PROCESSING, CHARACTERIZATION, AND PERFORMANCE OF EIGHT FUELS FROM LIPIDS

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ABSTRACT. *Test quantities of ethyl and methyl esters of four renewable fuels were processed, characterized and performance tested. Canola, rapeseed, soybean oils, and beef tallow were the feedstocks for the methyl and ethyl esters. A complete set of fuel properties and a comparison of each fuel in engine performance tests are reported. The study examines short term engine tests with both methyl and ethyl ester fuels compared to number 2 diesel fuel (D2). Three engine performance tests were conducted including an engine mapping procedure, an injector coking screening test, and an engine power study.*

The gross heat contents of the biodiesel fuels, on a mass basis, were 9 to 13% lower than D2. The viscosities of biodiesel were twice that of diesel. The cloud and pour points of D2 were significantly lower than the biodiesel fuels. The biodiesel fuels produced slightly lower power and torque and higher fuel consumption than D2.

In general, the physical and chemical properties and the performance of ethyl esters were comparable to those of the methyl esters. Ethyl and methyl esters have almost the same energy. The viscosity of the ethyl esters is slightly higher and the cloud and pour points are slightly lower than those of methyl esters. Engine tests demonstrated that methyl esters produced slightly higher power and torque than ethyl esters. Fuel consumption when using the methyl and ethyl esters is nearly identical. Some desirable attributes of the ethyl esters over methyl esters were: significantly lower smoke opacity, lower exhaust temperatures, and lower pour point. The ethyl esters tended to have more injector coking than the methyl esters, and the ethyl esters had a higher glycerol content than the methyl esters.

Keywords. *Fuels, Vegetable oils, Transesterification.*

Vegetable oil as an alternative fuel has been under study at the University of Idaho since 1979 (Peterson et al., 1990). Since then researchers at Idaho have pioneered the use of rapeseed oil as a diesel fuel substitute. Although short term tests using neat vegetable oil showed promising results, longer tests led to injector coking, more engine deposits, ring sticking, and thickening of the engine lubricant. This experience led to the use of modified vegetable oil as a fuel. Although there are many ways and procedures to convert vegetable oil into a diesel-like fuel, the transesterification process was found to be the most viable oil modification process for Idaho researchers.

Transesterification is the process of using an alcohol (e.g., methanol or ethanol) in the presence of a catalyst, such as sodium hydroxide or potassium hydroxide, to chemically break the molecule of the raw renewable oil into methyl or ethyl esters of the renewable oil with glycerol as a by-product. The University of Idaho Department of Biological and Agricultural Engineering operates an oil extraction plant of 19 L/h capacity and a batch esterification reactor of 750 L capacity. Recipes have been developed for producing both ethyl and methyl esters of renewable oils. Fuel tests currently performed by the Department of Biological and Agricultural Engineering are heat of combustion, viscosity, flash point, pour point, cloud point, density, specific gravity, API gravity, residual catalyst, and alcohol content. Facilities are available to conduct fuel performance evaluation in engines, Engine Manufacturer's Association (EMA) engine durability tests, injector coking tests, and vehicle performance tests. Transesterified vegetable oils have proven to be a viable alternative diesel engine fuel with characteristics, based on the above mentioned tests, similar to those of diesel fuel.

LITERATURE REVIEW

The emergence of transesterification can be dated back to as early as 1846 when Rochleder described glycerol preparation through ethanolysis of castor oil (Formo, 1954). Since that time alcoholysis has been studied in many parts of the world. Other researchers have investigated the important reaction conditions and parameters on the alcoholysis of triglycerides, such as fish oils, soybean, rapeseed, cottonseed, sunflower, safflower, palm, peanut and linseed oils, with several different catalysts, at room temperature and with applied heat, to produce ethyl and methyl esters (Chancellor and Reubach, 1985; Clark et al., 1984; DuPlessis and DeVilliers, 1985; Feuge and Gros, 1949; Freedman and Pryde, 1982; Freedman et al., 1984; Harrington and D'Arcy-Evans,

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1985; Kusy, 1982; Lago et al., 1985; Nye and Southwell, 1983; Peterson and Scarrah, 1984; Romano, 1982; Schwab et al., 1987; Stern et al., 1985; Stern et al., 1986). Lago et al. (1985) proposed the use of ethanol for both the oil extraction and the esterification process. Clark et al. (1984) transesterified soybean oils into ethyl and methyl esters, and compared the performances of the fuels with diesel. DuPlessis and DeVilliers (1985) have produced both methyl and ethyl esters of degummed sunflower oil using NaOH catalyst. Stern et al. (1986) worked on a process with at least two esterifications. The first esterification was catalyzed by an acidic chemical and the second by an alkali. Almost all the investigators indicated that for a successful transesterification, preheating and/or heating the mixture of oil, alcohol, and catalyst during the reaction was necessary to get satisfactory results. It is the authors' conclusion that the application of heat during the reaction is not economically sound because of the additional cost and reduced energy efficiency.

