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KNOCK-LIMITED PERFORMANCE OF ETHANOL BLENDS IN A SPARK-IGNITION ENGINE

F. J. Ferfecki
Borg Warner Research
Des Plaines, IL 60016

S. C. Sorenson
Department of Mechanical and Industrial Engineering
University of Illinois at Urbana-Champaign
Urbana, IL 61801

ABSTRACT

An experimental study was performed to determine the effect of varying percentages of ethanol in the fuel using a CFR engine operated at knock-limited compression ratio and maximum power spark timing. Blends of 85 octane primary reference fuel and ethanol in concentrations between 10 and 25 percent by volume were tested for performance, fuel economy, and exhaust emissions. The results indicated that when the engine was operated at knock-limited conditions at a constant equivalence ratio, the use of ethanol resulted in a reduction in petroleum fuel usage of 10 percent greater than the volumetric percentage of the ethanol used in the blend. These results were independent of the amount of ethanol used in the blend. Under these conditions, as the ethanol concentration was increased, BMEP and BSHC increased, BSNO and BSCO remained essentially constant, and exhaust temperature decreased.

LIST OF SYMBOLS

BMEP	Brake Mean Effective Pressure (KPa)
BSCO	Brake Specific Carbon Monoxide (g/kW-hr)
BSFC	Brake Specific Fuel Consumption (g/kW-hr)
BSHC	Brake Specific Hydrocarbon Emissions (g/kW-hr)
BSNO	Brake Specific Nitric Oxide Emissions (g/kW-hr)
FA	Fuel-Air Ratio (grams fuel/grams air)
HC	Uburned Hydrocarbons
NO	Nitric Oxide
ppm	parts per million

INTRODUCTION

In recent years, the use of ethanol as a substitute for conventional petroleum based fuels has become increasingly attractive to the agricultural community, both as a means for securing a more reliable supply of fuel and as a method of increasing the demand for agricultural products from which ethanol can be made. The introduction of gasoline-ethanol (gasohol) mixtures into the automobile market has been the first step in this process. In Brazil, programs are underway to develop engines running on higher amounts of ethanol (Leshner, et al., 1980). In order to increase the attractiveness of the use of ethanol as a supplement or substitute for petroleum fuels, it is important to have a clear understanding of the effects of the use of ethanol in internal combustion engines. Conventional U.S. of ethanol in gasoline engines utilizes a mixture of 10 percent ethanol in gasoline and substitutes this for the pure gasoline fuel without engine modifications. This does not take advantage of the higher octane number of the ethanol as compared to regular gasoline and can have some effect on the fuel-air ratio of the intake mixture which, in turn, affects fuel economy and all exhaust emissions (Obert, 1973).

Consequently, it is of interest to explore the possiblities for the use of ethanol-gasoline blends of varying compositions and under carefully controlled engine operating conditions to see if there is a more effective way of using the ethanol to take advantage of its higher octane rating without having a significant deterioration of fuel economy and exhaust emissions. While the use of gasoline is not as important to the agricultural community as diesel fuel on a useage basis, improved techniques for the use of ethanol in gasoline engines would have a strong positive influence on the future of ethanol as a motor fuel and the subsequent demands for agricultural products which can be used to produce ethanol.

OBJECTIVES

The two main objectives of this study were:

1. To study petroleum based fuel blended with ethanol at different engine operating conditions to determine effects on performance, fuel economy, and exhaust emissions.
2. To use various percentage ethanol petroleum blends to determine if there is an optimum ethanol percentage from a petroleum replacement standpoint.

Ethanol has a greater effect on the octane rating of lower octane fuels (Keller, 1979). Consequently, an 85 octane base fuel was used to take full advantage of the octane increase due to the ethanol. The use of a low octane base fuel also serves to minimize refinery energy needed to make the base fuel (Lawrence, et al., 1980).

Blends of 0 to 25 percent ethanol, on a volume basis, were used in this study. With ethanol percentages greater than 25 percent, phase separation due to water getting into the fuel could be a major problem (Wigg, 1974). Recent developments in fuel injection technology indicate that it may soon be practical to use one pump to feed both ethanol and petroleum fuels to an engine, thus eliminating the need for fuel tank blends (Fugisawa and Yokota, 1981)

EQUIPMENT

The tests in this experiment were performed on a single cylinder variable CFR (Cooperative Fuel Research) engine coupled to an electric dynamometer. The engine has facilities for variable compression ratio operation and has high pressure intake port fuel injection. Engine specifications and experimental conditions are given in Table 1. Fuel properties are given in Table 2.

Variables measured were mass flow rate of air, mass flow rate of fuel, brake power, and exhaust temperature. Cylinder pressure as a function of time was monitored on an oscilloscope and a standard knock level was determined by the magnitude of the pressure oscillations resulting from knock. Exhaust gas emissions were also measured. Unburned hydrocarbons were measured with a flame ionization detector, carbon monoxide and carbon dioxide with nondispersive infrared analyzers, and NO with a chemiluminescent analyzer. The system used, shown in Fig. 1, closely follows the procedures established for small engine exhaust emission measurement established by the Society of Automotive Engineers (SAE, 1977).

TEST PROCEDURES

In order to eliminate any effects due to spark timing, all of the following tests were run at maximum power spark advance. To study the effects of ethanol blends at different operating conditions, the following three sets of tests were performed.

1. Baseline tests were run using 85 octane base fuel for the range of equivalence ratio in Table 1. The compression ratio was adjusted for trace knock, detected on the oscilloscope, for each equivalence ratio. Spark advance was adjusted to maximum power spark advance for each equivalence ratio.

2. Series A tests used blends of 10, 15, 20, and 25 percent ethanol, on a volume basis, in the 85 octane base fuel. Each fuel blend was tested over the same equivalence ratio range that was used in the baseline tests. Compression ratio and spark advance were adjusted, as functions of equivalence ratio, to the values of these found for the 85 octane base fuel in the baseline tests. This test series shows the effect of substitution of ethanol-gasoline blends for gasoline at the maximum power conditions obtainable with the gasoline fuel.

3. Series B tests used the same blends of ethanol in the 85 octane base fuel as were used in Series A. Each blend was tested at its knock limited compression ratio throughout the equivalence ratio range. Series B tests followed the baseline test procedures of optimizing compression ratio and using maximum power spark advance for each equivalence ratio for each blend.

RESULTS

The knock limited compression ratios obtained are given in Fig. 2. The compression ratios for the 85 octane fuels defined the compression ratio-equivalence ratio relationship that was used for the blends of test Series A. The results for test Series B show the beneficial effect of ethanol addition to an 85 octane number base fuel. The octane steadily increased as the ethanol percentage increased up to 25 percent for the entire equivalence ratio range.

Performance and emission results from test Series A are presented in Figs. 3, 4, and 5. The fuel air equivalence ratio was used as the abscissa since the stoichiometric fuel-air ratio increased as the percentage of ethanol increased. Thus, at a constant equivalence ratio, as the percent of ethanol increases, the actual fuel-air ratio supplied to the engine must increase.

