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Performance and Emission Characteristics of a Diesel Engine Operating on Safflower Seed Oil Methyl Ester

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ABSTRACT

This study focused on the evaluation and testing of safflower seed oil methyl ester as a diesel fuel alternative. The kinematic viscosity and ASTM fuel properties of the methyl ester fuel were within the limits specified for Grade No.2-D diesel fuel. Engine tests were performed on a four-cylinder, direct-injection CI engine using methyl ester and reference diesel fuel; engine performance and exhaust emission characteristics were determined. Safflower seed oil methyl ester revealed similar engine performance characteristics to the reference Grade No.2-D diesel fuel. Lower CO and HC emissions were obtained when methyl ester was used, and the negligible amount of sulfur content was an additional advantage of methyl ester over diesel fuel.

Index Entries: Diesel engine; engine performance; emissions; methyl ester; safflower seed oil.

INTRODUCTION

Worldwide concern over the foreseeable exhaustion of fossil energy resources, and availability and price of liquid fuels created substantial interest in alternative fuel sources, and biomass seems to be one of the promising solutions for current and future energy demands. Most of the

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energy-intensive sectors of society, such as agriculture, highway and railroad transportation, construction, and the military, are highly dependant on diesel fuel. Therefore, most of the recent research activities were directed toward substituting for fossil-based diesel fuel, which, once again, brought vegetable oils into focus (*1–3*). Utilization of vegetable oils is particularly attractive for farmers since it provides an opportunity to become energy self-sufficient by on-farm production of their own fuel. It is estimated that diverting 10% of the total acreage to vegetable-oil-originated liquid fuel production can supply all the liquid fuel demand of a typical farm (*4–6*).

Although Rudolph Diesel fueled one of his engines with peanut oil showing the possible use of vegetable oils in diesel engines (*7*), the direct use of vegetable oils in diesel engines causes severe problems because of their high viscosity and low volatility. High viscosity leads to poor atomization and incomplete combustion of the fuel, formation of excessive carbon deposits on the injection nozzles and in the combustion chamber, and contamination of the lubricating oil with unburnt residues. It is known that the performance of a direct-injection diesel engine is greatly affected by the injection and spray characteristics. Fuel atomization and mixing in the combustion chamber are directly influenced by the viscosity of the fuel injected. Therefore, in their pure form, vegetable oils are not suitable for use in modern diesel engines (*8–11*). Conversion of vegetable oils to fatty esters through the transesterification process with short-chain alcohols is an effective way of eliminating the high-viscosity problem. Methyl esters of vegetable oils have several outstanding advantages: They can readily be used without any modifications of the engine, their storage and handling require no special precautions, they have the same fuel economy and engine performance as diesel fuel, and because of their origin, they are environmental friendly (*12–14*). Recently, the production of a new biofuel, which is the transesterification product of soybean, rapeseed, or sunflower oils with methanol, has started on an industrial scale, and it is being tested for its performance on different types of vehicles in several European countries (*15,16*).

Although the importance of alternative fuels has always been considered within the State Development Plans of Türkiye, there has not been much effort in establishing an integrated system for such purpose so far. Completion of the South East Anatolia irrigation project provides a good opportunity for Türkiye to invest in an appropriate oil seed that can be cultivated easily in the area and initiate its own biofuel production program. Safflower may be one such prospective candidate since it is an oil seed of minor importance for the edible oil industry in Türkiye (*17*). Therefore, the aim of this study was to investigate the performance and emission characteristics of a compression ignition engine operating on safflower seed oil methyl ester as compared to the reference Grade No.2-D diesel fuel.

Table 1
Fuel Properties of Safflower Seed Oil Methyl Ester and Grade No.2-D Diesel Fuel

Properties	Method*	Grade No.2-D diesel fuel	Methyl ester
Density (kg/m^3)	D-4052	861.2	887.8
Cetane number (measured)	D-613	42.9	49.8
Flash point (°C)	D-92	–	180
	D-93	52	149
Pour point (°C)	D-97	−18	−6
Copper corrosion 3 h @ 100°C	D-130	1a	1a
Elemental composition (wt%)			
Carbon		87.19	77.43
Hydrogen		12.32	11.48
Oxygen		0.22	11.05
Sulfur		0.26	0.02
Nitrogen		0.01	0.01
Gross heating value (MJ/kg)	D-240	45.25	40.06

*ASTM test method.

