refined, extractor Regent oil; (4) degummed, R500 (high erucic), expeller oil; and (5) degummed, refined R500 (high erucic), expeller oil. Stage of refinement of type of canola oil has little significant effect on maximum power or fuel consumption. Figure 8 shows duplicate runs with the #3 fuel, and Figure 9 with #5 fuel tends to verify this conclusion. All other fuels wer similar.

Emission Studies

In the work done to date, only a preliminary study has been made of exhaust emissions on the Petter engine. In general, the particulate level when burning canola oil was 20-60% of the level when burning diesel fuel, depending on engine load. This result is in agreement with the smoke opacity readings taken on the Petter engine. It was also found that the aldehyde and NO_X levels were significantly lower with canola oil – for example, aldehydes for canola oil were ca. 60% of the levels for diesel fuel.

Future Studies

The results to date have been sufficiently encouraging to warrant further investigation, including: a study of engine deposits with various fuels; a study of lubricating oil contamination; a detailed analysis of exhaust emissions; continual work with small extractors; further investigation of various esters of canola oil; further investigation of the low temperature problems, and possible solutions; and endurance tests.

ACKNOWLEDGMENTS

Funding for this project was provided by Agriculture Canada via a Department of Supplies and Services contract. Valuable assistance was provided by F.B. Dyck and M.A. Stumborg. Program management was provided by B. Zuk and economic factor calculations by E. Coxworth, both of the Saskatchewan Research Council, Saskatoon, Saskatchewan.

REFERENCES

1. Batel, von W., M. Graef, G.J., Mejer, R. Miller, and F., Schoedder, Grundl. Landtechnik 30:40 (1980).
2. Pernkopf, J., Report to the CENECA Colloquium Agriculture and Energy, Paris, 1980. Report obtained from E. Nyborg, PAMI, Humboldt, Saskatchewan.
3. Pratt, G., Scientists Report on Switching Sunoil for Diesel Fuel, Ag. Energy 2(20) (1981).
4. Krochta, J.M., Biomass Alcohol for California: A Potential for the 1980s, University of California, Davis, 1981.
5. Stirling, B., The Use of Non-Renewable Energy on Saskatchewan Farms, Saskatchewan Science Council, 1979.
6. Fats and Oils in Canada, Annual Review, 1981, Rapeseed Association of Canada, Table 4, p. 10.

☆Effects of Processing and Chemical Characteristics of Plant Oils on Performance of an Indirect-Injection Diesel Engine

C.R. ENGLER and **L.A. JOHNSON**, Food Protein Research and Development Center, Texas Engineering Experiment Station, and **W.A. LEPORI** and **C.M. YARBROUGH**, Department of Agricultural Engineering, Texas Agricultural Experiment Station, College Station, TX 77843

ABSTRACT

Engine performance curves were obtained for crude, degummed, and degummed-dewaxed sunflower oils and for crude, degummed, and alkali refined cottonseed oils using a single-cylinder, precombustion chamber design diesel engine. Crude oils gave very poor performance and are considered unsuitable for use as alternative diesel fuels. Performance curves for processed sunflower and cottonseed oils were slightly better than for diesel fuel, but increased carbon deposits and lubricating oil fouling were noted. Although processed oils may be acceptable fuels for short-term use, they are not recommended as alternative diesel fuels at this time.

INTRODUCTION

Farmers are looking to alternative fuels for security during emergency petroleum shortages, as a new outlet for farm products and also as a way to achieve greater independence. The most appealing alternative fuels are those which can be used with minimal modification of existing engines. For the farm sector, which has become heavily reliant on diesel power, much attention has been focused on plant oils as direct substitutes for diesel fuel.

Although there are many reports that diesel engines will operate on plant oils, either alone or blended with diesel fuel, there is no clear definition of characteristics a plant oil should have to be a good substitute diesel fuel. In addition, long-term effects of alternative fuels on factors such as maintenance and engine wear have only recently been reported.

Reports comparing different types of plant oils in a given engine show wide differences in performance characteristics (1-4). These differences likely are related to chemical or physical properties of the oils such as viscosity, fatty acid composition, degree of unsaturation, molecular weight and contents of minor compounds. However, those studies have not included characterization of test fuels to allow a determination of why the fuels gave different engine performance results.

