Fumigation with Propane and Transesterification Effects on Injector Coking with Vegetable Oil Fuels

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ABSTRACT

A series of short term test cycles with a direct injection CI engine were used to determine the relative merits of fumigation with propane and transesterification in reducing injector coking problems that occur with the use of vegetable oil fuels. The test procedure outlined is suggested as a rapid method for screening alternative fuels. The engine injectors are used as a measure of engine deposits resulting from use of fuels. A fixed nominal rate of 10% fumigation with propane was investigated in an attempt to reduce injector coking with oleic and linoleic safflower oils. Variable nominal rates of 5, 10 and 15% propane fumigation were used in an effort to reduce injector coking with winter rape oil. Linoleic safflower ester, oleic safflower ester and high erucic acid rapeseed ester were also compared with No. 2 diesel fuel in a separate test to determine the relative importance of esterification and level of unsaturation on injector coking.

The 10% propane fumigation reduced injector coking caused by oleic safflower oil by 64%, to a level not significantly different from diesel fuel. Ten percent fumigation did not significantly reduce injector coking caused by linoleic safflower oil. The 10% nominal rate of fumigation reduced injector coking caused by winter rape oil by 21%, the 15% nominal rate had no significant effect, and the 5% nominal rate increased coking.

Linoleic safflower ester and rapeseed ester used as fuels formed significantly lesser and equal amounts of injector deposits, respectively, than the diesel fuel standard. Oleic safflower ester resulted in the formation of significantly more deposits than diesel fuel.

Except when using the ester, the engine fueled with vegetable oil exhibited power and torque characteristics similar to that when fueled with number 2 diesel. The reduction in power and torque experienced with ester fuels was expected based on the decreased heat of combustion values.

INTRODUCTION

Previous studies with vegetable oil fuels (Peterson et al., 1983) have revealed problems with injector coking and deposits in the combustion chamber which can cause serious engine malfunctions. Researchers at the University of Idaho have been using a short term engine test procedure to determine the amount of carbon deposition on injector nozzles. This procedure requires about one hour of engine test time. It is useful as a screening tool for evaluating the potential of a fuel for use in the engine and thus to decrease the total number of expensive longer term test cycles that would be required.

This paper reports on the use of this short term test cycle, hereafter called the "torque test", to evaluate the potential of propane fumigation and methyl esters as diesel fuel substitutes. Two different studies will be reported. The first study utilizes diesel fuel, winter rape oil with 0, 10 and 15% propane fumigation and a blend of 50% winter rape and 50% diesel. The second study involves a comparison of diesel fuel, ester of oleic safflower oil (OSE), ester of linoleic safflower oil (LSE) and ester of winter rape oil (RE).

Fumigation, as used in this study, involves the injection of a mixture of liquid fuels through the conventional fuel injection system, and the induction of a gaseous fuel with the intake air. The majority of fuel energy is in a liquid form, with a small percent of the input energy coming from the inducted gas.

Transesterification of vegetable oils involves reacting an alcohol with the oil in the presence of an alkaline catalyst to remove glycerol from the fatty acid producing an ester with a molecular weight about one-third the original value. The transesterified fuel used in this study was obtained by chemically reacting methanol with winter rapeseed oil, oleic safflower oil and linoleic safflower oils. The reaction was carried out at room temperature with potassium hydroxide as a catalyst. In the first series of engine tests the resulting methyl ester was then blended volumetrically in equal parts with diesel fuel. In the second series of tests the three esters were used as the only liquid fuel in the engine.

LITERATURE REVIEW

Fumigation

The use of multiple fuels in a CI engine may be accomplished by several methods. Fuel blending mixes the fuels together prior to injection into the combustion chamber by the conventional fuel injection system. Fumigation, on the other hand, involves the induction of a portion of the fuel with the intake air while the main fuel charge is injected in the usual manner.

Most previous studies involving the induction of a gaseous fuel into a dual fuel engine were either for the purpose of obtaining additional power from the engine (Miller, 1968; Derry, 1954; McLaughlin et al., 1952), or for utilizing a large quantity of the gasesous fuel (Lalk and Blacksmith, 1982; Bro and Pedersen, 1977; Clark and Bunch, 1962; Mitchell and Whitehouse, 1955). It

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was usually found that more complete combustion could be obtained with no power increase, or power could be increased with no additional smoke and incomplete combustion.

Carbon monoxide (CO), oxides of nitrogen (NO_x), and black smoke in the exhaust gas of a CI engine are indicative of incomplete combustion. Karim and Barn (1980) conducted studies involving the fumigation of methane, propane, hydrogen, and ethylene. It was found that the fumigation of these gases resulted in reduced concentration of CO, NO_x, and black smoke at high loads. It was further concluded that propane has "little or no tendency of pyrolysis to liberate soot."

Lyn and Moore (1951), and Lyn (1953) found that propane fumigation decreased ignition delay, smoothed engine knock, and allowed fuels of various, non-optimum cetane rating to be used. McLaughlin et al. (1952) concluded that propane fumigation of a CI engine reduced smoke and engine deposits through cleaner combustion. Lalk et al. (1982) and Derry (1954) reported similar findings of reduced smoke with fumigation.

