hybrid fuel contained 25% soybean oil, 50% diesel oil, 20% 1-butanol and 5% 190-proof ethyl alcohol. It also performed better than the 25% blend of sunflower oil in diesel oil. The better performance was attributed to the solvent action and cooling effect of the alcohols in keeping the injector needles and orifices clean.

SIMPLE ESTERS

A third method for reducing viscosity is the conversion of the triglyceride oils to simple esters, which, in effect, reduces the molecular weight of the original oil to 1/3 of its former value, reduces the viscosity by a factor of ca. 8 and increases the volatility. Clark et al. (7) found that engine performance with soybean methyl or ethyl esters differed little from diesel oil in the 200-hr EMA screening test, with the exception of some fuel filter plugging, apparently caused by gum formation in the esters. Emission characteristics were good except that NOX levels were consistently higher than for diesel oil. Dilution of lubricating oil was noted, but was not a problem as long as the normal 100-hr oil change interval was observed. They conclude that the methyl and ethyl esters of soybean oil could be used as alternative fuels on a short-term basis, provided certain fuel quality standards are met.

A recent brief report by Quick, Woodmore and Wilson (8) indicates that methyl esters of linseed oil can fuel a direct-injection engine for as long as 1000 hr, in contrast to engine failure in a few hours when linseed oil itself is used. This evidence again supports the importance of viscosity compared with the effect of polyunsaturation.

With simple esters of vegetable oils yielding such good results as alternative fuels for farm tractors, increased knowledge on the transesterification process for preparing the esters becomes very important. Freedman et al. (9) found that this reaction is 99% complete within 1 hr at 60 C and with in 4 hr at 32 C when strong alkali (sodium hydroxide or methoxide) catalysts and a molar ratio of alcohol to triglyceride of 6:1 are used. The presence of moisture and free fatty acid, which destroy the catalysts, needs to be avoided in the reactants.

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The Effects of Vegetable Oil Properties on Injection and Combustion in Two Different Diesel Engines

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ABSTRACT

Four different vegetable oils, each in at least 3 different stages of processing, have been characterized according to their physical and chemical properties, their injection and atomization characteristics, and their performance and combustion characteristics in both a direct-injection and an indirect-injection diesel engine. The injection and atomization characteristics of the vegetable oils are significantly different than those of petroleum-derived diesel fuels, mainly as the result of their high viscosities. Heating the oils, however, results in spray characteristics more like those observed with diesel fuel. The 2 engine types demonstrated different sensitivities to the composition of the various oils. The combustion characteristics and the durability of the direct-injection engine were affected by the oil composition. The indirect-injection engine, however, was not greatly affected by composition. Two different preliminary specifications have been proposed: a stringent specification including compositional requirements for direct-injection engines, and a less stringent specification for indirect-injection engines. The specifications are discussed in terms of the data and the rationale used in their development. Some precautions concerning the application of the specifications are also presented.

INTRODUCTION

The use of vegetable oils as fuels for diesel engines is not a new concept. Since the invention of the diesel engine, however, the development of this engine has been based on the availability of petroleum-derived diesel fuel which, in turn, has been tailored to meet the needs of the current engines. During this period, a wealth of empirical knowledge has been developed that serves as the data base for the current diesel fuel specifications. Periodically, the vegetable-oil fuel concept has been reintroduced, usually during periods of petroleum shortages. In most cases, interest faltered because of renewed availability of more economical petroleum-derived fuels. As a result, vegetable oils have not been developed as potential fuels, nor have the necessary physical and chemical properties been defined to make them totally acceptable as a fuel source.

The 1973 oil embargo signaled the beginning of a new period of petroleum shortages. As a result, international interest in the use of vegetable oil as diesel fuel has been renewed once again. Much of the current work is being performed in countries that have little or no internal petroleum resources, e.g., South Africa (1), Brazil and Australia (2,3). Work has been progressing in the United States at Ohio State University (4), North Dakota State University (5,6), Southwest Research Institute (7), University of Idaho (8), University of Alabama (9) and at several engine manufacturers including International Harvester

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Presented at the AOCS Annual Meeting in Chicago, May 1983.

(10), John Deere (11), Caterpillar (12) and Perkins (13). Preliminary work done at Southwest Research Institute (SwRI) with blends of No. 2 diesel fuel (No. 2-D) with food-quality peanut and cottonseed oils has indicated that the combustion performance of the fuels is excellent as long as the viscosity does not become excessive (14). This work was done with blends ranging from neat No. 2-D to neat vegetable oil, in a very quiescent, direct-injection research engine (an engine extremely dependent on a high degree of atomization). Other work (15) done at SwRI with vegetable oils has been involved with the characterization of various oils according to the properties generally associated with diesel-fuel specifications.

The problems associated with using vegetable oils as fuels for diesel engines manifest themselves most obviously in terms of durability. Assuming that the fuel can be delivered to the injection pump, the most catastrophic characteristics include nozzle coking, deposits, ring sticking related to deposits and dilution of lubricating oil. As indicated previously, all of these symptoms can be explained by improper injection and atomization characteristics, which, in turn, can be explained by the high viscosity of the oils. The other theories to explain durability problems relate to the fact that the oils are chemically much different than No. 2-D. The chemical effects could be important if the vegetable oils are subject to pyrolysis, polymerization and other reactions that lead to the durability problems. All of the problems are related to incomplete combustion of the fuel. Obviously, if all of the fuel is mixed with air and burned in regions away from the cylinder walls, the problems would not appear. Therefore, researchers hypothesized that their occurrence would coincide with observable decreases in combustion efficiency and could possibly be detected in thermal efficiency, regardless of the direct cause. In addition, researchers hypothesized that the differences in the structures of the oils, mainly the degree of unsaturation, could have measurable effects on engine performance (independent of the occurrence of the durability problems), thereby obviating costly engine endurance tests.

Basically, 3 different theories can be postulated to explain the various durability problems that have been observed in engines fueled with vegetable oil. They are: (a) the high viscosity of the vegetable oils results in degraded fuel atomization, which, in turn, results in the observed durability problems, (b) the durability problems associated with the use of the vegetable oil fuels result directly from chemical structure of the oils and the effect of this structure on the combustion chemistry; (c) the durability problems are a result of incomplete combustion of the fuels (either spray or chemically induced) and the subsequent reaction of the fuels and partial combustion products on the metal surfaces and in the lubricating oil.

