

# Experimental Investigation of SI Engine Performance Using Oxygenated Fuel

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*The current experimental study aims to examine the effects of using oxygenates as a replacement of lead additives in gasoline on performance of a typical SI engine. The tested oxygenates are MTBE, methanol, and ethanol. These oxygenates were blended with a base unleaded fuel in three ratios (10, 15, and 20 vol.%). The engine maximum output and thermal efficiency were evaluated at a variety of engine operating conditions using an engine dynamometer setup. The results of the oxygenated blends were compared to those of the base fuel and of a leaded fuel prepared by adding TEL to the base. When compared to the base and leaded fuels, the oxygenated blends improved the engine brake thermal efficiency. The leaded fuel performed better than the oxygenated blends in terms of the maximum output of the engine except in the case of 20 vol.% methanol and 15 vol.% ethanol blends. Overall, the methanol blends performed better than the other oxygenated blends in terms of engine output and thermal efficiency. [DOI: 10.1115/1.1615254]*

## Introduction

The anti-knock quality of the gasoline fuel used in spark-ignition internal combustion engines can be enhanced by the addition of lead alkyls but this results in the formation and emission of toxic lead compounds. A recent practice is to enhance the anti-knock property of the fuel by using certain high-octane oxygen-containing organic compounds called oxygenates. The use of oxygenates to replace the lead additives in gasoline is considered now as an alternative. The aim of this experimental work is to help in understanding the effect of the most popular oxygenates on the performance of typical automotive engines. The most commonly used oxygenates are MTBE (methyl tertiary butyl ether,  $C_4H_9-O-CH_3$ ), methanol ( $CH_3-OH$ ), and ethanol ( $C_2H_5-OH$ ). MTBE is manufactured from isobutane ( $(CH_3)_3CH$ ) and methanol, while methanol is manufactured from natural gas or synthesized from a variety of materials such as coal, municipal wastes, and biomass. Ethanol is derived from the direct fermentation of sugars, fermentation of starches and cellulose after chemical or enzymatic pretreatment, or made from petroleum sources.

These three oxygenates have different chemical and physical properties when compared to gasoline. These differences are expected to influence the performance and combustion products of gasoline-oxygenate blends. The study offers a comparison between the oxygenated and leaded fuels in terms of engine performance.

## Experimental Setup

The experiments were conducted using a six-cylinder engine. This engine is manufactured by Mercedes-Benz and has a swept volume of  $2960\text{ cm}^3$ . It has a bore of 88.5 mm, a stroke of 80.2 mm, a compression ratio of 9.2, and a maximum power of 132 kW at 5700 rpm. The engine is equipped with the KE-Jetronic continuous fuel injection system. The engine has an electronic ignition system with an electronic spark timing adjustment. The temperatures of cooling water and lubrication oil are controlled by two fitted heat exchangers. The engine is coupled to an eddy-current dynamometer. This eddy-current dynamometer is electronically controlled and water cooled. It has a maximum power

of 257 kW, a maximum torque of 1400 Nm, and a maximum speed of 8000 rpm. The effects of blending the oxygenates with unleaded gasoline on exhaust emissions of SI engines are presented in [1,2]. The detailed description of the test equipment used in this study is given in [3].

## Test Fuels

A base fuel was prepared by mixing 20% of naphtha with 80% of reformat on volumetric basis. A leaded fuel was prepared by adding tetra ethyl lead (TEL) to the base fuel. The addition of TEL brought the lead concentration in the fuel to 0.4 g pb/liter. The tested oxygenates are the MTBE (methyl tertiary butyl ether), methanol, and ethanol. Each one of the three oxygenates is blended with the base fuel in three ratios: 10, 15, and 20 vol.%. The MTBE/base blends were designated MTBE10 (10 vol.% MTBE+90 vol.% base), MTBE15, and MTBE20. The methanol/base blends were designated METH10, METH15, and METH20. The ethanol/base blends were designated ETH10, ETH15, and ETH20.

The purity of the MTBE was 98.71 wt.%, and the purity of methanol was 99.99 wt.%. The ethanol had a purity of 91.0 wt.%, and contains 7.8 wt.% of water. The presence of water is known to affect the miscibility of alcohol in gasoline. A blend of alcohol and gasoline tolerates the presence of water up to certain percentage, then any additional water will cause the alcohol to separate from the gasoline. Ethanol is known to have appreciably more tolerance to water than methanol. In the case of the ethanol/base blends prepared in the current study, the phase separation was

**Table 1 Properties of the oxygenates tested in this study**

Property	MTBE	Methanol	Crude Ethanol
Weight percent oxygen	18	50	39
Reid vapor pressure (kPa)	61.2	37.1	17.5
Boiling temperature, °C	53.3	63.5	75.6
Specific gravity @ 15.56°C	0.7461	0.7954	0.816
Research octane number	116*	133*	129*
Lower heating value (MJ/kg)	35.2**	20.0**	24.77***
Latent heat of vaporization (kJ/kg)	340**	1160**	950***
Stoichiometric A/F ratio	11.76	6.47	8.3****

\*Obtained from SAE handbook [9] for pure MTBE, methanol, and ethanol.

\*\*Obtained from Ref. [10].

\*\*\*Obtained from Ref. [10] for ethanol and adjusted for the presence of water.

\*\*\*\*Calculated for ethanol and adjusted for the presence of water.

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**Table 2 Properties of the test fuel**

Fuel Property	Base	Leaded	MTBE10	MTBE15	MTBE20	METH10	METH15	METH20	ETH10	ETH15	ETH20
Specific gravity @ 15.56°C	0.7697	0.772	0.7638	0.7633	0.7628	0.7692	0.7697	0.7707	0.775	0.775	0.777
Rvp, kPa	35.0	33.6	41.0	41.6	42.4	57.4	61.6	66.5	59.5	58.1	54.6
Research octane number	84.7	92	87.9	89.8	91.7	88.2	91.6	94.4	88.4	91.5	93.4
Heat of vaporization, kJ/kg*	350	350	349	349	348	428	466	505	413	445	476
Weight percent oxygen*	0	0	1.77	2.66	3.55	5.15	7.71	10.27	4.08	6.10	8.11
Heating value, MJ/kg*	44	44	43.144	42.715	42.283	41.528	40.298	39.073	41.97	40.97	39.97
Stoichiometric A/F*	14.6	14.6	14.33	14.19	14.05	13.77	13.35	12.94	13.95	13.62	13.3
Hydrocarbon types, vol.%**											
N-Paraffins	8.78	8.78	7.91	7.47	7.03	7.91	7.47	7.03	7.91	7.47	7.03
Iso-Paraffins	43.60	43.60	39.24	37.06	34.88	39.24	37.06	34.88	39.24	37.06	34.88
Naphthenes	3.83	3.83	3.45	3.26	3.07	3.45	3.26	3.07	3.45	3.26	3.07
Aromatics	42.54	42.54	38.28	36.16	34.03	38.28	36.16	34.03	38.28	36.16	34.03

\*Typical or calculated values and, if applicable, adjusted for the presence of added oxygenate.

\*\*Analysis was conducted on reformat and naphtha then calculated and, if applicable, adjusted for the presence of oxygenates.

encountered only with the ETH10 blend (10 vol.% ethanol+90 vol.% base) at a room temperature of about 20°C. No signs of phase separation were noticed beyond that temperature. In order to emulsify ethanol with base blends during operation, a circulation pump was fitted in the fuel tank to ensure continuous mixing of the fuel.

The relevant physical and chemical properties of the test fuels were determined. Tables 1 and 2 list those properties for the oxygenates and the test fuels, respectively. Some of the listed properties were not measured but rather obtained from the cited literature.