Nye and Southwell (1983) were the only workers to report a successful process for the transesterification of rapeseed oil at room temperature by systematically optimizing the other variables. In Idaho, a considerable number of graduate students have investigated the optimization of the reaction variables — temperature, agitation time, catalyst amount, ratio of alcohol to rapeseed oil, and degree of lipid conversion (Bam, 1991; Feldman, 1991; Jo, 1984; Madsen, 1985; Melville, 1987; Mosgrove, 1987; Perkins et al., 1991). Based on their bench-scale results, workers at the UI Biological and Agricultural Engineering Department developed a small pilot plant system for rapeseed methyl and ethyl ester production (Peterson et al., 1991). A separate alcohol-catalyst mixer, made of a 208 L plastic barrel, serves as an accessory to the reactor. The reactor and the oil press constitute the farm-scale rapeseed oil and Biodiesel processing plant.

The Dangerous Properties of Industrial Materials (Sax, 1975) reports that handling methanol is hazardous. The statement applies to those involved in handling the ethanol and methanol and is not meant that the methyl ester is more hazardous than the ethyl esters. Chase (1995) reports that there are food grade sources of methyl esters used in food processing.

Ethanol is a preferred alcohol in this process compared to methanol because it is derived from agricultural products and is renewable and biologically less objectionable in the environment. Success of rapeseed ethyl ester (REE) production would mean that Biodiesel's two main raw materials would be agriculturally produced, renewable and environmentally friendly.

ENGINE PERFORMANCE TESTS

In a summary of 22 short term engine tests conducted at 12 locations worldwide (Peterson, 1986) in which neat vegetable oil was compared to diesel as a fuel, peak engine power on the vegetable oil fuels ranged from 91 to 109% of that produced when the same engine was operated with diesel fuel. In these tests, 16 of the 22 reported peak power equal to or exceeding that when the engines were operated on diesel. Fuel consumption was generally slightly higher, reflecting the reduced energy content of the vegetable oil. Thermal efficiencies are also generally reported to be slightly higher than for diesel fuel. Peterson et al. (1987) ran a series of short term engine tests to evaluate the effects of transesterification of winter rapeseed oil on injector coking. The results showed the transesterification treatment to decrease the injector coking to a level significantly lower than that observed with no. 2 diesel.

Einfalt and Goering (1985) evaluated the methyl ester of soybean oil, Wagner et al. (1984) investigated three soybean oil esters (methyl, ethyl, and butyl), Kaufman and Ziejewski (1984) evaluated methyl ester of sunflower oil, and Zhang et al. (1988) evaluated methyl esters of winter rape oil in 200 h EMA test cycles. They concluded that the performance of the esters of vegetable oil did not differ greatly from diesel. The brake power was nearly the same as with diesel fuel, while the specific fuel consumption was higher than diesel. Based on crankcase oil analysis, engine wear rates were low but some oil dilution did occur. Carbon deposits inside the engine were normal with the exception of intake valve deposits.

Although most researchers agree that vegetable oil ester fuels are suitable for use in compression ignition engines, a few contrary results have also been obtained. Vinyard et al. (1982) reported an extensive coking problem while using degummed sunflower ethyl ester. The ester produced unacceptable coking levels after only 50 h of operation under part load, even when diluted with up to 30% diesel fuel.

The results of these studies point out that most vegetable oil methyl esters are suitable as diesel substitutes but that more long term studies are necessary for commercial utilization to become practical.

UNIVERSITY OF IDAHO 1000 HOUR TESTS

Tests at the University of Idaho (Perkins et al., 1991) have shown that engine durability when using RME as fuel was equivalent to diesel fuel in direct injection diesel engines. Three engines, one fueled with 100% methyl ester of winter rapeseed oil (100 RME), one with a 50% number 2 diesel, 50% methyl ester (50RME-50D2) of winter rapeseed oil blend, and one with a reference fuel of 100% number 2 diesel (100 D2), were investigated in both 200 h Engine Manufacturer's Association (EMA) test cycles (Zhang et al., 1988) and in 1000 h test cycles by extending the EMA test procedure for alternate fuels (EMA, 1982). It was found that methyl ester of winter rapeseed oil was equivalent to number 2 diesel when compared on the basis of long term performance and engine wear. The primary factors which were evaluated included engine brake power and torque, injector tip coking, and engine component wear (based on oil analysis). The only noticeable adverse effect of the ester fuel was a slight decrease in engine oil viscosity.