Although some evidence exists that fuel chemistry affects durability problems, the majority of evidence indicates that the high viscosity of the oils is the major factor controlling the onset and severity of durability problems. The high viscosities of the vegetable oils could also be the cause of the discrepancies encountered between the cetane ratings and their actual knock characteristics in real engines. The cetane rating is actually a measure of the ignition quality of the fuel and is affected by the atomization and vaporization processes encountered in the cetane rating engine. With high viscosity fuels, the degree of atomization would be expected to decrease, resulting in a longer ignition delay time and a lower cetane rating. Real engines would not necessarily have the same sensitivities to vegetable oils as the cetane engine.

The objective of the work was to develop a definition of vegetable-oil fuels for diesel engines that can be used as the basis for a future vegetable-oil fuel specification. In order to meet the overall objective of the project, the work has generally been considered in terms of 3 specific objectives: (a) characterization of the physical and chemical properties of a variety of oils from the standpoint of desirable diesel fuel properties; (b) characterization of the injection and atomization characteristics of variety of oils; (c) characterization of the engine combustion, performance and durability of a variety of oils.

EXPERIMENTAL APPARATUS AND PROCEDURE

Fuel Characterization

The selection of vegetable oils for use as test fuels in this program represented a compromise between the range of fuel properties covered, the range of processing steps considered and the use of oils that could realistically be considered as emergency or supplemental farm fuels in the United States. The vegetable-oil samples included 4 soybean (crude, degummed, once-refined and hydrogenated), 4 sunflower (crude, once-refined, dewaxed and deodorized), 3 cottonseed (crude, once-refined and deodorized) and 3 peanut (crude, once-refined and deodorized) oils. Note that the goal of physical and chemical characterization of the test oils was to document the properties of oils as well as to determine the applicability of the various ASTM fuel tests and the AOCS vegetable-oil tests to the specification of vegetable-oil fuels. Where necessary, the standard methods were modified to accommodate characteristics of the vegetable oils.

Injection and Atomization Characteristics

A device has been designed and built at Southwest Research Institute to provide a means for examining diesel injection in an environment that is thermodynamically very similar to that encountered in an engine. The system consists of a bomb, a fuel injection system and a high-speed motion picture camera.

The purpose of the bomb is to allow observation of the characteristics of diesel-type fuel-injection sprays in a high-temperature and high-pressure environment. The design temperature and pressure are 500 C and 4.14 MPa. The temperature is maintained using electrical resistance heaters. A quiescent, inert atmosphere of nitrogen is used to prevent autoignition of the test fuel. The bomb has a cylindrical geometery with quartz-glass end plates that allow direct visual observation through the bomb. Figure 1 is a cross-sectional view of the injection and atomization bomb. As can be seen, the injection nozzle is installed in the center section so that 1 of the 4 spray cones is perpendicular to the axis of the cylinder. The nozzle is equipped with a needle lift indicator and a line pressure transducer. High-speed movies were taken using a Hycam II, 16 mm high-speed motion picture camera. The film speed for all the movies was set at 25,000 quarter frames per second, or 40 μs between frames. A complete description of the apparatus is presented in reference 16.

Movies of the spray of all of the oils were obtained at 2 different fuel temperatures. The conditions in the bomb at the time of injection were always set at 4.14 MPa and 482 C. The fuel temperatures for the tests were 40 C and 145 C. The 40 C temperature was selected to provide a direct comparison between the vegetable oils and the baseline No. 2-D at a typical fuel-line temperature. At 145 C, the viscosities of all the vegetable oils are in the range of 4.0 cSt, ca. the same viscosity as the baseline No. 2-D at 40 C (2.4 cSt). Thus, comparisons are possible at the same fuel temperatures and also at similar fuel viscosities.

The movies of the injection sprays were analyzed using a

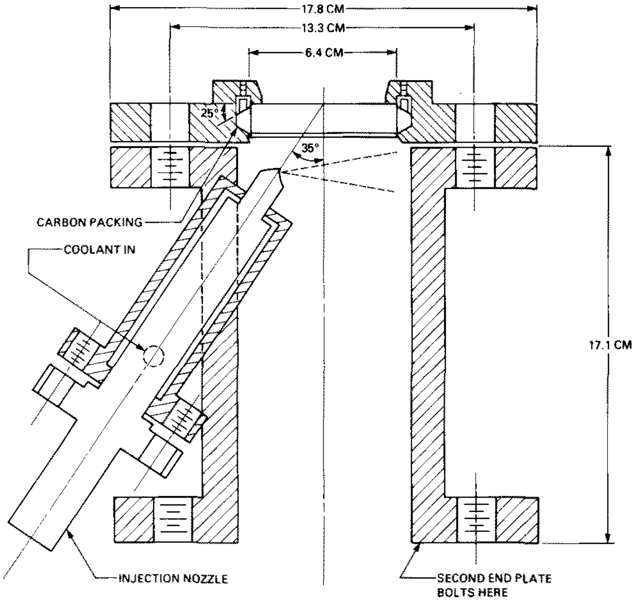

FIG. 1. Schematic of the injection and atomization bomb.

Vanguard Motion Analyzer, which allowed reduction of the penetration rate and cone angle data to computer cards. The computer cards were then read into the computer where the data were manipulated and stored in files. Typical time resolution of the data was 20 quarter frames before the spray impinged on the bomb wall opposite the injection nozzle.

Engine Combustion, Performance and Durability

Two test engines representative of those used in farming were selected for this program. The engines are turbocharged versions of the Caterpillar D-3306 design. Table I is a listing of the specifications of both engines. Note that both engines have the same bore, stroke and displacement, but one is a direct-injection (DI) engine whereas the other is an indirect-injection (IDI) engine. Also, differences are associated in the injectors and combustion chamber designs. The DI engine has multiple-orifice injectors centrally located in the head and "Mexican hat" type combustion chambers machined into the pistons. The IDI version has single-orifice, "capsule" type injectors installed in the prechamber, whereas the pistons are only slightly dished with additional recesses for valve clearance. Both engines were equipped with in-line jerk pumps designed with helical return ports. The speed governors were removed from the injection pumps of both engines so that fuel control was accomplished by direct action on the rack, which rotated the pump plungers, determining the timing of the opening of the helical return port.

