KNOCKING THE NO_x OUT OF BIODIESEL

A demonstration of emulsified B20 fuel sets a new benchmark for a renewable fuel component.

By Thomas Houlihan

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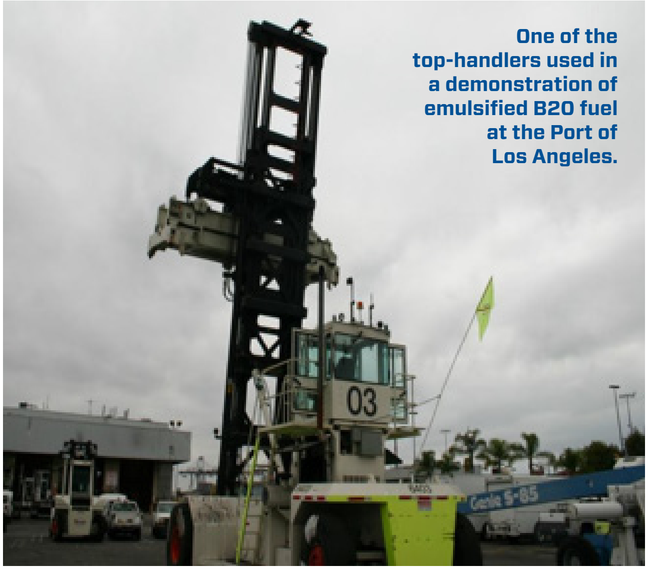
There are plenty of arguments to support the use of biodiesel fuel blends in the U.S. fuel supply. And of course, we have all heard arguments against it. You can make a biodiesel fuel blend from many base biofuel sources—waste animal fat, used cooking oil, and many different kinds of plants. Many of the biodiesel fuel blends used in the United States contain a base biofuel made from soybeans. In other countries, primary sources of base biofuels range from palm oil to sunflowers.

Biodiesel fuel blends deliver benefits in reduced engine emissions of particulate matter. When a base biofuel is burned in a mixture with a conventional petroleum-based diesel fuel, the amount of particulate matter in engine exhaust decreases as the biofuel component of the blend increases.

What's more, since passage of the 2005 Energy Policy Act, the U.S. government has looked toward biofuels—not only biodiesel, but also ethanol, which is mixed with gasoline—as a means of reducing emissions of greenhouse gases. The act set targets for the amount of biofuel that must be mixed with transportation fuels sold in the United States. The target is 7.5 billion U.S. gallons in 2012.

The Energy Independence and Security Act of 2007 extended the target to 36 billion U.S. gallons by 2022. The Renewable Fuel Standard included in the 2007 bill was a notable first step toward reducing global warming pollution from our nation's transportation fuels. By setting standards for renewable fuels, the legislation unlocked the potential to lower global warming pollution from cars and light trucks by as much as 6 percent as of 2022, while displacing up to 15 percent of projected U.S. gasoline consumption.



One of the top-handlers used in a demonstration of emulsified B20 fuel at the Port of Los Angeles.

Of course, no change comes without controversy. Not everyone agrees that the burning of fossil fuels is contributing to global climate change. However, curbing greenhouse gases is not the only reason for considering the use of biodiesel fuel blends. The base biofuels in biodiesel fuel blends also replace petroleum that must be imported to produce fuel. Although they probably will not replace petroleum-based fuels entirely and so create energy independence, base biofuels in biodiesel fuel blends can help reduce demand in the U.S. for imported oil. That could have significant economic as well as political benefits for the country.

BASE BIOFUEL CHARACTERISTICS

Questions have been raised about the efficiency of producing and consuming base biofuels, chiefly: Does production of the base biofuels consume more energy than the fuels will provide? A University of Minnesota study—published in the July 2011 *Proceedings of the National Academy of Sciences*—has shown that both corn grain ethanol and soybean biodiesel produce more energy than is needed to grow the crops and convert them into biofuels. According to the study, soybean biodiesel returns 93 percent more energy than is used to produce it, while corn grain ethanol currently provides 25 percent more energy than production consumes

So far, it looks like a clear win for biodiesel fuel blends.

But there is one side effect of the fuels that presents a serious potential problem: the burning of biodiesel fuel blends produces more nitrogen oxides than the burning of petroleum-based fuels. Most of the biodiesel fuel blends in use today are a mixture of 20 percent biofuel and 80 percent petroleum. Particulate matter emissions from this biodiesel fuel blend, often called a B20 biodiesel fuel, are about 12 percent lower than those from a petroleum-derived diesel fuel. However, NO_x emissions from this regular B20 biodiesel fuel are 2 percent higher than those from a petroleum-derived diesel fuel.