Lower intake charge temperatures should cause NO concentration to decrease (Huls, et al., 1967). Ethanol's higher heat of vaporization is expected to have a larger cooling effect on the intake charge temperature than on the 85 octane base fuel. In agreement with this, Fig. 4 shows reduced concentrations of NO at equivalence ratios near that for peak NO. Exhaust temperature and equivalence ratio are important factors in the emission of unburned hydrocarbons (Huls, et al., 1967). The compression ratio was not changed with the different blends in these tests. Hydrocarbon concentrations did not change noticeably with the addition of ethanol at given equivalence ratios as would be expected due to the constant exhaust temperature and equivalence ratio as indicated in Fig. 5.

It can be seen from those results that when ethanol-gasoline blends were used in an engine operating at a constant equivalence ratio and compression ratio, the only significant change observable was an increase in the overall fuel consumption. At equivalence ratios leaner than 0.95, there was a slight decrease in NO emissions with increasing ethanol content. At richer equivalence ratios, there was not as noticeable an effect on NO emissions.

The large increases in compression ratio in the Series B tests show that the ethanol addition had a large effect on the octane rating of the fuel. It should be noted that the intake system in the CFR engine used in this test resembles that of the RON (Research Octane Number) method more than the MON (Motor Octane Number) method. As stated previously, the ethanol has larger effects on RON. The RON method would be a better method to see the effects of alcohol additions because it is unlikely that the manifold temperatures would reach those of the MON method because of the larger amount of heat needed to vaporize the alcohol (Nichols, 1980).

The heating value of ethanol is lower than the heating value of the 85 octane base fuel as shown in Table 2. As increased ethanol amounts are used, the mass flow rate of the fuel needs to increase to maintain a given equivalence ratio. This increase in mass flow rate offsets the lower energy content of the ethanol to give the same power but causes the BSFC to increase with an increase in the percentage of ethanol.

The Series B tests indicate that the ethanol increased the octane number since higher compression ratios than Series A tests could be used before knocking occurred. The Series B test results, shown in Figs. 6, 7, and 8, indicate that at knock limited compression ratio BMEP increased with the addition of ethanol at constant equivalence ratio. The addition of ethanol had no noticeable effect on the BSFC. The above results are due to the higher thermal efficiencies which result from the higher compression ratios. Higher efficiences offset the effect of the lower energy content and higher fuel-air ratio of the ethanol blends. The HC emissions increased with the addition of ethanol since the exhaust temperature decreased. The higher compression ratios increased peak NO concentration but peak BSNO showed a change of less than 3 percent for a 25 percent ethanol blend since the power also increased. The ethanol had little effect on BSCO.

At a constant equivalence ratio as the compression ratio increases, more power was obtained by operating at a higher thermal efficiency. Thus, the BMEP's obtained from the Series B tests were higher than those of Series A, while the fuel consumptions were lower. The octane rating increase due to the ethanol was such that at knock limited power, the fuel consumption was independent of the amount of ethanol used. NO concentration increased in the Series B tests occur due to the higher combustion temperatures at the higher compression ratios. The increases in NO concentration were most noticeable at leaner mixtures. .rom the Series A test results, one would expect the increase in NO concentration with the ethanol blends to be lower than the NO concentration with a higher octane base fuel due to increased intake charge cooling while the increase in BMEP would be expected to be the same. Lower exhaust temperatures, due to the high compression ratios, caused BSHC to increase with increased ethanol percentage.

DISCUSSION

The results of the above tests can be used to simulate alternative strategies for using ethanol blends in an engine. Different cases were studied to determine the performance trade-offs and petroleum fuel use reduction resulting from the ethanol addition.

Case 1 is an example intended to simulate an engine operating at knock limited compression ratio and an equivalence ratio of 1.0 and compares baseline and Series B test data. Modern automobile engines with three-way catalysts operate under conditions of a constant equivalence ratio of 1.0 (Mooney, et al., 1979). The results are shown in Fig.9.

For this case, the ethanol replaced a larger percentage of the petroleum fuel than its volume percentage in the fuel for all the blends. The percentage reduction in petroleum use was approximately 10 percent more than the volume percentage of ethanol for all blends. The compression ratio can be increased from 6.1 for the base fuel to 8.1 using the 25 percent blend. The BSNO was only increased 3 percent with a 25 percent ethanol blend while the NO concentration increased 20 percent with the 25 percent blend. The increase in BSHC was about 25 percent for the 25 percent blend due mainly to the exhaust temperature decrease from 728 C to 673 C. The BSFC remained nearly constant due to the increase in thermal efficiency. BSCO decreased slightly due to the increase in power with ethanol addition. The required engine displacement for a constant power output with the 25 percent ethanol blend was about 16 percent less than that required with the base fuel.

Case 2 simulates the effect of adding ethanol to an engine operating at a constant equivalence ratio of 1.0 without any compression ratio adjustments. Series A and baseline test results were compared at stoichiometric conditions in Case 2. The results are shown in Fig. 10. For this case, BSNO, BSHC, BSCO, exhaust temperature, and BMEP were not affected by the use of ethanol blends. The BSFC increased due to the lower energy content and the higher fuel-air ratio of the blends. It can be seen that the reduction of petroleum useage was less than the volume percentage of ethanol used.

Case 3 simulates the effects of the addition of ethanol to an engine that is being run at an equivalence ratio of 0.9 for minimum BSFC with knock limited compression ratio used for each blend. The results are shown in Fig. 11. As in Case 1, by taking advantage of the increased octane rating of the ethanol blends, the ethanol can replace a larger percentage of the base fuel than its fuel concentration. Case 3 shows that, as ethanol was added, a smaller displacement engine was needed for a constant power output. The reduction in displacement was 15.75 percent for a 25 percent blend. The main problem with taking advantage of the octane increase was the increase in hydrocarbon emissions due to the lower exhaust temperature caused by the increased compression ratio. BSNO and BSCO were unchanged by ethanol addition for this case, although the magnitude BSNO was high because of the lean mixture.

Case 4, shown in Fig 12, simulates an engine that is initially set to run at a fuel-air ratio of maximum power. The ethanol blends were then assumed to be added without any modifications to the engine and it was assumed that a carburetor or fuel injector would supply the same volume and flow rate of fuel to the engine regardless of the amount of ethanol in the blend. Due to the leaning effects from the ethanol addition at constant fuel flow rate, the equivalence ratios of the blends became progressively leaner as the ethanol percentage increased. This case is typical of what occurs in a conventional engine in which gasohol is substituted directly for gasoline. In this case, the initial equivalence ratio was 1.15 for the 85 octane base fuel. The volumetric fuel flow rate was held constant and the leaning effect of the ethanol causes equivalence ratios to decrease as more ethanol was used. Figure 12 shows that there was a small decrease in BMEP and a slight increase in BSFC with the addition of ethanol with this approach. It can be seen that BSHC decreased about 20 percent using a 25 percent ethanol blend. Large increases in BSNO were observed, i.e., a 116 percent increase for the 25 percent blend. The BSNO could reach a maximum if equivalence ratios less than 0.92 were encountered. There was a significant decrease in BSCO emissions with the ethanol addition, a gain due to the leaning effect.