Both engines were started using the factory-installed 24-volt starting systems. Engine load (power output) was dissipated using an eddy-current dynamometer coupled to the engine with short drive shaft. A Digalog dynamometer controller was used to maintain the desired engine speed to ± 1%. A 2200 N load cell was used to measure the dynamometer torque reaction.

A fuel-handling system was installed in the test cell and used to heat the fuel, control the fuel flow rate, measure the rate of fuel consumption and transfer fuel from the fuel tank to the engine. The fuel flow rate was determined gravimetrically using an Analog Model AN 5322 Load Cell Digitizer in conjunction with GSE Model 4400 weighing platform. The inlet air-flow rate to the engine was measured using a Neptune Eastech 4 in. diameter, vortex-shedding flow meter.

Gaseous exhaust emissions (NO/NO_X, CO_2, CO, O_2 and unburned hydrocarbons) were determined using Beckman exhaust emissions analyzers. The results from the analysis of the exhaust gases were used to calculate the air-fuel ratio. The calculated air-fuel ratio agreed favorably with those determined from the fuel and air flow measurements.

Water-cooled piezoelectric pressure transducers (AVL Model 12 QP300CYK) were installed in the access ports, which were machined in the heads at number one cylinder of both engines. A second transducer was installed in the prechamber of the IDI engine. The charge generated in the transducer was amplified using a Kistler Model 504 charge amplifier. The output from the charge amplifier was displayed on digital oscilloscope along with a top-dead-center (TDC) mark and the injector needle lift signal. The pressure signal was also supplied to a high-speed data acquisition system that was used to compute heat release rates and indicated power using methods described by Obert (17) and other authors (18,19). Analysis of the heat release rate data was performed using techniques developed for this study by Ryan et al. (20).

The engines were operated over a speed-load matrix consisting of 8 test points: 4 loads (100%, 75%, 50%, 25% of rated) each at 2 engine speeds. The "intermediate speed" was 1500 RPM for both engines, corresponding to the speed for peak torque; rated speed was 2200 RPM for the IDI engine and 2000 RPM for the DI engine. Power conditions were determined by the diesel fuel baseline data; these same power levels were used with the test fuels rather than reestablishing maximum power for each test fuel. All of the vegetable-oil tests were performed with the oil temperature at the injection pump maintained at 145 C,

TABLE I

Test Engine Specifications

Engine:	3306 PC/TC[a]	3306 DI/TC[a]
Configuration:	inline 6 cylinder	inline 6 cylinder
Displacement:	10.2 liter	10.2 liter
Comb. chamber:	Pre-chamber, flat piston	DI, "Mexican Hat" Piston
Bore X stroke	12 cm X 15.2 cm	12 cm X 15.2 cm
Maximum power:	138 kW @ 2200 RPM	154 kW @ 2000 RPM
Maximum torque:	710 N-m @ 1500 RPM	866 N-m @ 1500 RPM
Compression ratio:	17.5	14.6[b]
Pump type:	inline, 9 mm plungers	inline, 9 mm plungers
Injector type:	single fixed orifice	multiple orifice pencil
Injector timing (°BTDC @RPM)[c]:	12 @ 1500, 11.7 @ 2000	17.5 @ 900, 15 @ 1400

[a] PC = percombustion chamber, TC = turbocharged, DI = direct-injection, BTDC = before-top-dead-center.
[b] Determined by SwRI.
[c] Diesel timing light.

the temperature at which the viscosities of the vegetable oils are similar to that of the baseline No. 2-D.

The experimental procedure consisted of stabilizing the engine on a test point defined by the speed and brake power. When the fuel temperature was stabilized, the high-speed data acquistion system was activated, the fuel flowrate measurement was made, the exhaust emissions were measured and the various engine operating conditions were recorded (temperatures, manifold pressure, intake airflow rate, etc.). The cylinder pressure data for all runs were stored on computer discs until the end of the day, at which time the data were reduced and the various heat release rate and combustion parameters were output in hard copy. All of the data, including the fuel properties, the engine performance and emissions data and the engine combustion data, were input to a Hewlett-Packard Series 1000 computer equipped with a database management system (Image 1000) incorporated as part of the operating system.

RESULTS AND DISCUSSION

Fuel Characterization

In general, the properties of the test oils were typical of types of oils used in this study. The property data for the test oils are presented in Tables II through VII. The properties of the baseline No. 2-D are presented in Table VIII. Some difficulty was encountered with direct application of some of the standard ASTM procedures. The stability test (ASTM-D 2274) is designed to measure the stability of distillate fuels under accelerated oxidation conditions. When attempted with the vegetable oils, the high viscosities of the oils made the initial filtration impossible. The steam jet gum determination (ASTM-D 381) was designed to determine the existent gum in No. 2-D. When applied to the vegetable oils, we found that the vegetable oils would not evaporate at the conditions specified in the procedure. Particulate contamination (ASTM-D 2276) is generally performed on aviation turbine fuels. The vegetable oils would not flow through the specified filter. The results presented in Table III are those of a modified procedure in which the vegetable oils have been diluted with either toluene or heptane before filtering.

Other determinations that require some discussion are surface tension (ASTM-D 971) and the JFTOT measurements (ASTM-D 3241) (Table IV). The surface-tension measurements were included in the oil characterizations because of the effect of surface tension on the injection and atomization characteristics of a fuel. In the case of the vegetable oils, the total variation in surface tension was 4% over the entire range.

The Jet Fuel Thermal Oxidation Tester (JFTOT-ASTM-D 3241-77) provides a measure of the tendencies of gas turbine fuels to deposit decomposition products on high-temperature components of the fuel system. The JFTOT results presented in Table IV indicate that the propensity of the oils to form thermal decomposition deposits decreases, in most cases, as processing increases. The results appear to correlate somewhat with oil type or iodine value as indicated by the fact that the most saturated oil (peanut) demonstrated the lowest overall average rating. The JFTOT tests may provide a measure of the propensity of the oils to coke the injection nozzles. Based on the results, the degree of unsaturation appears to affect the deposition tendency and this, in turn, agrees with most theories on the coking mechanism.

Viscosities of vegetable oils at 40 C are more than an order of magnitude larger than those typical of No. 2-D, which are in the order of 2 cSt at 40 C (Table V). As shown in Table V, viscosity and density are influenced by type, i.e., composition, of the vegetable oil, but they are not strongly affected by the extent of processing, except for hydrogenation, which has a major effect on composition.