OBJECTIVES

1. Produce test quantities of ethyl and methyl esters of rapeseed oil, soybean oil, canola, and tallow using the two procedures currently developed.
2. Determine the complete set of fuel specifications on each of the fuels according to the requirements set forth in the ASAE Engineering Practice, ASAE EP 552.
3. Compare the performance of each of these fuels in short term engine performance tests.

MATERIALS AND METHODS

Seventy gallons of each of the esters were produced using the process developed by University of Idaho researchers. The feedstocks for these fuels were as follows: rapeseed from Dwarf Essex variety seed; canola from Stonewall variety seed; beef tallow purchased from Iowa Beef Products in Kennewick, Washington; and soybean oil purchased from Foodservices Brokerage Co. in Spokane, Washington. In addition to these eight fuels, 75 gallons of methyl soyate were purchased from Interchem, Inc., Overland Park, Kansas (Midwest Biofuels). The rapeseed and canola oils were expelled at the University of Idaho's Agricultural Engineering farm scale process facility and were used in the as-expressed and filtered condition with no degumming or winterization. The soybean oil and beef tallow were food grade and the processing was not stated. Each fuel, excluding the methyl soyate from Interchem, was processed at this facility. Phillips 66 Company low sulfur diesel reference fuel was used as the baseline fuel.

The nomenclature for these fuels is as follows: R — rapeseed, C — canola, T — tallow, S — soybean, with the following letters ME for methyl ester and EE for ethyl ester. MWF represents Midwest Biofuels methyl soyate, and D2 — Phillips low sulfur diesel reference fuel.

FUEL CHARACTERIZATION

The fuels were characterized by evaluating the parameters required in ASAE EP 552. The tests for specific gravity, viscosity, cloud point, pour point, flash point, heat of combustion, total acid value, catalyst, and fatty acid composition were performed at the Analytical Lab, Department of Biological and Agricultural Engineering, University of Idaho. The boiling point, water and sediment, carbon residue, ash, sulfur, cetane number, copper corrosion, Karl Fischer water, particulate matter, iodine number, and the elemental analysis were performed at Phoenix Chemical Labs, Chicago, Illinois. The HPLC and titration analysis for total and free glycerol, percent of oil esterified, free fatty acids, and mono-, di-, and trigylicerides were performed by Diversified Labs Inc., Chantilly, Virginia.

ENGINE PERFORMANCE TESTS

All engine performance tests were conducted in the engine performance lab at the University of Idaho. The equipment used and tests conducted are described below. The short term tests were performed with an in-line four cylinder John Deere 4239T turbocharged, direct injected diesel engine. It has a displacement of 3.9 L (239 in.^{3}), a high idle of 2,650 rpm, 61 kW (82 hp) at 2,500 rpm, and 290 Nm (214 ft lbf) torque at 1,500 rpm. It is attached to a General Electric 119 kW (159 hp) cradle dynamometer. The engine was not modified in any way for use with the renewable fuels.

A Hewlett Packard data acquisition unit (model 3497-A) and a personal computer were used to collect data every thirty seconds for each of the tests. Torque, power, opacity, fuel consumption, and temperatures (oil, exhaust, inlet air, ambient air, and exhaust at the opacity meter) were monitored throughout the testing.

FUEL FLOW EQUIPMENT

The fuel delivery and return lines were adapted with quick couplers for fast and clean changing of the different fuels. Individual 19 L (5 gal) metal fuel tanks were modified with a fuel filter and flexible fuel lines that could be connected to the engine quick couplers. Fuel flow rate was determined with an electric, 45.4 kg (100 lb) scale accurate to 23 g (0.05 lb) with RS232 capability.

OPACITY METER

A Telonic Berkley model 200 portable opacity meter was connected to the data acquisition unit. The opacity meter consists of a light source positioned on one side of the exhaust stream and a photo resistor mounted on the opposite side. The meter provides an output voltage ranging from 0 to 1.00 V. One hundred percent opacity (1.0 V) corresponds to no light transmission whereas 0% opacity corresponds to complete light transmission. The uncertainty of this reading is ± 1% opacity.

Smoke density is a function of smoke particles per unit gas volume, the size distribution of the smoke particles, and the light absorption and the scattering of the particles. Opacity is converted to smoke density with the use of the Beer-Lambert Law relationships between transmittance and the effective optical length. Smoke density has units of m^{-1} and should be reported at a standard temperature of 100°C for comparative purposes (Proposed SAE J1667).

INJECTOR COKING

The injector coking tests were performed using the procedure described by Korus et al. (1985). The engine was operated for 10 min at each interval for data collection.