MATERIALS AND METHODS

Crude safflower oil obtained from the Yenice variety of safflower seed that is grown in the Thrace region of Türkiye was transesterified using methanol in the presence of the alkali catalyst potassium hydroxide in order to reduce its viscosity (*18*). Methyl ester obtained from Yenice safflower seed oil and reference Grade No.2-D diesel fuel have similar fuel properties (Table 1).

Yenice safflower seed oil methyl ester was tested in a direct-injection compression ignition engine and compared with Grade No.2-D diesel fuel. The engine performance tests were carried on an Acadia Hercules D-2000 four-cylinder engine. The specifications of the test engine are given in Table 2. The engine performance tests were conducted at six engine speeds (1200, 1400, 1600, 1800, 2000, and 2200 rpm) using reference diesel fuel and at four engine speeds (1200, 1600, 1800, and 2200 rpm) using the ester fuel under full load conditions. Inlet and exhaust temperatures, barometric pressure, engine and dynamometer speeds, dynamometer force, and fuel consumption were recorded every 2 min during the tests. Inlet air and exhaust gas temperatures were recorded using type T (copper-constantan) and type K (chromel-alumel) thermocouples, respectively. A digital tachometer was used to measure the engine and dynamometer speeds. The engine was loaded using a Heenan & Froude hydraulic dynamometer. Fuel consumption was measured with a Mettler PS 15 balance

Table 2
Specifications of the Test Engine

Engine	Hercules D-2000 NA/DI*
Configuration	Inline, 4 cylinder
Piston displacement	3240 cm^3
Combustion chamber	Direct injection
Bore × stroke	9.5 × 11.4 cm
Compression ratio	19:1
Pump type	Single plunger
Injector type	CAV multihole
Injector timing	12° BTDC

*NA = naturally aspirated, DI = direct injection.

accurate to 0.001 kg. Exhaust emissions (HC, CO, and CO_2) were measured on-line using a Horiba, Model Mexa-534GE digital exhaust gas analyzer. A filter system composed of several filtering media and a moisture trap was used at the exhaust outlet of the engine to eliminate the particulates and to capture the moisture in the exhaust gas before entering the exhaust gas analyzer (*18,19*). In the beginning of the test, the engine was fueled with reference diesel fuel and allowed to warm up for about 20 minutes until engine temperatures stabilized. The two fuel filters were by passed before switching to methyl ester to prevent dilution of the ester fuel with diesel.

RESULTS AND DISCUSSION

Transesterification of safflower seed oil with methanol provided a significant decrease in viscosity (ASTM D-445). Variations in viscosity of Yenice safflower seed oil, methyl ester, and Grade No.2-D diesel fuel with temperature are given in Fig. 1. Viscosity of Yenice safflower seed oil methyl ester (4.07 cSt) at 40°C was slightly higher than that of diesel fuel (3.03 cSt), but much lower than that of the parent safflower seed oil (29.36 cSt). The increase in temperature further reduced the difference between the viscosities of methyl ester and the Grade No.2-D diesel fuel.

The ester product had lower gross heating value (40.06 MJ/kg) as compared to that of diesel fuel (45.25 MJ/kg). This was because of the higher oxygen content (11.05%) of methyl ester. A low sulfur content, high flash point, and high cetane number were the advantageous characteristics of methyl ester over the Grade No.2-D diesel fuel. Extremely low sulfur content of ester fuel means a drastic decrease in SO_2 emissions, the principal source of acid rain. The high flash point provides additional safety in storage and transportation of the fuel. The higher cetane number shortens the ignition delay and the engine operates more smoothly (*20*).

