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A Study on Diesel Engines with Alcohol Fuels*

(Engine Performance with Ethanol-castor Oil Fuel Blends)

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As an alternative fuel for diesel engines, the addition of castor oil to ethanol was investigated.

The paper describes in detail the influences of amounts of additives, heating of intake air, and increase of the compression ratio on startability and engine performance. Cycle to cycle variation of combustion is also discussed.

As a result of the experiment, it was found that smokeless and low NO_x diesel combustion could be made at satisfactory thermal efficiency with 40 % castor oil added to ethanol. Besides, the combustion variation was found to be closely related to the ignition lag or its variation, and was greatly reduced with a decrease in ignition lag, particularly at light load and low engine speed.

Key Words: Internal Combustion Engine, Diesel Combustion, Ethanol Blended Fuel, Startability, Engine Performance, Cycle to Cycle Variation of Combustion

1. Introduction

Alcohol is attracting attention as a substitute for conventional fuels. In the case of alcohols, the smokefree operation and reduction of NO_x are very advantageous.

However, because of their low cetane number, alcohol fuels are not easy to use in diesel engines.

A number of methods for using alcohols have been tried in diesel engines: an auxiliary injection method(1)(2), a carbureted method(3), a spark assisted method(4), and alcohols blended with diesel fuel or additives. Particularly, the last method gives good combustion of the alcohol fuel without major changes in the engine.

The purpose of this investigation is to analyze the startability, the combustion characteristics, and the cycle to cycle variation of combustion in a diesel engine operation with the ethanol-castor oil blend. Castor oil dissolves well in ethanol, and it plays a role in improving the ignition of the blended fuel.

Compared with conventional diesel fuel operation, the results of the experiments showed that similar startability and stable ignition could be obtained with proper amounts of castor oil in ethanol. At 40 vol% castor oil in the fuel, the brake specific heat consumption became the smallest. Smoke density and NO_x concentration were improved with the use of the fuel. The cycle to cycle variation of

combustion, which in this study is characterized by the variation of peak pressures, was strongly affected by the length of the ignition lag.

2. Experimental Apparatus and Procedure

Two kinds of pre-combustion chamber diesel engines were used in the experiments. The main specifications of the engines are shown in Table 1. Engine A was employed for the experiments on the startability and engine performance, and engine B was used for measuring the cycle to cycle variation of combustion.

The fuel was composed of ethanol (99.5 vol%) and castor oil (specific gravity 0.96), and gas oil was used for reference operation. Castor oil, which

Table 1 - Specifications of the test engines

Test Engine	A	B
Engine name	Mitsubishi DV-4	Yanmar TS-180C
Combustion chamber	Pre-chamber	Pre-chamber
Bore x Stroke	95 x 110 mm	102 x 106 mm
Stroke volume	780 cc	866 cc
Compression ratio	19.0	21.0
Rated power	13.4 kW/3200 rpm	11.0 kW/2400 rpm
Volumetric ratio of pre-chamber to clearance volume	42.5 %	46.5 %
Area ratio of connecting passage to the section of cylinder	0.572 %	0.733 %
Fuel injection pump	Bosch XND-PE4A	Bosch XND-PE4A
Injection nozzle	DP-PN4SD24	DP-PN4SD24
Nozzle opening pressure	11.8 MPa (120 kgf/cm ²)	14.8 MPa (148 kgf/cm ²)

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consists of ricinoleic acid, was used as an ignition improver and it showed good solubility in ethanol. When the temperature was above -20°C , castor oil dissolved well in ethanol. In order to improve the ignition, the addition of hexyl-nitrate to ethanol was also examined. Hexyl-nitrate is one of the most effective additives for increasing the ignitability, but it is unstable and extremely expensive.

The pressure in the main combustion chamber was measured by a strain gauge type pressure transducer and the fuel injection timing was determined by a displacement transducer. NOx concentration was measured with a CLD analyzer.

The cycle to cycle variation was characterized by the standard deviation of the peak pressure as in spark ignited engines(5)(6). The peak pressure variation in the cylinder was determined with a rapid recording system consisting of a high-speed analog digital (A/D) converter and a computer.

3. Experimental Results and Discussion

3.1 Startability with the Ethanol-castor Oil Blended Fuel

Fig. 1 shows the relationship between the cooling water temperature which gives continuous ignition within 50 cycles after fuel injection and the amount of castor oil in the fuel. The intake air temperature was maintained at 20°C and the engine speed at 600 rpm. The results with hexyl-nitrate are also shown in the figure. Continuous ignition is achieved in the area above the curve. When the amounts of castor oil or hexyl-nitrate increase, the startability is significantly improved.

