Effects of Fuel Blending Stocks and MTBE on Combustion Characteristics in a SI Engine

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ABSTRACT

In this paper, the combustion characteristics of the spark ignition engine were studied by using six gasoline blending stocks as fuel in running ASTM-CFR engine with different compression ratio, air-fuel ratio and ignition timing. The TOYOTA single cylinder research engine was also tested by using MTBE-gasoline blends based on the above stocks with constant compression ratio (8.5:1) and different speed (900,1500, 2100 rpm) at Minimum advance for Best Torque. The flame propagation time were measured by the ionization probe technique and the combustion interval were computed by simulation program. The fuel properties such as research octane number, distillation temperature, Reid vapor pressure, API etc. were analyzed by means of ASTM method. The chemical structure, mass/volume fraction of paraffins, olefins, naphthenes, aromatics and average molecular weight of fuels were found according to PONA (Paraffins, Olefins, Naphthenes, Aromatics) analysis method. The maximum flame propagation time of blending stocks was recorded by BTX C_9^+ which belongs to aromatic group. The minimum fuel consumption of blending stocks is HCC gasoline. The combustion interval increased as the addition of the MTBE increasing. Ignition delays for MTBE-gasoline blends were observed to increased with the concentration of MTBE increasing. The shortest ignition delay and combustion interval of MTBE-gasoline blends occured near 1.1 equivalence ratio. CO and HC emissions with MTBE-gasoline are lower than those of clear gasoline and higher NO_x emissions at same operating conditions.

INTRODUCTION

The search for antiknock compounds has been long and continuing. Research dates back to early 1900's. In 1921, tetraethyllead was discovered to be a powerful antiknock additive and since that time, its use has been the most effective method of improving the octane of gasoline.

Then in the 1960's and early 1970's concern about the effect of auto emissions led to legislative restriction on automotive exhaust emissions. Resulting legislation required gradual removal of lead compounds from gasoline. Up to now, low-leaded or lead free gasoline are dominant in the world market, however this has increased the necessity for high octane blending components.

Methyl tertiary-butyl ether (MTBE) which is synthesized from methonal and isobutylene, is more compatible with gasoline and is one component now used for enhancing the octane of motor gasoline. MTBE has been in commercial use in many countries. Some technical assessments of the use of MTBE as automotive fuels have been made (1-7)*. In those papers, the research has been directed for the considerable toward determining the octane number, fuel properties, engine performances and emissions, but the ignition delay and combustion interval are absent. Specially, there are quite different results for emissions investigation. Furthermore, in this paper, emissions have been measured with same equivalence ratio and air-fuel ratio respectively. Since the stoichometric value of equivalence ratio in the mixture could be changed with the additional value of MTBE.

The major purpose of this paper is to analyze the ignition delay, combustion interval of MTBE-gasoline and the effect of various blending stocks by heat release simulation program. The experiments were carried out, using six kinds of blending stocks (HCC, reformate, light cracking C_5/C_9, reformate C_5/C_9,BTX C_9^+, FCC) (10)* with CFR engine. The HCC gasoline was obtained from gasoil through Hydro-catalytic cracking process. The product of reforming process was reformate. The C_5/C_9 light cracking was the residue which C_6-C_8 was extracted from the product of heavy naphtha steaming cracking process. The reformate C_5/C_9 was the residue which C_6/C_8 was extracted from heavy naphtha. BTX C_9^+ was the residue which C_6-C_8 was extracted from the product of reforming process. The FCC was obtained from vacuum gasoil through the fluidized bed catalytic process. On the other hand, the premium gasoline (P-G), clear gasolien(E00) and three kinds of MTBE gasoline (E00+5%MTBE=E01, E00+8%MTBE=E02, E00+11%MTBE=E03) were tested also by TOYOTA single cylinder engine.

EXPERIMENTAL

Test Fuels

Common properties such as octane number, Reid vapor pressure, distillation temperature, H/C ratio and PONA of tested fuel were studied. The measured results are shown in Table 1 and Table 2, respectively.

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* Numbers in parentheses designate references at end of paper.

Table 1. The physical properties of blending stocks.