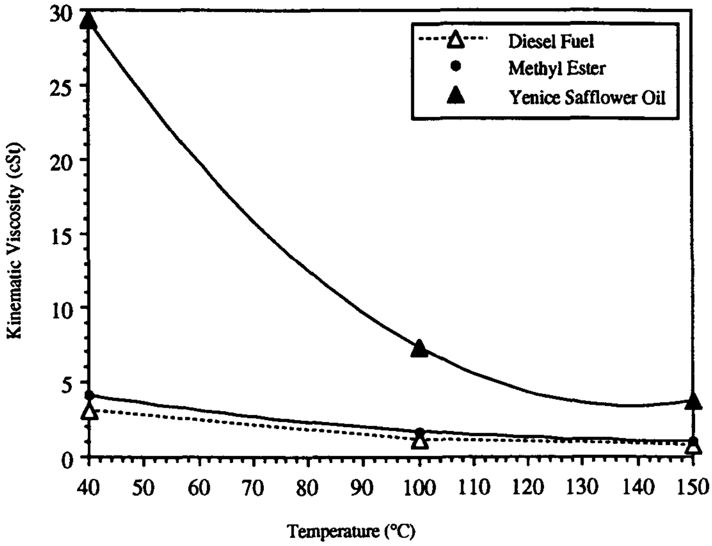

Fig. 1. Variations in viscosity of Yenice safflower seed oil, methyl ester, and Grade No.2-D diesel fuel with temperature.

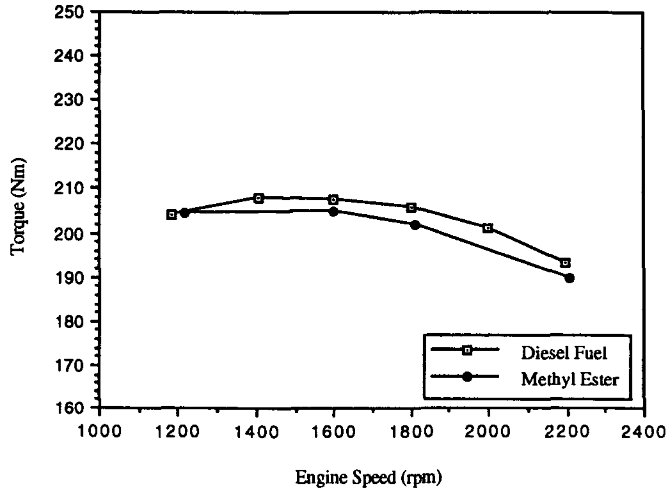

Fig. 2. Brake torque vs engine speed for methyl ester and grade No.2-D diesel fuel.

The engine performance using safflower seed oil methyl ester differed little from the engine performance operating on diesel fuel. Variations of the brake torque, brake power, and brake mean effective pressure with engine speed at full load are shown in Figs. 2–4. Maximum brake torque and brake mean effective pressure of the engine were obtained at an engine speed of 1600 rpm. The torque output at that speed was 208 Nm with the reference Grade No.2-D diesel fuel and 205 Nm with methyl ester fuel.

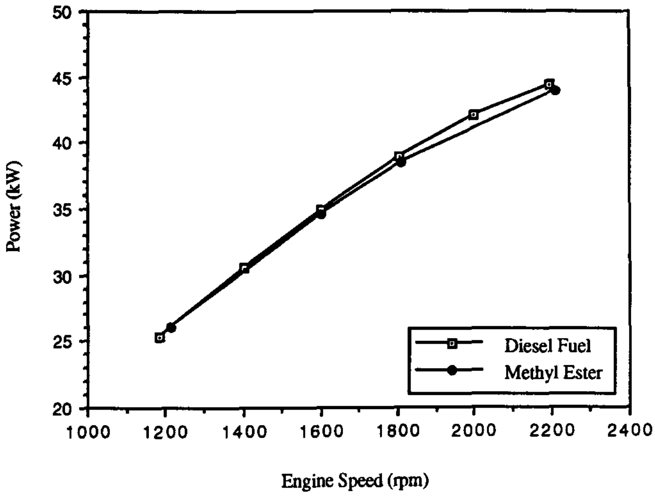

Fig. 3. Brake power vs engine speed for methyl ester and grade No.2-D diesel fuel.

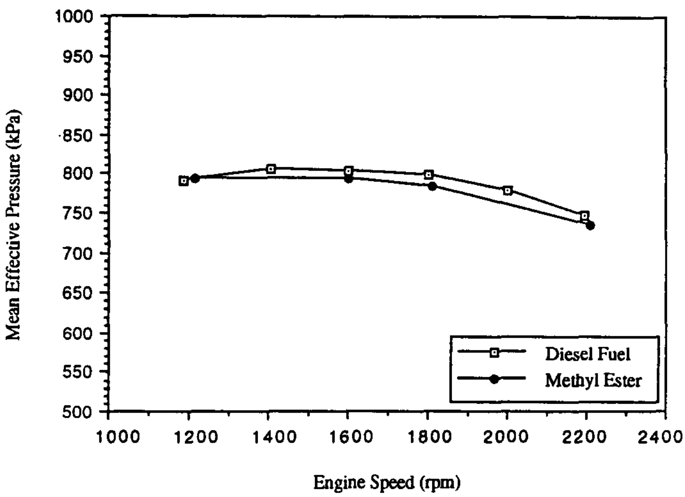

Fig. 4. Brake mean effective pressure vs engine speed for methyl ester and grade No.2-D diesel fuel.