Increasing fuel temperature has the effect of increasing the cetane ratings of both vegetable oil and No. 2-D fuels, probably as the result of lowering viscosity and improving the spray characteristics and fuel evaporation. Thus, the cetane rating for degummed soybean oil increased from 36.6 at 38 C to 39.3 at 145 C with the same compression ratio at both temperatures. Previous results have shown that similar behavior can be expected for the other vegetable oil samples (15).

The various vegetable oil samples had many similar characteristics, differing mainly in fatty acid composition (Table VI) and contaminant levels (water and particulate matter Table III). Flow properties, viscosity (Table V), pour and cloud point (Table II) of the vegetable oil, however, were significantly different from those of No. 2-D. These properties and the 6-10% higher densities could

TABLE II

ASTM Fuel Properties Related to Temperature

Fuel[a]	Cloud point (C)	Pour point (C)	Flash point (C)	Boiling point IBP[b] (C)	Boiling point FBP[c] (C)
Crude cottonseed (C/CSO)	0	-3	300	339.9	683.3
Once-refined cottonseed (R/CSO)	0	-4	325	358.7	681.4
Bleached and deodorized cottonseed (RBD/CSO)	-1	-4	323	355.5	681.9
Crude peanut (C/PNO)	10	2	296	345.3	680.5
Once-refined peanut (R/PNO)	10	0	325	359.4	680.0
Fully-refined peanut (RBD/PNO)	10	1	330	361.3	679.5
Crude soybean (C/SBO)	-6	-10	312	344.2	679.5
Degummed soybean (DG/SBO)	-7	-10	315	360.7	679.1
Once-refined soybean (R/SBO)	-1	-9	320	360.7	681.4
Light hydrogenated soybean (H/SBO)	32-37	2	325	359.4	681.4
Crude sunflower (C/SNO)	-10	-9	314	358.1	682.8
Once-refined sunflower (R/SNO)	16	-11	328	358.7	682.3
Dewaxed sunflower (DW/SNO)	16	-9	322	358.7	681.4
Deodorized sunflower (RBD/SNO)	-7	-9	323	360.0	681.9

[a] C = crude; R = refined; RBD = refined, bleached and deodorized; DG = degummed; H = hydrogenated; DW = dewaxed; CSO = cottonseed oil; PNO = peanut oil; SBO = soybean oil; SNO = sunflower oil.

[b] IBP = initial boiling point, 0.1% evaporated.

[c] FBP = final boiling point, 99.5% evaporated.

TABLE III

ASTM Fuel Properties

Fuel[a]	Heat of combustion MJ/kg Gross	Net	Particulate Matter mg/100 ml	Water Karl-Fischer wt%	Ash wt%	Copper corrosion rating[c]
C/CSO	39.400	36.958	385.0	0.112	0.23	1A
R/CSO	39.849	37.418	15.6	0.064	0.01	1A
RBD/CSO	39.993	37.517	17.0	0.012	N.D.[b]	FP
C/PNO	39.614	37.102	20.2	0.122	N.D.	FP
R/PNO	39.749	37.241	3.0	0.059	N.D.	1B
RBD/PNO	39.929	37.433	27.8	0.020	N.D.	1A
C/SBO	39.388	36.981	101.0	0.036	0.08	FP
DG/SBO	39.388	36.952	14.7	0.068	0.04	FP
R/SBO	40.204	37.760	1.0	0.066	N.D.	FP
H/SBO	39.820	37.332	2.4	0.030	N.D.	FP
C/SNO	39.956	37.528	187.0	0.066	0.03	FP
R/SNO	40.060	37.616	1.6	0.104	N.D.	1B
DW/SNO	40.075	37.626	2.0	0.089	N.D.	1B
RBD/SNO	40.135	37.688	1.6	0.020	N.D.	1A

[a] C = crude; R = refined; RBD = refined, bleached and deodorized; DG = degummed; H = hydrogenated; DW = dewaxed; CSO = cottonseed oil; PNO = peanut oil; SBO = soybean oil; SNO = sunflower oil.

[b] Detection limit = 0.01%, ND = not detected.

[c] Copper corrosion rating: FP = freshly polished; 1A = slightly tranished, light orange; 1B = slightly tarnished, dark orange.

TABLE IV

AOCS and Other Properties

Fuel[a]	Free fatty acid wt% as oleic	Peroxide number ppm O	Iodine value	Surface tension dynes/cm	Thermal[d] oxidation JFTOT rating
C/CSO	–[b]	2.46	109.18	31.95	4+
R/CSO	0.0192	149.0	109.00	32.60	4
RBD/CSO	0.0340	137.0	108.94	32.55	1
C/PNO	–	48.5	92.36	32.22	1
R/PNO	0.0730	240.0	95.09	31.89	1
RBD/PNO	0.0629	21.3	95.32	32.28	2
C/SBO	0.0810	43.2	129.57	32.01	4+
DG/SBO	–	53.8	128.13	32.13	4
R/SBO	0.0220	162.0	130.81	32.13	0
H/SBO	0.0270	8.41	102.49	–[c]	1
C/SNO	0.0620	262.0	131.93	32.01	4+
R/SNO	0.1710	246.0	134.50	32.82	2
DW/SNO	0.0585	304.0	132.01	33.20	1
RBD/SNO	0.0555	72.5	132.99	32.82	3

[a] C = crude; R =refined; RBD = refined, bleached and deodorized; DG = degummed; H = hydrogenated; DW = dewaxed; CSO = cottonseed oil; PNO = peanut oil; SBO = soybean oil; SNO = sunflower oil.

[b] End point not detectable because of interfering background color.

[c] Oil too viscous for determination.

[d] JFTOT = jet fuel thermal oxidation test; JFTOT rating: 0 = no deposits; 4 = severe deposits.

adversely affect the spray characteristics in fuel-injection systems that are designed tightly around No. 2-D specifications. The differences in chemical composition between the vegetable oil (Tables VI and VII) and No. 2-D fuels will also have significant effects on ignition and combustion characteristics, and these effects probably are reflections of the high flash points for the vegetable oils (300-330 C vs 52 C for No. 2-D).