TORQUE TESTS

The torque tests were performed with the engine operating at 2,600 rpm to 1,300 rpm in 100 rpm increments with the same data collection procedure as previously described. The engine was operated for 2 1/2 min at each interval for data collection.

MAPPING ENGINE PERFORMANCE

The engine mapping tests were performed using the procedure described in "Procedure for Mapping Engine Performance-Spark Ignition and Compression Ignition Engines" (SAE J1312, 1990). The mapping tests were performed at 2,500, 2,250, and 2,000 rpm with loadings of 100, 75, 50, 25, and 0% of maximum power. The engine was operated for 5 min at each data collection interval.

ENGINE WARM-UP AND COOL-DOWN

Each test started with a warm-up and ended with a cool-down period. The warm-up period consisted of a two min interval on D2 at low idle. Then there was an eight minute interval with the fuel to be tested. During this eight minute period there is a gradual increase in load and rpm to the rated power and load. The cool-down period consisted of 10 min on D2 at low idle. For both the warm-up and cool-down periods the return fuel line was placed into a separate container.

EXPERIMENTAL DESIGN

The engine performance data were collected using a randomized complete block experimental design. Each fuel was tested once in each block in random order for each of the three blocks. This resulted in a total of 30 each of the injector coking tests, torque tests, and fuel mapping studies.

FUEL PREPARATION

The eight Biodiesel fuels were processed in a batch type reactor. The methyl ester process utilized 100% molar excess alcohol (preferably absolute or 100% pure), or a molar ratio of 6:1 alcohol to oil ratio. Based on the amount of input oil by weight, 1.1% of potassium hydroxide (KOH) was used. The following equations were used for the quantities processed:

$$\text{MeOH} = 0.225 \times \text{Oil} \qquad \text{KOH} = \text{Oil}/100$$

where

Oil = desired amount of oil (L)
MeOH = amount of methanol needed (L)
KOH = amount of potassium hydroxide required (kg)

The ethyl ester process utilized 70% stoichiometric excess ethanol (absolute, 100% pure), or a molar ratio of 5.1:1 ethanol to oil ratio. Based on the amount of input oil by weight, 1.3% of KOH was used. The following equations were used for the quantities processed:

$$\text{EtOH} = 0.2738 \times \text{Oil} \qquad \text{KOH} = \text{Oil}/85$$

where

Oil = desired amount of oil (L)
EtOH = amount of ethanol needed (L)
KOH = amount of potassium hydroxide required (kg)

The following transesterification procedure is for the methyl and ethyl ester production. The catalyst is dissolved into the alcohol by vigorous stirring in a small reactor. Pure methanol is very flammable and its flame is colorless when ignited therefore the use of explosion proof electrical equipment is required. The oil is transferred into the biodiesel reactor and then the catalyst/alcohol mixture is pumped into the oil and the final mixture stirred vigorously for two hours. A successful reaction produces two liquid phases: ester and crude glycerol. Crude glycerol, the heavier liquid, will collect at the bottom after several hours of settling. Phase separation can be observed within 10 min and can be complete within two hours after stirring has stopped. Complete settling can take as long as 20 h. After settling is complete, water is added at the rate of 5.5% by volume of the oil and then stirred for 5 min and the glycerol allowed to settle again. After settling is complete the glycerol is drained and the ester layer remains. Washing the ester is a two step process which is carried out with extreme care. A water wash solution at the rate of 28% by volume of oil and 1 g/L of tannic acid water is added to the ester and gently agitated. Air is carefully introduced into the aqueous layer while simultaneously stirring very gently. This process is continued until the ester layer becomes clear. After settling, the aqueous solution is drained and water alone is added at 28% by volume of oil for the final washing.

RESULTS

A total of over 150 h were logged on the John Deere diesel engine and 2250 L of fuel were consumed during the performance testing.

FUEL CHARACTERIZATION

A complete summary of the fuel characterization data is listed in table 1 for each of the fuels used in this study. Comments on each parameter would be excessively lengthy; however, some deserve attention.

Viscosity. The biodiesel fuels had viscosity from 1.3 to 2.1 times that of D2. SME and MWF had the lowest viscosities of the biodiesels and RME and REE the highest viscosities.

Cloud and Pour Point. All the biodiesels have higher cloud and pour points than D2. RME and REE had the lowest pour points only 1 and 5°C, respectively, higher than D2 while the tallow esters were 28 and 32°C higher than D2. The soy esters were 13 to 19°C higher than D2.

Sulfur. All of the biodiesel fuels contain considerably less sulfur than even the low sulfur diesel fuel used for comparison. The biodiesel fuels were 0.55 to 0.22 that of D2.