### Test Conditions

All the performance tests were carried out with the spark timing being manually adjusted to the maximum brake torque (MBT) timing, and the engine operating with a stoichiometric mixture.

The temperatures of the cooling water and the lubrication oil were controlled by two fitted heat exchangers. In all the tests, the cooling water temperature was kept at 80±5°C. The temperature of the lubrication oil was kept at 80±2°C during the exhaust emission tests, and ranged from 80°C to 95°C during the performance tests. The test room temperature was kept at 25±2°C during the exhaust emission tests and ranged from 20°C to 30°C during the performance tests. The recorded atmospheric pressure in the test room ranged from 99.4 kPa to 100.9 kPa. The engine performance results were corrected to the reference conditions (standard dry-air absolute pressure=99 kPa, standard temperature =25°C).

### Results and Discussion

The performance was evaluated in terms of the maximum output and the brake thermal efficiency of the engine. The maximum output was measured in a wide-open throttle variable-speed test. In the same test, the corresponding values for the brake thermal efficiency were evaluated. The brake thermal efficiency was also evaluated at a constant-speed constant-load test as a function of the equivalence ratio. The MBT timing values and the exhaust gas

temperatures were closely examined in order to help in understanding the performance results and explaining the variations between the fuels.

**Variable-Speed Test.** The engine maximum output and brake thermal efficiency were evaluated as a function of engine speed. During the test, the spark timing was adjusted to maximum brake torque (MBT) timing and the mixture was set to stoichiometric. Table 3 shows the values of the MBT timing versus engine speed for all the tested fuels. These values represent the MBT timing at wide-open throttle and stoichiometric mixture. The MBT timing is given in terms of crankshaft degrees before the top center (btc).

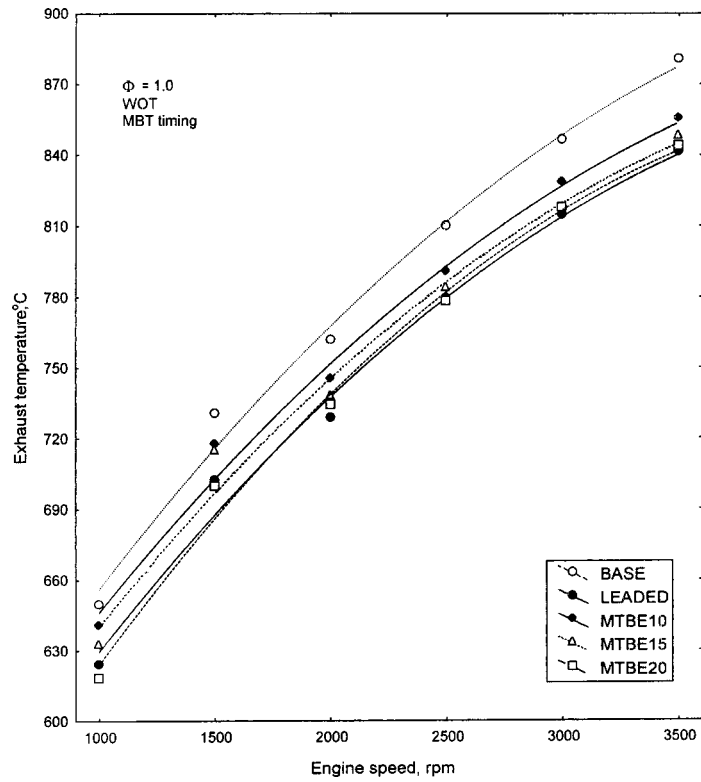
Figures 1, 2, and 3 show the variation of exhaust gas temperature corresponding to the current test for all the tested fuels. These exhaust temperatures were measured near the outlet of the exhaust manifold. In general, the highest exhaust temperature is observed with the base fuel, and the lowest with the leaded fuel. In addition, the exhaust temperature decreases as the oxygenate ratio in the blend increases. These variations in exhaust temperatures can be attributed to the increase in thermal efficiency and/or the decrease in the combustion temperatures. The increase in thermal efficiency means that a larger portion of combustion heat has been converted into work and therefore lower exhaust temperatures are expected. In addition, the lower combustion temperatures characterizing the oxygenated blends are expected to result in lower exhaust temperatures.

**Maximum Engine Output.** The engine maximum output was measured in terms of the maximum brake torque exerted by the engine at different engine speeds. The brake mean effective pressure (bmep) is usually used instead of the brake torque to represent the engine output. The bmep is a more universal term than the brake torque since it is independent of the engine.

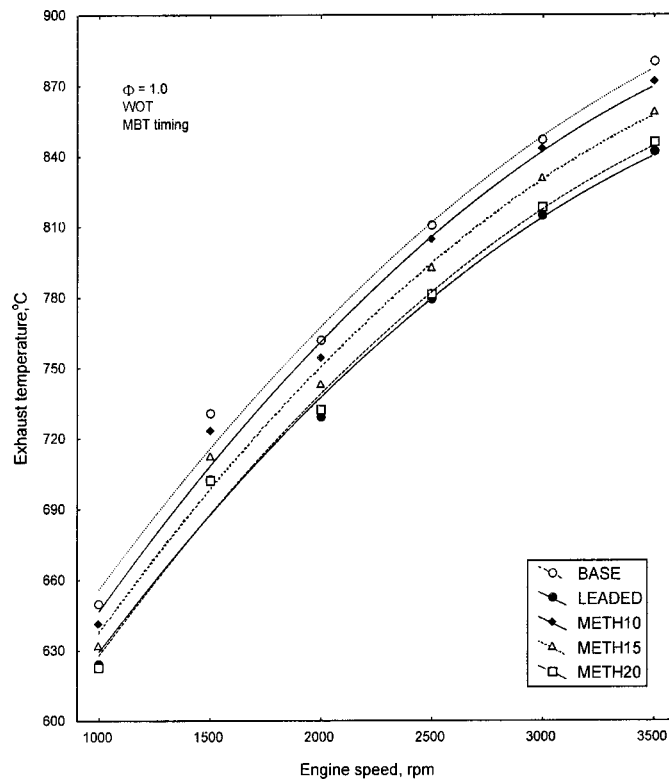
The maximum brake torque and bmep results versus engine speed for all the tested fuels are shown in Figs. 4, 5, and 6. The points indicate the measured values while the lines indicate the least-squares polynomial fit. Consistent and persisting fluctuations in the maximum torque measurements were observed. These fluctuations were closely examined and eventually linked to abnormal vibrations in the test setup. To reduce the fluctuation error, the

**Table 3 MBT spark timing at wide-open throttle and  $\Phi=1.0$** 

Speed, RPM	Base	Leaded	MTBE10	MTBE15	MTBE20	METH10	METH15	METH20	ETH10	ETH15	ETH20
1000	6	13	9	10	12	12	13	14	10	13	14
1500	13	20	15	16	20	18	19	20	17.5	22	23
2000	18	28	23	25	28	25	25	27	24	27	28
2500	21	31	26	28	31	28	29	30	26	31	32
3000	24	33	28	32.5	33	31	31	32	30	34	35
3500	25	35	31	32	35	33	33	33	32	35	36.5