Injection and Atomization Characteristics

Diesel engine fuel-injection systems are designed to inject fuel into the combustion chamber in a very precise and consistent manner. The requirements for the system include precise fuel metering, accurate injection timing, proper rate of injection, proper spray pattern and fuel atomization for the given engine and sharp initiation and termination of injection (17). Controlling these factors is essential to prevent misfire, surge or overfueling, engine knock, smoke, deposits and lubricating oil contamination. In most combusting chamber designs, the fuel injection system must propel the fuel into the air to provide good atomization but must not allow the fuel to impinge on surfaces within the combustion chamber. The fuel properties that affect the performance of a given injection system include viscosity, density and surface tension. The performance is generally measured in terms of penetration rate, maximum penetration distance and cone angle.

Penetration rate is defined as the time rate at which the tip of the spray advances away from the injection nozzle. As indicated previously, a compromise must be made between the penetration rate and the maximum penetration distance because a high rate of penetration is desirable, but fuel impingement is undesirable.

Cone angle is defined in terms of the angle encompassed by the spray with the apex located inside the injection nozzle. Cone angle is a measure of the air entrainment of

TABLE V

Viscosity and Specific Gravity as Functions of Temperature

Fuel[a]	Viscosity centistokes @ C			Specific gravity @ C H_2O @ 15.6 C		
	20	40	100	20	40	100
C/CSO	76.44	34.89	8.03	0.92204	0.90889	0.86992
R/CSO	70.38	32.56	7.65	0.92286	0.91001	0.87154
RBD/CSO	75.23	34.25	7.91	0.92419	0.91040	0.87199
C/PNO	80.02	36.33	8.20	0.92363	0.90591	0.86872
R/PNO	82.27	37.16	8.37	0.91962	0.91292	0.87340
RBD/PNO	82.79	37.38	8.43	0.91450	0.90159	0.86256
C/SBO	65.80	32.23	7.66	0.91546	0.90198	0.86658
DG/SBO	66.46	31.28	7.57	0.91469	0.90182	0.86355
R/SBO	64.26	30.55	7.47	0.92054	0.90878	0.86842
H/SBO	—[b]	37.54	8.38	0.91671	0.90288	0.86803
C/SNO	65.70	30.96	7.55	0.92545	0.90867	0.86974
R/SNO	64.66	30.69	7.52	0.92078	0.90785	0.86935
DW/SNO	64.78	30.61	7.53	0.92230	0.90747	0.87042
RBD/SNO	67.08	31.67	7.67	0.92165	0.90747	0.86902

[a] C = crude; R = refined; RBD = refined, bleached and deodorized; DG = degummed; H = hydrogenated; DW = dewaxed; CSO = cottonseed oil; PNO = peanut oil; SBO = soybean oil; SNO = sunflower oil.

[b] Below cloud point.

TABLE VI

Analysis of Vegetable Oils Weight Percentage of Fatty Acid Methyl Esters

Fuel[a]	Lauric	Myristic	16:0 Palmitic	18:0 Stearic	18:1 Oleic	18:2 Linoleic	18:3 Linolenic	20:0 Archadic	22:0 Behenic	22:1	24:0
C/CSO	–	0.8	21.8	2.6	17.7	56.2	0.2	–	0.5	–	0.2
R/CSO	–	0.8	22.0	2.6	17.7	55.8	0.2	–	0.5	–	0.2
RBD/CSO	–	0.8	21.9	2.7	18.1	55.6	0.3	–	0.3	–	0.2
C/PNO	–	0.5	10.3	2.6	45.9	33.5	0.9	–	4.0	–	2.2
R/PNO	–	0.3	10.2	2.7	46.1	33.5	0.9	–	4.2	–	2.1
RBD/PNO	–	0.3	10.6	2.6	46.1	32.6	0.9	–	4.1	0.6	2.2
C/SBO	–	0.2	9.7	4.6	23.6	56.7	4.2	–	0.4	0.3	0.2
DG/SBO	–	0.5	10.2	4.4	24.6	55.5	3.9	–	0.7	–	0.3
R/SBO	–	0.4	10.7	4.8	23.8	55.2	4.4	–	0.5	–	0.2
H/SBO	–	0.4	9.5	4.9	50.3	32.8	1.3	–	0.3	0.3	0.2
C/SNO	–	0.5	5.8	4.8	18.3	68.6	0.2	–	0.8	0.5	0.5
R/SNO	–	0.4	6.2	4.8	17.6	69.3	0.2	–	0.9	0.4	0.3
DW/SNO	–	0.5	6.2	4.7	19.4	67.4	0.2	–	0.8	0.4	0.3
RBD/SNO	–	0.5	6.0	4.8	18.9	67.9	0.3	–	0.9	0.5	0.3

[a] C = crude; R = refined; RBD = refined, bleached and deodorized; DG = degummed; H = hydrogenated; DW = dewaxed; CSO = cottonseed oil; PNO = peanut oil; SBO = soybean oil; SNO = sunflower oil.

TABLE VII

Elemental Analysis

Fuel[a]	Carbon wt%	Hydrogen wt%	Oxygen wt%	Nitrogen wt%	Sulfur wt%	Phosphorus wt%	Chlorine wt%
C/CSO	76.8	11.5	11.0	0.035	N.D.[b]	0.062	N.D.
R/CSO	77.2	11.5	10.6	0.002	N.D.	N.D.	N.D.
RBD/CSO	77.5	11.7	10.7	0.006	N.D.	N.D.	N.D.
C/PNO	77.4	11.8	10.2	0.003	N.D.	N.D.	N.D.
R/PNO	77.3	11.8	10.3	0.001	N.D.	N.D.	N.D.
RBD/PNO	77.3	11.8	10.3	N.D.	N.D.	N.D.	N.D.
C/SBO	76.9	11.3	10.7	0.009	N.D.	0.027	N.D.
DG/SBO	77.3	11.5	10.7	0.004	N.D.	0.015	N.D.
R/SBO	77.4	11.5	10.5	0.001	N.D.	N.D.	N.D.
H/SBO	77.4	11.7	10.7	N.D.	N.D.	N.D.	N.D.
C/SNO	77.5	11.4	10.5	0.004	N.D.	0.007	N.D.
R/SNO	77.6	11.5	10.6	0.001	N.D.	N.D.	N.D.
DW/SNO	77.7	11.5	10.5	0.002	N.D.	N.D.	N.D.
RBD/SNO	77.7	11.5	10.4	0.004	N.D.	N.D.	N.D.