Blending stock / property	C_5/C_9 Reformate	BTX C_9^+	Reformate	HCC gasoline	FCC gasoline	C_5/C_9 Steam cracking
paraffins mass,% / Volume,%	34.81 / 40.74	0 / 0	52.51 / 58.77	84.51 / 86.68	35.0 / 38.36	14.13 / 16.70
Olefins mass,% / Volume,%	0.79 / 0.79	0 / 0	0 / 0	0 / 0	17.13 / 18.26	23.34 / 26.40
Aromatics mass,% / Volume,%	45.66 / 40.63	~~0~~/50 / 0	43.94 / 37.82	2.29 / 1.74	30.99 / 26.89	54.54 / 48.87
Naphthanes mass,% / Volume,%	18.74 / 17.84	0 / 0	3.33 / 3.17	13.20 / 11.59	9.14 / 8.80	7.98 / 8.04
Hydrogen Content, %	11.8	10.4	15.6	16.8	13.3	11.3
RON	99.4	136.0	92.2	82.5	91.7	98.9
Stoichiometric A/F, g/g	14.13	13.82	15.0	15.22	14.47	14.02
Reid vapor pressure, KPa	50.0	———	19.31	78.96	44.14	46.56
Gross heating Value, kcal/kg	10570	10229	11183	11521	10920	10729
10% Distilled Temperature,°C	40	144.3	73.3	43.3	50.0	49.4
50% Distilled Temperature,°C	166.1	146.7	104.4	52.2	96.7	148.9
90% Distilled Temperature,°C	177.8	156.3	146.7	123.3	190.0	167.8
Average molecular weight	137	108	96.0	81.7	93.0	120.0

Table 2. Fuel properties of MTBE-gasoline blends.

fuel / property	clear gasoline	clear gasoline +5% MTBE	clear gasoline +8% MTBE	clear gasoline +11% MTBE
RON	95.4	95.9	96.3	96.9
RVP, KPa	49.6	50.3	51.0	49.6
10% Distilled Temperature, °C	52.2	52.7	52.2	51.2
50% Distilled Temperature, °C	122.2	113.3	103.3	98.8
90% Distilled Temperature, °C	176.6	175.0	173.3	173.3
Hydrogen / Carbon mole ratio	1.77	1.795	1.81	1.825
Oxygen / Carbon mole ratio	———	0.008	0.0128	0.0176
Stiochiometric A/F ratio, g/g	14.46	14.32	14.24	14.16
Paraffins mass, % / Volume, %	37.91 / 41.33	———	———	———
Olefins mass, % / Volume, %	11.62 / 12.73	———	———	———
Aromatics mass, % / Volume, %	39.19 / 34.92	———	———	———
Naphthenes mass, % / Volume, %	11.28 / 11.02	———	———	———

Test Engine and Equipment

In order to clarify the influence of combustion characteristics of various fuels on the performance of SI engine, the following items are studied.

- general performance
- rate of heat release
- apparent flame propagation velocity
- emission characteristics

The layout of the test rig and equipment are shown in Fig. 1. The general specification of test engines are shown in Table 3.

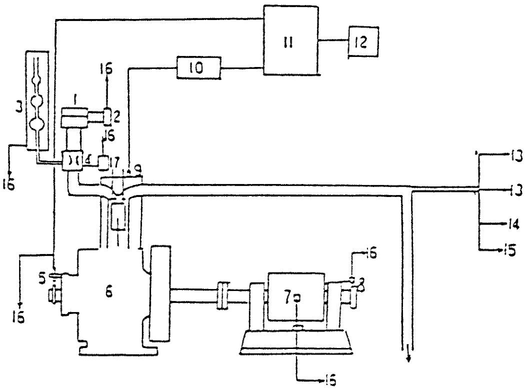

Fig. 1 Schematic diagram of experimental apparatus.

1	Air flow meter
2	Δp transducer
3	Fuel flow meter
4	Carburetor
5	Trigger pulse generator
6	Test engine
7	DC dynamometer
8	Tachometer
9	Pressure transducer
10	Charge amplifier
11	CB-366
12	Printer
13	HC/CO analyzer
14	NO_x analyzer
15	Air-fuel ratio analyzer
16	Control panel
17	Throttle controller

Table 3 Specification of test engines

	CFR Engine	TOYOTA Engine
Bore x Stroke mm x mm	82.55 x 114.3	85x86
Displacement cc	612	488
Compression ratio	variable	8.5
Rod length mm	254	147
Cooling system	steam(100°c)	water

Measurement Equipments and Data Analysis

The ionization probe was set upon the engine head as shown in Fig. 2.