Alcohol has been widely experimented with both as a means of dual fueling the CI engine, and in conjunction with the use of vegetable oils. Braun et al. (1982) used various blends of diesel fuel, soybean oil, and ethanol to obtain fuels with viscosities approaching that of diesel fuel. Fifty hours of testing resulted in no excess carbon buildup. However, some difficulties were encountered in keeping the fuel blend from separating.

Fujisawa and Yokota (1981) developed an injection system that provided mixing of the fuels in the high pressure line between the injection pump and the injector. The high pressure of the line helped maintain the emulsion. In this set up, mixtures of diesel fuel and vegetable oil can be handled by conventional means, with the alcohol being mixed in after the fuel pump.

Shropshire and Bashford (1984) used various configurations and types of nozzles to fumigate ethanol into a CI engine. Problems encountered resulted partly from the inability of the intake manifold to uniformly distribute the mixture of air, fuel vapor, and liquid fuel.

Fuel Performance of the Esters of Vegetable Oils

Wagner et al. (1984) conducted 200-h engine tests with soybean oil ester fuel on the same type of engine as used at the University of Idaho (John Deere 4239T). Engine performance with the methyl, ethyl, and butyl esters was nearly the same as with diesel fuel. There was no difference in thermal efficiency resulting from use of the various fuels to power the engine. The esters showed slight power loss and increased fuel consumption, which was attributed to the lower ester heating values. Engine wear was normal. There was, however, increased carbon deposition on the pistons with the methyl and butyl fuels. Emissions of oxides of nitrogen were significantly higher for the esters. They concluded that the esters could be used on a short-term basis and that further testing be done to determine long-term ester fuel effects.

Klopfenstein and Walker (1983) studied the efficiencies of various esters as diesel fuels. Most of the ester fuels had higher thermal efficiencies than did No. 2 diesel fuel. They suggested that ethyl esters of monounsaturated or short-chain fatty acids should make good fuels and that longer-term testing be done for further evaluation.

Nye and Southwell (1983) carried out short-term tests on rapeseed esters. The esters were reported to be similar to rapeseed oil with respect to power and fuel consumption and superior to the oil with respect to exhaust particulates. The cylinders, piston rings, and injectors were inspected, but no definite conclusions could be made due to the short test length.

Fort et al. (1982) evaluated cottonseed oil and esters of cottonseed oil as diesel fuel at the Southwest Research Institute with 200-h engine tests. A 50-50 cottonseed-diesel blend showed excessive carbon deposits and engine wear. The 100% cottonseed ester test engine had nearly normal wear and excessive deposits were found only in the top ring grooves. The study concluded that esters of vegetable oils appear to have technical potential as a diesel fuel substitute.

Blackburn et al. (1983) examined the performance of lubrication oils in soybean ester fueled diesel engines as part of their program at Shell Brazil S. A. The study found the soybean ester fuel to be satisfactory in terms of power, smoke, and fuel consumption. However, the level of crankcase lubricant contamination by the ester was unacceptably higher for many current direct injection diesel engines. The initial loss of crankcase oil viscosity due to ester dilution may result in engine damage because of inadequate lubrication. They claimed lubricant failure was due to the rapid oxidative degradation, probably leading to depletion of the antioxidant reserves of the lubricant. With the lubricants tested, the only way to ensure satisfactory lubrication was by drastically reducing oil change periods.

Lubrication oil contamination by soybean methyl esters was also studied by Romano (1982) of Brazil. After 200 to 250-h, the lube oil lost its lubricating characteristics with the formation of a gelatinous deposit which caused metal wear. The deposits were related to direct chemical attack by oxygen of the air — autoxidation. Antioxidants were mixed with the lubricants in an attempt to reduce vegetable oil fuel oxidation. This, however, was not successful in these tests.

Ventura et al. (1982) tested vegetable oil esters in Mercedes Benz direct injection engines. They report that the engines operated normally throughout the endurance testing. No signs of excessive carbon build-up were found in the combustion chamber and injector nozzle holes were not obstructed. The engine lube oil experienced an increase in viscosity which he suggests may have been due to polymerization of the ester in contact with the lube oil. Two vehicles have been field tested on 100 percent soybean oil ester for over 10,000 km. The main problem experienced was cold starting.

Hawkins and Fuls (1982) in a South African report were very encouraged about the long-term use of ethyl esters. An injector tip inspection at 1200 operating hours showed carbon deposits comparable to those of diesel engines with all the holes unobstructed. Lubricating oil had to be checked regularly for loss of dispersancy to prevent the oil galleries from clogging.

OBJECTIVES

The objectives of this study were:

1. Determine the effect of propane fumigation on injector coking when used with high erucic rape, high

oleic safflower, and high linoleic safflower oils as fuels in a CI engine.

2. Assess the effect of different rates of fumigation on injector coking caused by rape oil.

3. Observe the comparative effectiveness of transesterification and propane fumigation in injector coking when used with winter rape oil-diesel fuel mixtures as fuel.

4. Compare the degree of injector coking produced by three vegetable oil esters and No. 2 diesel in short term engine tests.