[a] C = crude; R = refined; RBD = refined, bleached and deodorized; DG = degummed; H = hydrogenated; DW = dewaxed; CSO = cottonseed oil; PNO = peanut oil; SBO = soybean oil; SNO = sunflower oil.

[b] N.D. = not detected.

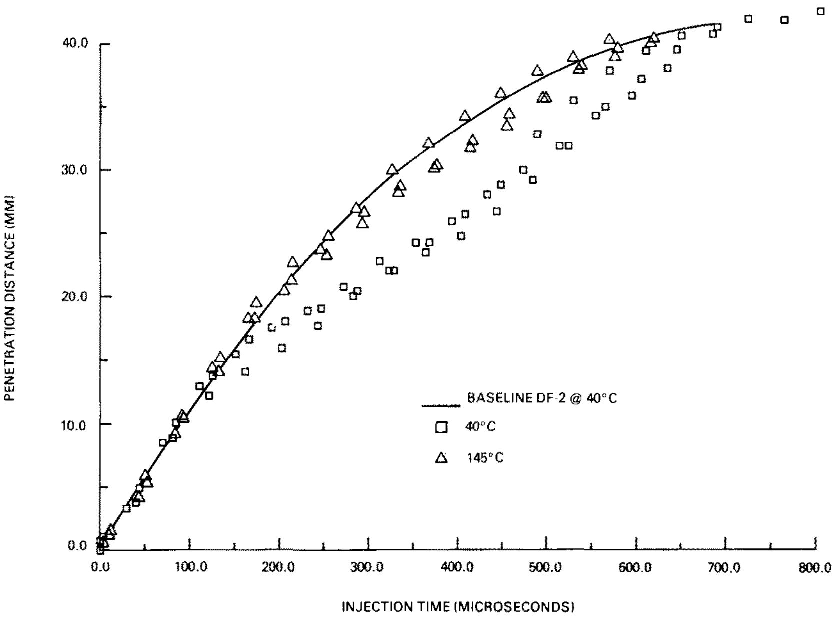

FIG. 2. Injection bomb–high-speed movie data penetration distance vs time for the cottonseed oil.

the spray, or in other words, the fuel air mixing within the jet. Typically, an increase in the cone angle is accompanied by a decrease in the penetration rate.

An increase in fuel viscosity will generally result in an increase in the penetration rate and a corresponding decrease in the cone angle. Because the viscosities of the vegetable oils are so much higher than that of No. 2-D, it was hypothesized that the injection process would be affected to such a degree that fuel impingement would occur in engines operating on the vegetable oils. Such impingement would, in turn, result in deposition and lubricating-oil dilution. The tendency for vegetable oils to cause nozzle coking can also be explained by the high viscosity because the increased viscosity can prolong the end of injection, after injection and nozzle dribble.

All of the vegetable oils displayed very similar spray characteristics and very similar dynamic characteristics in the injection system. The vegetable oils produced much higher overpressures in the injection line than the baseline fuel when both were tested at the same temperature. The high viscosity of the vegetable oils also resulted in dampening the pressure oscillation in the line after injection, as indicated by reductions in the amplitude and frequency of the line pressure signal.

Comparing the line pressure signals for the baseline No. 2-D at 40 C and those of the vegetable oils at 145 C, conditions of approximately equivalent viscosities, revealed that the difference in overpressures for these conditions was much smaller than at the equivalent temperature conditions. In addition, the dampening of the pressure oscillations was reduced so that the traces for the oils at 145 C looked very similar to those of the baseline fuel at 40 C.

Figure 2 is a plot of tip penetration distance vs time for the cottonseed oils at 40 C (the squares) and at 145 C (the triangles). Comparing all of the vegetable oils revealed that no significant differences exist between the 4 different types of oil or between the various degrees of processing at a given oil temperature. Oil temperature does, however, have a significant and very similar effect on all of the oils; this is shown very clearly in Figure 2 for the cottonseed oils. The initial penetration rates for both temperature conditions are very similar. At ca. 150 μs, or 15 min, the data for the 40 C oils indicate a slower penetration rate than the 145 C data. In other words, increasing the temperature of the oils resulted, in all cases, in an increase in the penetration rate. Accompanying the increases in penetration rate were corresponding decreases in the cone angle, contrary to the expected increase in cone angle that occurs with No. 2-D.

Typically, a decrease in the viscosity of a fuel is expected to result in a decrease in the penetration rate and an increase in the cone angle. Heating the vegetable oils from 40 C to 145 C resulted in an order of magnitude decrease in viscosity. As mentioned previously, however, the decrease in viscosity was accompanied by an increase in penetration rate and a decrease in cone angle, the opposite of the expected results. In addition, the penetration rates for the oils at 40 C were lower than those of the No. 2-D at 40 C. In all cases, heating the oil resulted in increasing the penetration so that the penetration plots were similar to that of the baseline No. 2-D.

Engine Combustion, Performance and Durability

Engine performance data consist of the normal measures of brake engine performance, including power (Bhp), mean effective pressure (BMEP), specific fuel consumption (BSFC) and specific energy consumption (BSEC). Because the engine power output was always recovered (independent variable), the variables of most concern in these experiments were those related to fuel consumption or efficiency. The specific energy consumption appears to be an ideal dependent variable because it is independent of the fuel, unlike the specific fuel consumption, which is dependent on the energy content of the fuel (heat of combustion).

Figures 3 and 4 are scatter plots of the data (BSEC vs Bhp) for all of the fuels for the DI and the IDI engine. To see any fuel-related trends from these figures is difficult because the data are very similar for all fuels. In order to determine the fuel effects on engine performance, statistical analysis was performed on the data. The engine heat release data were used to aid in the interpretation of the performance data.

