodiesel concentrations reduce the NOx emissions from diesel engines without the requirement for engine modifications.

References

Agarwal, A. K. (2007). "Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines." Progress in Energy and Combustion Science 33(3): 233-271.

Alahmer, A., J. Yamin, et al. (2010). "Engine performance using emulsified diesel fuel." Energy Conversion and Management 51(8): 1708-1713.

Kannan, G. R. and R. Anand (2011). "Experimental investigation on diesel engine with diestrol-water micro emulsions." Energy In Press, Corrected Proof.

Kass, M. D., S. A. Lewis, et al. (2009). "Utilizing Water Emulsification to Reduce NOx and Particulate Emissions Associated with Biodiesel." 52(1): 5-13.

Leong, T. S. H., T. J. Wooster, et al. (2009). "Minimising oil droplet size using ultrasonic emulsification." Ultrasonics Sonochemistry 16(6): 721-727.

Lif, A. and K. Holmberg (2006). "Water-in-diesel emulsions and related systems." Advances in Colloid and Interface Science 123-126: 231-239.
Lin, C.-Y. and K.-H. Wang (2004). "Diesel engine performance and emission characteristics using three-phase emulsions as fuel." Fuel 83(4-5): 537-545.

- Tables
- Figures

Participation Summary

Educational & Outreach Activities

PARTICIPATION SUMMARY:

Education/outreach description:

- Two papers were presented at the American Society of Agricultural and Biological Engineers (ASABE) 2010 and 2011 Regional and Annual International Meetings. A manuscript about the engine test system is in progress.

Project Outcomes

Project outcomes:

The diesel engine test stand have been used for three undergraduate classes in freshmen, sophomore and senior levels. These courses are introduction to agricultural systems management, internal combustion engines and agricultural equipment and machinery. So far the system was demonstrated to more than 120 students.

Information Products

- An instrumented diesel engine test stand for research and education of alternative fuels (Article/Newsletter/Blog)

This site is maintained by SARE Outreach for the SARE program and is based upon work supported by the National Institute of Food and Agriculture, U.S. Department of Agriculture, under award No. 2019-38640-29881. SARE Outreach operates under cooperative agreements with the University of Maryland to develop and disseminate information about sustainable agriculture. USDA is an equal opportunity provider and employer.