**Fig. 1 Exhaust gas temperatures at wide-open throttle for the MTBE blends**



**Fig. 2 Exhaust gas temperature at wide-open throttle for the methanol blends**

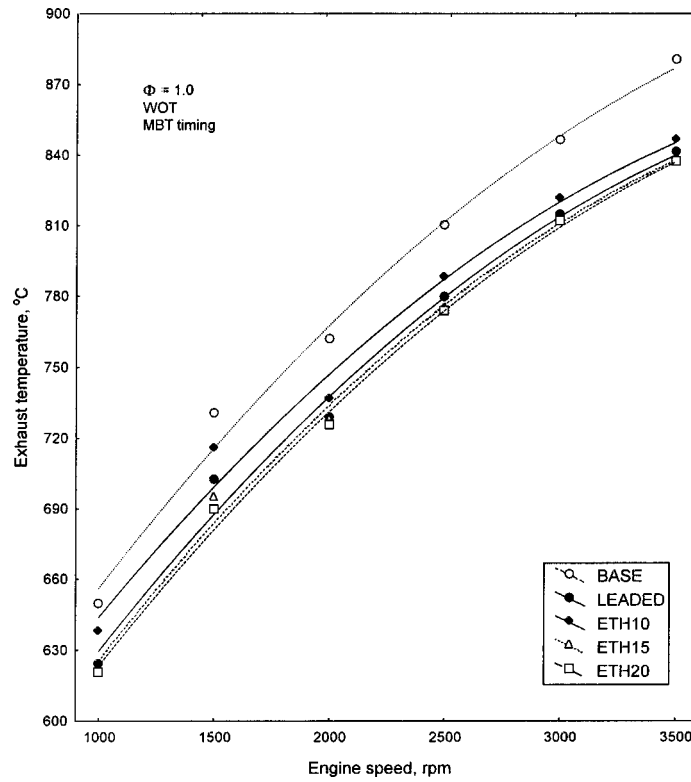


Fig. 3 Exhaust temperature at wide-open throttle for the ethanol blends

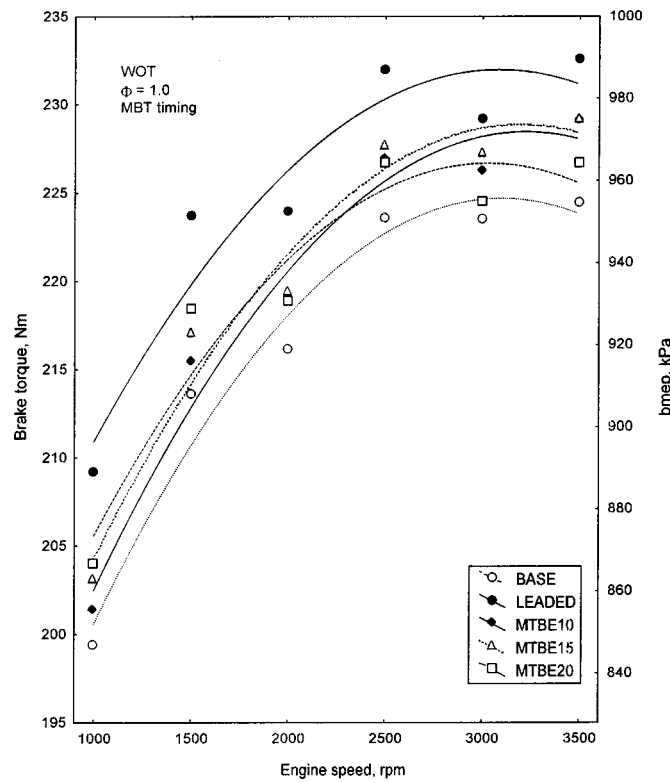


Fig. 4 Brake torque and mean effective pressure at wide-open throttle for the MTBE blends

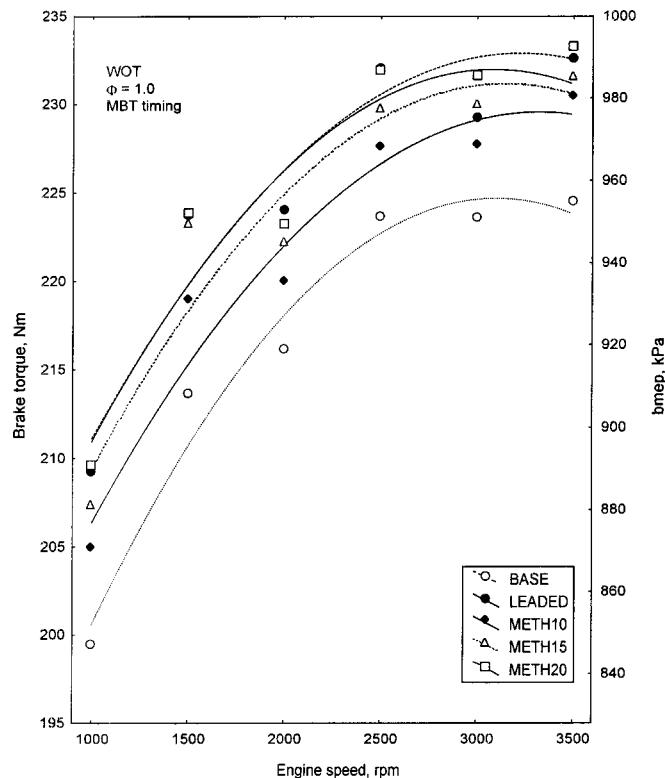


Fig. 5 Brake torque and mean effective pressure at wide-open throttle for the methanol blends

average of three readings of each test condition is recorded. The confidence of torque measurement is found to be 95%. A possible cause of these abnormal vibrations is a misalignment of the shaft connecting the engine with the dynamometer.

The base fuel produced the lowest brake torque among all the tested fuels. The leaded fuel exhibited a substantial increase in the brake torque with respect to the base fuel. This substantial increase is a result of the improved anti-knock behavior due to the addition of TEL, which raised the octane number from 84.7 for the base fuel to 92 for the leaded fuel. The improved anti-knock behavior allowed a more advanced MBT timing that results in higher combustion pressure and thus higher exerted torque (and bmep).

Generally, the results of MTBE blends (Fig. 4) indicate an increase in brake torque with respect to the base fuel. The significance of this increase varied with engine speed and MTBE ratio in the blend. At lower speeds, increasing MTBE ratio in the blend resulted in a gradually slight increase in the brake torque. At higher speeds, however, a considerable increase in the brake torque was obtained with the blend containing 10 vol.% of MTBE (MTBE10), but further addition of MTBE eventually led to the decline of brake torque. The gain in brake torque obtained with MTBE blends can be attributed to the improvement in anti-knock behavior, which allows more advanced MBT timing and thus higher output. As the MTBE ratio in the blend increases, the variation in the instantaneous oxygen/fuel equivalence ratio due to the change of fuel oxygen content in the combustion chamber and decreasing heating value of the fuel tend to affect the combustion flame temperature which in turn offset the improvement in performance. The positive effect of MTBE on maximum brake power has been reported also by Wang et al. [4].

The results for the methanol blends (Fig. 5) indicate an increasingly improving brake torque with the increasing methanol ratio in the blend. The improvement in the brake torque persists over the whole range of the tested engine speed. This gain in brake torque obtained with methanol blends can be attributed to the

better anti-knock behavior of these blends and the improvement in engine volumetric efficiency. The research octane numbers (RON) for the methanol blends are significantly higher than that of the base fuel (Table 2). This improved anti-knock behavior allows a more advanced MBT timing, as evident from Table 3, and thus a higher engine output. The improvement in engine volumetric efficiency is a result of the higher latent heat of vaporization characterizing the methanol blends. The latent heat of vaporization is the amount of heat required to vaporize the liquid molecules of the fuel prior to the combustion process. Most of this latent heat is provided by the air accompanying the fuel in its way to the engine cylinder, particularly in the case of port fuel injection systems. The absorption of heat from the air cools it and makes it denser. This allows more air mass to be admitted into the cylinder during the induction process and thus increasing the volumetric efficiency. Alcohols in general are characterized by their higher latent heat of vaporization when compared to the typical gasoline. Increasing alcohol ratio in a gasoline-alcohol blend will increase the latent heat of vaporization of the blend and thus improve the engine volumetric efficiency. Alcohols, on the other hand, have lower heating values when compared to gasoline, which means a lower energy release during combustion and a lower work transfer during expansion process. However, the gain in brake torque due to the improvement in anti-knock behavior and the volumetric efficiency seems to outweigh the losses due to the lower heating. The gain in maximum brake power due to the addition of methanol was reported also by Tsao and Lee [5].