More than 70 vol% castor oil added to the fuel allows starting at room temperature, while 15 vol% hexyl-nitrate gives similar startability. Thus, the amount of castor oil required to get good startability at room temperature is five times the amount of hexyl-nitrate.

Fig. 2 shows the relationship between the amount of castor oil in the fuel and the cooling water temperature for two compression ratios. When the compression ratio decreases, the amount of castor oil necessary for good startability increases significantly. This implies that an

Fig. 1 - Startability with the ethanol-castor oil and -hexyl nitrate blends (compression ratio: 19.0)

Fig. 2 - The effect of the compression ratio on starting

increase in the gas temperature in the cylinder improves startability considerably.

Fig. 3 shows the relationship between the gas temperature at the compression end and the amount of castor oil necessary for starting. The gas temperature in the cylinder is calculated from the adiabatic change. An increase in the proportion of castor oil reduces the compression end temperature required for starting.

Assuming that starting is achieved at a certain ignition lag, Wolfer's equation (7) becomes:

$$\frac{E}{R \cdot T_c} = D \quad (1)$$

where:

T_c : Compression end temperature for starting
 E : Activation energy
 R : Gas constant
 D : Constant

With the hypothesis that E decreases in proportion to the inverse of the castor oil/fuel ratio (X_m), equation (1) becomes:

$$\frac{E}{R \cdot D} = \frac{B}{X_m + A} + C = T_c \quad (2)$$

where:

X_m : Percentage of castor oil in the fuel mixture (vol%)
 A, B, C : Constants

Fig. 3 - The relationship between the amount of castor oil and the compression end temperature for starting

From the results shown in Fig. 3, the values of the constants can be determined as: $A=10$ (vol%), $B=2535$ (K), $C=924$ (K). Consequently the compression end temperature for starting may be expressed as:

$$T_c = \frac{2535}{X_m + 10} + 924 \quad (\text{K}) \quad (3)$$

When a glow plug is installed, a lower T_c is required for starting.

3.2 Engine Performance with the Ethanol-castor Oil Blended Fuel

Engine performance and combustion characteristics were investigated for the ethanol-castor oil blended fuel.

Fig. 4 shows the effect of the castor oil/fuel mixing ratio on the engine performance. Here, the engine was operated at 2000 rpm, at a brake mean effective pressure (BMEP) of 0.29 MPa. The injection timing was fixed to give the best brake specific heat consumption (BSHC). BSHC becomes lowest at a castor oil content of 40 vol%, while the peak pressure, the maximum rate of pressure rise, and engine noise become highest at the same mixture ratio. The smoke density gradually increases with an increase in the castor oil amount.

$$1 \text{ MJ}/(\text{kW}\cdot\text{h}) = 175.7 \text{ kcal}/(\text{PS}\cdot\text{h})$$

$$1 \text{ MPa} = 10.2 \text{ kgf}/\text{cm}^2$$

Fig. 4 - Changes in engine performance for different amounts of castor oil in fuel (Engine speed: 2000 rpm, BMEP: 0.29 MPa)

The fact that BSHC is lowest at the castor oil/fuel mixing ratio of 40 vol% may be due to the degree of constant volume of combustion being highest as seen in Fig. 4.

Fig. 5 shows the indicator diagrams and the rates of heat release for three castor oil/fuel mixing ratios: 20, 40, and 70 vol%. At the castor oil/fuel mixing ratio of 20 vol%, a very large heat release of pre-mixed combustion occurs after the top dead center (TDC). In the case of the 70 vol% castor oil, the combustion duration increases slightly, resulting in a decrease in the degree of constant volume combustion.

$$1 \text{ MJ}/(\text{kmol}\cdot\text{°CA}) = 238.8 \text{ kcal}/(\text{kmol}\cdot\text{°CA})$$

$$1 \text{ MPa} = 10.2 \text{ kgf}/\text{cm}^2$$

Fig. 5 - Indicator diagrams and rates of heat release for three different amounts of castor oil in fuel

3.3 A Comparison between Operation with Ethanol-castor Oil Blended Fuel and Gas Oil

In the following experiment, the amount of castor oil in the fuel was maintained at 40 vol%, and the injection timings were fixed to give the lowest BSHC at a BMEP of 0.29 MPa.