NO_x emissions are precursors in the formation of smog and acid rain. Much has been done to date to reduce NO_x emissions from vehicles and factories. So the question arises: Would increasing the use of biodiesel fuels take us a step backwards in our NO_x emission reduction efforts?

In 2010, my company—Alternative Petroleum Technologies—completed a successful demonstration at the Port of Los Angeles that shows a means of addressing the NO_x issue associated with biodiesel fuels. APT field-tested the use of an emulsified B20 biodiesel fuel—with a 6.5 percent water content—in diesel-powered equipment at the port waterfront. The emulsified B20 biodiesel fuel neutralized the NO_x emissions normally generated by regular B20 biodiesel fuel while decreasing particulate matter emissions by 40 percent.

The demonstration at the port, combined with results from laboratory tests, showed that emulsified biodiesel fuels not only could be used safely in diesel engines, but also that emulsified biodiesel fuels could offer significant benefits for air quality. In order to understand this dual efficacy of emulsified B20 biodiesel fuel, it is necessary to review the principles of fuel combustion and examine how water in emulsified fuel can affect the process.

Combustion of liquid hydrocarbon fuels in a power system requires the fuel to be atomized. Atomization breaks fuel into small droplets that can be more readily ignited. When droplets enter the high-temperature combustion zone, they begin to burn in a charring fashion—from the surface of the droplet inward.

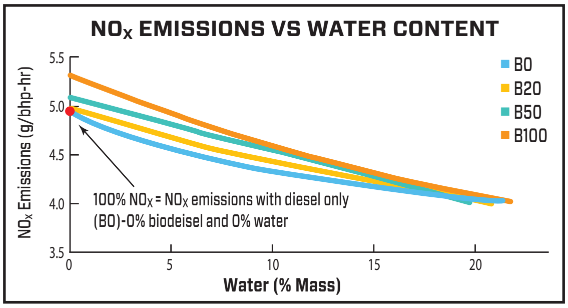
The high pressure of the atomization system, whether it is the injector in a diesel engine or a fuel nozzle in a boiler, gives the fuel droplets high momentum—and therefore a high velocity. As a consequence of this high velocity, burning is often not completed before the fuel leaves the high-temperature combustion zone. As a result, unburned fuel products (particulates) enter into the flow of power system exhaust gases.

Simultaneous with this generation of particulate emissions, the generation of NO_x proceeds from the exposure of nitrogen in the fuel and in the combustion air to the high temperature refining atmosphere of the combustion zone.

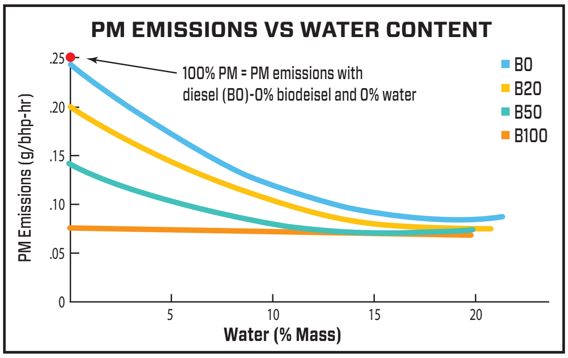
Water in an emulsified fuel produces two profound effects upon combustion. First, water in the atomized fuel immediately evaporates into steam as it enters the combustion zone. In a process that has been called a "micro-explosion," this production of steam disrupts the surrounding fuel medium, which breaks up and forms micro-scale droplets. Breaking into smaller droplets increases the total surface area of the fuel mass subjected to combustion. Hence, the chance of unburned particles of fuel oil escaping from the combustion zone is significantly reduced, and the production of particulate emissions is thereby decreased.

The second effect of water on the combustion process arises from the high heat capacity of the water in the emulsified fuel that tends to decrease the temperature of the combustion zone. This decrease in temperature leads to a less energetic oxidation of nitrogen in the fuel and in the combustion air and therefore inhibits NO_x generation. These determinations on NO_x reduction were realized in several applications of emulsified diesel fuel products that were based upon Alternative Petroleum Technologies' emulsion technology developments.

Believing that emulsion technology could likewise alleviate the NO_x increases shown in the combustion of biodiesel fuels, APT applied to the Technology Advancement Program of the Ports of Long Beach/Los Angeles to test the hypothesis.



Screening tests of emulsified fuels at SwRI found that NO_x emissions for ultra-low sulfur diesel and various biodiesel blends decreased as the water content increased.



Particulate matter emissions for various emulsified fuels studied by SwRI decreased with additional water content to about 20 percent by mass—except for B100.

The subsequent effort was accomplished in three phases. The first two phases involved laboratory testing of regular and emulsified biodiesel fuel blends. The last phase featured real-time operations with emulsified biodiesel fuels at the Port of Los Angeles waterfront.