The results for the ethanol blends (Fig. 6) show that there is a significant improvement in brake torque with the 10 vol.% ethanol blend (ETH10) when compared to the base fuel. At low engine speeds, further increase of ethanol ratio had no effect on the brake torque. At high speeds, the 15 vol.% ethanol blend (ETH15) performed slightly better but further addition of ethanol resulted in a decline in the brake torque. Similar to the methanol blends, the gain in brake torque can be attributed to the improvement in anti-knock behavior and volumetric efficiency. However, the improve-

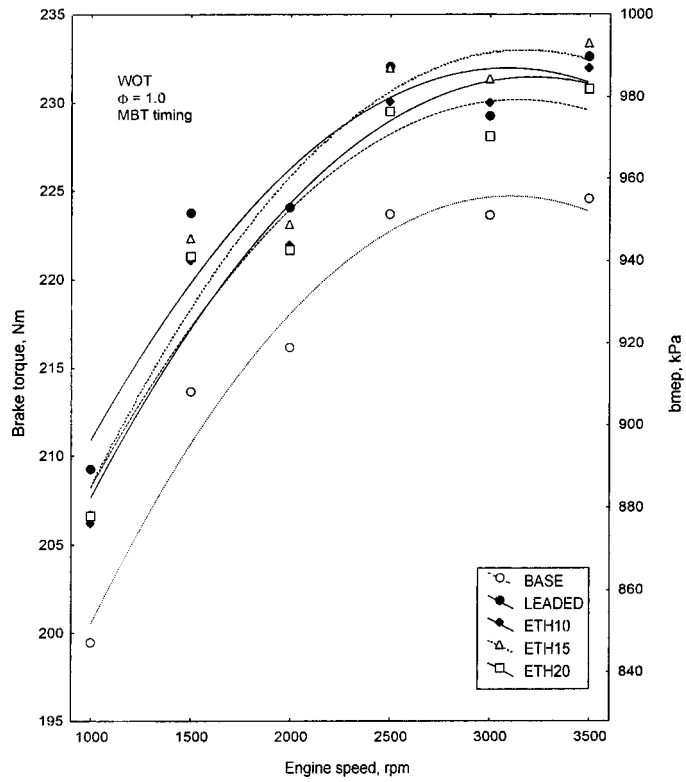


Fig. 6 Brake torque and mean effective pressure at wide-open throttle for the ethanol blends

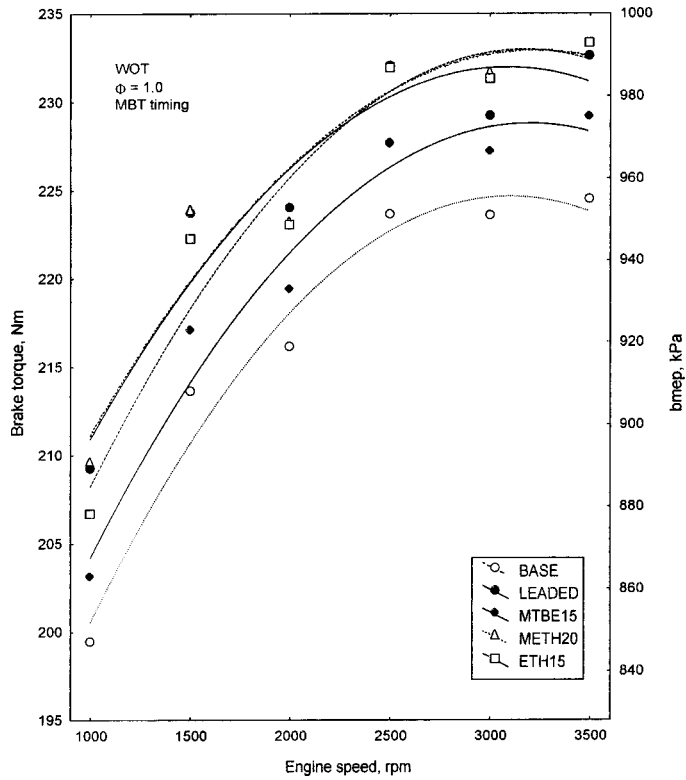
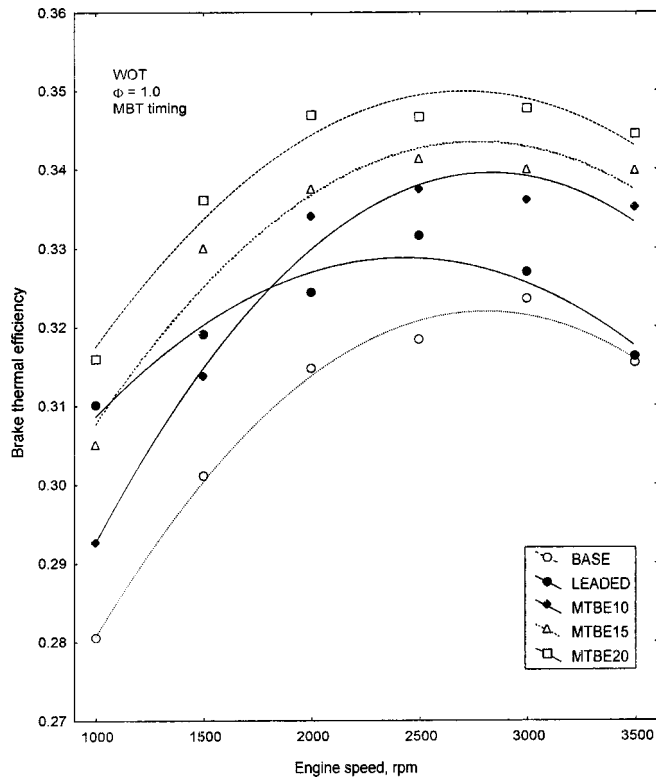
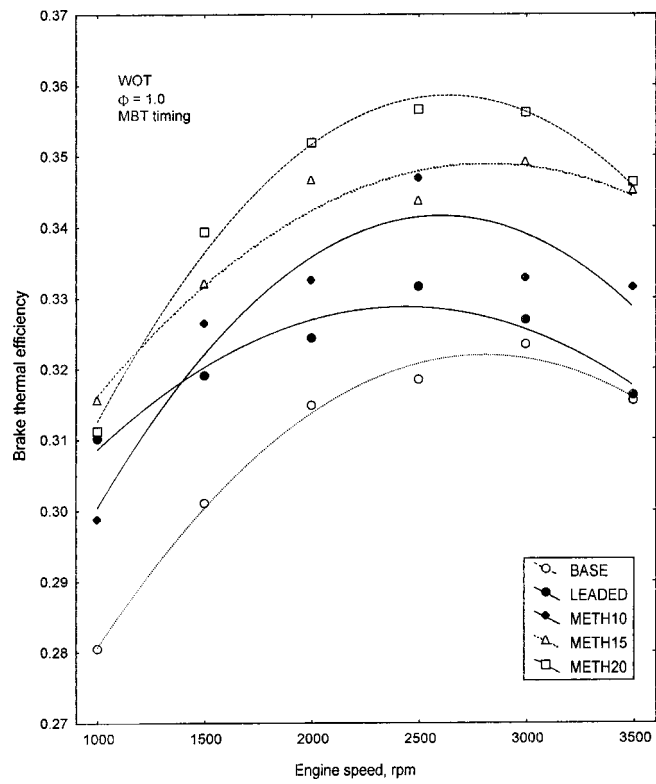