MATERIALS AND METHODS

Test Equipment

A John Deere 4239T stationary CI engine was used for the torque tests conducted in this study. It is a 4-cylinder, 4-stroke, turbocharged, direct injection engine with a 106.5 mm bore and 110 mm stroke. It has a displacement of 3917 cc, a compression ratio of 16.2:1, and a rated maximum power output of 66 kW at 2500 rpm. The engine was connected to a General Electric dynamometer with a maximum capacity of 112 kW.

The liquid fuel delivery system incorporated a 3 way, 2 position, hand operated valve to allow rapid change from one fuel to another. Additionally, an electric fuel pump was used to facilitate flow of more viscous vegetable oil blends through the fuel filter. The gaseous fuel induction system consisted of manual and electrical shut-off valves, and a needle valve for flow regualtion. Main (liquid) and auxiliary (gaseous) fuel consumption were measured with two digital scales, each accurate to 0.20 kg. Fuel consumption data were manually recorded.

Engine torque and speed were also manually recorded. Engine speed was monitored by means of a magnetic induction-type transducer located in close proximity to a gear on the tail shaft of the dynamometer. A Digitec HT series tachometer indicated the engine speed directly in RPM. Torque was measured indirectly by means of a load cell mounted under the torque arm of the cradled dynamometer. The reading from a digital multimeter in millivolts was converted to Newton-meters through use of a previously established calibration curve.

Iron-constantan (type J) thermocouples connected to a Digitec Model 590JC Data Logger and Scanner Slave monitored, at 2 min intervals, several important temperatures, including crankcase, coolant, intake, exhaust, and fuel. The timer and clock display of the data logger also served to coordinate the test procedures and manual data recording.

Fuel Abbreviation

In the interests of clarity and space, a fuel abbreviation system similar to one used by Peterson et al. (1983) were used. Percentages of fuel blends and auxiliary fuel rates are identified as follows:

AABB + CCDD + EEFFF

AA — percent of volume of fuel BB in liquid blend
CC — percent by volume of fuel DD in liquid blend
EE — percent by weight of auxiliary fuel FFF fumigated into intake air
D2 — Phillip's No. 2 Diesel Reference Fuel
WR — Winter rape seed oil (Dwarf Essex)
RE — Rape oil methyl ester
SO — High oleic acid safflower seed oil
SL — High linoleic acid safflower seed oil
LSE — Linoleic safflower methyl ester
OSE — Oleic safflower methyl ester
LPG — Propane (Liquefied Petroleum Gas)

For example, a liquid fuel blend of 50% winter rape seed oil and 50% #2 diesel with 10% propane fumigation would be designated as:

50WR + 50D2 + 10LPG

Note: This adds to more than 100%; the abbreviation indicates an equal mixture of winter rape and diesel in the liquid fuel blend then with 10% of the fuel to the engine being in gaseous form.

Fuel Specifications and Description

Table 1 shows the relevant physical and chemical properties of the fuels tested.

TABLE 1. CHEMICAL PROPERTIES OF FUELS TESTED. ANALYSIS WAS CONDUCTED BY PHOENIX CHEMICAL LABORATORY, INC., CHICAGO, IL.

Test	100D2	50S0+50D2	50SL+50D2	50WR+50D2	100RE
Cetane rating	47.8	–	–	42.3	54.4
Flash, C (PMCC)	80	92	92	89	84
Cloud point, °C.	-12	-13	-13	-11	-2
Pour point, °C.	-29	-15	-15	-18	-9
Water and Sediment, %.	Trace	Trace	0.01	0.1	Trace
Ramsbottom Carbon on 10% residuum, %.	0.17	0.16	0.17	0.18	0.1
Ash, %.	0.01	0.01	0.01	0	0
Viscosity @ 40 °C., cs.	3.2	11.25	10.04	10.18	6.7
Viscosity @ 100 °C., cs.	1.26	3.31	3.16	3.13	2.39
Sulphur, %.	0.29	0.13	0.12	0.2	Trace
Copper corrosion, 3 h. @ 50 °C.	Slight Tarnish, la	Slight Tarnish, la	Slight Tarnish, la	Slight Tarnish, la	Slight Tarnish, la
Existent gum, (steam jet) mg/100 mL	21.6	44.9	46.6	40.08	43.9
API Gravity @ 15.6 °C.	33.1	27.8	27.1	28.4	29
Heat of combustion, kJ/kg gross	45224	42349	42200	42698	40449
Particulate matter, mg/100 mL.	0.2	0.2	0.1	11.31	3.98

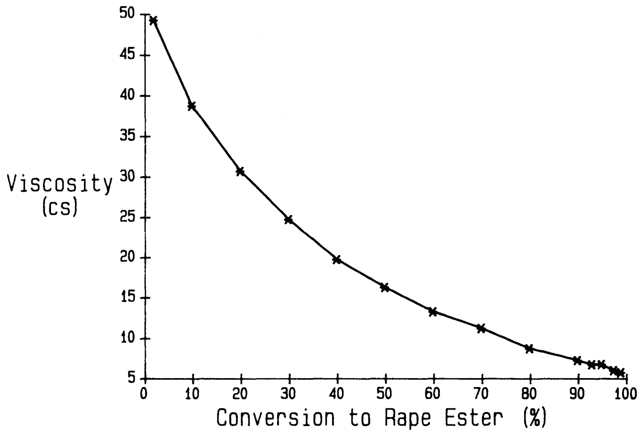

Fig. 1—Viscosity of winter rape ester as a function of percent conversion from the neat vegetable oil at 37.8°C.

