Performance and Emissions Characteristics of a Diesel Engine with Some Bio-oil Fuels

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ABSTRACT

The performance and exhaust emissions of a diesel engine using light oil, heated rice-bran oil, heated rice-bran oil treated with ultrasonic wave, used frying oil, used frying oil treated with ultrasonic wave, methyl esters of rice-bran oil and used frying oil have been compared. All the fuels performed satisfactorily in a precombustion chamber-type diesel engine without injection pump recalibration or any engine modification at the range of engine speed from 1600 to 2800 rpm at its full load during a short period, with the rice-bran oil and rice-bran oil treated with ultrasonic wave requiring somewhat preheating when ambient temperature was below 15℃. General performance and emissions characteristics of light oil and bio-oils were comparable, with the bio-oil based fuels giving very low SO_2 and lower smoke readings.

INTRODUCTION

Recently the use of bio-oils in diesel engines has received considerable attention due to the forseeable depletion of world oil supplies, the interest in cleaner burning fuel and the reduction in exhaust emissions from the IC engine. Most engines tested were the direct injection type(Zubic et al,(1984), Ali et al.(1996)). However, Mazed et al.(1985) reported that an indirect injection fuel system performed at a higher thermal efficiency. Therefore, a precombustion chamber-type diesel engine was used in this study.

The purpose of this study was to compare short term performance and emissions characteristics of the test engine burning several kinds of bio-oils as fuel relative to light oil in preparation for emergency use in the event of severe diesel fuel shortages. We included methyl ester of rice-bran oil and and applied ultrasonic energy to highly viscous bio-oils. These methods seem to have never been tried yet.

MATERIALS AND METHODS

Fuel Description
    The fuels tested were light oil(abbreviation used: L), heated rice-bran oil (H.R.B.), heated rice-bran oil treated with ultrasonic wave(U.H.R.B.), used frying oil(U.F.), used frying oil treated with ultrasonic wave(U.U.F.), methyl esters of rice-bran oil(R.B.E.) and used frying oil(U.F.E.). Their properties are given in Tabel 1. The light oil and the rice-bran oil were commercial products for, respectively, diesel engines and cooking. The used frying oil was collected after pure soybean oil was used in cooking at the Univ. restaurant. The fuel temperature of heated rice-bran oil and heated rice-bran oil treated with ultrasonic wave before being fed into the engine was about 50℃ - 60℃.

The frequency of ultrasonic wave applied was 28.5 kHz. The two methyl esters were supplied by Gyeongsang Nat'l Univ.

Vegetable oils are organic substances consisting of higher fatty acids. Transesterification of vegetable oil involves reacting an alcohol(e.g. methanol) with the oil in the presence of an alkaline catalyst to remove glycerol from the fatty acid producing the corresponding ester (e.g. methyl ester) with a molecular weight about one-third the original value. Usually such processed vegetable oils give rise to improved flowability of the oil and reduced deposits on engine parts(Nye et al.(1983), Zubic et al.(1984), Oh et al.(1989), Bhattacharyya and Reddy(1994)).

Equipment and Procedure

Fig. 1 is a schematic of the engine and instrumentation placement. A three-cylinder, precombustion chamber-type four-stroke cycle diesel engine was used for all tests. Its rated power was 14 kW at 2800 rpm. Table 2 presents specifications of the tested engine. The engine was coupled to an eddy current dynamometer(1 WB 15, Vibro-Meter) and tested at full throttle. The engine speeds selected were from 1600 to 2800 rpm including the speeds which produces rated output and maximum torque. The engine was operated without injection pump recalibration or any engine modification except that the original muffler was replaced with two flexible stainless pipes for collecting exhaust gases.

The inlet air flow was measured with an sharp-edge orifice type meter. The data of atmospheric pressure were obtained at Chinju meteorological observatory. The temperature of the inlet air, exhaust gases, cooling water, lubrication oil, fuel, and the relative humidity were recorded for each test run.

Fig. 2 shows the ultrasonic generator and the vibration horn for bio-oils. The ultrasonic generator consisted of an oscillation part, an amplifier and a matching part. This generator produces electric sine wave which is transmitted to the oscillator assembly at matching impedance, thus yielding ultrasonic wave. The oscillator assembly consisted of bolted Langevin vibration transducer(BLT) and vibration horn, made of PZT and duralumin, respectively, was installed between fuel filter and fuel feed pump to add the ultrasonic wave of 28.5 kHz to the bio-oils. A heater for preheating the highly viscous rice-bran oil was fabricated(3 kW, 300℃, 16 ℓ).