Most of the trends in this case were due to the leaning effect of the ethanol. In Case 3, it was seen that at constant equivalence ratio, and compression ratio, the only parameter affected was the BSFC. Table 3 shows the BSFC's of the 85 octane base fuel when it is run at equivalence ratios equal to those of the ethanol blends and shows that leaning the mixture in itself saves fuel. For example, the 20 percent blend ran at an equivalence ratio of 1.076 and the reduction in the petroleum use was 21.0 percent but if the base fuel is run at an equivalence ratio of 1.076 rather than 1.15, there is a 6.01 percent reduction in fuel consumption. The effective net reduction in petroleum fuel to the ethanol addition then becomes 15.0 percent.

SUMMARY AND CONCLUSIONS

At a constant compression ratio, it was shown that the effects of the ethanol addition were dependent on whether the equivalence ratio or the volumetric flow rate of fuel was held constant. At a constant equivalence ratio, the BSFC increased while the BMEP, BSHC, BSCO, and exhaust temperature remained constant with the addition of ethanol. A slight decrease in BSNO was noticed. The reduction of petroleum use was approximately 78 percent of the volume percentage of ethanol used.

At constant compression ratio and volumetric fuel flow rate, BSHC, BSCO, and BMEP decreased slightly while BSFC and exhaust temperature increase slightly with ethanol addition and BSNO increased significantly. The reduction in petroleum use was a function of the initial equivalence ratio. For an initial equivalence ratio of 1.15, the ethanol replaced its volume in petroleum fuel while for an initial equivalence ratio of 1.05, the ethanol reached slightly less than its volume in petroleum fuel.

At knock limited compression ratio and the constant equivalence ratio BMEP, BSHC, and compression ratio increased with ethanol addition. There was a decrease in exhaust temperature and a slight increase in BSNO with ethanol addition. BSFC and BSCO were unaffected by ethanol addition. The ethanol replaced about 10 percent more than its volume percentage in petroleum fuel.

The various cases show, in the percentage range of blends tested, that there does not seem to be an optimum blending percentage. At knock limited compression ratios, ethanol replaced about 110 percent of its volume percentage in petroleum for all blends. At constant equivalence ratio and compression ratio, the ethanol replaced about 78 percent of its volume percentage in petroleum fuel for all blends. For constant compression ratio and volumetric fuel flow rate, the 10 percent blend gave slightly higher relative petroleum replacement for an initial equivalence ratio of 1.15, but for an initial equivalence ratio of 1.05, this effect was not seen.

It is concluded that there are two preferred methods to be used in blending alcohol with gasoline:

1. The first choice is building higher compression ratio engines to take advantage of the higher octane numbers of the blends and paying an HC penalty which may not be significant if a catalytic converter is used. In this case, a higher thermal efficiency is realized and the volume of petroleum fuel replaced is greater than the volume of ethanol used. The increase in BMEP would also permit use of smaller engines.
2. A second choice would be to run current type engines at constant equivalence ratio to prevent emission and power sacrifices and utilize a lower octane base fuel for the blends. In this way, higher fuel consumption of the engine could be partially offset by lower refining losses.

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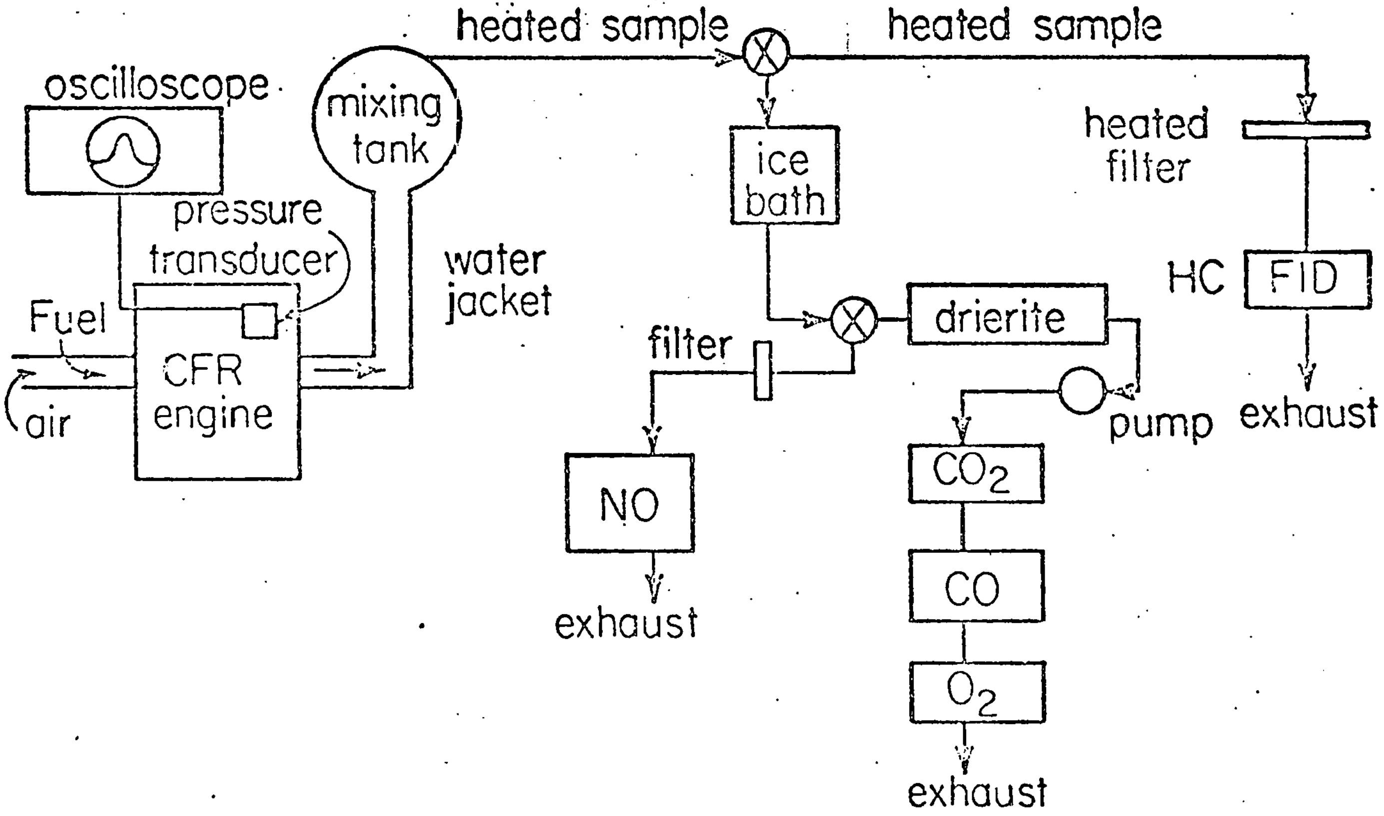