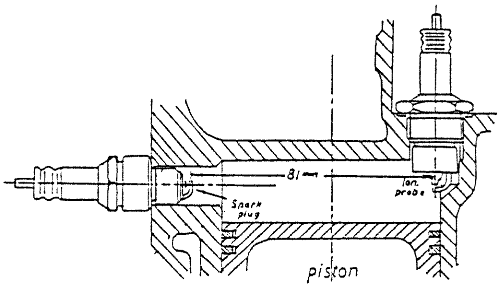

Fig. 2 The combustion chamber of CFR engine with the layout of ionization probe.

The apparent flame propagation velocity (8)* was calculated by using the measured period from the ignition beginning time to the arrival time at ionization probe. The period from the ignition time to arrival time at an ionization probe was estimated by averaging the values of about a hundred trials.

In order to get accurate response, AVL transducer, type 8Q 500c, has been used in this work. The pressure transducer adaptor was designed and mounted to be flushed with the cylinder head surface in order to ensure proper cooling of the transducer and eliminate any erratic operation. The specified constant water flow rate was required. The transducer was used in conjunction with a kistler 5007 charge amplifier.

An optical pick-up, Ono Sokki model pp917 & pp916, was attached on the extension of a crank shaft to detect signals for TDC. To observe ignition and combustion behavior in detail, the Model CB-366 combustion analyzer developed by Ono Sokki Co. LTD. was used. This instrument has eight categories of analysis functions such as pressure history diagram, indicate mean effective pressure and heat release rate etc.

Ignition Delay and Combustion Interval (9)*

We defined the crank angle which corresponds to 10% of the total heat release (i.e. 0.1Q) as the start of combustion, the duration of crank angle from ignition to the start of the combustion as the ignition delay, the crank angle corresponding to 90% of total heat release (i.e. 0.9Q) as the end of combustion and that interval between the start of combustion and the end of combustion as the combustion interval. The rate of heat release was used to calculate ignition delay and combustion interval.

Rate of Heat Release --

The Gas pressure in the cylinder was recorded on a data recorder accompained with timing pulses of every one deg-CA and a timing mark of TDC. The pulses and the pressure signals were digitalized with clocks of 1 deg-CA then transfered to CB-366. An ensemble averaged pressure of 360 cycle data was calculated for each sampled crank angle.

Exhaust gas analysis

Nondisperive infrared analyzer, Horiba MEXA-441F, was used for CO and HC, chemiluminescence detector, Horiba-1120CLT-H, was used for NO_x. The Air-fuel ratio was measured by the Beckman air fuel ratio analyzer.

Experimental test matrix are shown in table 4.

Table 4 Operation Condition

	CFR Engine	TOYOTA Engine
Engine speed rpm	900	900, 1500, 2100
Inlet mixture temperature, °c	80	ambient temperature
Equivalence ratio	0.7- 1.3	0.7-1.4
Ignition timing	14-34 deg BTDC	MBT

The combustion characteristics of blending stocks was studied by CFR engine and MTBE-gasoline blends was investigated by TOYOTA single cylinder engine.

Road Test

Two local passanger cars were used to measure fuel economy of MTBE gasoline on the road. During road tests, the test fuel was switched alternately with clear gasoline and MTBE blending gasoline. The fuel economy was determined daily by the actual kilometers per liter consumed.

RESULTS AND DISCUSSION

MTBE-Gasoline

Fuel Properties

The effects of MTBE on gasoline distillation were shown in Fig. 3, increasing the addition of MTBE decreased the evaporated temperature which could improve the performance of warm up. In Table 1, the relation of RON and MTBE volume fraction was near linearly proportional to the clear gasoline. Addition of MTBE up to 11% volume fraction, the RVP was net significantly different.

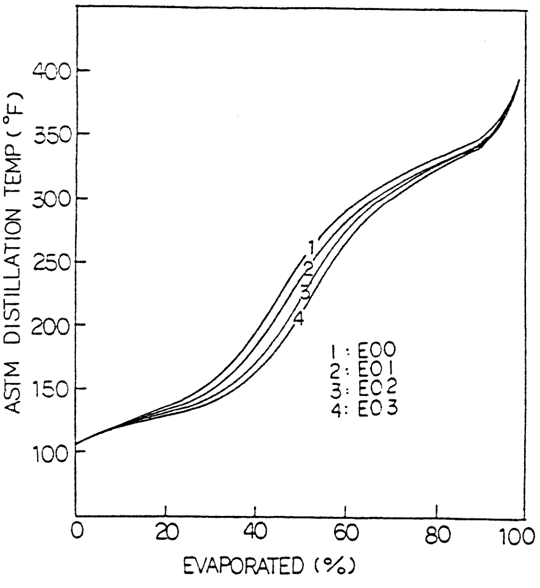

Fig. 3 Effect of MTBE on gasoline distillation.