Performance results reported for a given type of oil also show considerable variation, particularly for cottonseed oil. Satisfactory results with cottonseed oil have been reported (5, 6). However, unsatisfactory results reported for cottonseed oil include excessive carbon formation at the injector nozzle tip (7), corrosion of engine parts (1), and complete inability to run engines (8, 9). Despite the corrosion resulting from use of cottonseed oil, Chowhury (1) reported that cottonseed oil gave the highest thermal efficiency of all fuels tested, including diesel fuel. Although Ryan et al. (9) reported lack of ignition using 100% cottonseed oil, satisfactory performance was reported using a 90% cottonseed/10% diesel blend. These conflicting results with cottonseed oil may have been caused by differences in test engine designs, processing of oils used, or environmental factors (e.g., temperature).

In this paper, performance characteristics of a single-cylinder diesel engine using various sunflower oil (SFO) and cottonseed oil (CSO) fuels are reported. These data allow comparison of effects on engine performance of different types of oils and also of processing an oil through various stages of refining.

EXPERIMENTAL PROCEDURES

Crude, screwpressed sunflower oil and crude, screwpressed cottonseed oil were purchased from Texas oilseed crushers. The crude sunflower oil was heated to 65 C for one hour and filtered through 10-μm filters to remove particulate matter. Portions of each type of crude oil were degummed, and some of the degummed SFO was also winterized to remove waxes. A portion of crude CSO was alkali refined. Processed oils were filtered through 10-μm filters. Table 1 lists the fuels tested.

The test engine was a Yanmar TS50C single-cylinder, water-cooled, precombustion chamber design diesel engine. Complete engine specifications are listed in Table II. Instrumentation on the engine included type T (copper-constantan) thermocouples to measure lubrication oil, coolant and inlet air temperatures; a type K (chromel-alumel) thermocouple to measure exhaust temperature; a magnetic pickup digital tachometer to monitor engine speed; and a hydraulic dynamometer to measure torque.

Fuel consumption was measured with a Harvard trip balance accurate to 0.1 g. Time for the engine to consume a fixed amount of fuel (60 or 100 g) was measured manually with an electronic stopwatch.

The engine was broken in by running 50 hr under no-load conditions as recommended by the manufacturer. Additional break-in periods were allowed after replacement of any major wearing parts.

The injector and precombustion chamber of the engine were removed and cleaned prior to performance testing of each fuel. The engine was fueled with the test fuel and allowed to warm up until engine temperatures stabilized. The engine governor was then adjusted so that the manufacturer's maximum one hour rating of 3.73 kW (5 hp) at 2400 rpm was achieved. The load and speed were then reduced to obtain the manufacturer's continuous rated load, 2.98 kW (4 hp) at 2000 rpm. Fuel consumption was measured for 100, 80, 60 and 40% of the manufacturer's continuous rated load at 2000 rpm. Engine coolant and lubricating oil were checked before and after each run. Lubricating oil was changed on the manufacturer's published interval, or more frequently, depending upon the condition of the oil after each run.

Test fuels were characterized using AOCS standard procedures (10) for the following properties: iodine value, saponification value, free fatty acids, peroxide value, ash, specific gravity, refractive index, flash point and phosphatides. Heats of combustion were measured using bomb calorimetry.

TABLE I

Test Fuels

Filtered crude screwpressed sunflower oil (CSFO)
Degummed sunflower oil (DGSFO)
Degummed, dewaxed sunflower oil (DWSFO)
Crude screwpressed cottonseed oil (CCSO)
Degummed cottonseed oil (DGCSO)
Alkali refined cottonseed oil (ARCSO)

RESULTS AND DISCUSSION

Engine performance curves were obtained for all test fuels except crude sunflower oil (CSFO). Although the engine would run on CSFO, operation was very rough and the lubricating oil rapidly became contaminated with solids. Consequently the test was terminated before a performance curve could be obtained.

Fuel consumption data for DGSFO (degummed) and DWSFO (degummed-dewaxed) are shown in Figure 1 along with the baseline data for diesel fuel. To allow direct comparison with diesel fuel, the SFO data have been converted to diesel equivalent brake specific fuel consumption, i.e., data have been corrected for differences in heats of combustion between SFO and diesel fuel. These data show that, on a diesel equivalent basis, consumption of either DGSFO or DWSFO is slightly less than diesel fuel. The engine started easily and ran well on both DGSFO and DWSFO. There were more carbon deposits when burning these SFO fuels but they were soft and easily removed with a scraper.