The diesel fuel used was Phillips 2D Reference Fuel. It had a gross heat of combustion of 45,200 kJ/kg. The gaseous auxiliary fuel was a commercially available propane. It has a gross heating value of approximately 45,900 kJ/kg.

All liquid fuel blends used in the tests consisted of equal portions by volume of the indicated vegetable oil and diesel fuel. The winter rape seed oil fuel when mixed 50/50 with diesel fuel had a gross heat of combustion of 42,700 kJ/kg, 5.6% less than the diesel fuel used. The oil was expressed using a CeCoCo expeller operated by the University of Idaho Agricultural Engineering Department. The oil was stored to allow the particulate matter to settle out and was then subjected to a filtering system with a final mesh size of 4 microns as suggested by Peterson et al. (1983b).

The rape oil methyl ester was produced by the University of Idaho Chemical Engineering Department. Dwarf Essex variety winter rape seed was processed with a CeCoCo expeller and then transesterified at room temperature. After final washing, the methyl ester was subjected to the same filtering system as the rape seed oil. The pure ester had a gross heat of combustion of 40,400 kJ/kg, 10.6% less than diesel fuel.

The high oleic and high linoleic safflower oils were obtained from a commercial processor. The oleic safflower oil blended with diesel fuel had a gross heat of combustion of 42,350 kJ/kg, 6.4% less than diesel. When blended with diesel, the linoleic safflower fuel had a gross heat of combustion of 42,200 kJ/kg, 6.7% less than diesel.

Fig. 1 shows the relationship between winter rapeseed oil/ester composition and viscosity at 37.8°C. The pure oil had a viscosity of about 50 cs, which was lowered to 6.0 cs at 99% ester. This curve can be used to determine the degree of conversion to ester of a rapeseed oil sample based on viscosity.

The tests involving fumigation used propane to replace part of the liquid fuel. Percent replacement calculations were based on consumption at 2500 rpm. For example, if a baseline test of 50WR+50D2 indicated fuel consumption at 2500 rpm to be 90 kg/h, the 50WR+50D2+10LPG test would set the auxiliary fuel rate at 9 kg/h at 2500 rpm. Table 2 summarizes the actual replacement rates. Differences from nominal rates were a result of diminished liquid fuel consumption at lower engine speeds, without a like decrease in the gaseous fuel delivery.

TABLE 2. ACTUAL LIQUID FUEL REPLACEMENT OF THE FUMIGATED FUELS. ACTUAL PERCENT REPLACEMENT IS BASED ON DATA COLLECTED DURING THREE REPITITIONS OF THE ENTIRE TEST CYCLE.

Fuel	Liquid fuel used, Kg	Nominal % replaced	Actual % replaced
50WR+50D2	16.24	–	–
50WR+50D2+05LPG	14.42	5	11.2
50WR+50D2+10LPG	13.82	10	14.9
50WR+50D2+15LPG	12.45	15	23.3
50SO+50D2	16.28	–	–
50SO+50D2+10LPG	14.34	10	11.9
50SL+50D2	16.57	–	–
50SL+50D2+10LPG	15.00	10	9.5

Torque Tests

A torque test was used as described by Wagner (1984) and Korus et al. (1985) as a means of producing rapid injector coking. A single set of injectors was used and cleaned after each run.

To begin a test, clean injectors were installed, and the engine warmed up at low idle for 5 min on the reference fuel. The engine speed was gradually increased over the next five minutes to 2500 rpm. The engine was then loaded, using the dynamometer, to 2500 rpm at full throttle. At this time, the fuel selection valve was switched to the vegetable oil blend. After the fuel system was purged of air and the reference fuel, the test was started.

Data collection took place at 200 rpm increments, starting at 2500 rpm and working down to 1500 rpm by increasing the dynamometer load and keeping the engine speed control at maximum setting. Each engine speed was maintained for 10 min. Two minutes time were allowed between speed settings to adjust the load.

Each vegetable oil was run without fumigation in order to establish a baseline. Baseline fuel consumption and power were then used to calculate fumigation rates and loading. Torque tests involving fumigation were conducted much the same as the baseline tests with one exception, while baseline tests were conducted at maximum pump delivery, the engine speed control was adjusted for each speed setting in the fumigated tests. When adding propane to the air intake of the engine power outputs higher than the baseline (not to mention the engine's rating) can be produced. Therefore, both the governor and load were adjusted to maintain torque and power curves identical to the baseline figures. This method allows for partial replacement of the liquid fuel, as opposed to "overfueling".

At the conclusion of each test, the engine was returned to the reference diesel fuel and the engine cooled for 10 min prior to shutdown of the engine to rid the fuel system of any vegetable oil. New fuel filters were used with each change in liquid fuel blend to avoid potential contamination through mixing in filters.