Fig. 7 Brake torque and mean effective pressure at wide-open throttle for the best performing blends compared to the base and leaded fuels



**Fig. 8 Brake thermal efficiency at wide-open throttle for the MTBE blends**



**Fig. 9 Brake thermal efficiency at wide-open throttle for the methanol blends**

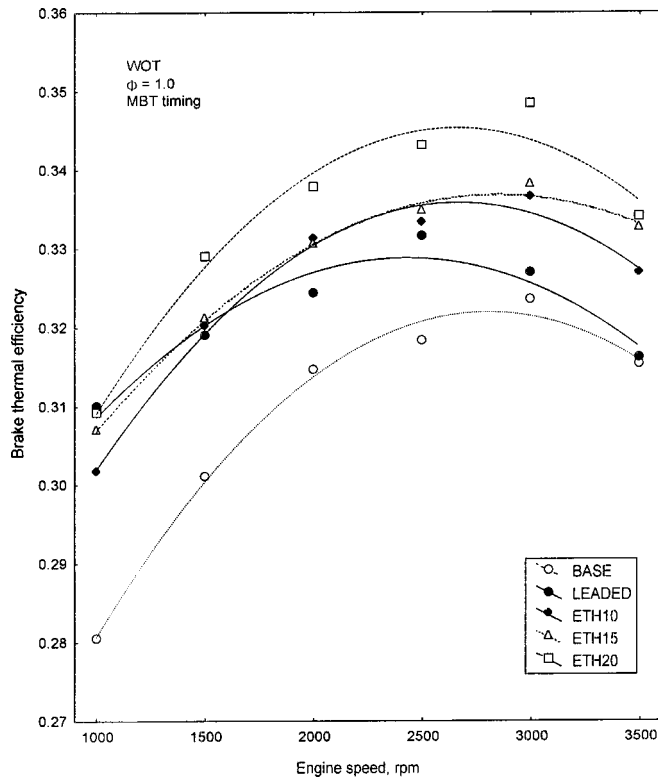


Fig. 10 Brake thermal efficiency at wide-open throttle for the ethanol blends

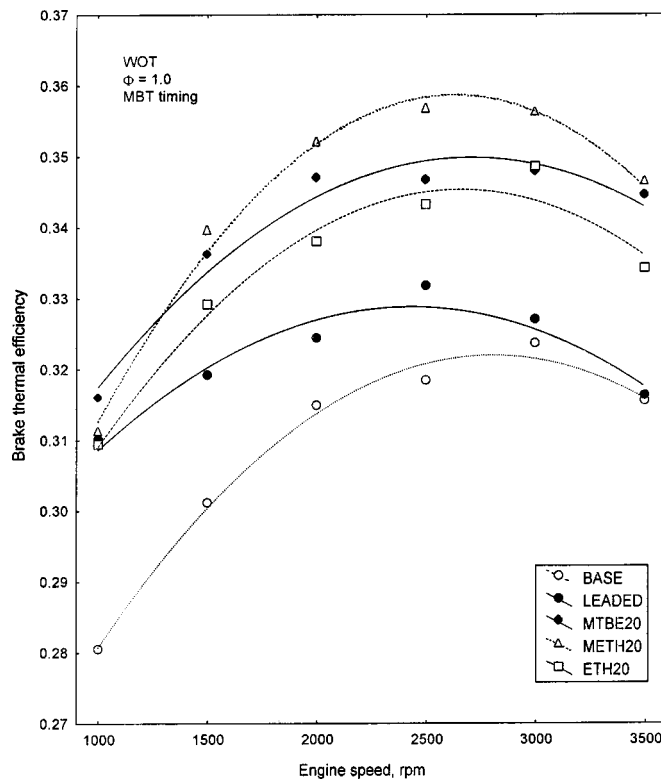


Fig. 11 Brake thermal efficiency at wide-open throttle for the best performing blends compared to the base and leaded fuels

**Table 4 MBT spark timing at 2000 rpm and bmep=680 kPa**

$\Phi$	Base	Leaded	MTBE10	MTBE15	MTBE20	METH10	METH15	METH20	ETH10	ETH15	ETH20
0.8	32	37.5	36	37	37.5	36	37	37.5	34	35	37
0.9	29	32	31	32	33	31	32	33	31	32	34
1.0	28	30	29	30	31	28	29	30	29	30	31
1.1	26	28	27	28	29	27	28	29	27	28	30
1.2	25	26	26	27	28	26	27	28	26	27	29

ments seem to be significant only with low ethanol ratios (up to 15 vol.% in this case). As the ethanol ratio in the blend increases, the variation in the instantaneous oxygen/fuel equivalence ratio due to the change of fuel oxygen content in the combustion chamber and decreasing heating value of the fuel tend to affect the combustion flame temperature which in turn offset the improvement in performance. In general, the three ethanol blends resulted in higher brake torque than the base fuel. This result does not agree with the results reported by Rajan [6]. Rajan reported a sharp decrease in engine output in the case of 20 vol.% hydrated ethanol (about 6% water in ethanol).

The results for the best performing blends in terms of the maximum brake torque compared to the base and leaded fuels are shown in Fig. 7. The performance of METH20 and ETH15 is comparable with that of leaded fuel and represents a gain of about 5% in the brake torque when compared to the base fuel. The best performing MTBE blend, which is the MTBE15, shows a gain of only about 2%.

**Brake Thermal Efficiency.** Brake thermal efficiency is defined as the ratio between the engine brake power and the rate of fuel energy input.

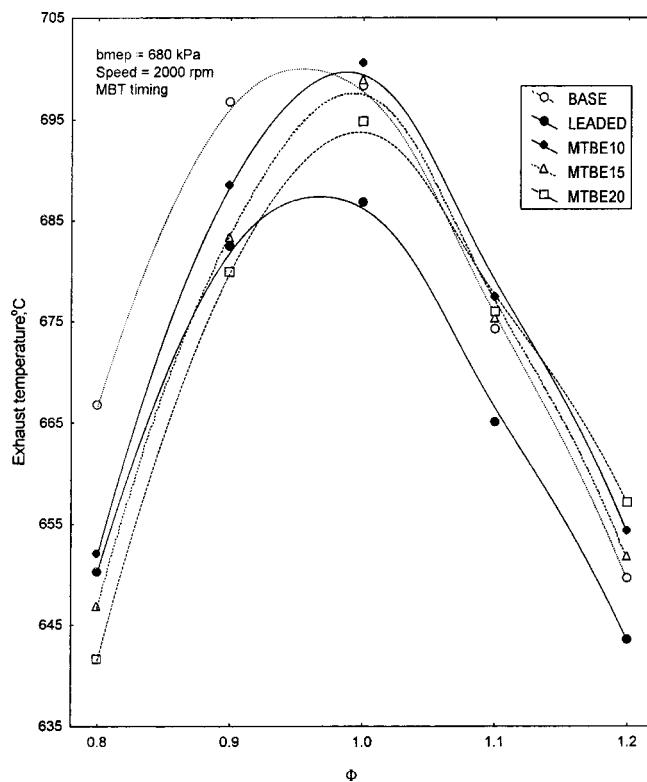
Figures 8, 9, and 10 show the brake thermal efficiency results for the variable-speed test at wide-open throttle, stoichiometric mixture, and MBT timing. In general, the brake thermal efficiency improves with increasing speed up to about 2500 rpm where it

becomes maximum then starts to decline as the speed increases. Among all the tested fuels, the base fuel obtained the lowest brake thermal efficiency along the whole range of the test speed. The results for the leaded fuel show a significant improvement in the brake thermal efficiency at lower speeds with respect to the base fuel (about 10.7%). As the speed increases, however, this improvement continues to decline and eventually vanishes. This indicates that the effect of improved anti-knock behavior of the leaded fuel on the thermal efficiency lessens as the engine speed increases.