Thermal efficiency, the percentage of energy in the fuel converted to useful work, also can be used to compare fuel consumption data. Figure 2 shows thermal efficiency data for the SFO fuels, and again the data indicate that DGSFO and DWSFO are slightly more efficient than diesel fuel.

An independent check of trends shown for thermal efficiency can be obtained by comparing exhaust temperatures. Figure 3 shows somewhat lower exhaust temperatures for DGSFO and DWSFO which is indicative of higher thermal efficiency. At higher thermal efficiencies, more of the energy input in the fuel is converted to work, thereby reducing exhaust temperatures.

Data for cottonseed oil fuels are shown in Figures 4-6. Fuel consumption data reduced to a diesel equivalent basis (Fig. 4) indicate that consumption of DGCSO (degummed) or ARCSO (alkali refined) was slightly less than for diesel fuel. However, fuel consumption for CCSO (crude) was significantly higher. Corresponding trends in

TABLE II

Engine Specifications

Make	Yanmar
Model	TS50C
Type	4 cycle horizontal diesel
No. of cylinders	1
Bore X stroke mm (in.)	70 X 70 (2.756 X 2.756)
Displacement L (in.^{3})	0.269 (16.42)
Continuous rating output kW/rpm (hp/rpm)	2.98/2000 (4/2000)
1 hr rating output kW/rpm (hp/rpm)	3.73/2400 (5/2400)
Specific fuel consumption kg/kW hr (1b/hp hr)	2.883 (.4740)
Compression ratio	24.5
Combustion system	Precombustion chamber
Lubrication system	Forced with trochoid pump
Cooling system	Super condenser
Oil pan capacity L (qt)	1.5 (1.585)
Cooling water capacity L (qt)	1.3 (1.374)
Dry weight kg (b)	61 (134)

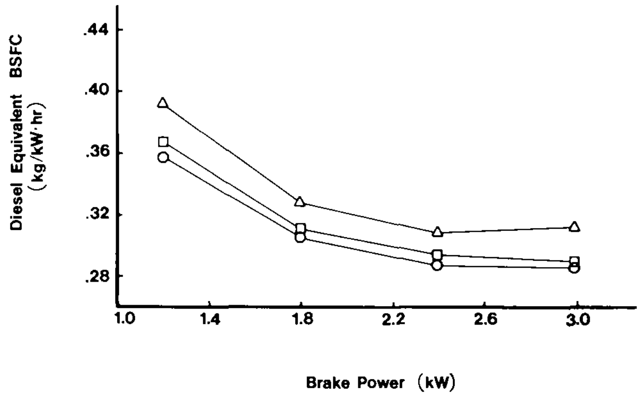

FIG. 1. Diesel equivalent specific fuel consumption for sunflower oil fuels. Degummed SFO (○); degummed-dewaxed SFO (□); diesel baseline (△).

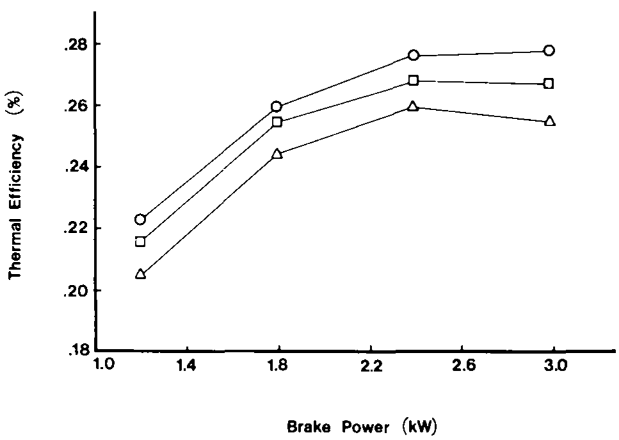

FIG. 2. Thermal efficiency for sunflower oil fuels. Degummed SFO (○); degummed-dewaxed SFO (□); diesel baseline (△).