Ignition Delay and Combustion Interval

The ignition delays and combustion intervals of MTBE-gasoline blends were observed to increase with the additional amount of MTBE at same equivalence ratio as shown in Fig. 4, Fig. 5 and same air-fuel ratio which shown in Fig. 6, Fig. 7. The minimum ignition delay and combustion interval occurred at 1.1 equivalence ratio.

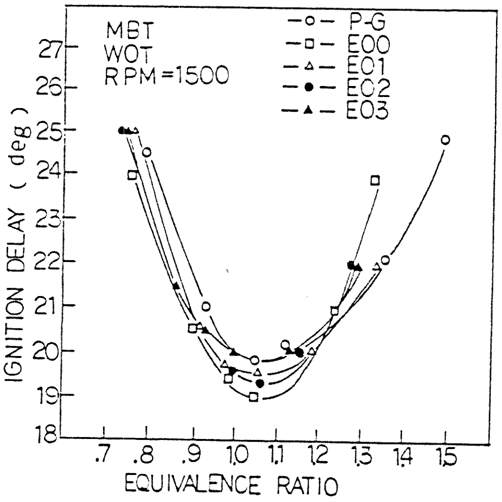

Fig. 4 Effect of MTBE on ignition delay with various equivalence ratio.

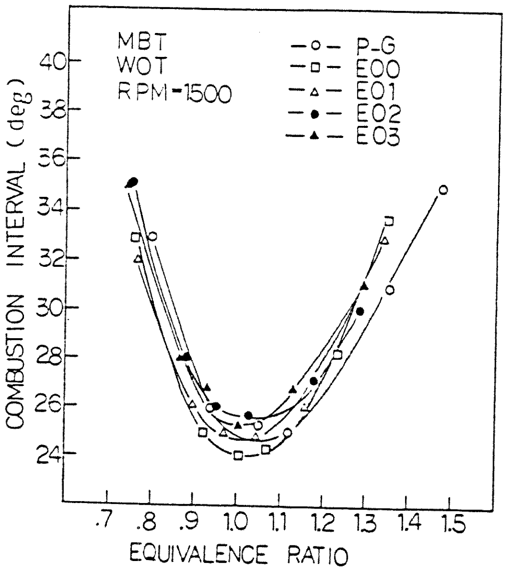

Fig. 5 Correlation of MTBE and combustion interval with various equivalence ratio.

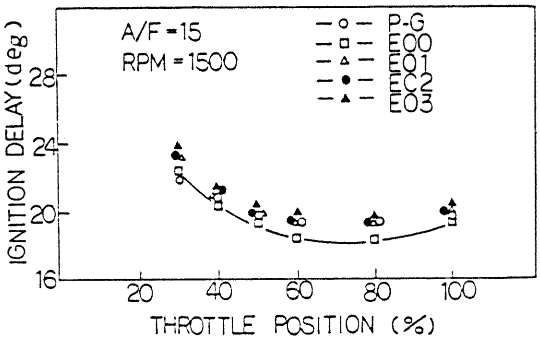

Fig. 6 Effect of MTBE on ignition delay at different throttle position.

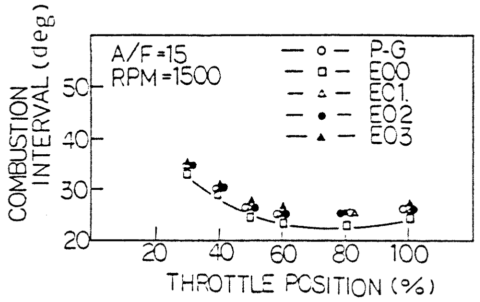

Fig. 7 Correlation of MTBE and combustion interval at different throttle position.

Exhaust Gas Emissions

At same equivalence ratio, the addition of MTBE in gasoline had no significant changes in HC, CO and NO_x as shown in Fig. 8, Fig. 9, Fig. 10. But at the same air-fuel ratio, HC and CO decreased with increasing the addition of MTBE in gasoline which shown in Fig. 11, Fig. 12 and NO_x increased as shown in Fig. 13.