Fig. 6 shows a comparison between the engine performance with ethanol-castor oil blended fuel and that with gas oil. From partial loads to the middle load range, the BSHC with the ethanol-castor oil blended fuel and gas oil show a similar drop, while it increases slightly in the higher load range. Both the rate of pressure rise and the noise increase significantly with ethanol-castor oil, while the smoke and NOx concentration decrease over the whole load range.

The main causes of the differences in BSHC may be explained as follows. Fig. 7 shows the degree of constant volume of combustion, and cooling loss to water. The BSHC with the ethanol-castor oil (40 vol%) blended fuel increases 3 % over that with gas oil, depending on the decrease in the constant volume of combustion.

$$1 \text{ MJ}/(\text{kW}\cdot\text{h}) = 175.7 \text{ kcal}/(\text{PS}\cdot\text{h})$$

$$1 \text{ MPa} = 10.2 \text{ kgf}/\text{cm}^2$$

Fig. 6 - A comparison of the engine performance with the ethanol-castor oil blend and that with gas oil

$$1 \text{ MJ}/(\text{kW}\cdot\text{h}) = 175.7 \text{ kcal}/(\text{PS}\cdot\text{h})$$

Fig. 7 - BSHC, the degree of constant volume of combustion, and the cooling loss to water in the ethanol-castor oil and conventional gas oil operation (BMEP: 0.51 MPa)

$$1 \text{ MJ}/(\text{kmol}\cdot\text{°CA}) = 238.8 \text{ kcal}/(\text{kmol}\cdot\text{°CA})$$

Fig. 8 - A comparison of the rate of heat release with the ethanol-castor oil (40 vol%) blend and that with gas oil (BMEP: 0.54 MPa)

Fig. 8 shows the rate of heat release curves in conventional operation with gas oil and with ethanol-castor oil blend. With use of the ethanol-castor oil blends, both the rate of pre-mixed heat release and the heat generation interval increase slightly. This behavior may reduce the degree of constant volume of combustion and increase the BSHC.

3.4 The Major Causes of Cycle to Cycle Variation under Light Loads at Low Engine Speeds

When the ethanol-castor oil blended fuel is used, stable operation in diesel engines is obtained with difficulty under light loads at low engine speeds.

Fig. 9 indicates the number of cycles necessary for an accurate measurement of the peak pressure variation. In the figure, the number of cycles is plotted on the ordinate, and the abscissa denotes the

1 MPa = 10.2 kgf/cm²

Fig. 9 - Number of cycles given an accurate mean value of the maximum combustion pressure

difference between the mean peak pressure for n cycles, $(\bar{P}_{\max})_n$, and the mean peak pressure for an infinite number of cycles, $(\bar{P}_{\max})_{\infty}$. The two curves in the figure show the theoretical values, and inside them the difference between $(\bar{P}_{\max})_n$ and $(\bar{P}_{\max})_{\infty}$ can be obtained statistically with a probability of 99 %. They are obtained from the equation:

$$|(\bar{P}_{\max})_n - (\bar{P}_{\max})_{\infty}| = 2.58 \sigma_{P_{\max}}/n$$

where:

$\sigma_{P_{\max}}$: Standard deviation of peak pressure (MPa)

In Fig. 9, the results were calculated with a standard deviation of $P_{\max}$ ($\sigma_{P_{\max}}$) = 0.3 MPa. Since the mean values of the peak pressures which converge rapidly over about 50 cycles are sufficient for measurement of the peak pressure variation, in this investigation we used data for 100 cycles.

Fig. 10 shows the relationship between $\sigma_{P_{\max}}$ and the operating engine loads at 800 rpm and at 2400 rpm. The value of $\sigma_{P_{\max}}$ decreases substantially with an increase in load for both engine speeds. Below a BMEP of 0.2 MPa, $\sigma_{P_{\max}}$ increases sharply for the low engine speed.

Generally, heating the air in the intake pipe is effective for reducing the combustion variation. Fig. 11 shows the effect of heating the intake air on the reduction of the combustion variation. With use of the ethanol-castor oil blend, $\sigma_{P_{\max}}$ decreases significantly with an increase in the intake air temperature, and it becomes almost the same as with gas oil over 40°C. Like the engine speed, the load and the temperature of the intake air are closely related to the gas temperature in the cylinder. In Fig. 12 $\sigma_{P_{\max}}$ is plotted against the calculated compression end temperature for various engine speeds, loads, and intake air temperatures.