Heat of Combustion. All of the biodiesel fuels were lower in heat content than D2 by an average of 11.8% on a mass basis. Since the biodiesel fuels have a 4.1% higher specific weight, the energies average 8.2% lower on a volume basis.

Percent Esterified. The methyl esters were 97.5% esterified while the ethyl esters were only 94.3% esterified. SME and RME had the highest esterified values of the methyl esters and TEE the highest of the ethyl esters. CEE was the lowest level.

Total Glycerol. Glycerol levels were consistently higher than the 0.25% allowed in the proposed ASTM standard based on the analysis provided. SEE was highest at 1.88% and TME lowest at 0.6%. The average total glycerol was 0.87% for the methyl esters and 1.4% for the ethyl esters. Note that the commercial biodiesel had a total glycerol content of 1.25%

Alcohol and Catalyst. All of the biodiesel fuels had less than 1% alcohol. Residual catalyst varied form 11 to 36 parts per million (ppm).

A hypothetical molecular weight (table 2) was calculated for each of the biodiesel fuels. The fatty acid compositions and the theoretical formulas were determined using a weighted average of the fatty acid composition.

INJECTOR COKING

A visual inspection of the injector tips would indicate no difference between the biodiesel fuels compared to when tested on diesel fuel. Typical injector coking photographs are shown in figure 1. A worst case with biodiesel is a level of 3.0 shown in the figure. Figure 2 shows the injector coking for each fuel. The data is an average of three runs, four injectors for the four cylinder engine, and two orientations for a total of 24 samples averaged for each fuel. The overall injector coking is low, especially when compared with older tests that included runs with raw vegetable oil.

Table 3 is a summary of the injector coking, viscosity, percent oil esterified, total glycerol, and heat of combustion data for the 10 fuels used in these tests. Linear regression (Steele and Torrie, 1960) was used to compare each of these parameters with the others. It was hypothesized that the total glycerol would be responsible for an increase in injector coking, however the r-squared value (coefficient of determination) was less than 0.01 between these

Table 1. Fuel characterization data

	RME	REE	CME	CEE	TME	TEE	SME	SEE	MWF	D2
Fuel specific properties										
Specific gravity, 60/60	0.8802	0.876	0.881	0.878	0.874	0.869	0.886	0.881	0.885	0.8495
Viscosity, cSt @ 40°C	5.65	6.17	4.754	4.892	4.814	5.036	3.891	4.493	3.9	2.98
Cloud point (°C)	0	–2	1	–1	16	14	3	0	–1	–12
Pour point (°C)	–15	–15	–9	–6	14	12	–3	–3	0	–20
Flash point (°C)	179	185	163	177	160	185	188	171	185	87
Boiling point (°C)	347	273	334	346	313	327	339	357	229	186
Water and sediment (% vol.)	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005
Carbon residue (% mass)	0.08	0.06	0.065	0.07	0.056	0.052	0.068	0.071	0.082	0.16
Ash (% mass)	0.002	0.002	0.002	0	0.001	0	0	0	0.001	0.002
Sulfur (% wt)	0.012	0.014	0.009	0.009	0.01	0.009	0.012	0.008	0.02	0.036
Cetane number	61.8	64.9	57.9	59.6	72.7	72.4	54.8	52.7	58.4	46
Heat of combustion, gross (MJ/kg)	40.54	40.51	39.90	40.03	39.92	40.09	39.77	39.96	39.61	45.42
Copper corrosion	1A	1A	1 A	1A	1A	1A	1A	1A	1A	1A
Karl Fischer water (ppm)	757	761	1087	1119	1142	1005	1062	1200	759	38
Particulate matter (mg/L)										
Total	1.1	1.9	0.9	1.1	1.9	0.8	0.9	1.1	15.65	0.9
Non-combustible	< 0.1	0.9	0.1	0.1	0.9	< 0.1	< 0.1	0.1	2.15	< 0.1
Elemental analysis										
Nitrogen (ppm)	10	11	12	12	9	10	1	2	5.7	
Carbon (%)	78.7	76.83	77.67	76.71	76.42	76.58	82.44	83.4	77.54	86.67
Hydrogen (%)	12.66	11.8	12.57	11.38	12.59	11.57	12.9	11.87	11.64	12.98
Oxygen (%) (by difference)	9.22	11.36	9.75	11.9	10.98	11.84	4.65	4.72	10.82	
Acid value	0.128	0.097	0.104	0.141	0.114	0.096	0.111	0.1	0.18	0.002
Iodine number	91.9	96.7	102.8	101.6	49.1	47.2	103.6	43	81.3	9
Ester specific properties										
Percent esterified	98.02	94.75	96.35	92.31	97.81	95.62	98.17	94.54	97.11	
Free glycerol (% mass)	0.4	0.72	0.71	0.52	0.2	0.2	0.62	0.7	0.42	
Total glycerol (% mass)	0.86	0.93	0.87	1.18	0.6	1.42	0.75	1.88	1.25	
Free fatty acids (% mass)	0.57	0.58	0.42	0.42	0.37	0.39	0.6	0.21	0.37	
Monoglycerides (% wt)	0	0.58	0.78	1.55	0.22	1.42	Trace	1.85	1.76	
Diglycerides (% mass)	1.35	1.33	1.88	1.54	0.81	1.68	1.41	2.02	0.65	
Triglycerides (% mass)	0.45	2.17	0.76	2.42	1.16	0.99	0.05	1.38	0.05	
Alcohol content (% mass)	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	
Catalyst (μg/g)	11	12	24	26	30	28	21	36	21	
Fatty acid composition (%)										
Palmitic (16:0)	2.7	2.6	4.0	4.0	23.3	23.6	9.9	10.0	10.1	
Stearic (18:0)	0.9	0.9	2.4	2.4	17.9	18.0	3.8	3.8	3.8	
Oleic (18:1)	12.6	12.8	65	65.1	38.0	38.5	19.1	18.9	20.5	
Linoleic (18:3)	12.1	11.9	17.3	17.4	0.0	0.0	55.6	55.7	56.1	
Linolenic (18:3)	8.0	7.7	7.8	7.6	0.0	0.0	10.2	10.2	8.8	
Eicosenoic (20:1)	7.4	7.3	1.3	1.3	0.0	0.0	0.2	0.2	0.0	
Behenic (22:0)	0.7	0.7	0.4	0.4	0.0	0.0	0.3	0.3	0.0	
Erucic (22:1)	49.8	49.5	0.1	0.2	0.0	0.0	0.0	0.0	0.0	