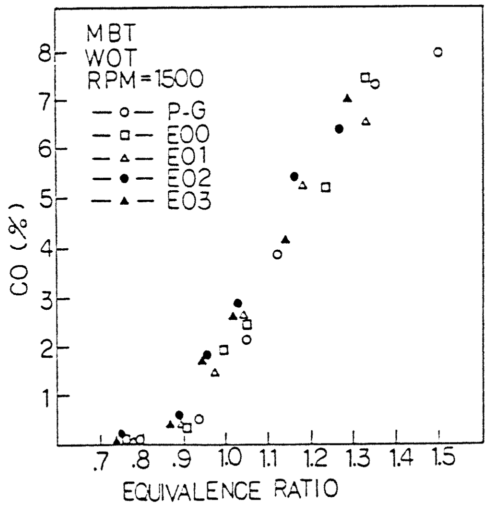

Fig. 8 Effect of MTBE on carbon monoxide emissions with various equivalence ratio.

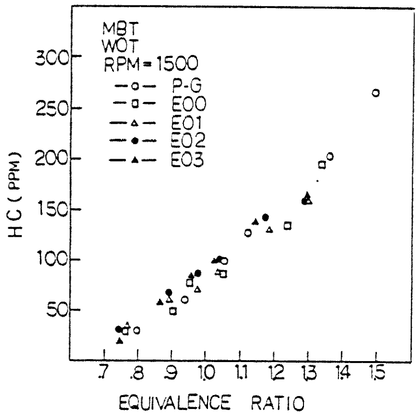

Fig. 9 Effect of MTBE on hydrocarbon emission with various equivalence ratio.

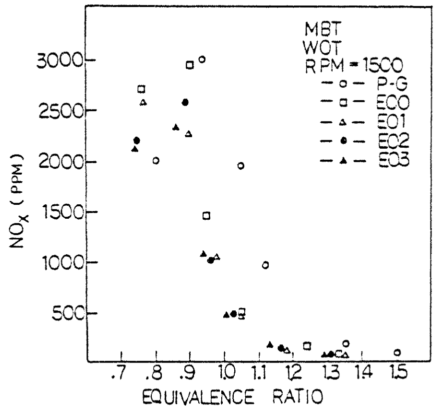

Fig.10 Effect of MTBE on oxides of nitrogen emissions with various equivalence ratio.

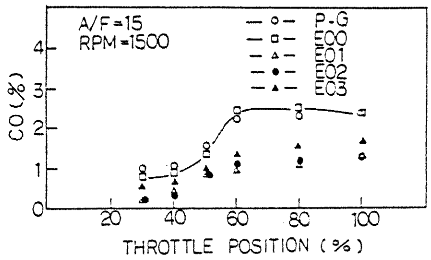

Fig.11 Variation of MTBE on carbon monoxide emissions at different throttle position.

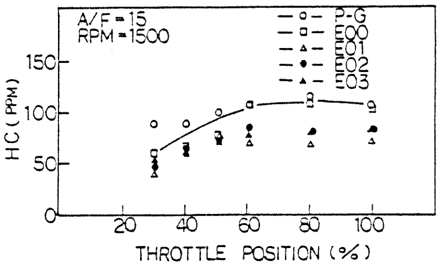

Fig.12 Variation of MTBE on hydrocarbon emissions at different throttle position.

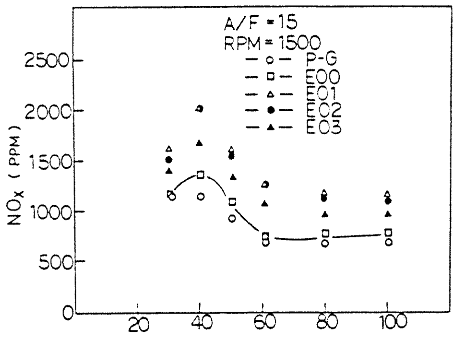

Fig.13 Variation of MTBE on oxides of nitrogen emissions at different throttle position.

Fuel Consumption and Power

There were no significant changes in fuel consumption of single cylinder test as shown in Fig. 14, and road test. These were slight higher indicate mean effective pressure when MTBE added up to 11% in clear gasoline as shown in Fig. 15. It may be due to improvement of combustion.