Exhaust gas analysis was performed using Kane-May Quintox combustion analyser. The exhaust gas sample was taken from the exhaust pipe connected to the exhaust manifold and fed through a hose to the analyzer to measure SO_2 and NOx concentrations. Smoke was measured using filter paper reflection type smokemeter(Daebon, BBC-1000).

After data for a given fuel had been obtained, the engine was shut off and the fuel was bled from the fuel system. The fuel filters were changed, and then the system was refilled with the next fuel to be tested. The engine was run long enough to remove all observable residual of the foregoing fuel from the fuel return line before the flow was routed back to the fuel filter.

RESULTS AND DISCUSSION

Torque

Fig. 3 shows torques from different fuels at full load condition. All the fuels tested yielded maximum torques at around 1900 rpm. As a whole within the experimental condition ranges noted previously, the decreasing order of the torque from different fuels was torque from light oil> torque from used frying oil treated with ultrasonic wave> torque from used frying oil> torque from heated rice-bran oil treated with ultrasonic wave> torque from heated rice-bran oil>torque from methyl ester of used frying oil> torque from rice-bran methyl ester.

At 1900 rpm where maximum torque appeared within the experimental condition ranges, light oil, used frying oil treated with ultrasonic wave and used frying oil yielded 60.5 - 60.4 N·m being the highest among all the fuels, and next to them heated rice-bran oil treated with ultrasonic wave and heated rice-bran oil yielded the torques being about 1.3% less than in the case of light oil. Next to

those values methyl ester of used frying oil yielded the torque being about 3.8% less than in the case of light oil. The lowest torque appeared in the case of rice-bran methyl ester, being about 6.1% less than in the case of light oil. Similar observations were reported by Ju et al.(1995). The reason for the torque of the light oil can be explained mainly in view of its highest calorific value among the tested fuels(Borgelt et al.(1994)).

The order of torques of fuels other than the light oil seems to have been caused by complex interaction effects of the factors such as calorific value, density and viscosity, etc. Without recalibration of the injection pump, the higher fuel densities and viscosities of bio-oils such as used frying oil treated with ultrasonic wave, used frying oil, heated rice-bran oil treated with ultrasonic wave and heated rice-bran oil could cause fuel flow and energy delivery increases that yielded torque increase(Barsic and Humke(1982)).

The torques from bio-oils treated with ultrasonic waves in the case of rice-bran oil and used frying oil yielded generally higher values than the ones from the untreated oils. This result can be attributed to the improvement of combustion performance due to the effects of improvement of fuel atomization and of raised fuel temperature caused by ultrasonic waves added to the fuels(Yang et al.(1994), Ju et al.(1995)).

Brake Specific Fuel Consumption
Fig. 4 shows the relation of brake specific fuel consumption versus engine speed at full load. As shown in Fig. 4 the brake specific fuel consumptions from all of the bio-oils tested are higher than the values from the light oil over the whole range of engine speed adopted in the test, which is similar to the observations reported by Borgelt et al.(1994) and Ju et al.(1995).

At the engine speed of 1900 rpm, the highest brake specific fuel consumption appeared in the case of heated rice-bran oil, being 14.9% higher than the one from the light oil, and the lowest one among the ones from bio-oil appeared in the case of methyl ester of used frying oil, being 11.8% lower than the one from the light oil.

At the range of engine speed from 1900 rpm and 2200 rpm, the decreasing order of the torque from different fuels was BSFC of heated rice-bran oil> BSFC of used frying oil> BSFC of heated rice-bran oil treated with ultrasonic wave> BSFC of used frying oil treated with ultrasonic wave> BSFC of rice-bran methyl ester> BSFC of methyl ester of used frying oil> BSFC of light oil.

This result could be attributed mainly to lower calorific values and viscosities of the fuels, in that this order almost reflected the inverse order of the magnitude of the lower calorific values of all the tested fuels, and in that without recalibration of the injection pump, the higher fuel densities and viscosities of bio-oils compared to light oil could cause fuel flow increases(Barsic and Humke(1982), Goering et al.(1982)).

Adding ultrasonic wave energy to two neat bio-oils, i.e., rice-bran oil and used frying oil, were effective with respect to brake specific fuel consumptions. The same effect was observed in the case of esterification of these two neat bio-oils but to a greater extent. The result can be attributed to the general effects caused by ultrasonic wave energy added to liquid and esterification of bio-oils(Barsic and Humke(1982), Yang et al.(1994)).