Table 2. Hypothetical formulas, apparent molecular weights and fatty acid compositions of the fuels tested

Fuel	Hypothetical Formula	Molecular Weight
CEE	$C_{20}H_{37}O_2$	309.4
CME	$C_{19}H_{35}O_2$	295.3
MWF	$C_{19}H_{34}O_2$	292.2
REE	$C_{22}H_{43}O_2$	340.1
RME	$C_{21}H_{38}O_2$	323.4
SEE	$C_{20}H_{36}O_2$	306.4
SME	$C_{19}H_{34}O_2$	292.4
TEE	$C_{19}H_{38}O_2$	300.8
TME	$C_{18}H_{36}O_2$	286.7

parameters. The most significant values in this comparison for the biodiesel fuels were heat of combustion and viscosity ($r^2 = 0.9$), and the molecular weight and heat of combustion ($r^2 = 0.78$) (see fig. 3). The r^2 values for injector coking versus molecular weight and viscosity were 0.61 and 0.68, respectively.

TORQUE TESTS

Figure 4 compares power and torque of the ethyl esters and diesel fuel and figure 5 compares power and torque of the methyl esters versus diesel fuel. The biodiesel fuels on the average decrease power by 4.9% compared to that of diesel at rated load.

Peak torque is less for the ester fuels than for diesel but occurs at lower engine speed and generally the torque curves are flatter. It is interesting to note that at 1,700 rpm the engine torque is reduced 5% while at 1,300 rpm it is reduced only 3%. Evidently the biodiesel fuel combustion is enhanced at the increased time provided by the lower engine speed, however, thermal efficiency was not improved at the same rpm.

Exhaust temperatures for ethyl ester biodiesel, methyl ester biodiesel, and d2 are shown in figure 6. Ethyl esters had slightly lower exhaust temperatures than methyl esters. Smoke density was calculated using the data collected during the torque test for each fuel. Figure 7 shows smoke density at a standard temperature of 100 °C at five different loadings. Smoke density decreased by an average of 75%

Figure 1–Typical injector coking photographs, clean (top), diesel (second), biodiesel average (third), and worst case biodiesel (bottom). Sample coking indices are shown: clean (top), 1.0 (second), 2.2 (third), and 3.0 (bottom).

for the biodiesel fuels compared to D2. TME and SME produced the least smoke.

MAPPING ENGINE PERFORMANCE

Table 4 presents the engine mapping data for all the fuels at 3 engine rpms in accordance with SAE J1312. This table shows the power (kW) and the actual fuel consumption (g/s). A visual example of the results at each RPM is shown for CEE in figure 8.

Figure 9 is a summary of the brake mean effective pressure (bmep) versus fuel consumption for all of the biodiesel fuels compared to D2. The data points are shown for each biodiesel fuel, however because of their proximity

Figure 2–Injector coking vs. fuel type for 9 biodiesel fuels and D2.