Blending Stocks

Apparent Flame Propagation Velocity

The relation between the apparent flame propagation velocity and equivalence ratio was described in Fig. 16. Ignition timing being at 27 deg-BTDC under CR=5 and CR=7, for both compression ratio, the apparent flame propagation velocity of $BTXC_9^+$ fuel was the slowest that had the largest RON 136 among the different blending stocks and the smallest RON HCC was fast. RON may be influenced by the different apparent flame propagation. If yhe apparent flame propagation velocity was fast, the burn rate would be fast. The burn rate determined the pressure-temperature history of the end gas. The hot products in the burned zone compressed the end gas, increasing its pressure and temperature, and increased its tendency to autoignite. A fast burn rate also reduced the time for heat losses to occur and this also increased the tendency of the end gas to auto-ignite.

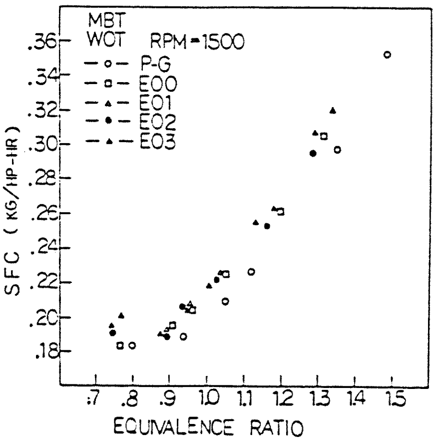

Fig.14 Influence of MTBE on fuel consumptions with various equivalence ratio.

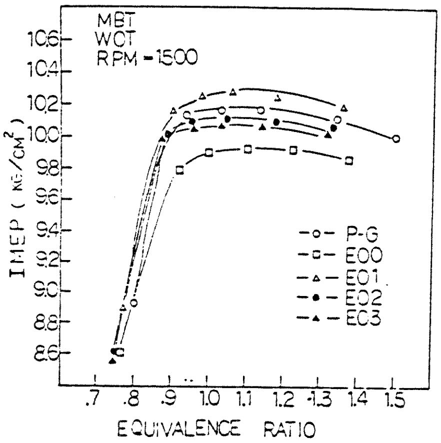

Fig.15 Influence of MTBE on indicate mean effect pressure with various equivalence ratio.

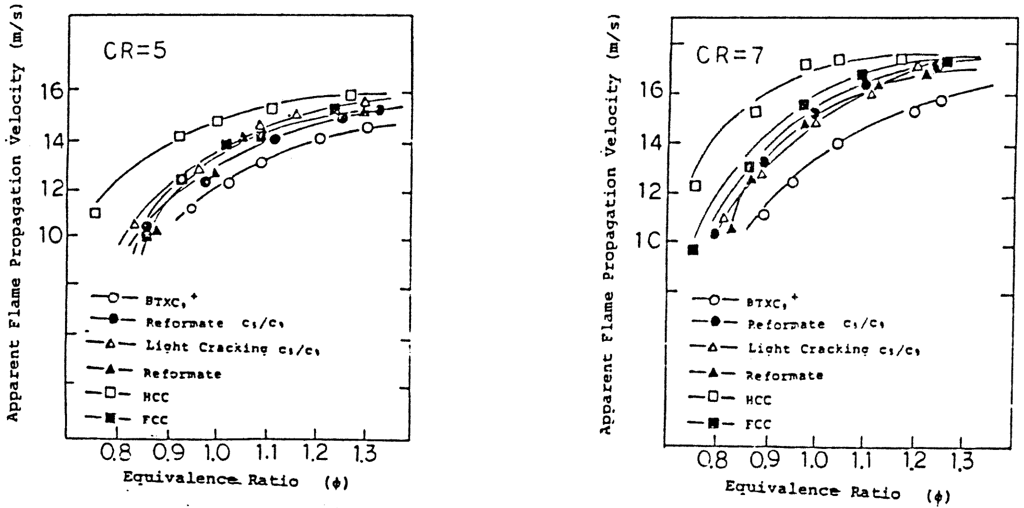

Fig. 16 The relation between apparent flame propagation velocity and equivalence ratio under compression ratio 5 and 7.