Figure 1 Schematic Diagram of Experimental Apparatus

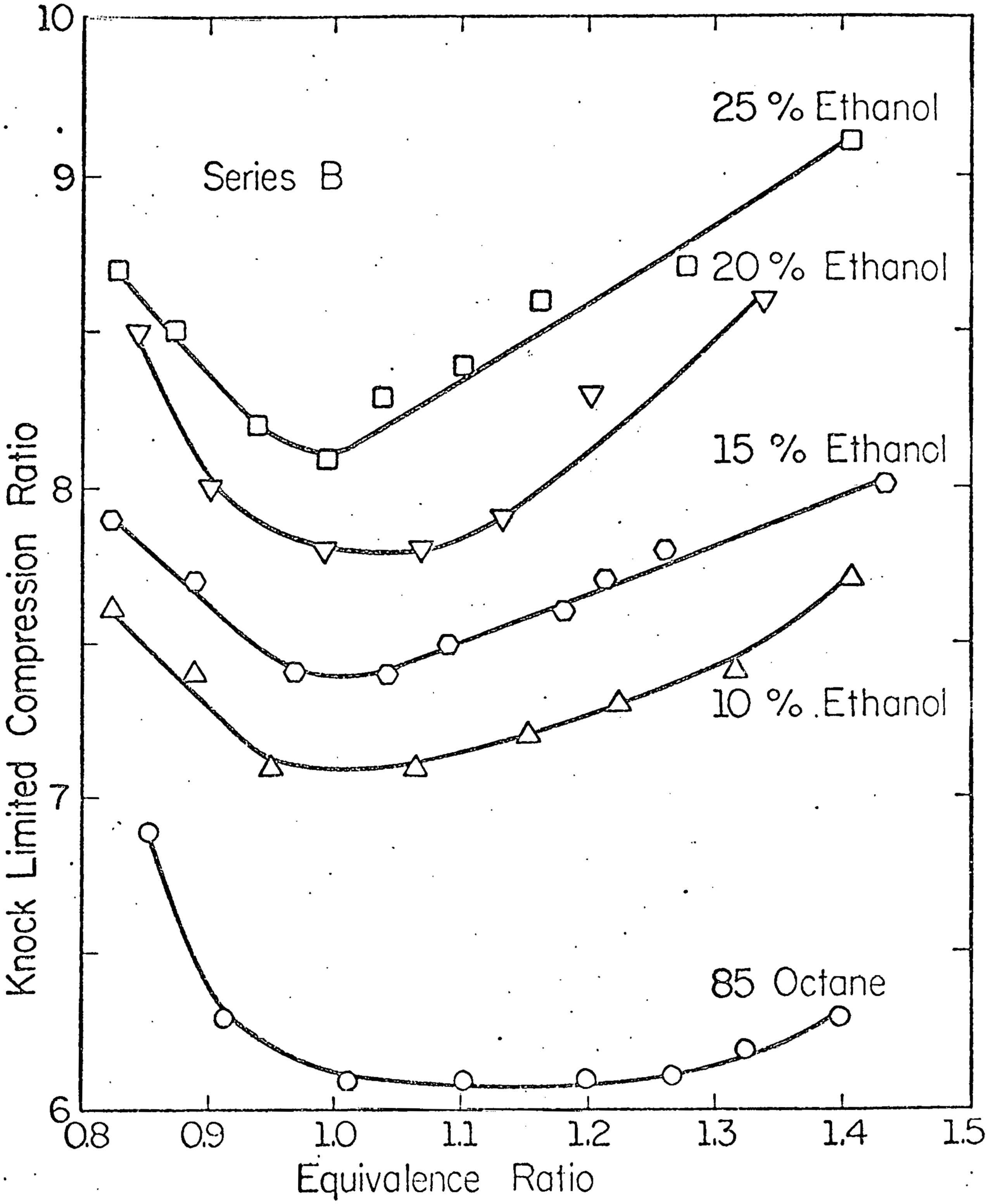

Figure 2 Effect of Percent of Ethanol in Blends on Knock Limited Compression Ratio

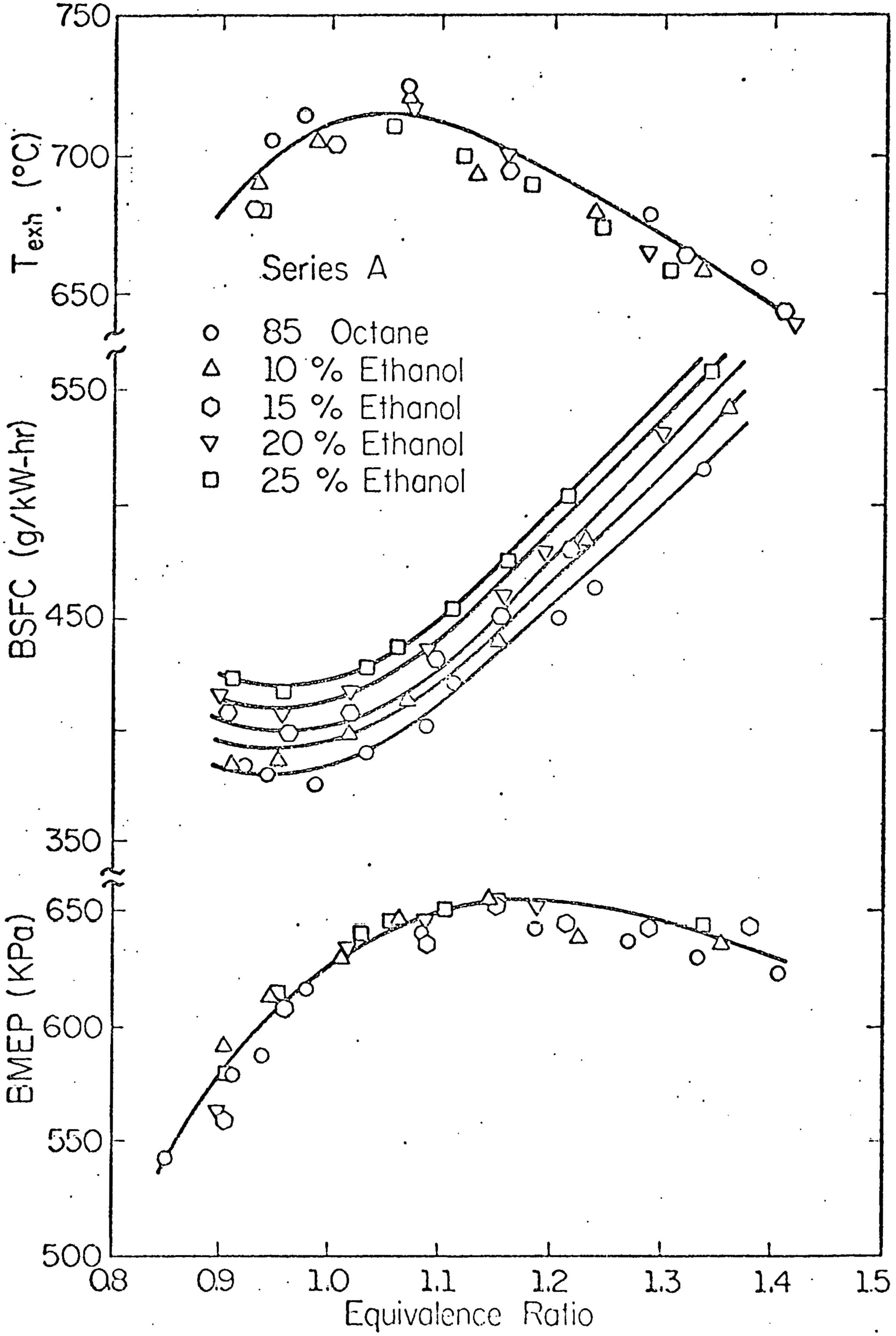

Figure 3 Effect of the Percent of Ethanol in Blends on Power, Fuel Consumption and Exhaust Temperature at Constant Compression Ratio