Table 3. Injector coking compared with viscosity, percent esterified, total glycerol, and heat of combustion for the fuels tested

	Injector Coking area/D2 area	Viscosity @ 40°C (cSt)	Percent Esterified (% by mass)	Total Glycerol (% by mass)	Heat of Combustion (MJ/kg)
CEE	2.88	4.89	92.31	1.18	40.03
CME	2.17	4.75	96.35	0.87	39.90
MWF	2.15	3.90	97.11	1.25	39.61
REE	3.16	6.17	94.75	0.93	40.15
RME	3.08	5.65	98.02	0.86	40.54
SEE	2.18	4.49	94.54	1.88	39.96
SME	2.14	3.89	98.17	0.75	39.77
TEE	3.06	5.04	95.62	1.42	40.09
TME	2.18	4.81	97.80	0.60	39.92
Diesel	1.00	2.98	N.A.	N.A.	45.42

Figure 3–Viscosity and heat of combustion of nine biodiesel fuels.

Figure 4–Power and torque for ethyl ester biodiesel fuels and D2.

Figure 5–Power and torque for methyl ester biodiesel fuels and D2.

Figure 6–Exhaust temperatures for the average of methyl esters, ethyl esters, and D2.

Figure 7–Smoke density from nine biodiesel fuels and D2 as measured in a torque test. Data shown is for 1,800 to 1,400 rpm.

to each other, a line is drawn through the average of the biodiesel fuel consumptions. The average biodiesel fuel consumption is 7% higher than that of diesel fuel. Figure 10 compares thermal efficiencies versus bmep for the biodiesel fuels compared to D2. The data showed that Biodiesel fuels have a slightly higher thermal efficiency compared to D2 in the mid power range.

CONCLUSIONS

A complete set of fuel characteristics for a variety of biodiesel fuels and D2 are presented. Performance tests demonstrated that these fuels are similar to diesel fuel. In general, the testing performed has shown that torque and power are similar to D2, and as the molecular weight of the biodiesel decreases so does the torque and power. Injector coking is greater for the ethyl esters which are also higher in total glycerol, even though statistically there is no

Table 4. Engine performance mapping test

		CEE		CME		Diesel		REE		RME	
RPM	Load (%)	Power (kW)	Fuel Flow (g/s)	Power (kW)	Fuel Flow (g/s)	Power (kW)	Fuel Flow (g/s)	Power (kW)	Fuel Flow (g/s)	Power (kW)	Fuel Flow (g/s)
2,500	100	59.6	5.14	59.5	5.08	63.1	4.70	61.4	5.15	61.4	5.13
	75	44.7	4.03	44.6	4.06	47.4	3.73	46.1	4.07	46.1	4.17
	50	29.9	3.23	29.8	3.12	31.8	3.00	30.7	3.15	30.8	3.27
	25	15.1	2.32	15.0	2.27	16.1	2.22	15.5	2.39	15.6	2.29
	0	2.7	1.66	2.7	1.59	2.7	1.44	2.7	1.59	2.6	1.59
2,250	100	58.7	4.68	58.8	4.70	64.0	4.51	60.4	4.67	60.3	4.75
	75	44.0	3.65	44.5	3.78	48.0	3.53	45.3	3.73	45.3	3.65
	50	29.5	2.80	29.6	2.82	32.1	2.65	30.4	2.75	30.4	2.95
	25	14.8	1.97	14.9	1.99	16.3	1.84	15.4	1.99	15.3	2.07
	0	2.2	1.23	2.2	1.29	2.1	1.18	2.2	1.26	2.2	1.23
2,000	100	58.1	4.43	58.1	4.53	61.6	4.25	58.6	4.48	59.2	4.54
	75	43.7	3.40	43.6	3.38	46.1	3.23	44.0	3.38	44.5	3.45
	50	29.2	2.49	29.2	2.57	31.1	2.34	29.6	2.49	30.0	2.52
	25	14.8	1.66	14.7	1.71	15.6	1.49	14.9	1.64	15.2	1.71
	0	1.7	1.01	1.8	1.01	1.7	0.88	1.8	0.96	1.9	0.96