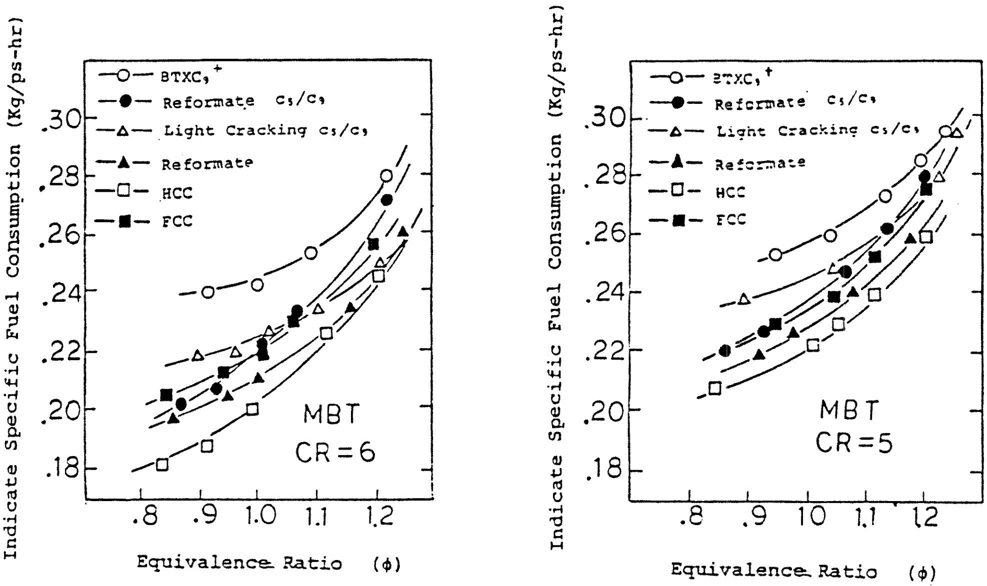

Fig. 17 The relation between indicate specific fuel comsumption and equivalence ratio under compression ratio 5 and 7.

Indicate Specific Fuel Consumption

The relation between the fuel consumption and equivalence ratio at ignition timing, MBT, under CR=5 and CR=7 was shown in Fig. 17. The largest quantities of specific fuel consumption among blending stocks was $BTXC_9^+$, the smallest was HCC

Combustion Characteristic Times and General Engine Performance. The combustion characteristic times was covered by the ignition delay, time giving maximum rate of heat release and the combustion interval as shown in Fig. 18.

A: Ignition Delay (10% Heat Release Point)

B: Time giving Maximum Rate of Heat Release

C: Combustion Interval (90% Heat Release Point)

Fig. 18 combustion characteristic times

The effect of ignition timing on the indicate mean effective pressure, the maximum rate of heat release and the combustion characteristic time was shown in Fig. 19.

It was recognized that the largest mean effective pressure could be obtained when the ingition delay occurring near TDC. In the case of equivalence ratio ϕ=1.0, MBT of blending stocks, HCC, FCC, Reformate, Light cracking C_5/C_9 and Reformate C_5/C_9 appeared between 22 deg-CA and 26 deg-CA. MBT was 30 deg-CA for $BTXC_9^+$ because of the slowest burn rate. The crank angle at maximum heat release appeared only after TDC except HCC, because it took shorter time from ignition to maximum heat release. The minimum indicate mean effective pressure was $BTXC_9^+$, these of other blending stocks were not significiently different.
The effect of compression ratio on lean limit of six blending stocks was shown in Fig. 20. The higher the compression ratio was, the better the lean limit would become. HCC had the best lean limit and $BTXC_9^+$ has the worst that observed from the behavior of six blending stocks. It was showed that HCC was more economic in fuel consumption with leaner air-fuel ratio.

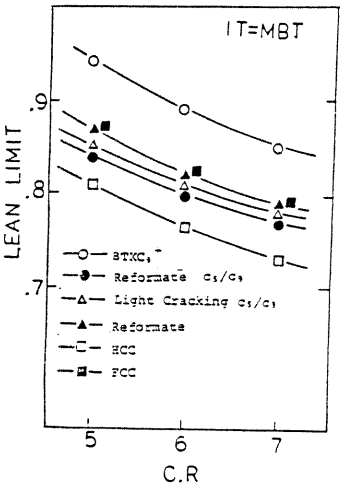

Fig. 20 The relation between lean limit and compression ratio with six blending stocks.