Injector Photographs

After the engine cooled, the injectors were removed and each one photographed at two orientations. A Wild Heerbrugg light microscope and 35 mm camera were used at a magnification of 16X. 35 mm copy film produced a silhouette image from which 20 cm by 25 cm prints were made. The areas of the coked injectors were measured using a digitizer and microcomputer. The areas required scaling to compensate for the slight variations in enlarging that took place in the photographic printing process. Following scaling, the area of the clean injector was subtracted out and a coking index was calculated by dividing the mean coked area for the test fuel by the mean coked area for No. 2 diesel fuel and multiplying by 100. This normalizes the values to compensate for differences in test conditions. Coking indices were examined to determine if there were any significant differences between fuels. Data input consisted of entering the index observed for each of the four injectors photographed at the two orientations for each replication of each fuel, the result being 240 data points. Each data point was specifically labelled as to the fuel, replication, injector, and orientation from which it was derived. Duncan's multiple-range test was used to find significant differences in injector coking between fuels.

Experimental Design

Altogether, 13 fuels were used in these tests: No. 2 diesel, a neat winter rape oil blend, methyl ester of winter rape at 50% and 100%, methyl ester of linoleic safflower, methyl ester of oleic safflower, a neat winter rape oil blend with 5, 10, and 15% propane fumigation, a neat linoleic safflower blend, a neat linoleic safflower blend with 10% propane fumigation, a neat oleic safflower blend, and neat oleic safflower blend with 10% propane fumigation. All of the liquid fuel blends were equal mixtures by volume of the vegetable oil and No. 2 diesel.

The ten fuels in the first three tests were conducted in random order by replication, i.e., the fuels were arranged in random order, and each used once, for the first replication. The fuels were randomized again for the second and third replications, and the tests carried out to completion. The tests with the 100% ester fuels were randomized separately in a second series of tests, or runs, following the completion of the first series of tests. Diesel reference fuel was tested in each replication to provide a standard of comparison both for injector coking and engine performance.

RESULTS AND DISCUSSION

The injector coking index varied widely among the different fuels examined. Injector coking results are displayed in Fig. 2 and 3. Fixed rate fumigation with

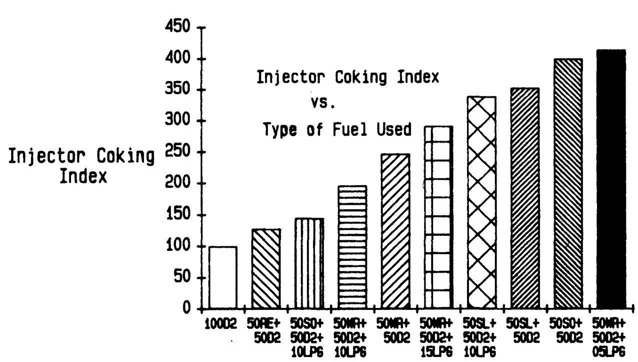

Fig. 2—Injector coking index vs. type of fuel used comparing diesel, propane fumigation and vegetable oil blends.

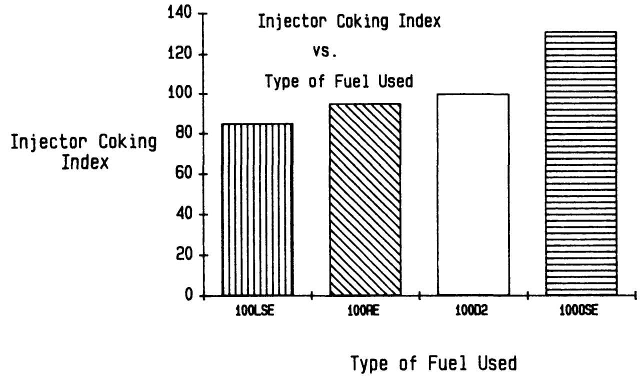

Fig. 3—Injector coking index vs. type of fuel used comparing diesel and three vegetable oil esters.

oleic safflower oil and all of the ester fuels resulted in reduced injector coking. Table 3 and 4 show that the coking with these fuels was not statistically different from the coking due to diesel fuel. The 10% nominal rate of fumigation with winter rape oil (50WR+50D2+10LPG) reduced injector coking, but not to the level observed with diesel fuel.

The 5 and 15% fumigation rates with winter rape oil (50WR+50D2+05LPG and 50WR+50D2+15LPG) resulted in increased injector coking. While the increase for 50WR+50D2+05LPG was quite large, the increase for 50WR+50D2+15LPG was slight, and statistically insignificant.

Figs. 4, 5, and 6 show typical injector tip photographs. In Fig. 4, it can be seen that the injectors used with 100D2, 50RE+50D2 and 50SO+50D2+10LPG experienced very little carbon build up. Fig. 5 shows the moderate to severe coking found with the variety of fuels which include winter rape in the blend, and Fig. 6

TABLE 3. INJECTOR COKING RESULTS FROM THE PROPANE FUMIGATION TEST WITH VEGETABLE OILS. DUNCAN'S MULTIPLE RANGE TEST FOR TEST #1. MEANS WITH THE SAME LETTER ARE NOT SIGNIFICANTLY DIFFERENT.