The results for the MTBE blends, shown in Fig. 8, indicate a significant improvement in brake thermal efficiency. As the MTBE ratio in the blend increases, the brake thermal efficiency continues to improve achieving a maximum gain of about 12.5% with respect to the base fuel at low speeds (1000 rpm).

The improvement in the brake thermal efficiency with the three MTBE blends persists over the whole range of test speed. This improvement can be attributed to the more advanced MBT timing allowed by the improved anti-knock behavior, and the lower heat losses due to the lower combustion temperatures. The MTBE blends have lower heating values than that of the base fuel and, therefore, their combustion temperatures are expected to be also lower, [7]. The improvement in thermal efficiency observed here agrees qualitatively with the results reported by Wang et al. [4].

The results for the methanol blends, Fig. 9, show a continuous



**Fig. 12 Effect of equivalence ratio on exhaust gas temperature for the MTBE blends**

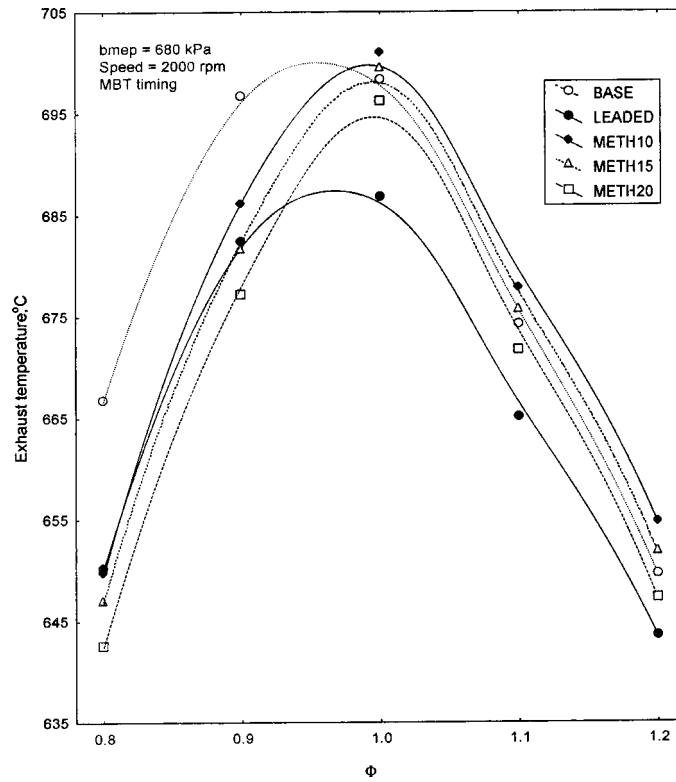


Fig. 13 Effect of equivalence ratio on exhaust gas temperature for the methanol blends

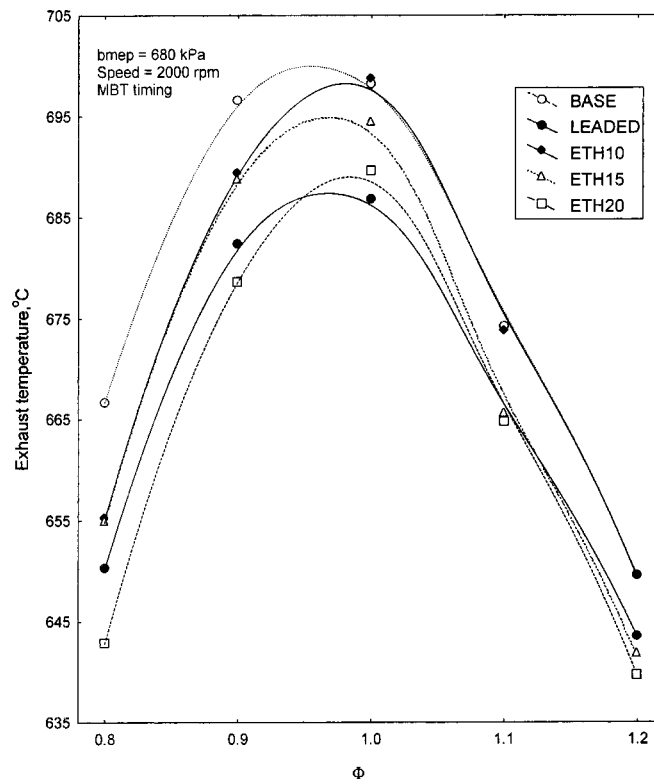
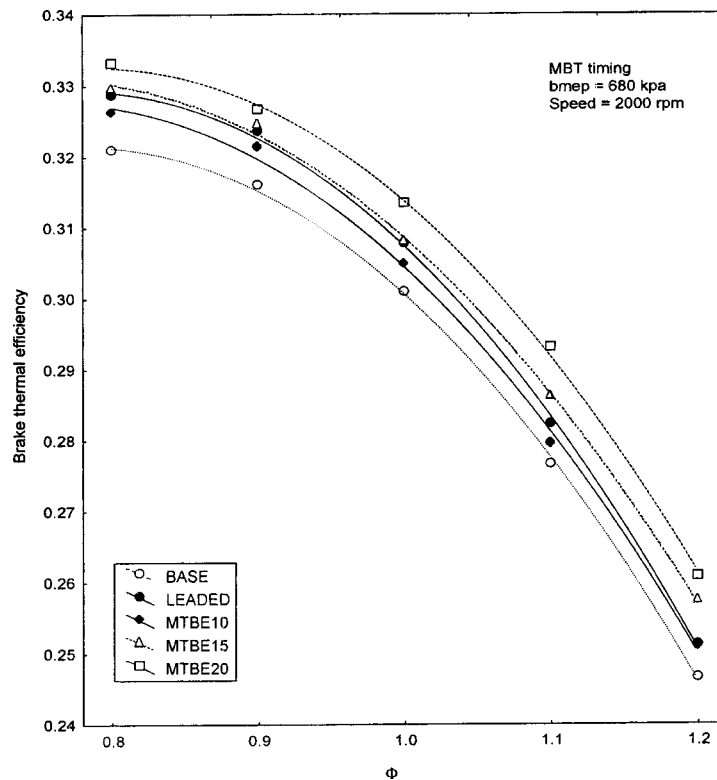


Fig. 14 Effect of equivalence ratio on exhaust gas temperature for the ethanol blends



**Fig. 15 Effect of equivalence ratio on brake thermal efficiency for the MTBE blends**

improvement in brake thermal efficiency as the methanol ratio in the blend increases. The improvement is maintained over the entire speed range and is maximum (about 12.5%) at midrange speed (about 2500 rpm). The improvement in brake thermal efficiency associated with the methanol blends is also due to the more advanced MBT timing and the lower heat losses. The heating values for the methanol blends are noticeably less than that of the base fuel due to the extremely low heating value of methanol, which is less than 50% of that of typical gasoline, [8]. The improvement in brake thermal efficiency due to the addition of methanol was also reported by Tsao and Lee [5] and Kowalewicz [8].