Filter Clogging Problem
Fig. 5 shows two paper elements of fuel filter after engine was operated using light oil and heated rice-bran oil, respectively, about two hours. In the case of heated rice-bran oil, the element of the filter left the sediment of the oil on the upper surface of the element. In this test, heated rice-bran oil had to be preheated to 50 - 60℃ using hot water because of its very poor flowability through the hose from fuel tank to the fuel injection pump under the condition of ambient air temperature below 15℃.

The other oils left little sediment compared to the one from heated rice-bran oil. But it is expected that there should be taken some countermeasures for using these two neat bio-oils as alternative fuels for long-term operation of diesel

engines(Barsic and Humke(1982), Bhattacharyya and Reddy(1994)).

Thermal Efficiency
Fig. 7 shows the thermal efficiencies of the tested engine when operating on the tested fuels. As shown in Fig. 7, results comparing the bio-oils with light oil generally show slight improvements in thermal efficiency when operating on bio-oils. These results can be attributed to the slower, less harsh burning of bio-oils, and the betterments of cooling loss and mechanical loss. Similar observations were reported by Geyer et al.(1984) and Oh et al.(1988).

Exhaust Emissions
Fig. 8 shows the relation of sulphur dioxide(SO_2) versus engine speed for light oil at full load. The sulphur dioxide was not detected from the bio-oils except the light oil at full load conditions with the gas analyzer used in these tests. This must be a result of high percentage of sulfur in light oil, being 0.093%, while the contents of sulfur of bio-oils other than the light oil were less than 0.01% as shown in Table 1. As shown in Fig. 8 lowest emission concentration of SO_2 being about 1.5 ppm was observed around at the speed where maximum torque appeared and the concentration became higher at the range of the speed below or above this speed. Similar trends were observed by Ju et al.(1995).
Fig. 9 shows the relation of oxides of nitrogen emission versus engine speed for seven fuels used for these tests at full load. For all the fuels at the range of 1900 rpm and 2200 rpm maximum concentration of NOx emission appeared. It seems that NOx was produced intensively owing to shift reaction at this range of speed where combustion reaction was most active considering that maximum engine torques were obtained at around 1900 rpm.
Comparing the NOx emission concentrations from bio-oils to that from light oil, at the engine speed of 1900 rpm, the bio-oils other than the methyl ester of used frying oil emitted 8.7% - 17.4% less concentrations compared with the one from light oil being 413.5 ppm; at the speed of 2200 rpm, all the bio-oils emitted 1% - 11% less concentrations compared with the one from light oil being 409.5 ppm; at the speed of 2500 rpm, the bio-oils other than used frying oil and used frying oil treated with ultrasonic wave emitted 3.2% - 6.5% less concentrations compared with the one from light oil being 345.8 ppm, which shows that the trend of NOx emission was changed with the engine speed. But overall, bio-oils emitted less NOx than did light oils(Peterson and Reece(1996)).
As for the variations of NOx emission concentration with the increase of the engine speed, the highest emission concentrations were observed from all the fuels at the range of 1900 rpm to 2200 rpm, and the emission concentrations decreased distinctly at around 2500 rpm, and at the speed more than 2500 rpm the emission concentrations increased or remained almost the same. This trend is almost opposite to the trend observed in the case of smoke emission as described later, being generally known as the trade-off between the two emissions(Zubik et al.(1984), Wade et al.(1987)).
Fig. 10 shows the relation of smoke emission versus engine speed for 7 fuels used for these tests at full load. In the case of light oil, emissions of smoke from the engine operating on the bio-oils were lower compared to the one from the engine operating on the light oil over the whole range of engine speed adopted in these tests. A possible explanation of these trends would stem from the relatively higher contents of oxygen in bio-oils, being about 9 to 10% oxygen by weight compared to the one in the light oil, being about 0.4% oxygen, so that bio-oils burn more completely and produce lesser black smoke(Cho(1985), Ishii and Takeuchl(1987), Oh et al.(1988)).
Emissions of smoke at 2200 rpm were, respectively, 9.5% point and 16.2% point less for used frying oil and for rice-bran methyl ester compared to the one from light oil being 51%, while the ones from the other bio-oils were intermediate between the ones from these two bio-oils.
Within the experimental condition ranges in these tests, the lowest emissions of smoke were observed in the case of two methyl esters, except at the speed of 1600 rpm for the rice-bran methyl ester. Similar trends were observed by Zubic et al.(1984). According to them, the decrease in smoke with these methyl esters could

be attributed to the fact that the more reactive species would be more likely to oxidize and less likely to produce smoke than the long chain hydrocarbons present in the pure light oil, since the methyl ester decomposes thermally to give a significant amount of alkenes during the ignition delay, the overall reaction path may be shortened compared to the light oil, giving faster reaction rates and the observed increases in premixed burning, cylinder pressure, and rate of cylinder pressure rise. The free radicals produced during the thermal decomposition would also accelerate the combustion process.