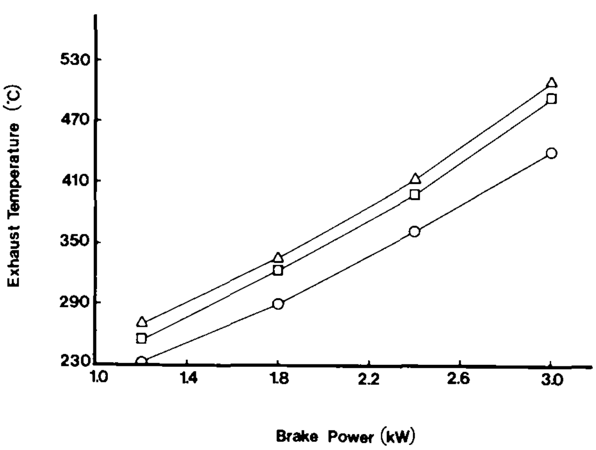

FIG. 3. Exhaust temperatures during sunflower oil tests. Degummed SFO (○); degummed-dewaxed SFO (□); diesel baseline (△).

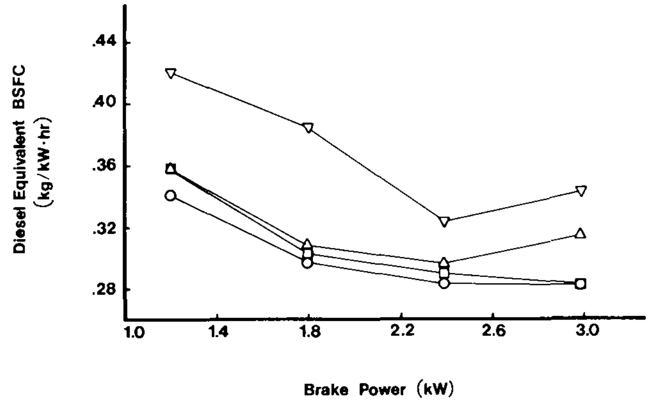

FIG. 4. Diesel equivalent specific fuel consumption for cottonseed oil fuels. Crude CSO (▽); degummed CSO (○); alkali refined CSO (□); diesel baseline (△).

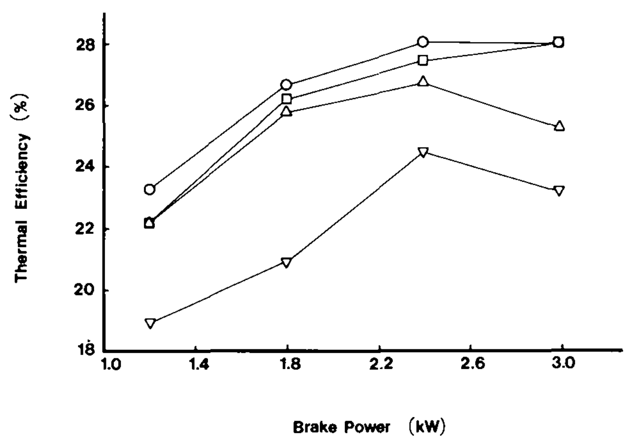

FIG. 5. Thermal efficiency for cottonseed oil fuels. Crude CSO (▽); degummed CSO (○); alkali refined CSO (□); diesel baseline (△).

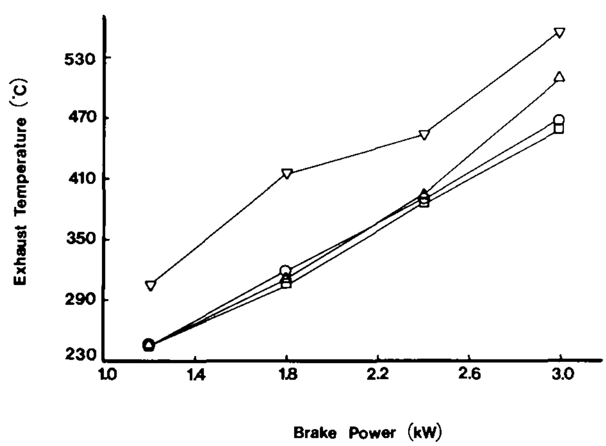

FIG. 6. Exhaust temperatures during cottonseed oil tests. Crude CSO (▽); degummed CSO (○); alkali refined CSO (□); diesel baseline (△).

thermal efficiency (Fig. 5) and exhaust temperature (Fig. 6) were observed. Thermal efficiencies for DGCSO and ARCSO were slightly higher than for diesel, and for CCSO they were significantly lower. Exhaust temperatures were nearly the same for DGCSO, ARCSO and diesel but significantly higher for CCSO.