LABORATORY TESTS

First, fuel screening tests were conducted at the Southwest Research Institute laboratories in San Antonio, Texas. The test engine was a Detroit Diesel (DDEC-60) inline, six-cylinder engine rated for 365 hp at 1,800 rpm. It was turbocharged and used a laboratory water-to-air heat exchanger for a charge air intercooler.

A series of test fuels—ranging from an ultra-low sulfur diesel fuel (designated B0) to a set of biodiesel fuel blends (B6, B20, B50, B100)—were emulsified with various water contents (2.7 percent to 18.5 percent by volume)—and run in the test engine, which was subjected to a Federal Test Procedure loading pattern on an eddy-brake dynamometer. Engine emissions (NO_x, PM, THC, CO, and CO_2) were monitored continuously throughout the FTP test cycles. Twenty five test runs were recorded during the fuel screening test period, each one in triplicate, for a total of 75 individual test runs.

Test data showed that NO_x emissions for emulsified biodiesel fuels diminished as the water content increased and converged to a value of 4 g/bhp-hr for a 20 percent water content. Likewise, PM emissions for emulsified biodiesel fuels decreased with increasing water content and converged asymptotically to around 0.07 g/bhp-hr for almost all the fuels. An exception was neat biodiesel fuel, B100, for which PM emissions were so low that the addition of water had virtually no effect.

Previous operations with high-water content (e.g., 20 percent) emulsified diesel fuels showed that the power loss experienced with such fuels was prohibitive. Hence, in the spirit of doing no harm to the environment, a 6.5 percent water content (by mass) was chosen for use in subsequent field demonstrations of emulsified B20 fuels. This water content insured that the NO_x emissions of emulsified B20 fuels were equal to those of ultra-low sulfur diesel fuels and thus effectively neutralized the NO_x emission increases normally experienced with regular B20 fuels.

Additional testing showed that the inclusion of a diesel oxidation catalyst unit further decreased PM emissions and virtually eliminated hydrocarbon emissions. As such, the screening tests inherently proved that three technologies—fuel emulsion, biodiesel (B20) fuel, and a DOC after-treatment unit—could be effectively combined to significantly decrease engine emissions without causing harm to an operating engine.

A second study was conducted at the Olson-EcoLogic Engine Testing Laboratories in Fullerton, Calif. The test engine was a Tier 2 model year 2004 Cummins QSM 11C engine rated for 330 hp at 2,100 rpm. The EPA and ARB standards for this engine are 4.9 g/bhp-hr for NO_x emissions and 0.15 g/bhp-hr for PM emissions. The same model engine would be used in the demonstrations at the waterfront in Phase 3.

Using pure diesel fuel as a baseline of 100 percent, PM emissions fell stepwise to 81 percent with a regular B20 fuel, to 71 percent with a 6.5 percent emulsified B20 (EB20) fuel, and to 60 percent with an EB20 fuel and an installed DOC unit. This progression indicates that biodiesel fuel, water emulsion, and DOC after-treatment technologies are truly complementary PM reduction techniques.

ON THE WATERFRONT

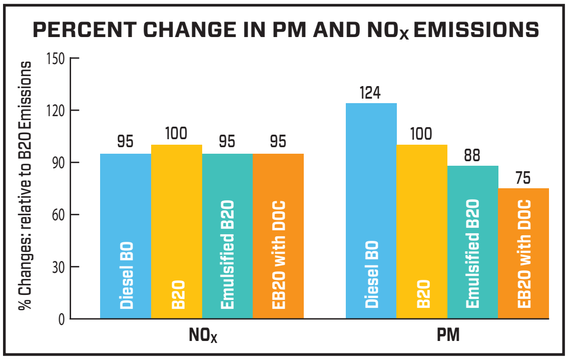
The waterfront demonstration compared the performance of three top-handler units operating on regular B20 fuel, three units operating on emulsified B20 fuel, and one on emulsified B20 fuel with a diesel oxidation catalyst unit. The demonstration began on August 12, 2010, when biodiesel fuel was loaded into three 2008 model Taylor top handler units at the Western Basin Container Terminal in the Port of Long Beach. Each unit was powered by a 330 hp Cummins QSM11 diesel engine.

Regular fueling practices were maintained during all subsequent operations at the waterfront. The three units operated a total of 697 hours over 27 days and consumed 2,908 gallons of soy-based B20 biodiesel. That averaged 4.17 gallons per hour, 4.3 percent more than the average of 4.0 gallons per hour for ultra-low sulfur diesel fuel use reported for the port top handler fleet of 140 vehicles.