As for the variations of smoke emission concentration with the increase of the engine speed, for all the fuels, the emission concentrations decreased from 1600 rpm to 2200 rpm, and increased from 2200 rpm to 2500 rpm, again decreased at the speed over 2500 rpm. This trend is almost opposite to the trend observed in the case of NOx emission as mentioned before, being generally known as the trade-off between the two emissions(Zubic et al(1984), Wade et al.(1987)).

As we have seen, general performance and emissions characteristics of light oil and bio-oils were comparable, with the bio-oil based fuels giving very low SO_2 and lower smoke readings. It can be concluded that these bio-oils can be used as alternative fuels for operating diesel engines similar to the precombustion chamber-type four-stroke cycle diesel engine used in this study without injection pump recalibration or any engine modification during a short term period in such an emergency event as severe diesel fuel shortages.

CONCLUSIONS

A 14 kW three-cylinder, precombustion chamber type diesel engine was tested for its short term performance and emissions evaluation at the range of engine speed from 1600 to 2800 rpm at its full load without injection pump recalibration or any engine modification using light oil, heated rice-bran oil, heated rice-bran oil treated with ultrasonic wave, used frying oil, used frying oil treated with ultrasonic wave, methyl esters of rice-bran oil and used frying oil

Within the scope of this experiment, the following conclusions were drawn :

The overall decreasing order of torque for fuels in the form of their name were light oil > used frying oil treated with ultrasonic wave > used frying oil > heated rice-bran oil treated with ultrasonic wave > heated rice-bran oil > methyl ester of used frying oil > rice-bran methyl ester.

Brake specific fuel consumptions for the bio-oils were higher than the one for the light oil.

Thermal efficiencies were slightly improved when operating on bio-oils compared with the results on the light oil.

Sulfur dioxide was detected only in the case of light oil.

The overall concentrations of oxides of nitrogen were lower for the bio-oils than the one for the light oil.

The concentrations of smoke were lower for the bio-oils than the one for the light oil.

It can be concluded that these bio-oils can be used as alternative fuels for operating diesel engines similar to the one used in this study without injection pump recalibration or any engine modification during a short term period in an emergency event.

ACKNOWLEDGEMENTS

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Table 1. Properties of the tested fuels

Item	Light Oil	Rice-bran Oil	Rice-bran Oil Ester	Used Frying Oil	Used Frying Oil Ester
Carbon(%)	85.7	77.2	76.8	76.7	76.9
Hydrogen(%)	13.6	11.6	12.4	12.0	11.5
Carbon residue(%)	0.20	0.307	0.091	0.262	0.053
Sulfur(%)	0.093	0.002	<0.01	<0.01	<0.01
Ash(%)	0.001	<0.01	<0.01	<0.01	
Specific Gravity(15/4℃)	0.848	0.920	0.877	0.919	0.881
Kinematic Viscosity (37.8℃,cSt)	2.982	63.350	5.057	36.202	4.574
Higher Calorific Value(kcal/kg)	10920	9500	9600	9450	9530
Lower Calorific Value(kcal/kg)	10244	8939	9001	8870	8974
Flash Point(℃)	47	>150	>150	>150	>150
Pour Point(℃)	-22	-5.0	-27.5	-27.5	