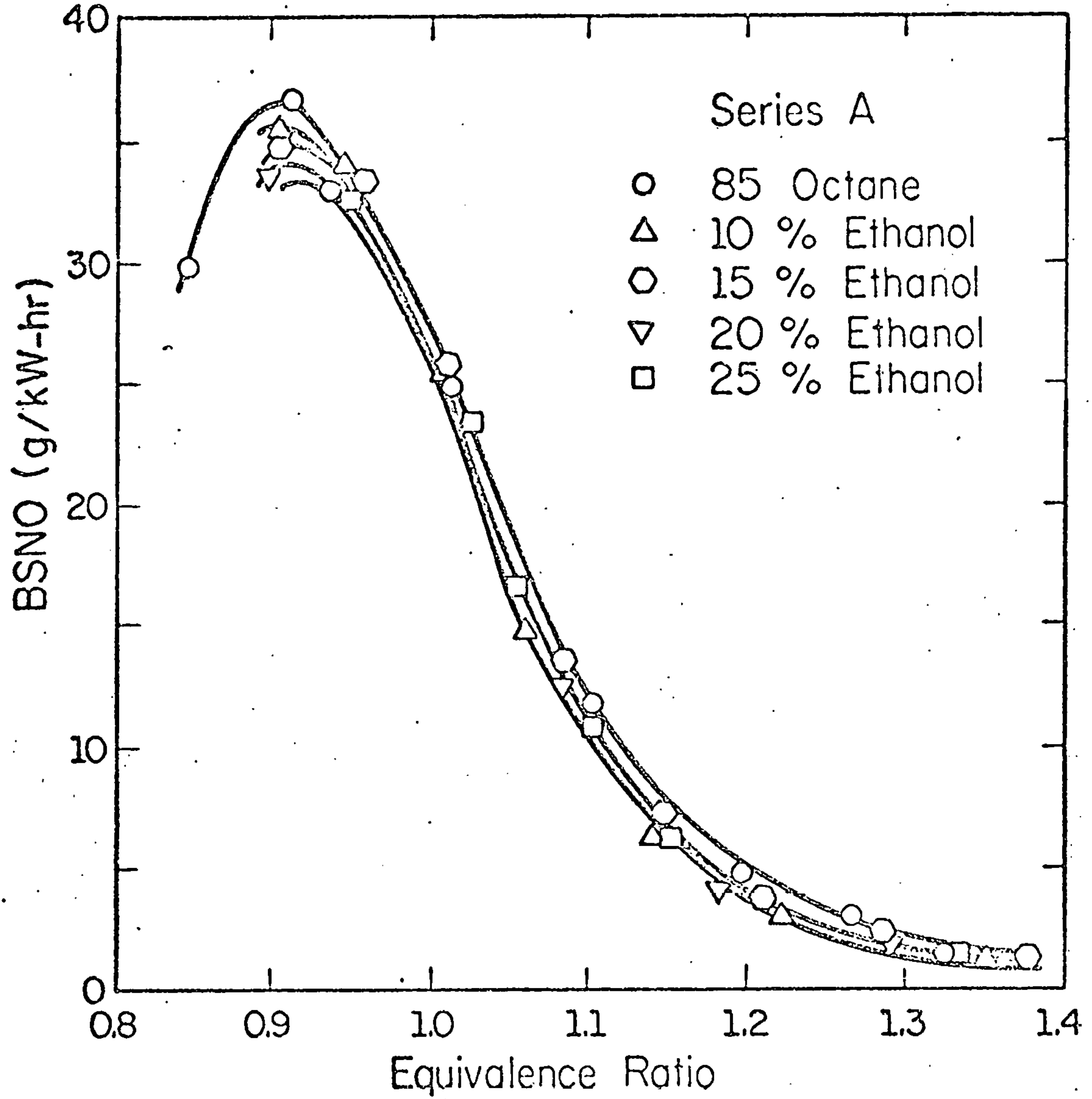

Figure 4 Effect of the Percent of Ethanol in Blends on Nitric Oxide Emissions at Constant Compression Ratio