Operations using emulsified B20 fuel began on Sept. 3. For this demonstration, the three top handlers ran 2,742 hours over 118 days and used 12,300 gallons of soy-based emulsified B20 fuel. That comes to 4.48 gallons per hour of a fuel that was 6.5 percent water by mass. Adjusted for water's heavier specific gravity and for the presence of the emulsion additive, total consumption of B20 fuel was 11,316 gallons, or an average of 4.12 gallons per hour. That is only 3 percent more than the average of 4.0 gallons per hour for the port's top handler fleet.

By achieving NO_x neutrality, emulsified biodiesel fuel allowed the full benefits of a biofuel to be realized. Not only were PM emissions reduced, but so were CO_2 emissions. Using the emissions calculator at the National Biodiesel Board website, it was found that 12,300 gallons of emulsified B20 fuel (containing 11,316 gallons of regular B20 fuel) reduced total carbon dioxide emission levels on the order of 36,500 pounds during the demonstration period of 118 days. Extending the calculation to a period of one year, the total reduction in CO_2 emissions for the three top-handlers would come to 112,867 pounds.

The introduction of water into the combustion process by the utilization of emulsified fuels results in the generation of a "triple crown" of benefits—the reduction in emissions of NO_x, particulate matter, and greenhouse gases. These results suggest that emulsified fuel technology is an effective and cost-beneficial emission-reduction technology. It is readily available to accommodate future requirements for hydrocarbon emissions and greenhouse gas emissions reductions.



NO_x emissions (left) of emulsified B20 were on par with those of ultra-low sulfur diesel. There was a stepwise reduction in PM emissions.

The introduction of water into the combustion process has an added benefit from an energy efficiency viewpoint for boiler systems. The added heat content of the water introduced into the combustion zone by an emulsified fuel means that the exhaust gases of the combustion process are more "energetic" than those of conventional fuels. Hence, as these more "energetic" combustion gases traverse the boiler heat transfer zones, they are able to transmit more heat by convection to the steam generating tubes resulting in an increase in fuel efficiency. This enhancement of system fuel efficiency leads to a reduction in hydrocarbon emissions and also to less formation of carbon dioxide.

Alternative Petroleum Technologies is very enthusiastic about the results of the port demonstration. However, no one is suggesting, of course, that the country should start a headlong conversion of its transportation system to biofuels. As we know, market forces—which include everything from the hard reality of production costs to arbitrary preferences based on old habits—will prevent that kind of drastic change any time soon. It probably would not be technically advisable either, as long as biodiesel continues to encounter problems involving cold weather performance and material compatibility. It is noteworthy that with its 2011 models, GM became the last of the Big Three to announce that new diesel engines would be fully compatible with a B20 biodiesel fuel.

Considering the number of trucks, trains, and other diesel-powered vehicles in use, biodiesel fuels—with a little twist of water—have the potential to make a significant contribution to improving both the air quality and perhaps the national economy of the United States. ■

TO READ MORE

The following publications discuss in more detail the combustion of emulsified fuels.

"Emulsified Biodiesel Fuel Effects on Regulated Emissions," P. Grimes, W. Hagstrand, A. Psaila, J. Seth, J. Waldron. DIESELNET Report, http://www.dieselnet.com/papers/1112grimes.pdf.

"Combustion and Micro-Explosion of Freely Falling Multi-Component Droplets," C.H. Wang, Q. Liu, C.K. Law. *Combustion and Flame* 56, 175-197 (1984).

"Combustion Characteristics of Water-in-Oil Emulsion Droplets," C.K. Law, C.H. Lee, N. Scrinivasan. *Combustion and Flame* 37, 125-143 (1980).

"Maximizing the Effectiveness of Water Blended Fuel in Reducing Emissions by Varying Injection Timing or Using an After-Treatment Device," D.A. Langer, N.K. Petek, E.A. Schiferl. SAE Paper No. 2001-01-0513.

"Comparative Assessment of Shell Aquadiesel," T. Beer, T. Grant, D. Olaru, H. Hatson. CSIRO Report H90A/2/F3.6X, Australian Greenhouse Office, December 2003.

TVA Technology Advancements Report, "Colbert Combustion Turbine Unit Number 1: A-55 Clean Fuels Test Burn," 4 December 1997.

"Verification Testing of Emissions From the Combustion of A-55 Clean Fuels in a Fire-Tube Boiler," C.A. Miller. U.S. Environmental Protection Agency Report EPA-600/R-98-035, April 1998.

"A-55 Emulsion Reburning Pilot Scale Tests and Design Studies," P.K. Maly, D.K. Moyeda, M.S. Sheldon, B.A. Folsom. Energy and Environmental Research Corp. Report, 13 August 1998.

(NOTE: A-55 was a predecessor company to Alternative Petroleum Technologies.)