Table 2. Specifications of the tested engine

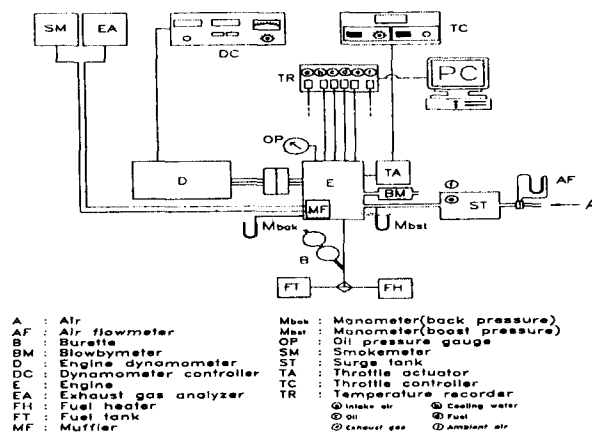| Item	Specification
Rated Output	14 kW / 2,800 rpm
Max. Torque	52.9 N·m / 1,800 rpm
PTO (horsepower)	13.5 kW / 2,800 rpm
Cooling method & cycle number	Pressurized-circulation type by cooling water pump, 4 cycles
Cylinder number & array	3-cylinders, vertical type
Cylinder diameter & Stroke	75 mm(inner), 70 mm(stroke)
Compression ratio	22:1
Displacement	927 cc
Fuel injection pump	Bosch k-type mini pump
Injection nozzle	DN12SD12 (throttle type)
Injection pressure	13.7 MPa
Injection time	BTDC 25°

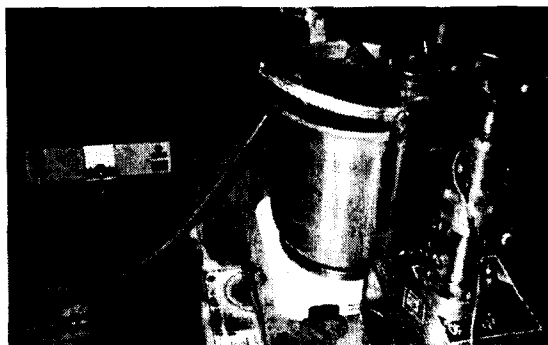**Fig. 1 Schematic diagram of the engine performance test system used.**

A	: Air	Mbak	: Manometer(back pressure)
AF	: Air flowmeter	Mbst	: Manometer(boost pressure)
B	: Burette	OP	: Oil pressure gauge
BM	: Blowbymeter	SM	: Smokemeter
D	: Engine dynamometer	ST	: Surge tank
DC	: Dynamometer controller	TA	: Throttle actuator
E	: Engine	TC	: Throttle controller
EA	: Exhaust gas analyzer	TR	: Temperature recorder
FH	: Fuel heater		① Intake air ③ Cooling water
FT	: Fuel tank		⑤ Oil ② Fuel
MF	: Muffler		② Exhaust gas ① Ambient air

Fig. 2 Photograph of the ultrasonic generator(left side) and the vibration horn(right side) for bio-oils.
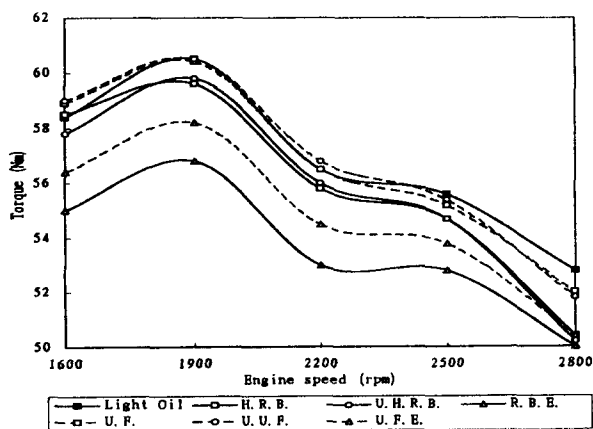
Fig. 3 Relation of torque vs. engine speed for 7 fuels at full load.
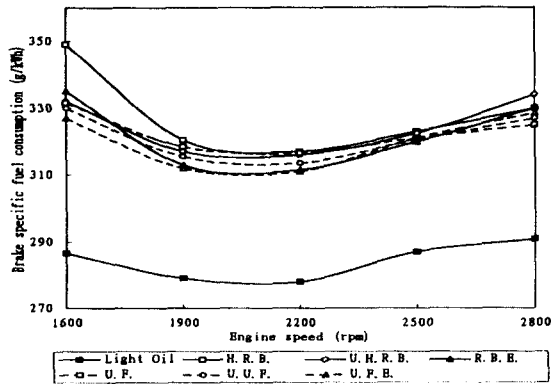
Fig. 4 Relation of brake specific fuel consumption vs. engine speed for 7 fuels at full load.
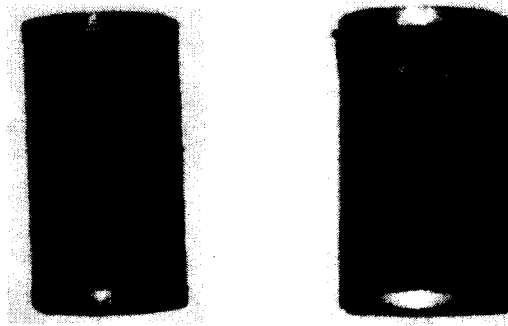