The engine started easily and ran well on both DGCSO and SRCSO fuels. Carbon deposits were somewhat greater than with diesel but could easily be removed with a scraper. Engine knock was somewhat louder with DGCSO and ARCSO than with diesel. Although a performance curve was obtained, the engine ran very poorly on CCSO. During operation on constant load, fuel consumption was observed to increase with time. Engine knock was very loud throughout the test. After the test, a mound of carbon ca. 6 mm high was found around the injector pintle, and openings between precombustion chamber and cylinder were partially plugged with carbon. Severe deposits were found on the valves, and the valve stem and guide on the exhaust valve was scored. A new head and valves had to be installed. Much of the poor performance with CCSO can be attributed to the use of unfiltered oil as engine performance in later tests with filtered CCSO gave results similar to DGCSO and ARCSO. However, engine deposits were still greater with filtered CCSO than with DGCSO or ARCSO.

Comparison of the diesel baseline data for the SFO fuels and CSO fuels indicates that the engine was operating more efficiently during the CSO fuel tests. Prior to testing SFO fuels, the engine had been operated only 50 hr for breaking in. Following the SFO fuel performance testing, a number of longer tests were run so that over 200 hr running time had accumulated before the CSO fuels were tested. Immediately before testing the CSO fuels, the piston rings were replaced and the engine was run through a 50-hr break-in period using diesel fuel.

To compare data for the SFO and CSO fuel tests, fuel consumption and thermal efficiency were normalized by taking ratios of test fuel data to their corresponding diesel baseline values. Normalized fuel consumption data (Fig. 7) indicate that the processed plant oil fuels (DGSFO, DWSFO, DGCSO and ARCSO) gave similar performance and all had slightly lower fuel consumption than baseline diesel. Poorer performance of crude CSO is indicated by large deviations from other test fuel data. Normalized thermal efficiencies show corresponding trends with crude CSO having much lower efficiency than other test fuels (Fig. 8).

Chemical and physical properties of SFO and CSO test fuels are given in Table III. Slight differences in iodine values (unsaturation), saponification values (molecular weight), amounts of free fatty acids, peroxide values

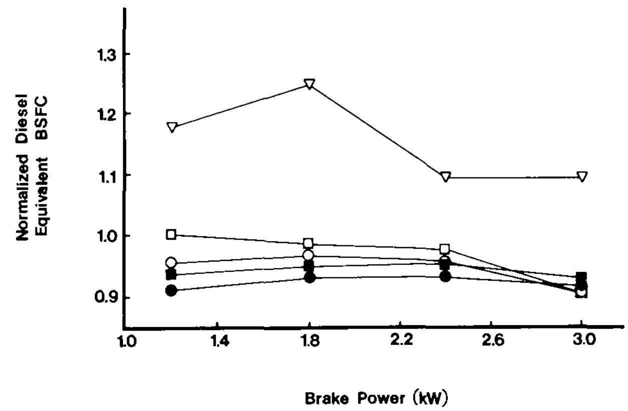

FIG. 7. Normalized diesel equivalent specific fuel consumption. Degummed SFO (●); degummed-dewaxed SFO (■); crude CSO (▽); degummed CSO (○); alkali refined CSO (□).

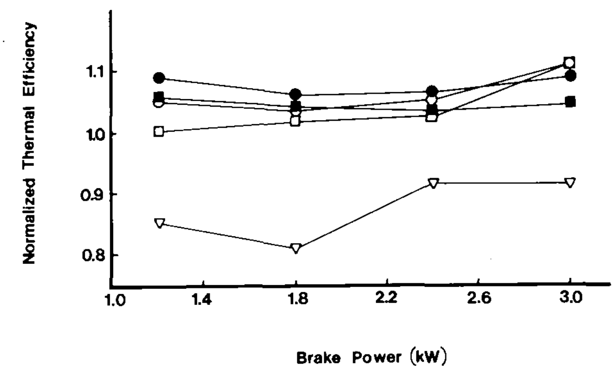

FIG. 8. Normalized thermal efficiencies. Degummed SFO (●); degummed-dewaxed SFO (■); crude CSO(▽); degummed CSO (○); alkali refined CSO (□).