Brake mean effective pressure at the same engine speed was 804 and 794 kPa for reference diesel and methyl ester fuels, respectively. At 2200 rpm, the power produced by the reference Grade No.2-D diesel fuel was 44.5 kW compared to 43.9 kW for the ester fuel. The slight drops (1.3%) in the brake torque, brake power, and brake mean effective pressure of the engine were related to the difference in the heating values of the two fuels. The heating value of methyl ester was lower (11.5% on mass basis and 8.7% on volume basis) than that of the reference diesel fuel. Clark et al. (*21*) explained the discrepancy in the difference of percent decrease in the

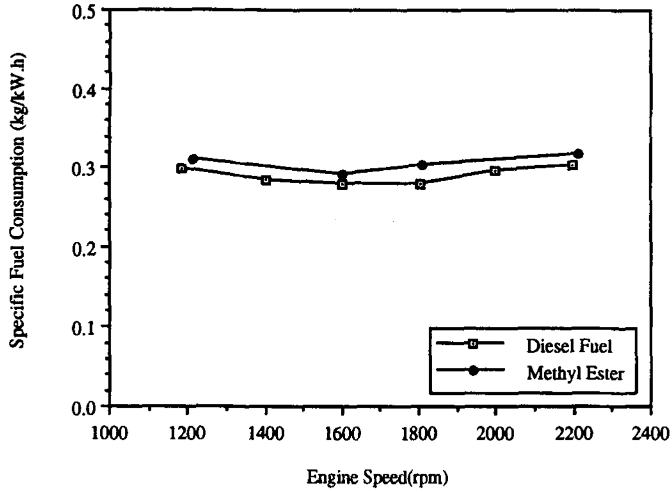

Fig. 5. Brake specific fuel consumption vs engine speed for methyl ester and grade No.2-D diesel fuel.

power output and the difference in the heating values of the two fuels with the volumetric basis fuel metering of the injection pump and lower density of reference diesel fuel. However, the difference between the power outputs (1.3%) and the volumetric energy density (8.7%) of the two fuels can further be attributed to the better combustion of the ester fuel.

Minimum brake-specific fuel consumption was obtained at an engine speed of 1600 rpm for both fuels (Fig. 5). Brake-specific fuel consumption values for methyl ester fuel (0.29 kg/kWh) were slightly higher than those for reference diesel fuel (0.28 kg/kWh). This was also primarily because of the lower gross heating value of ester fuel, which is 8.7% (volume basis) less than that of the diesel fuel. Hence, more fuel was needed to get the same amount of power output with the ester fuel.

Relatively high thermal efficiency values were observed with the ester fuel compared to reference Grade No.2-D diesel fuel (Fig. 6). The stoichiometric air-fuel ratio of methyl ester (12.3 kg air/kg fuel) was lower than that of the reference diesel fuel (14.2 kg air/kg fuel) because of its higher oxygen content. Therefore, the combustion of methyl ester was taking place in a leaner mixture as compared to the combustion of diesel fuel. This improved the combustion quality and resulted in higher thermal efficiency.

The HC and CO emissions of the engine were decreased both for the methyl ester and reference diesel fuels when the engine speed was increased (Figs. 7 and 8). HC and CO emissions were considerably reduced when methyl ester was used. This was attributed to the improved combustion quality resulting from the higher oxygen content of the ester fuel. The filters that were placed at the exhaust outlet of the engine were visually examined at the end of each test. Noticeably low particulate deposits were observed visually on the filter media with ester fuel compared to Grade No.2-D diesel fuel.