Duncan	Grouping	Mean injector coking index*	N	Fuel
	A	414	24	50WR+50D2+05LPG
B	A	400	24	50SO+50D2
B	C	353	24	50SL+50D2
D	C	339	24	50SL+50D2+10LPG
D	E	291	24	50WR+50D2+15LPG
	E	247	24	50WR+50D2
	F	196	24	50WR+50D2+10LPG
G	F	145	24	50SO+50D2+10LPG
G		128	24	50RE+50D2
G		100	24	100D2

*Coking index normalizes the average diesel coking area to 100.

TABLE 4. INJECTOR COKING RESULTS FROM THE TRANSESTERIFIED VEGETABLE OILS COMPARED TO DIESEL, 100% VEGETABLE OIL ESTERS FUELED THE ENGINE DURING THESE TESTS.

Duncan	Grouping	Mean injector coking index*	Number of observations	Fuel type
	A	131	24	OSE
	B	100	24	Diesel
C	B	95	24	RE
C		85	24	LSE

*Coking index normalizes the average coking area to 100.

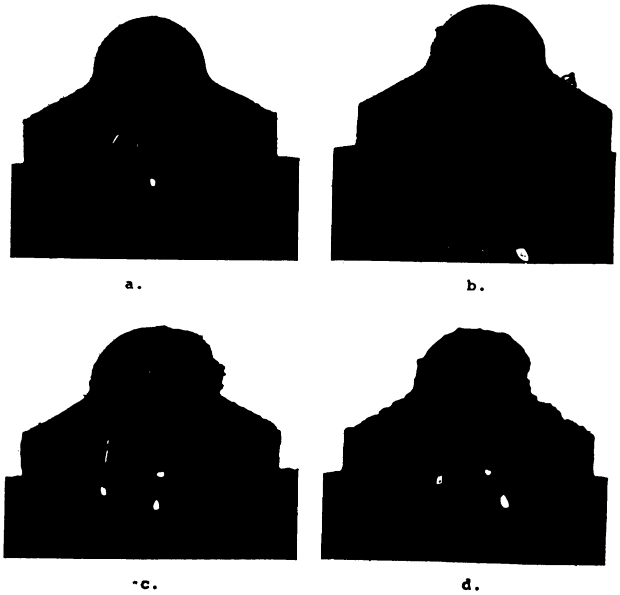

Fig. 4—Typical injector photographs. Shown are (a) Clean injector, (b) 100D2, (c) 50RE+50D2, (d) 50SO+50D2+10LPG.

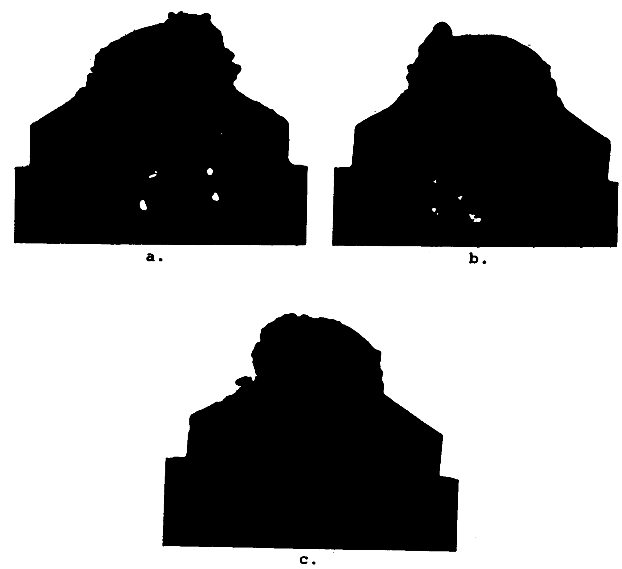

Fig. 6—Typical injector photographs depicting severe coking: (a)50SO+50D2, (b) 50SL+50D2, (c)50SL+50D2+10LPG.

depicts the relatively severe coking found with the safflower oil fuels and 50SL+50D2+10LPG.

Of the three vegetable oils involved in this study 50SO+50D2 and 50SL+50D2 were clearly the worst in terms of injector coking. Power and torque curves for the baseline and fumigated fuels were identical by design. Thermal efficiencies were essentially the same for all vegetable oil baseline runs, diesel fuel and the winter rape ester. No differences in efficiency were observed between the baseline and the 10% fumigated runs in the study.

Fumigation of propane at the 10% rate significantly reduced injector coking caused by oleic safflower oil by 63.7%. The mean injector coking index for 50SO+50D2 was 400. The injector coking index for 50SO+50D2+10LPG was 145, which was not significantly different from the reference fuel injector coking index of 100. The 10% rate of fumigation did not significantly reduce injector coking of linoleic safflower oil. The injector coking index for 50SL+50D2+10LPG was 339, which was not significantly different than the index of 353 observed for 50SL+50D2.