The results for the three ethanol blends, Fig. 10, also show an improvement in the brake thermal efficiency. A maximum gain of about 9% is achieved at midrange speeds with the ETH20 blend. The improvement in brake thermal efficiency noticed here can be also explained by the improvement in anti-knock behavior that allows a more advanced MBT timing, and the expected lower heat losses due to the lower combustion temperatures. Rajan [6] reported an improvement in the thermal efficiency with blends containing up to 10 vol.% hydrated ethanol (about 4% water in ethanol). Beyond this limit, however, Rajan reported a substantial decrease in the thermal efficiency. This contradicts the results in the current study which indicate a noticeable improvement in thermal efficiency in the case of 20 vol.% ethanol blend (which contains about 7% of water in ethanol).

Figure 11 shows the results of brake thermal efficiency for the best performing blends compared to the base and leaded fuels. The highest efficiency was obtained with METH20 blend followed by MTBE20 then ETH20. At low speeds, the improvement associated with the three blends is comparable to that of leaded fuel. As the speed increases, however, the brake thermal efficiency continues to improve in the case the three blends while declining in the case of leaded fuel.

**Variable Equivalence Ratio Test.** The effect of equivalence

ratio on the brake thermal efficiency was evaluated at a constant speed (2000 rpm), constant load (680 kPa), and MBT timing. The values for MBT timing corresponding to this test are given in Table 4. In general, the MBT timing retards towards the top center as the mixture is enriched. This can be attributed to the effect of equivalence ratio on the burning rate and therefore on the time required to complete the combustion. Usually, the maximum burning rate occurs at about 10% rich mixture (i.e.,  $\Phi=1.1$ ). Lean mixtures and extremely rich mixtures have low burning rates, and therefore, they need more advanced spark timing to attain the maximum brake torque. The results show also that the MBT timing advances as the oxygenate ratio in the blend increases. This is probably due to the improvement in anti-knock behavior of the blends due to the addition of oxygenates.

The exhaust gas temperatures, shown in Figs. 12, 13, and 14, peak at about stoichiometric ( $\Phi=1.0$ ) and sharply drop with lean and rich mixtures. This indicates that the flame temperature during combustion and the prevailing gas temperature at the end of the expansion process are higher in the case of stoichiometric than in lean or rich mixtures. Consequently, for stoichiometric mixture at the same exhaust flow rate, the heat loss is maximum. In general, the exhaust temperatures for the oxygenated blends were comparable to those of the base fuel in the case of rich mixtures but noticeably lower in the case of lean mixtures. The leaded fuel exhibited a consistent decrease in exhaust temperature with respect to the base fuel over the entire test range. The decreased exhaust temperature is a result of lower combustion temperature and/or improved thermal efficiency.

Figures 15, 16, and 17 show the brake thermal efficiency at different equivalence ratios for all the test fuels. The results indicate that the brake thermal efficiency is significantly influenced by the equivalence ratio. The efficiency drastically deteriorates with increasing richness of the mixture ( $\Phi>1.0$ ). On the other hand, the efficiency improves as the mixture is leaned out up to about  $\Phi=0.9$  after which the improvement slows down.

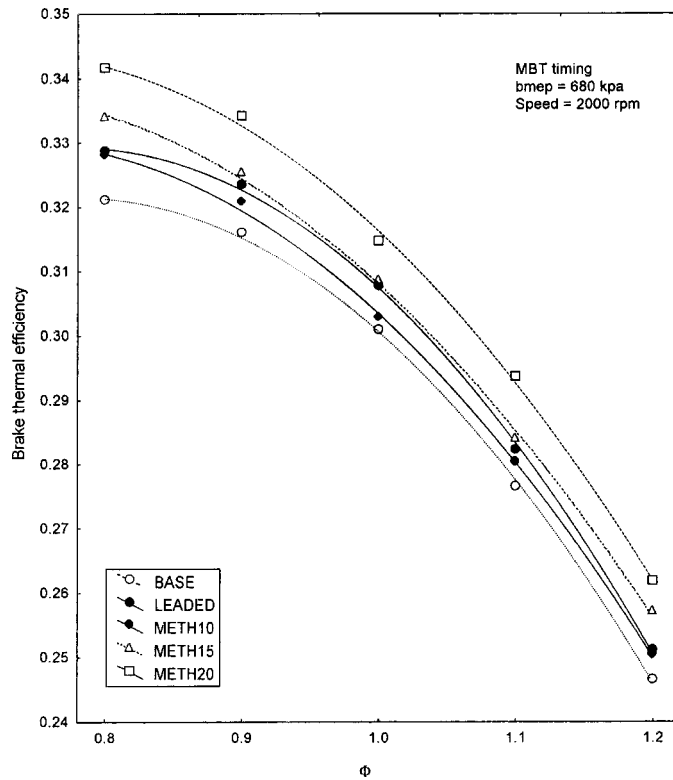


Fig. 16 Effect of equivalence ratio on brake thermal efficiency for the methanol blends

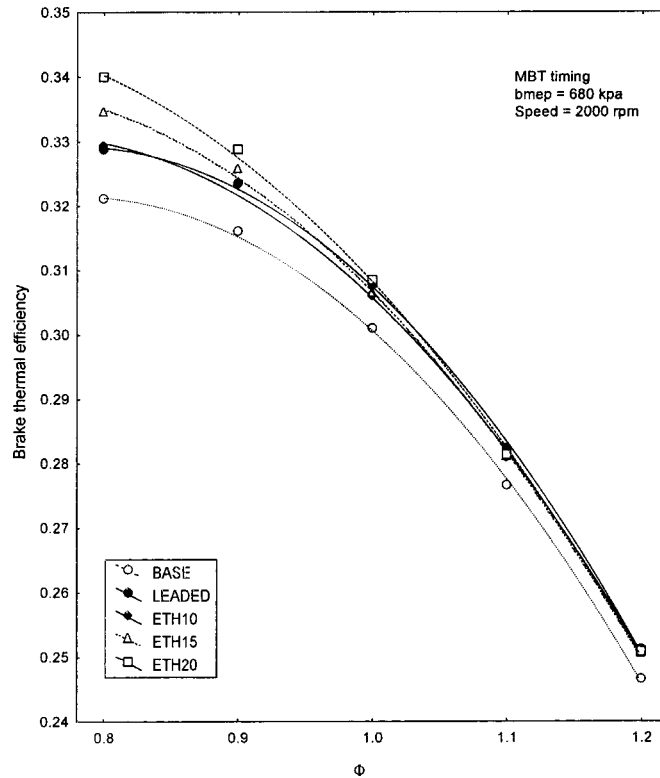
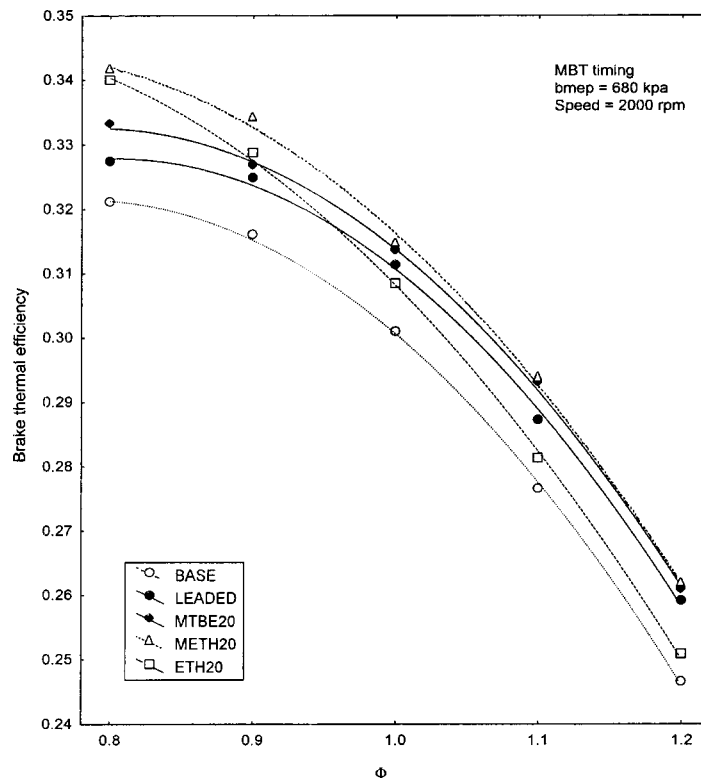


Fig. 17 Effect of equivalence ratio on brake thermal efficiency for the ethanol blends

Among all the tested fuels, the base fuel attained the lowest brake thermal efficiency values in the whole test range. In general, the addition of oxygenates resulted in a noticeable improvement

in the brake thermal efficiency. The results here indicate, however, less significant differences between the test fuels at part load than in the case of wide-open throttle tests.