(degree of oxidation) apparently have little effect on engine performance in short-term testing, as indicated by similar performance results for DGSFO, DWSFO, DGCSO and ARCSO. Very poor results for both crude oils (CSFO and CCSO) indicate that phosphatides are undesirable components in plant oils to be used as alternative diesel fuels.

On the basis of these results, both cottonseed oil and sunflower oil appear to be acceptable fuels for short-term engine operation if processed at least through a degumming

TABLE III

Fuel Properties

	CSFO	DGSFO	DWSFO	CCSO	DGCSO	ARCSO
Iodine value	130	128	130	110	109	109
Saponification value	197	201	208	192	190	189
Free fatty acids (%)	1.3	1.5	1.5	6.2	6.1	0.2
Peroxide value (meg/kg)	12	14	17	11	4	6
Heat of combustion (MJ/kg)	39.6	39.3	38.8	38.8	39.0	38.9
Ash (%)	0.01	0.01	0.01	0.2	0.01	0.002
Specific gravity, 25 C	0.918	0.920	0.920	0.921	0.918	0.922
Refractive index, 40 C	1.466	1.465	1.465	1.462	1.461	1.462
Flash point (C)	255	257	262	229	153	269
Phosphatides (%)	0.46	0.07	0.05	0.97	0.14	0

step. However, longer tests of 40 hr (11) indicated that much more rapid fouling of the lubricating oil occurs with these fuels and their use is not recommended at this time. Crude sunflower and cottonseed oils are definitely undesirable as alternative diesel fuels.

ACKNOWLEDGMENTS

This work was supported in part by research grants from the Texas Energy and Natural Resources Advisory Council and the US Department of Agriculture. B.M. Sridevi and S. Steele provided technical assistance.

REFERENCES

1. Chowhury, D.H., S.N. Mukerji, J.S. Aggarwal and L.C. Verman, Indian Vegetable Oils as Fuels for Diesel Engines, Department of Science Industries Research Bureau Bulletin (India), no. 19, 1942.
2. Baker, A.W., and R.L. Sweigert, A Comparison of Various Oils as Fuels for Compression-Ignition Engines, 19th National Oil and Gas Power Conference, Cleveland, OH, 1947.
3. Cruz, J.M., A.S. Ogunlowo, W.J. Chancellor and J.R. Goss, Biomass-Based Fuels for Diesel Engines, ASAE Pacific Region Annual Meeting, Hilo, HA, 1980.
4. Barsic, N.J., and N.L. Humke, Auto. Eng. 89(4):37 (1981).
5. deVedia, R.M., Diesel Power 22:1298 (1944).
6. Walton, J., Gas Oil Power 33:167 (1938).
7. Huguenard, M.C., M.S. Thesis, Ohio State University, Columbus, OH, 1951.
8. Miller, V., Prog. Farmer 95(6):22 (1980).
9. Ryan, T.W., W.E. Likos and C.A. Moses, paper no. CSS/CI-80-06, The Combustion Institute, Louisiana State University, Baton Rouge, LA, 1980.
10. Official and Tentative Methods of the American Oil Chemists' Society, 3rd edn., AOCS, Champaign, IL (revisions to 1980).
11. Engler, C.R., W.A. LePori, L.A. Johnson, R.C. Griffin, K.C. Diehl, D.S. Moore, R.D. Lacewell and C.G. Coble, Economic and Engineering Evaluation of Plant Oils as a Diesel Fuel, Final Report, Project 80-B-4-4A, Texas Energy and Natural Resources Advisory Council, Austin, TX.