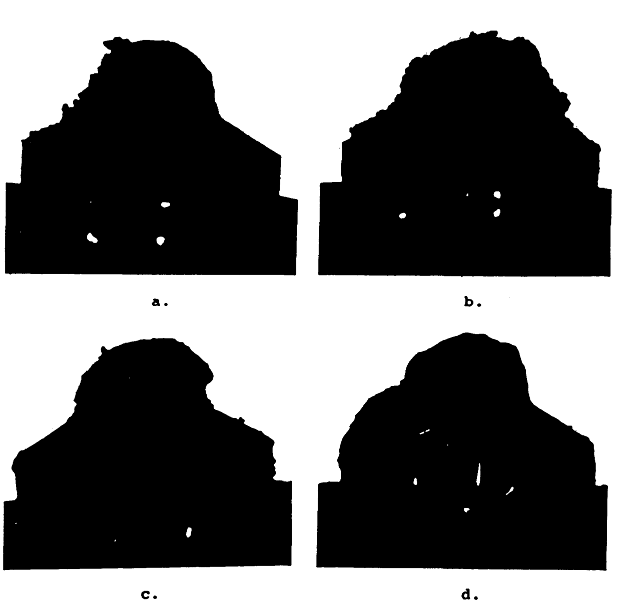

Fig. 5—Typical injector photographs showing moderate to severe coking. Shown are: (a) 50WR+50D2, (b)50WR+50D2+05LPG, (c)50WR+50D2+10LPG.

Propane fumigation appeared to have the most effect on the worst fuel. The 63.7% reduction observed with oleic safflower as fuel was the greatest reduction in this study. Some reduction in injector coking could be expected with fumigation due solely to the fact that less coking-prone fuel was used in each test. However, the 12% reduction in liquid fuel observed with the fumigated oleic safflower tests does not correspond to the nearly 64% decrease in coking. This decrease must be attributed to factors other than simple liquid fuel reduction.

The 4% increase in coking observed with fumigated linoleic safflower must likewise be caused by other factors. The 9.5% reduction in liquid fuel used for these tests would seemingly result in at least a 9 to 10% reduction in injector coking. As it turned out, no statistically significant difference in injector coking was observed.

Different results were obtained with 50SO+50D2+10LPG and 50SL+50D2+10LPG. The differencs in saturation of the two fuels appeared to have minimal effect on the baseline tests, i.e. when they were used without the propane, both fuels exhibited power and torque curves similar to diesel fuel and both caused severe coking of the injectors. When propane fumigation was added marked differences appeared. The propane reduced the injector coking tendency of the oleic safflower but not the linoleic safflower.

The 50WR+50D2 fuel was, by far, the least coking-prone baseline fuel blend containing a neat vegetable oil. The different rates of fumigation had quite varied effects on the tendency of this fuel to coke the injectors. Again, power and torque curves for the baseline and fumigated fuels were identical by design. Efficiencies measured in the baseline and fumigated tests were essentially the same. The 10% rate of fumigation significantly reduced injector coking, while the 5% rate significantly increased injector coking. The injector coking index for 50WR+50D2 was 247. The coking index for 50WR+50D2+10LPG and 50WR+50D2+05LPG were 196 and 414 respectively, both being significantly different than 50WR+50D2 according to Duncan's multiple-range test (Table 3).

The 15% rate of fumigation did not significantly affect injector coking of winter rape oil. 50WR+50D2 and 50WR+50D2+15LPG had coking indices of 247 and 291, indicating an apparent 17.8% increase in injector coking. This observed increase, however, was not statistically significant due to the variability in the replications.

Ester of Winter Rape Blend

Transesterification significantly reduced injector coking caused by winter rape oil. The 50RE+50D2 had an injector coking index of 128, which was significantly lower than the index of 247 observed for 50WR+50D2, and not significantly different than the index of 100 observed with 100D2. The ester appeared to burn quite well, with a thermal efficiency approximately equal to diesel fuel over the entire operating range of the engine. The power and torque curves were also similar in appearance to those of diesel fuel. The 2.4% decrease in power at rated speed, and similar small reductions throughout the operating range were to be expected, due to the lower fuel content of the ester. This small power decrease could probably be corrected by turning up the fuel pump.

100% Ester Fuels

In terms of injector coking 100LSE was the best fuel with significantly less deposits than diesel fuel. The amount of deposits with the 100RE fuel were not significantly different from LSE or diesel fuel. 100OSE was the worst ester fuel and had over 30% more coking than 100D2, 100RE and 100LSE. However, the ester fuel drastically reduced coking when compared to its parent oil as did the other esters tested. A 50-50 blend of oleic safflower oil and diesel, as reported above, had 300% more coking than 100% diesel, while the safflower ester showed only 25% more coking than 100% diesel. The amount of OSE coking was statistically significantly different from diesel however longer engine tests are required to determine what the long term effects of OSE fuel would be on engine performance and durability. Why OSE had significantly more coking than the other two ester fuels is not known. There may be factors involved other than viscosity and saturation.

The relative unimportance of fatty acid unsaturation can be shown in a comparison of LSE and OSE. Linoleic safflower oil is largely polyunsaturated, while the oleic variety is mainly monounsaturated. If unsaturation were the major cause of carbon deposits it would be expected that OSE fuel would give less coking than LSE. However, this was not the case. Also, LSE was not significantly different in coking from RE which is basically monounsaturated.