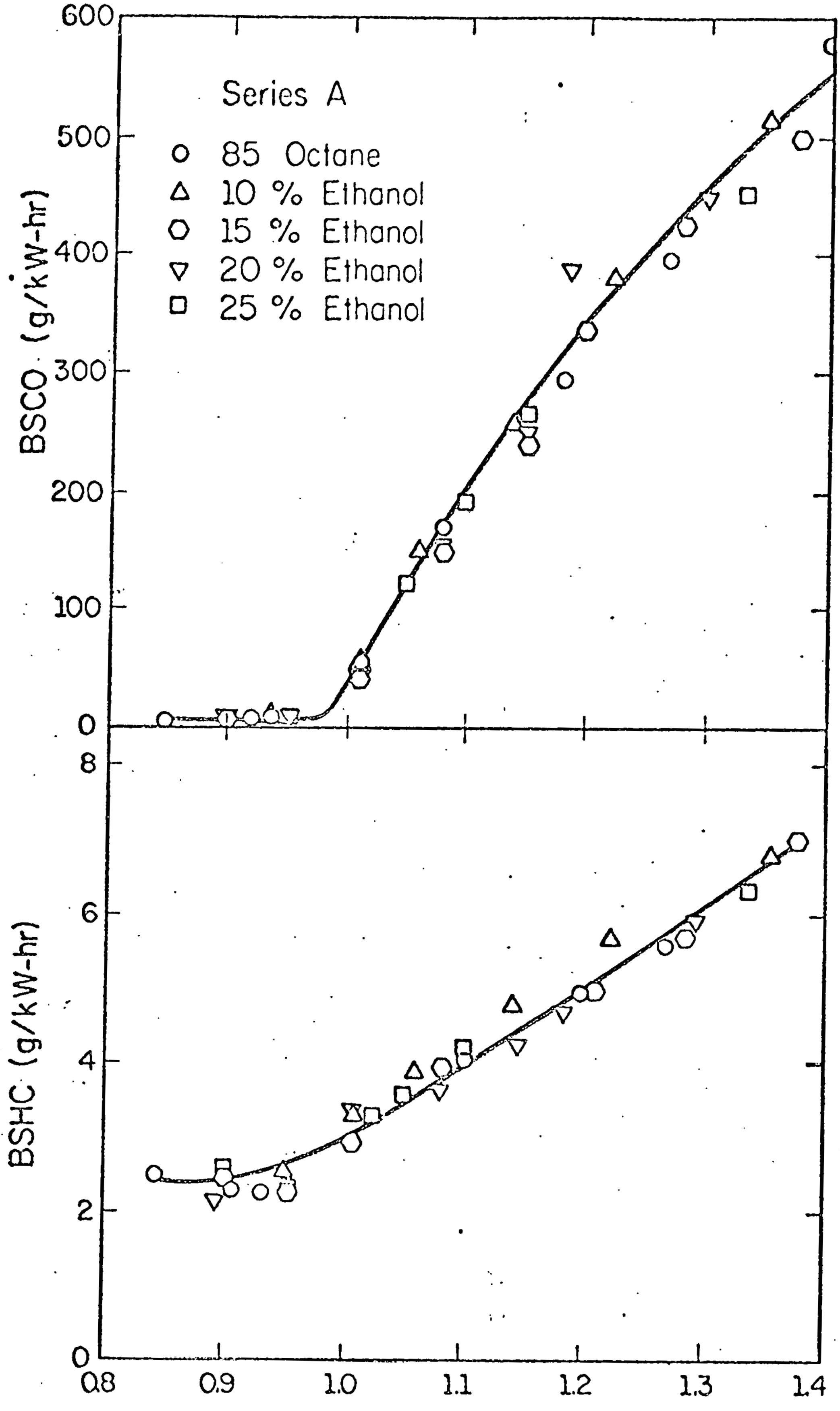

Figure 5 Effect of the Percent of Ethanol in Blends on Hydrocarbon and Carbon Monoxide Emissions at Constant Compression Ratio

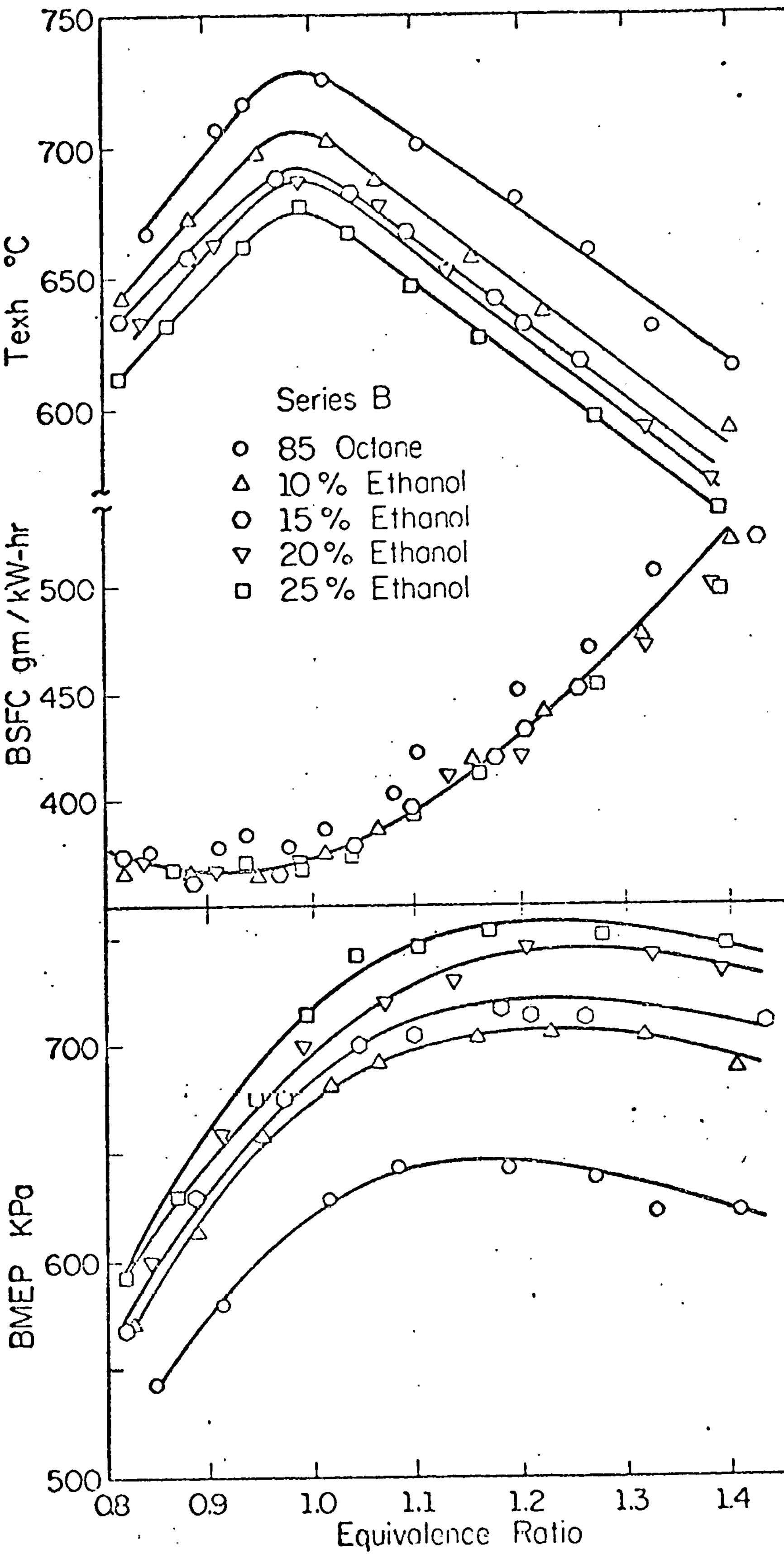

Figure 6 Effect of the Percent of Ethanol in Blends on Power, Fuel Consumption and Exhaust Temperature at Knock Limited Compression Ratio