		MWF		SEE		SME		TEE		TME	
RPM	Load (%)	Power (kW)	Fuel Flow (g/s)	Power (kW)	Fuel Flow (g/s)	Power (kW)	Fuel Flow (g/s)	Power (kW)	Fuel Flow (g/s)	Power (kW)	Fuel Flow (g/s)
2,500	100	60.3	5.22	59.2	5.11	59.6	5.15	58.6	5.01	58.9	5.10
	75	45.2	4.11	47.0	3.98	45.1	4.20	44.0	4.03	44.2	3.98
	50	30.3	3.23	35.3	3.23	29.8	3.15	29.6	3.15	29.5	3.20
	25	15.3	2.37	23.7	2.32	15.0	2.37	14.8	2.29	14.8	2.37
	0	2.8	1.66	12.0	1.56	2.8	1.64	2.5	1.64	2.6	1.54
2,250	100	59.7	4.73	2.0	4.71	58.7	4.72	58.0	4.65	58.8	4.78
	75	44.8	3.68	47.7	3.66	44.0	3.73	43.5	3.63	44.1	3.70
	50	30.1	2.95	35.8	2.85	29.7	2.80	29.3	2.82	29.7	2.85
	25	15.2	2.04	23.9	2.04	15.1	2.07	14.5	1.97	15.0	2.07
	0	2.2	1.29	12.1	1.26	2.3	1.31	2.1	1.29	2.2	1.31
2,000	100	58.4	4.46	1.6	4.41	58.3	4.48	57.3	4.40	57.7	4.43
	75	43.9	3.55	46.0	3.43	43.7	3.48	43.0	3.38	43.3	3.43
	50	29.5	2.57	34.4	1.64	29.0	2.54	28.7	2.47	28.9	2.55
	25	14.8	1.71	23.2	1.03	14.3	1.66	14.6	1.74	14.7	1.74
	0	1.7	1.06	11.3	11.24	1.8	1.04	1.7	0.98	1.8	1.01

Figure 8–Fuel consumption vs. bmep for canola ethyl ester at 3 rpms for the engine mapping test. This graph is typical of the nine biodiesel fuels.

Figure 10–Thermal efficiency vs. bmep for the nine biodiesel fuels and D2. Data is from the engine mapping test at 2,500 rpm.

correlation based on glycerol content alone. As the heat of combustion for the biodiesel fuels increases so does the viscosity and molecular weight.

In general, the physical and chemical properties and the performance of ethyl esters are comparable to those of the methyl esters. Ethyl and methyl esters have almost the same heat content. The viscosities of ethyl esters are slightly higher and the cloud and pour points are slightly lower than methyl esters. Engine tests demonstrate that methyl esters produced slightly higher power output and torque than ethyl esters. Fuel consumption when using the two different esters is nearly identical. Some desirable attributes of the ethyl esters over methyl esters are significantly lower smoke opacity, lower exhaust temperatures, and lower pour point.

Specific conclusions of this study are:

1. Fuel characterization data show some similarities and differences between biodiesel fuels and diesel.
   (a) Specific weight is higher for biodiesel, heat of combustion is lower, viscosities are 1.3 to 2.1 times that of D2.
   (b) Pour points for biodiesel fuels vary from 1 to 25°C higher for biodiesel fuels depending on the feedstock.
   (c) Sulfur content for biodiesel is 20 to 50% less than that of D2;
2. The percent oil esterified as determined by an outside lab was lower than expected. Methyl esters averaged 97.5% and ethyl esters 94.3% esterified.
3. Total glycerol was higher than expected averaging 1.1%. Methyl esters averaged 0.87% and the ethyl esters 1.4%.
4. The esters all have higher levels of injector coking than diesel fuel. Ethyl esters had higher levels than did the methyl esters. Injector coking was more related to apparent molecular weight and viscosity than to total glycerol. Visually all injector coking was low especially compared with older tests that included raw vegetable oils.
5. Smoke density, as determined by an opacity meter, decreased an average of 75% for the biodiesel fuels compared to D2. CEE and CME produced the most smoke of the biodiesel fuels and TME and SME the least smoke.
6. At rated load, engine power produced by the biodiesel fuels decreased an average of 4.9% compared to D2.
7. Peak torque for biodiesel at 1,700 rpm was reduced 5% on the average compared to D2 while at 1,300 rpm it was reduced only 3%, demonstrating the flatter torque curve characteristic of biodiesel.
8. The average biodiesel fuel consumption (g/s) on a mass basis was 7% higher than that of D2. On a volume basis (L/s) the consumption would be 6.7% higher than that of D2. The combined reduction in power and increased fuel consumption reflect the reduced heat of combustion of the biodiesel fuel. The split between reduced power (4.9%) and increased fuel consumption (6.7%) is most likely a function of the injector system.
9. Average thermal efficiencies for biodiesel fuel in the mapping test was insignificant by difference when compared to D2.

Figure 9–Fuel consumption vs. bmep for the nine biodiesel fuels and D2. Data is from the engine mapping test at 2,500 rpm.

Figure 10–Thermal efficiency vs. bmep for the nine biodiesel fuels and D2. Data is from the engine mapping test at 2,500 rpm.

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