When transesterified, the oils are reduced in molecular weight and viscosity, but the fatty acid chains are unaffected (Wagner et al., 1984). The 50-50 blends of diesel and vegetable oils used in this study caused significantly more injector coking than 100% diesel. The viscosities of 100RE, 100LSE, and 100OSE were 6.0, 4.4, and 5.0 cs respectively. Since esters of winter rapeseed and linoleic safflower oils had coking levels better or equal to diesel, while the oil blends did not, it appears that the lower viscosity is the major reason. Although 100OSE had significantly more coking than diesel it still was a reduction from the oleic oil and diesel blend, which again can probably be attributed to the lower viscosity of the OSE. The injector deposit results suggest that for certain vegetable oil fuels there is a cut-off point for maximum viscosity. Above the cut-off point coking levels would be excessive and below the cut-off point coking levels would be acceptable. For example, the blend of rapeseed oil and diesel with a viscosity of 11 cs showed significantly higher carbon deposits than diesel fuel, while RE, viscosity 6 cs, did not. So for winter rapeseed oil/ester the cut-off point would be between 6 and 11 cs. Other test results with vegetable oil blends also support this idea. Barenescu and Lusco (1982) reported that as a general trend the injector deposits increased in amount with the percentage of oil in the fuel blend and fuel viscosity increased accordingly. German et al. (1985) found that a 25% sunflower oil blend (viscosity 2x diesel) had a significantly lower amount of combustion carbon deposits than a 50% sunflower blend (viscosity 4x diesel). Although it is possible that the coking reduction was all or partially caused by the reduced amount of vegetable oil, instead of the lower viscosity, work by Ryan et al. (1984), supports the lower viscosity explanation. This study showed high viscosity vegetable oils had significantly different injection penetration rates than diesel, but heated oils with similar viscosities to diesel were not different from diesel fuel.

The thermal efficiencies measured when powering the engines with the test fuels were similar to that measured with the reference fuel. At speeds of 1500 to 1900 rpm the efficiencies measured with the ester fuels were equal or higher to that measured when using diesel, with OSE being associated with the highest efficiency. At higher speeds all the fuels were within 1% of each other. The highest efficiencies when using the ester fuels were calculated at low and medium engine speeds.

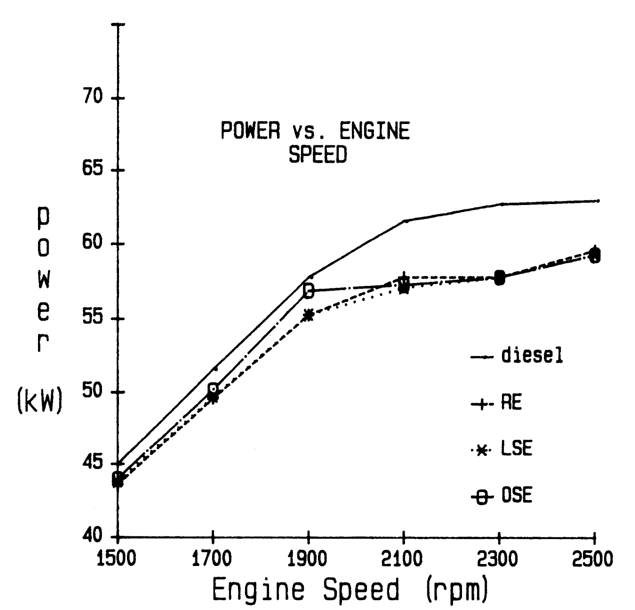

Fig. 7—Power curves comparing diesel fuel and three vegetable oil esters.

The ester fuels have a 9.5% lower heating value per kg and a 3% higher density than diesel. Since the engine fuel pump remained at the same volumetric setting throughout the tests the higher fuel consumption of the esters was due to the density difference. The lower power output of ester fuels, see Fig. 7, is expected because of the lower heating value of the esters versus the diesel. Higher thermal efficiencies by the esters compared to diesel would have been necessary for the esters to deliver the same amount of power as the diesel fuel, but their thermal efficiencies were about equal.

CONCLUSIONS

The short term "torque test" is suggested as a reliable method of screening alternative fuels for their propensity to form deposits in the combustion chamber (and specifically injector coking) prior to initiating longer term tests with the most promising fuels. Other conclusions are as follows:

Fumigation with oleic safflower oil reduced injector coking by 64%, to a level not significantly different from diesel fuel. Fumigation at the 10% nominal rate had no significant effect on injector coking caused by linoleic safflower oil. The different rates of propane fumigation had widely varied effects on the coking observed with high erucic winter rape oil.

A nominal rate of 5% fumigation increased the injector coking observed with winter rape oil by 68%. Ten percent fumigation with propane reduced the injector coking of winter rape oil by 21%. Fifteen percent fumigation did not significantly affect the injector coking of winter rape oil.

Transesterification reduced the injector coking observed with winter rape oil/diesel fuel 50% blends. The 48% decrease in injector coking was one of the most significant findings of this investigation.

In terms of injector coking 100LSE and 100RE were the best fuels with significantly less deposits than diesel fuel. 100OSE was the worst ester fuel and had significantly more coking than diesel, 100RE and 100LSE. In every case the ester fuels greatly reduced the amount of coking compared to previous studies reporting coking data for the neat vegetable oils. The reduced viscosity of the ester, 1.5 to 2 times that of diesel, is probably the most important factor contributing to the reduction. The ester fuels deliver 2 to 7% less power due to the lower heating value of the esters versus diesel fuel. The power losses might be corrected with fuel pump adjustments in future engine testing.

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