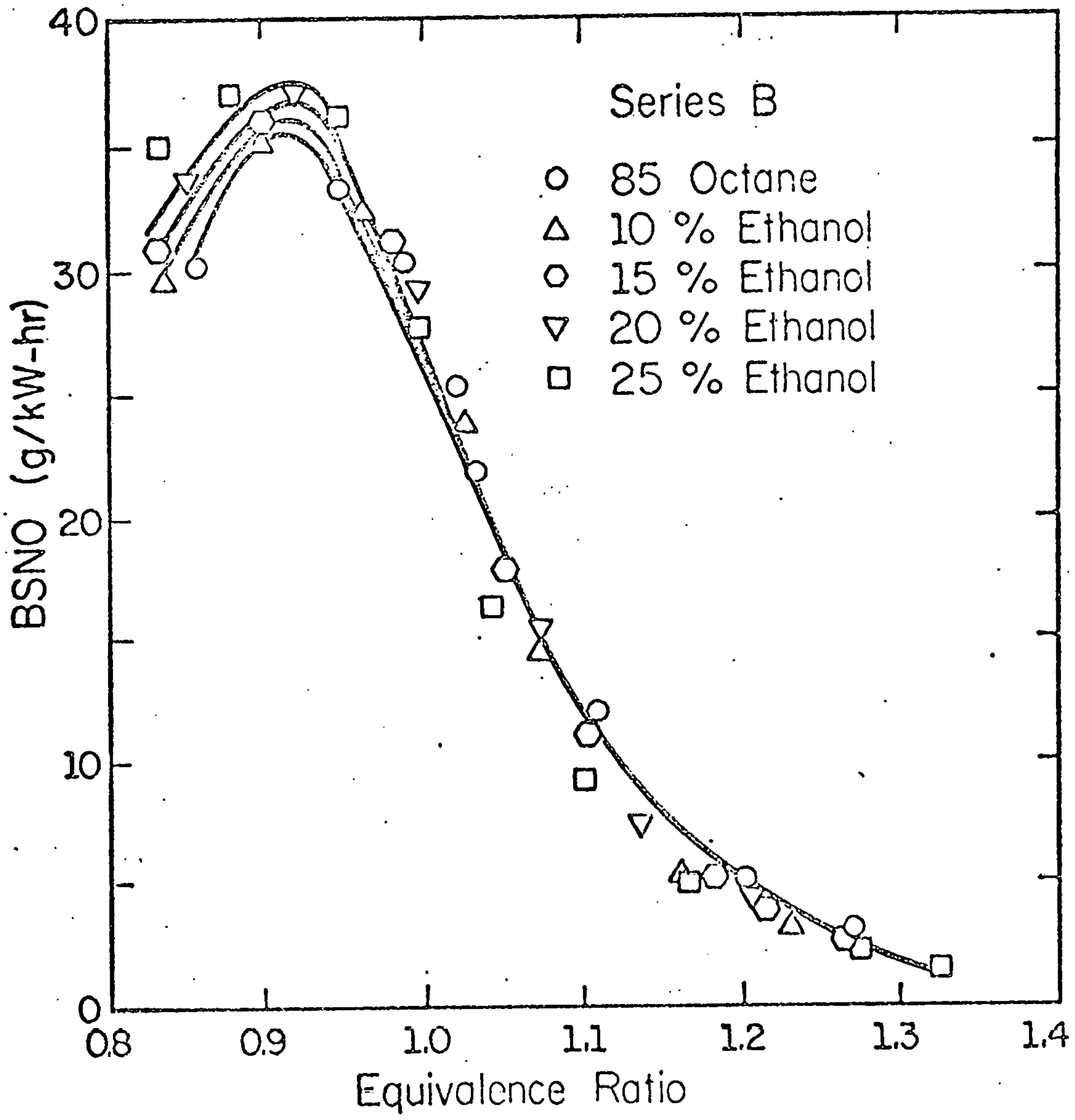

Figure 7 Effect of the Percent of Ethanol in Blends on Nitric Oxide Emissions at Knock Limited Compression Ratio

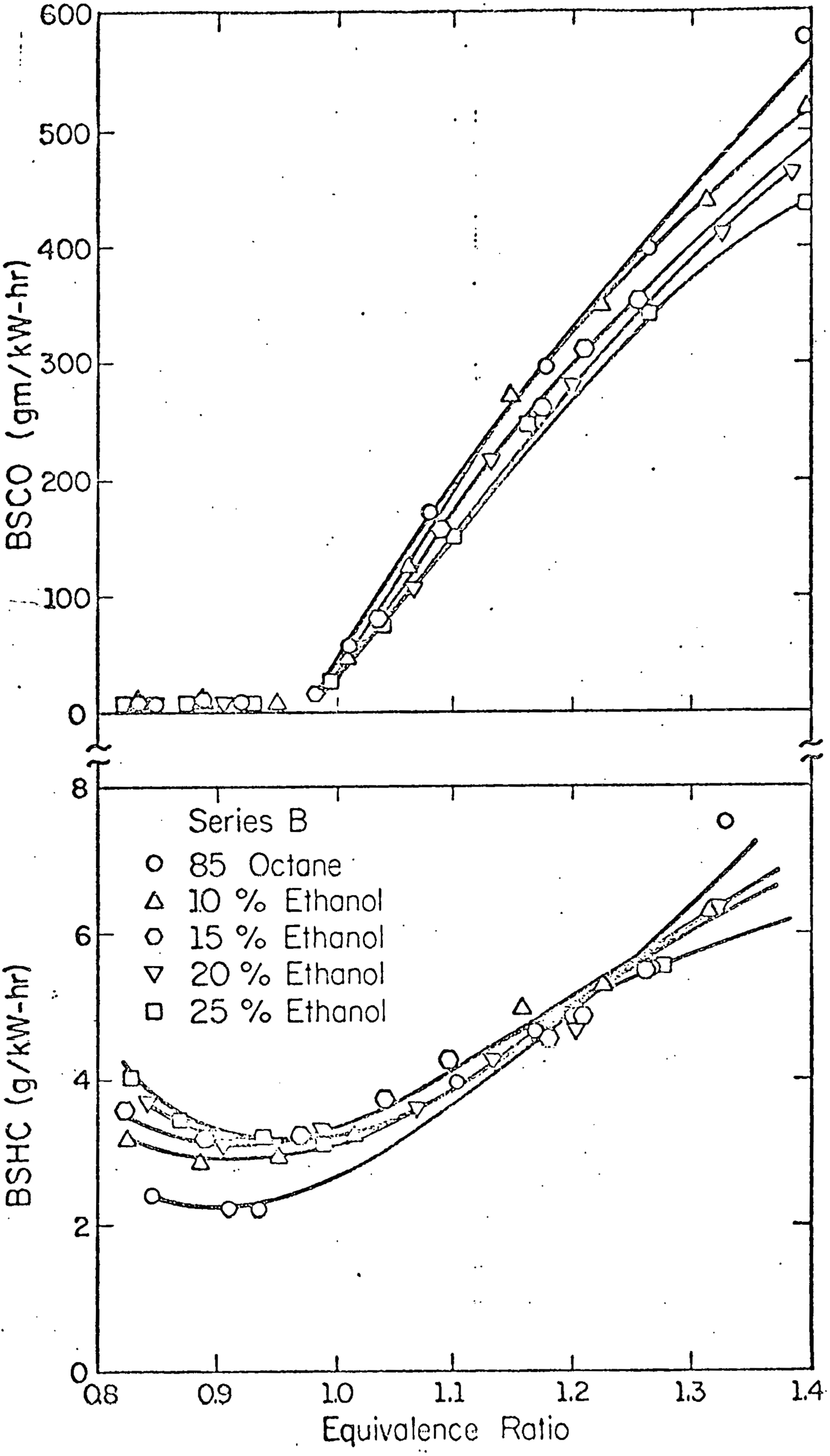

Figure 8 Effect of the Percent of Ethanol in Blends on Hydrocarbon and Carbon Monoxide Emissions at Knock Limited Compression Ratio