Efficiencies of Various Esters of Fatty Acids as Diesel Fuels

W.E. KLOPFENSTEIN[a] and H.S. WALKER[b], [a]Department of Biochemistry, and [b]Department of Mechanical Engineering, Kansas State University, Manhattan, KS 66506

ABSTRACT

Methyl esters of commercial grades of lauric, myristic, palmitic, stearic, linoleic and linolenic acids, as well as ethyl and butyl esters of oleic acid, were burned in a diesel engine to determine their efficiencies as fuels. Triolein and some common vegetable oils were burned as comparison fuels and No. 2 diesel fuel was used as a control. The fuels were tested in a single-cylinder direct-injection engine running at rated speed and load in short-term, performance engine tests. Specific fuel consumption and thermal efficiencies of the engine burning these fuels were then determined. Among the methyl esters of the saturated acids, thermal efficiency was inversely related to chain length of the fatty acid. Introduction of a double bond resulted in increased efficiency. Further increases in unsaturation had negligible effects on thermal efficiencies. Ethyl oleate had the highest thermal efficiency and butyl oleate had the lowest thermal efficiency of any of the ester fuels tested. Most of the ester fuels produced higher thermal efficiencies than did No. 2 diesel fuel. Triolein produced the lowest specific fuel consumption of the triglyceride fuels and peanut oil produced the lowest specific fuel consumption of the vegetable oils. The data suggest that ethyl esters of monounsaturated or short-chain fatty acids should make good alternative fuels and that they should be further evaluated in long-term engine tests.

INTRODUCTION

With the gradual depletion of the world petroleum supplies, provisions must be made for the continuation of energy sources for mechanized agriculture, most of which is powered by diesel engines. Vegetable oils are attracting considerable attention as diesel fuel extenders or substitutes either in the form of the triglycerides or transesterified with various monohydric alcohols. Most vegetable oils contain a common set of fatty acids (saturated fatty acids, 12-18 carbons), along with oleic, linoleic and sometimes linolenic acids, although the proportions of the individual acids may vary considerably from one oil to the next. Some oils contain characteristically high concentrations of less common fatty acids, for example, erucic acid in rapeseed oil and ricinoleic acid in castor oil. We undertook our study to determine whether the esters of any of these common fatty acids are especially desirable as diesel fuels.

PROCEDURE

Practical grades of saturated fatty acids from 12 to 18 carbons plus linoleic and linolenic acids were purchased from Eastman Kodak (Rochester, NY). Oleic acid was purchased from Fisher Scientific (Fairtown, NJ). Salad grade vegetable oils were purchased from local groceries. Linseed oil (raw) was obtained from a local lumber yard and cottonseed and castor oil were purchased from Eastman Kodak.

Esters of the fatty acids were prepared by refluxing overnight with a 4-fold molar excess of the alcohol containing 2% H_2SO_4 as catalyst. Esters were recovered by extraction with petroleum ether and water. The ether extracts were extensively washed with water and 5% $NaHCO_3$, dried over anhydrous Na_2SO_4 and the ether removed under vacuum on a rotary evaporator in a 50 C water bath. Fatty acid composition was determined by gas liquid chromatography on a Hewlett-Packard 5880A with columns packed with 10% DEGS on 100-120 mesh Chromosorb W.

The test engine was a Fairbanks-Morse model 45B-81 single-cylinder, direct-injection diesel rated at 5.25 hp at 1800 rpm, driving an electric dynamometer and running at rate load. Volumetric fuel consumptions were measured for each fuel by measuring the time required to burn 100 mL of fuel. At least four replicate readings were taken for each fuel. Volumetric fuel consumptions were converted to weight fuel consumptions using the densities, taken from literature data (1) or determined in the laboratory, of the individual esters at the test temperatures. Specific fuel consumptions in terms of grams per horsepower-hour (g/hp hr) were then calculated. Heats of combustion of the fatty acid esters were determined by bomb calorimetry using an Emerson calorimeter. Thermal efficiencies for the ester fuels in the engine were calculated by dividing the heat equivalent of the work produced by the engine by the heat of combustion of the fuel required to perform that work.

RESULTS AND DISCUSSION

The fatty acid compositions of all of the fuels used are listed in Table I. The saturated fatty acids ranged in purity from over 99% for 12:0 to less then 93% for 18:0. The unsaturated acids were less pure, ranging from 75% for 18:1 to less than 50% for 18:3. The fatty acid compositions determined for the vegetable oils were consistent with published compositions (2).

The engine ran well on all of the fuels tested except for