**Fig. 18 Effect of equivalence ratio on brake thermal efficiency for the best performing blends compared to the base and leaded fuels**

The results for the MTBE blends, shown in Fig. 15, indicate a continuous improvement in the efficiency as the MTBE ratio increases. This improvement is sustained over the entire tested range of equivalence ratio. The maximum gain in efficiency with respect to the base fuel is observed at the rich side ( $\Phi=1.2$ ) and is about 6%. The gain in efficiency decreases as the mixture is leaned out reaching about 3.8% at  $\Phi=0.8$ . In the case of the methanol blends, the efficiency also continues to improve as the methanol ratio increases in the blend at all equivalence ratios as shown in Fig. 16. However, the gain in efficiency in this case is almost constant at all equivalence ratios and is about 6%. Different from the MTBE and methanol blends, the ethanol blends at rich equivalence ratios ( $\Phi>1.0$ ) show a slight gain in efficiency (about 1.5%) with respect to the base fuel (Fig. 17). Furthermore, this slight gain in efficiency is not affected by the increase of ethanol ratio in the blend. As the mixture is leaned out, however, the gain in efficiency increases and the variation between the three ethanol blends becomes more noticeable. A maximum gain in efficiency of about 6% is observed for ETH20 at  $\Phi=0.8$ .

Similar to the previous test, the improvement in efficiency noticed in this test can be attributed to the more advanced MBT timing allowed by the improved anti-knock behavior, and/or the lower heat losses due to the lower combustion temperatures.

The brake thermal efficiency values as a function of equivalence ratio for the best performing blends compared to the base and leaded fuels are shown in Fig. 18. Again, the METH20 is the best performer at the whole test range. At the rich side ( $\Phi>1.0$ ), the results for the MTBE blends are comparable to those of METH20. At the lean side ( $\Phi<1.0$ ), the METH20 outperforms all other test fuels and is approached only by the ETH20 blend at  $\Phi=0.8$ . The performance of the leaded fuel at rich equivalence ratios is comparable to the best performing blend, but fall behind at the lean side.

## Conclusions

- The results from the variable-speed wide-open throttle (WOT) tests show that the leaded and oxygenated fuels performed better than the base fuel in terms of maximum brake mean effective pressure (bmep). The improvement in performance persists along the entire tested speed range. For leaded fuel, the average increase of maximum bmep with respect to the base fuel is about 4%. The improvement due to the addition of oxygenates varies with the oxygenate type and ratio in the blend but generally is less than that noticed with leaded fuel except in the case of the 20 vol.% methanol and 15 vol.% ethanol blends. The reduced knock propensity of the oxygenated fuel is significant in the engine performance over the base fuel.

- For lower ratios of oxygenates (up to 15 vol.%), the ethanol blends perform better than methanol and MTBE blends. For higher ratios, however, the methanol is the best oxygenate in terms of maximum bmep of the engine.

- The results show that the oxygenated fuels resulted in higher brake thermal efficiency than the base fuel and than leaded fuel particularly at higher engine speeds. Although less than the oxygenated fuels, the thermal efficiency improves with leaded fuel but this improvement declines as the engine speed increased until eventually vanishes at high speed of 3500 rpm.

- At midrange speed of 2500 rpm, the methanol blends are the best performers followed by MTBE, then ethanol blends. Methanol blends result in maximum increase in thermal efficiency of about 12.3% with respect to base fuel. The maximum increase in thermal efficiency is about 8.8% in the case of MTBE blends, and about 7.9% in the case of ethanol blends. Overall, the methanol blends are the best performers in terms of brake thermal efficiency at practical wide-open throttle conditions.

- The results from variable-equivalence ratio tests show that

the differences between fuels are less significant at part-load than in the wide-open throttle condition. With all the tested fuels, the brake thermal efficiency improves significantly as the equivalence ratio is decreased (i.e., as the mixture is leaned out).

- At stoichiometric mixture ( $\Phi=1.0$ ), constant load of 680 kPa, and constant speed of 2000 rpm, the best oxygenate in terms of brake thermal efficiency is ethanol for low oxygenate ratio (up to 10 vol.%) and methanol for higher ratio (15 and 20 vol.%). The maximum increase in thermal efficiency with respect to the base fuel is about 4.7% in the case of methanol, about 4.0% in the case of MTBE, about 2.3% in the case of ethanol, and about 3.3% in the case of leaded fuel.

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### References

- [1] Al-Farayedhi, A. A., Al-Dawood, A. M., and Gandhidasan, P., 2000, "Effects of Blending MTBE With Unleaded Gasoline on Exhaust Emissions of SI Engines," *ASME J. Energy Resour. Technol.*, **122**, pp. 239–247.
- [2] Al-Farayedhi, A. A., Al-Dawood, A. M., and Gandhidasan, P., "Effects of Blending Crude Ethanol With Unleaded Gasoline on Exhaust Emissions of SI Engine," Proceedings of the International Fall Fuels and Lubricants Meeting and Exposition, Baltimore, MD, Oct. 16–19, SAE Paper No. 2000-01-2857.
- [3] Al-Dawood, Ali M., 1998, "Effects of Blending MTBE, Methanol, or Ethanol With Gasoline on Performance and Exhaust Emissions of SI Engines," M.S. thesis, Mechanical Engineering Department, King Fahd University of Petroleum & Minerals, Dhahran.
- [4] Wang, X. et al., 1987, "Study of the Performance of MTBE Blended Unleaded Gasoline," SAE Paper No. 871268.
- [5] Tsao, K. C., and Li, C., 1984, "Performance Comparison of Gasoline-Methanol Emulsions as Spark Ignition Engine Fuels," SAE Paper No. 840241.
- [6] Rajan, S., 1984, "Water-Ethanol-Gasoline Blends Physical Properties, Power, and Pollution Characteristics," *ASME J. Eng. Gas Turbines Power*, **106**, pp. 841–848.
- [7] Piel, W. J., and Thomas, R. X., 1990, "Oxygenates for Reformulated Gasoline," *Hydrocarbon Process.*, **69**, July, pp. 68–73.
- [8] Kowalewicz, A., 1994, "Efficiency of the SI Engine Fueled With Methanol-Gasoline Blends," *Proc. Inst. Mech. Eng., Part D (J. Automob. Eng.)*, **208**, Part D: Journal of Automotive Engineering.
- [9] SAE Handbook, 1992, "Alternative automotive fuels," SAE J1297 JUN90, Vol. 3, Society of Automotive Engineers, Warrendale, PA.
- [10] Heywood, J. B., 1988, *Internal Combustion Engine Fundamentals*, McGraw-Hill, New York.