Fig. 5 Photograph of the fuel filter element used for light oil(left side) and heated r
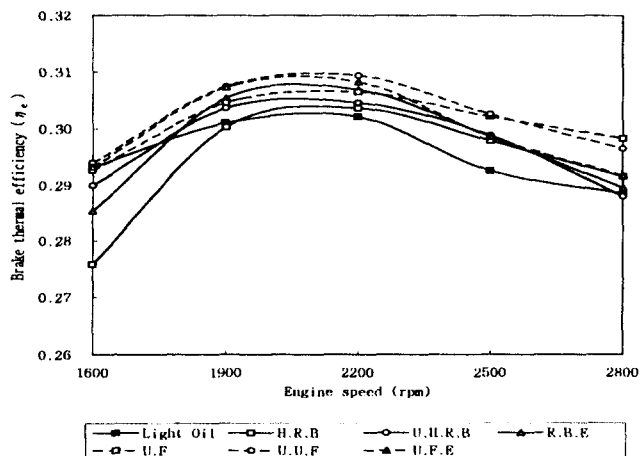ice-bran oil(right side) after about two hours' operation of the engine.

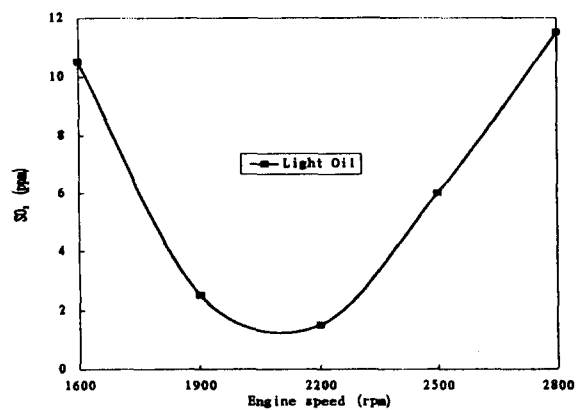Fig. 6 Relation of brake thermal efficiency vs. engine speed for 7 fuels at full load.

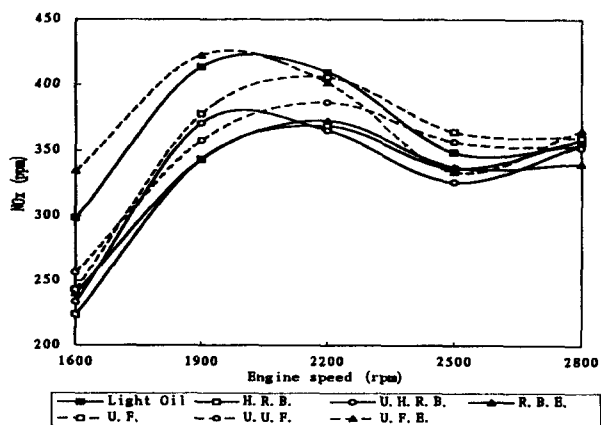Fig. 7 Relation of sulphur dioxide vs. engine speed for light oil at full load.

Fig. 8 Relation of oxides of nitrogen emission vs. engine speed for 7 fuels at full load.
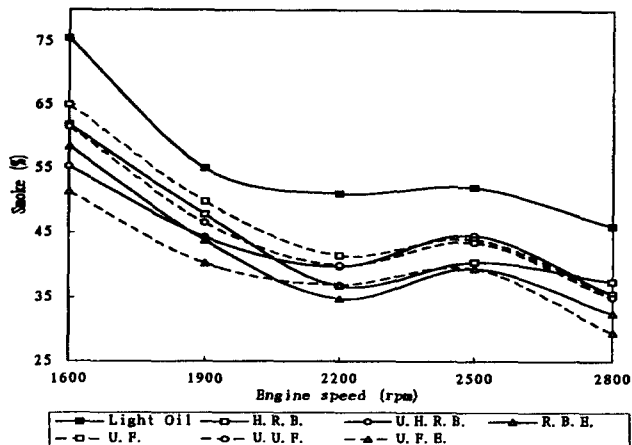

Fig. 9 Relation of smoke emission vs. engine speed for 7 fuels at full load.