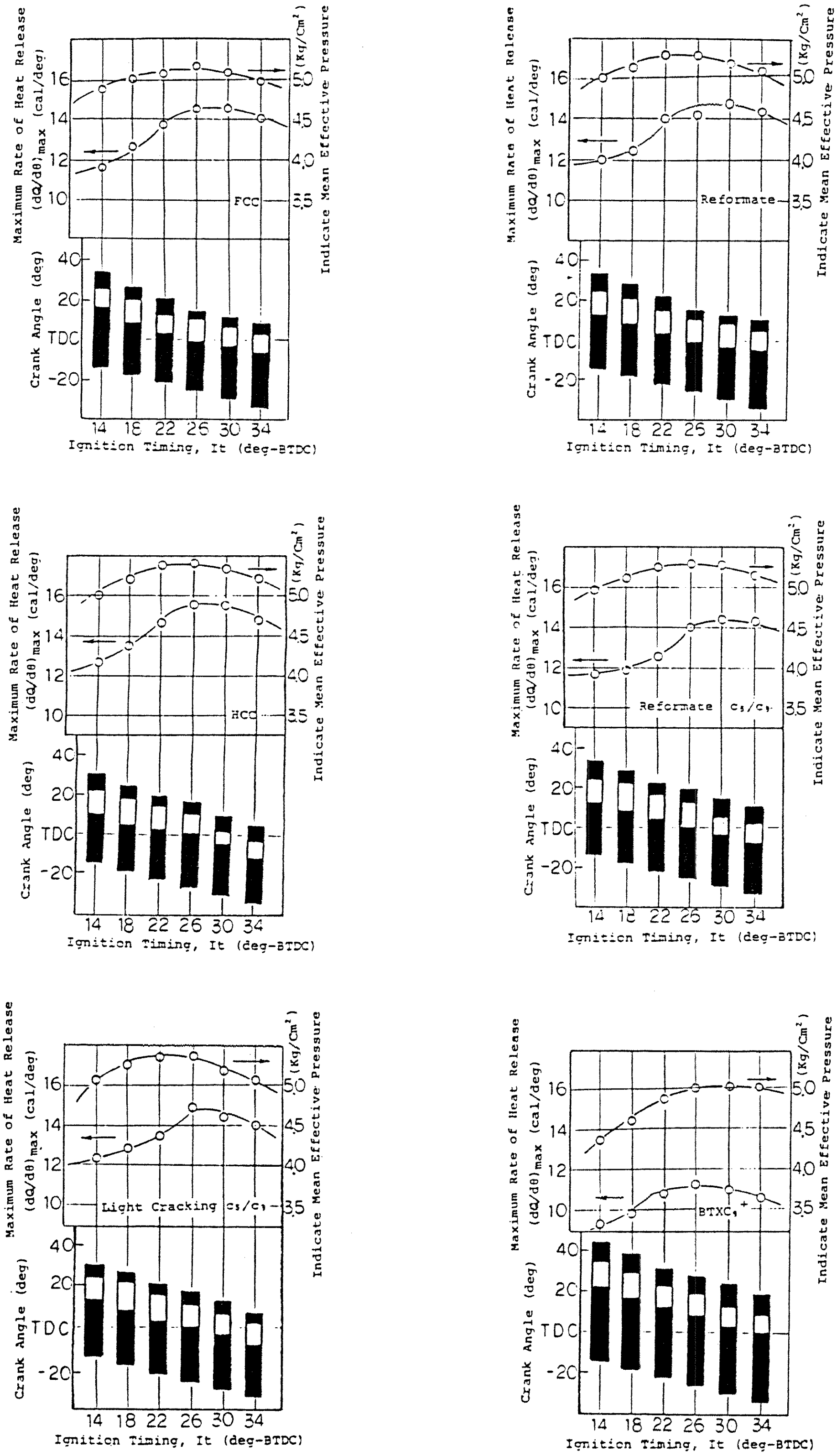

Fig. 19 Indicate mean effective pressure, maximum rate of heat release and combustion characteristic times as the function of ignition timing with equivalence ratio 1.0 under compression ratio 6 mapping with six blending stocks.

CONCLUSION

This study indicated that the blending stocks were not significantly different in combustion characteristics except $BTXC_9^+$. It also indicated that MTBE was a good octane enhancer that would improve octane rating of unleaded gasolines and decreased the CO and HC emissions with same air-fuel ratio. MTBE has been in commercial use for two Stroke engine in Taiwan and expect to successful application for vehicle fuel in the near future.

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