Analysis of variance (21) of the DI engine data indicated that, on the average, differences existed between the base-

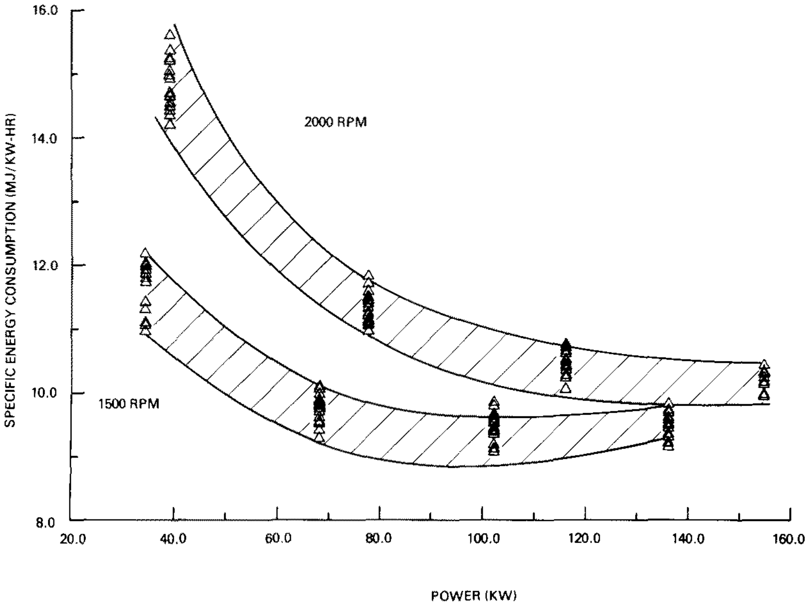

FIG. 3. BSEC vs power for all of the fuels in the direct-injection engine.

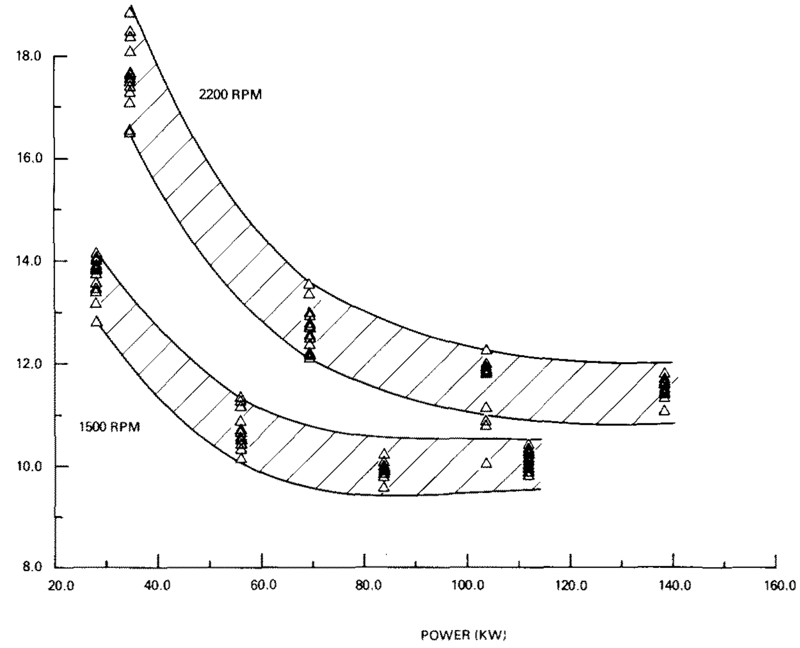

FIG. 4. BSEC vs power for all of the fuels in the indirect-injection engine.

line No. 2-D and the vegetable oils, but, on the average, the differences between the vegetable oils were very small. This analysis tended to verify the observations that were made on the data for both engines (Figure 3 and 4) concerning the small differences between the oils. Subsequent stepwise regression analysis of the mean adjusted vegetable-oil data indicated differences were attributable to the fuel. The most significant fuel properties for the DI engine were the linolenic-linoleic ratio, the iodine number and the nitrogen content. The oxygen content and the free fatty acids entered the analyses, but the significance of these terms was minor compared with the other terms. The inclusion of linolenic and linoleic acid contents and iodine number was expected because of the potential effects of the double bonds on the combustion chemistry. The nitrogen effect is suprising because of the small amount of nitrogen present in the oils, but the analysis does indicate that the effect is significant.

The IDI engine data were subjected to basically the same statistical analysis as DI engine data. The results of the initial regression analysis and the analysis of variance indicated basically the same trends as the DI engine data. The analysis of variance did indicate some interaction between the fuels and the test condition, but the interactions are very weak. Linear stepwise regression analysis indicated the most significant fuel properties were nitrogen content, oxygen content and free fatty acid content. The linolenic-linoleic ratio was entered, but the significance was much lower than the other terms.

In addition to the typical performance measurements described above, some measures of the durability characteristics of each oil were included in the performance testings. After each oil was tested, the injection nozzle from the number one cylinder was removed and examined for deposits. In addition, a lubricating-oil sample was removed and analyzed for contamination by the vegetable oils. The nozzles from the DI engine displayed some fuel sensitivity to deposition, with the light hydrotreated soybean oil displaying the least tendency for coking and the crude oils of sunflower, soybean and cottonseed all displaying strong coking tendencies. The nozzles from the IDI engine were all very similar to those removed from engines that had been run on No. 2-D—no apparent tendency was found for nozzle coking in the IDI engine. In addition, lubricating-oil contamination did not appear to be a problem in the IDI lubricating-oil contamination. Typically, the rate of dilution was ca. 0.15% per hour (volumetric basis) with the engine operating over the test matrix. The crude soybean oil had the highest dilution rate at 0.5% per hour.

Averaging over the speed and load range for each oil indicates that the rankings from lowest to highest BSEC for the DI engine (with lowest BSEC most desirable) are soybean, sunflower, peanut and cottonseed. All of the fuels had slightly better BSEC than the baseline No. 2-D except the crude cottonseed oil. In general, the crude oils performed worse than the other oils within a specific type. Examination of the heat release rate data indicates that the performance of the various types of oils and resulting rankings are related mainly to the combustion efficiency, with secondary effects resulting from the rate of combustion. This is shown in Figures 5 and 6, which are bar charts of the average BSEC and combustion efficiencies (averaged over speed and load), respectively, for the once-refined and crude oils. As can be seen, the oils with the lowest BSEC also have the highest combustion efficiencies.

The DI engine results indicate that high iodine values, in conjunction with large linolenic-linoleic ratios, are desirable for minimum BSEC, or for best combustion. This statement, however, assumes that the injection and atomization characteristics are adequate to allow for combustion of the fuels away from the cylinder walls. On the other hand, the lubricating oil dilution problems and nozzle coking problems appear to be somewhat aggravated by the use of the oils with the larger number of double bonds, especially in the linolenic acid structure. Thus, a compromise for current DI engine designs, where some fuel impingement is inevitable, involves the requirements for fuel heating and some limitation on linolenic acid content.