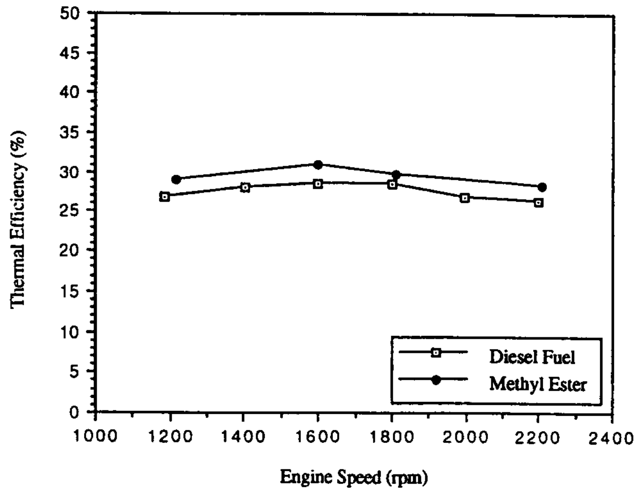

Fig. 6. Brake thermal efficiency vs engine speed for methyl ester and grade No.2-D diesel fuel.

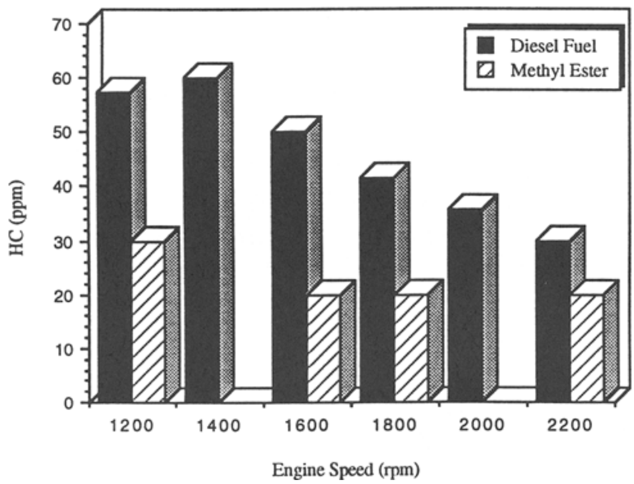

Fig. 7. HC emissions vs engine speed for methyl ester and grade No.2-D diesel fuel.

CONCLUSIONS

The viscosity of methyl ester at the temperature of 40°C was 4.07 cSt, which is within the limits specified for Grade No.2-D diesel fuel (1.9–4.1 cSt). The methyl ester had a lower gross heating value as compared to Grade No.2-D diesel fuel. The higher cetane number of methyl ester (49.8) is an advantage over Grade No.2-D diesel fuel. The extremely low sulfur content and high flash point are the other important advantages of methyl ester. Engine performance characteristics obtained with methyl ester

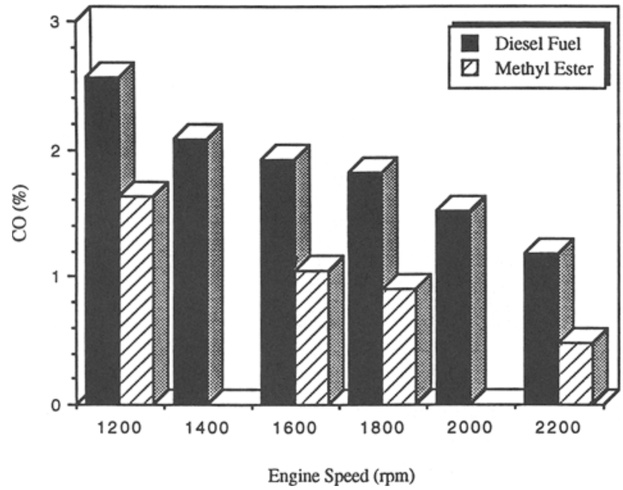

Fig. 8. CO emissions vs engine speed for methyl ester and grade No.2-D diesel fuel.

compared well to those of Grade No.2-D diesel fuel. A slight decrease was observed in brake power, brake torque, and brake mean effective pressure values of the engine operating on methyl ester as compared to Grade No.2-D diesel fuel. Brake-specific fuel consumption and brake thermal efficiency of the engine were higher when ester fuel was used. CO and HC emissions of the engine were reduced, and a significant decrease was observed in particulate emissions with the use of methyl ester. The fuel properties and results of the engine tests suggested that methyl ester obtained with the transesterification of Yenice safflower seed oil can be used as a fuel alternative for diesel engines. However, long-term engine tests must be conducted before commenting further on the convenience of the ester fuel for CI engines.

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