1 MPa = 10.2 kgf/cm²

Fig. 10 - The effect of the load on the peak pressure variation (intake air temperature: 30°C)

1 MPa = 10.2 kgf/cm²

Fig. 11 - The effect of the intake air temperature on the peak pressure variation

In the case of the ethanol-castor oil blend, $\sigma_{P_{\max}}$ decreases remarkably with increase of temperature in the cylinder.

The amount of the castor oil in the fuel affects $\sigma_{P_{\max}}$ greatly. Fig. 13 shows the relationship between $\sigma_{P_{\max}}$ and the castor oil/fuel mixing ratio in idling. The $\sigma_{P_{\max}}$ value decreases with increasing amount of castor oil at both engine speeds. The variation in peak pressure becomes smaller up to 40 vol % castor oil, when $\sigma_{P_{\max}}$ is 0.2 ~ 0.3 MPa.

From the experimental data, it has been verified that there is a relation between $\sigma_{P_{\max}}$ and the ignition lag, which is controlled by both the temperature in the cylinder and the ignitability of the fuel. Fig. 14 shows the relationship

1 MPa = 10.2 kgf/cm²

Fig. 12 - The relationship between the estimated compression end temperature in the cylinder and the peak pressure variation

1 MPa = 10.2 kgf/cm²

Fig. 13 - The amount of castor oil and its effect on the peak pressure variation (intake air temperature: 30°C, BMEP: 0 MPa)

between σ_{pmax} and ignition lag at the engine speed of 800 rpm. In the figure, the open and solid circles indicate the data for BMEP=0.0 and 0.2 MPa, and σ_{pmax} increases exponentially with an increasing ignition lag.

Fig. 15 shows the relationship between the mean value of the ignition lag and its standard deviation. When the ignition lag increases, its deviation increases signifi-

1 MPa = 10.2 kgf/cm²

Fig. 14 - The relationship between the mean ignition lag and the peak pressure variation

Fig. 15 - The relationship between the mean ignition lag and its variation

cantly. Considering all the results, it can be said that the main cause of peak pressure variation may lie in the increase of the ignition lag.

4. Conclusions

The results obtained in the present investigation may be summarized as follows:

1. It has been found that good solubility is obtained with all ethanol/castor oil mixing ratios at room temperature. Optimum BSHC and startability are obtained with 40 vol% castor oil in the ethanol-castor oil blended fuel.

2. Although engine noise increases slightly with the ethanol-castor oil blended fuel, both NO_x concentration and smoke density decrease significantly. However, a decrease in the degree of con-

stant volume of combustion causes an increase in BSHC at higher loads.

3. Cycle to cycle variation of combustion with the ethanol-castor oil blended fuel takes place at lower engine speeds in a lower load range. However, regardless of the engine speed, it becomes almost equal to that of gas oil when the BMEP is over 0.2 MPa. Our test results indicate that the major cause of cycle to cycle variations in combustion is the ignition lag or its variation. A reduction in the combustion variation is achieved by an increase in intake air temperature or castor oil content.

4. Startability with the ethanol-castor oil blended fuel can be expressed by a simple formula:

$$T_c = \frac{2535}{X_m + 10} + 924 \quad (K)$$

(T_c : Compression end temperature (K),
 X_m : Percentage of castor oil in the
 fuel mixture (vol%))

This indicates that the startability is improved with an increase in the castor oil amount. With use of hexyl-nitrate, the improvement achieved in ignitability is five times as great as that with use of castor oil.

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References

- (1) Murayama, T., et al., Trans. Japan Soc. Mech. Engrs. (in Japanese), Vol. 47, No. 417 (1981), p.904
- (2) Sudoh, H., et al., JSAE (in Japanese), 794-A4 (1978), p.27
- (3) Murayama, T., et al., Joint Symp. of Int. Comb. Engines by JSME and JSAE (in Japanese), No. 2 (1981), p.139
- (4) Miyamoto, N., et al., Joint Symp. of Int. Comb. Engines by JSME and JSAE (in Japanese), No.2 (1981), p.145
- (5) Patterson, D.J., SAE Trans., 660129 (1966), p.621
- (6) Kin, E., Combustion of Internal Combustion Engine (San-kai doh) (in Japanese), (1973), p.95
- (7) Wolfer, W.W., VDI-Forschung Heft, Nr. 392 (1938)