Within the range of the fuels tested in this program, the IDI engine did not appear sensitive to the chemical composition of vegetable oils in terms of the durability problems encountered in direct-injection engines. The engine did demonstrate a sensitivity in BSEC to the nitrogen, oxygen and free fatty acid contents of the oils.

The sensitivity to nitrogen was common to both engines. The nitrogen is most probably carried over in the oil extraction process in the form of protein. The role of the nitrogen is difficult to explain except in terms of possible chemical kinetic mechanisms where the nitrogen compounds act to inhibit the combustion process (the nitrogen effect was negative because BSEC increased with increasing nitrogen) by radical trapping or some other process.

The oxygen effect in the IDI engine was positive because the BSEC decreased with increasing fuel oxygen content. A possible explanation for this effect is that the combustion process in the IDI engine is initiated in the prechamber where the overall air-fuel ratio is extremely rich. The presence of the oxygen on the fuel side of the combustion process could serve to increase the initial combustion rate. Although the IDI engine is more tolerant of fuel differences than the DI engine, the baseline fuel performed, on the average, more efficiently than any of the vegetable oils in the IDI engine. In addition, all of the oils performed in a similar way, and all, including the No. 2-D, showed high BSEC than in the DI engine.

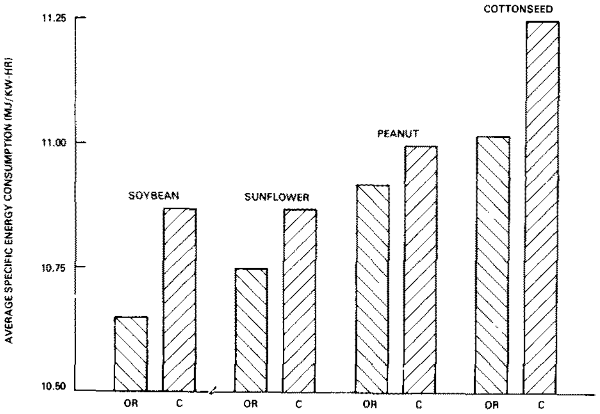

FIG. 5. Average BSEC for the once-refined (OR) and crude (C) oils in the direct-injection engine.

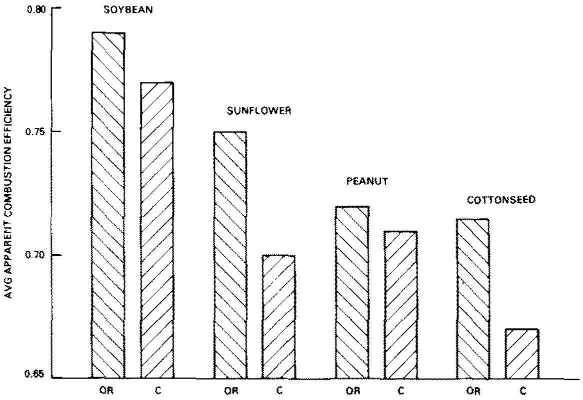

FIG. 6. Average apparent combustion efficiency for the once-refined (OR) and crude (C) oils in the direct-injection engine.

TABLE VIII

Properties of the Baseline Diesel Fuel (No. 2-D)

Viscosity (cSt. @ 40 C)	2.4
Pour point (C)	-22
Cloud point (C)	-14
Specific gravity (@ 15.6 C)	0.85
Flash point (C)	74
Steam jet gum (mg/100 ml)	3.9
Copper corrosion	1A
Ash (%)	0
Water (%)	0
Carbon (wt%)	86.5
Hydrogen (wt%)	12.8
Sulfur (wt%)	0.3
Heat of combustion (MJ/kg)	45.7
Cetane number	48

VEGETABLE-OIL FUEL SPECIFICATIONS

The results of this study indicate that a need exists for 2 different fuel specifications, one for direct-injection engines and one for indirect-injection engines. Table IX is a listing of the recommended preliminary specifications for both engine types and a listing of the current ASTM No. 2-D specification. Note that the DI engine requirements include fairly stringent limitations on the composition of the oils. The IDI requirements, on the other hand, do include a

TABLE IX

Recommended Preliminary Specification for Vegetable Oil Fuels for Diesel Engines as Compared to No. 2-D Specifications

	DI engines	IDI engines	ASTM
Cloud point (C), max (with heated tank)	22	22	—
Viscosity (cSt), max @ 140 C	5	5	—
Particulate matter (mg/L), max	8	8	—
Water (vol %), max	0.01	0.01	0.05
Copper corrosion (rating), max	3	3	3
Flash point (C), min	52	52	52
Heat of combustion (MJ/kg), min	39	39	—
Cetane number	35	35	40
Ash (wt%)	0.01	0.01	0.01
Linolenic/linoleic ratio, min[a]	0.07	—	—
Linolenic acid (wt%), max	5	—	—
Iodine number, max	135	135	—
Thermal and oxidative stability	?	?	—
Viscosity (cSt @ 37.8 C)	—	—	1.9-4.1

[a] Applies only when the linolenic acid content is greater than 1 %.

relatively mild limit on iodine number in an effort to eliminate such potentially bad fuels as linseed oil. The specifications for both engines also include a fuel temperature requirement of 140 C for acceptable viscosity. This was included for the IDI engines because the composition could become a factor with reduced atomization quality.

The purposes underlying the compositional limitations are to obtain maximum performance by maximizing the linolenic-linoleic ratio while limiting the linolenic acid content to obtain the desired durability characteristics. The iodine number limits the degree of unsaturation for those oil that contain little or no linolenic acid.

One important property missing from the specifications listed in Table IX is a measure of the thermal and oxidative stability. This property is important for the DI engine, but could also have an effect in some IDI engines. A specification has not been included because of the lack of an appropriate test for diesel engine fuels.

All of the other fuel properties recommended in the specification correspond to either the ASTM No. 2-D specification or the current military diesel fuel specification (VV-F-800). The exception is the cetane number. The current cetane procedure appears not to be applicable to the vegetable oils, but an acceptable value, as determined in this study, was included to provide some measure of the ignition quality of the oils.

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