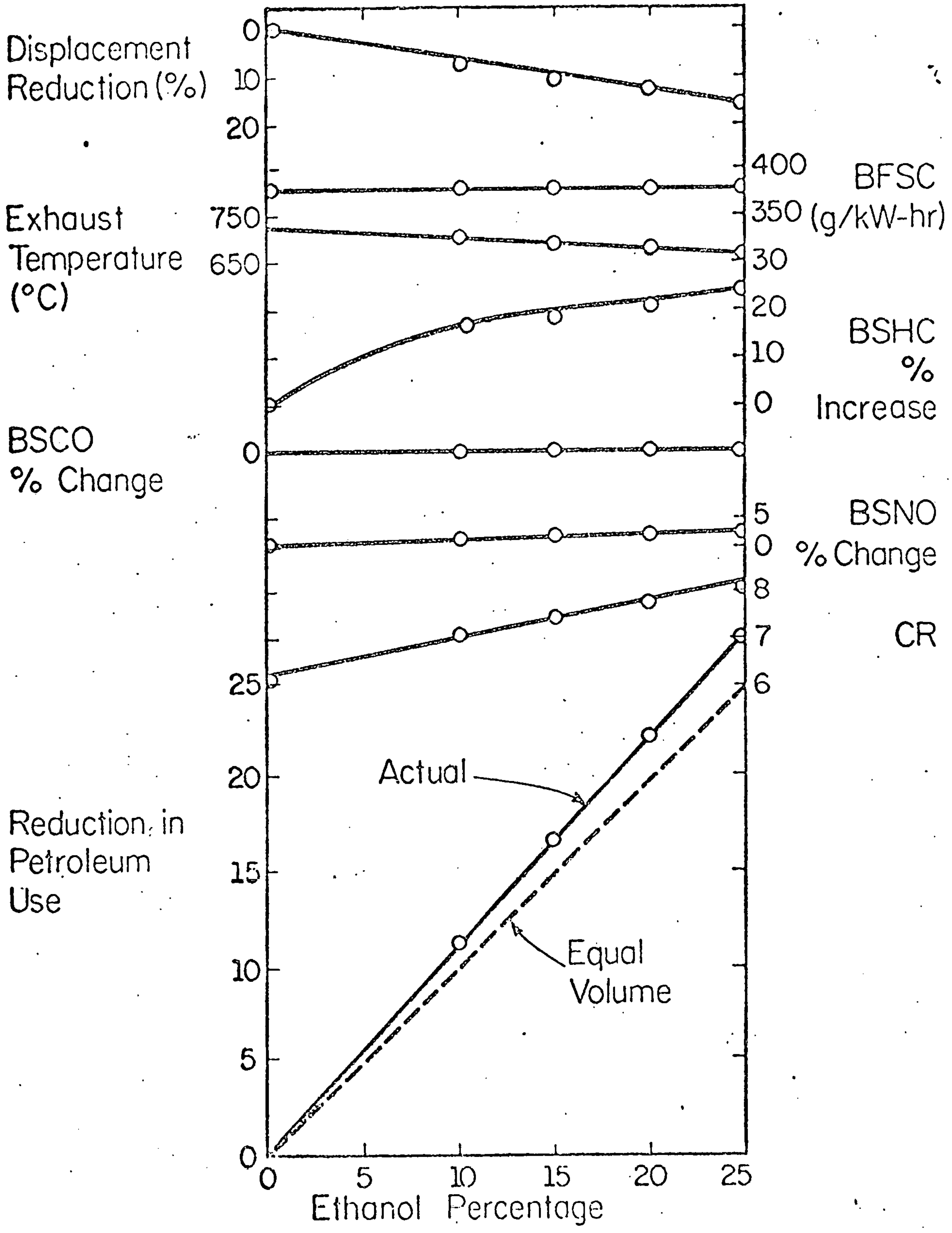

Figure 9 Effect of Ethanol Percentage on Engine Performance at an Equivalence Ratio of 1.0 and Knock Limited Compression Ratio

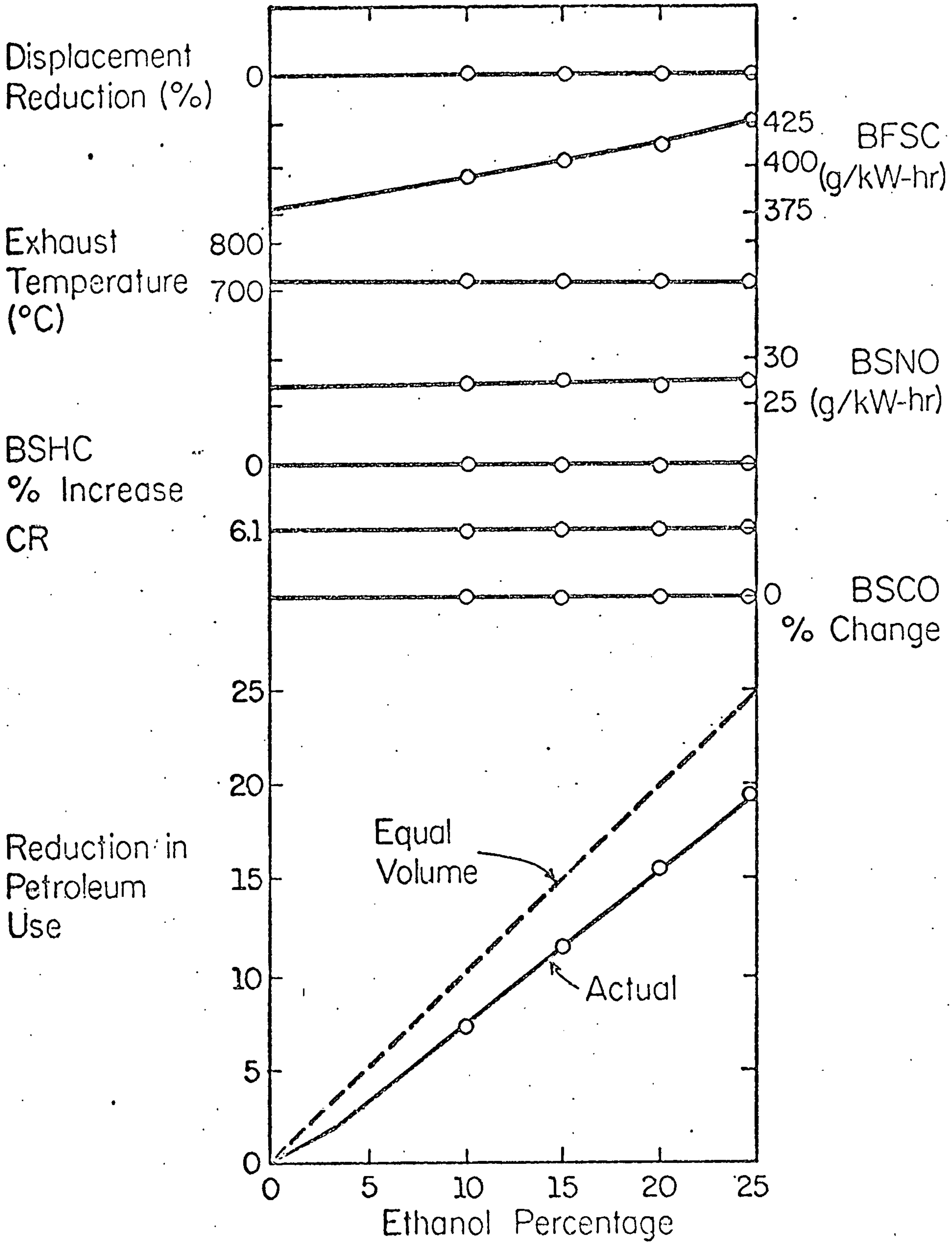

Figure 10 Effect of Ethanol Percentage on Engine Performance at an Equivalence Ratio of 1.0 and a Compression Ratio of 6.1

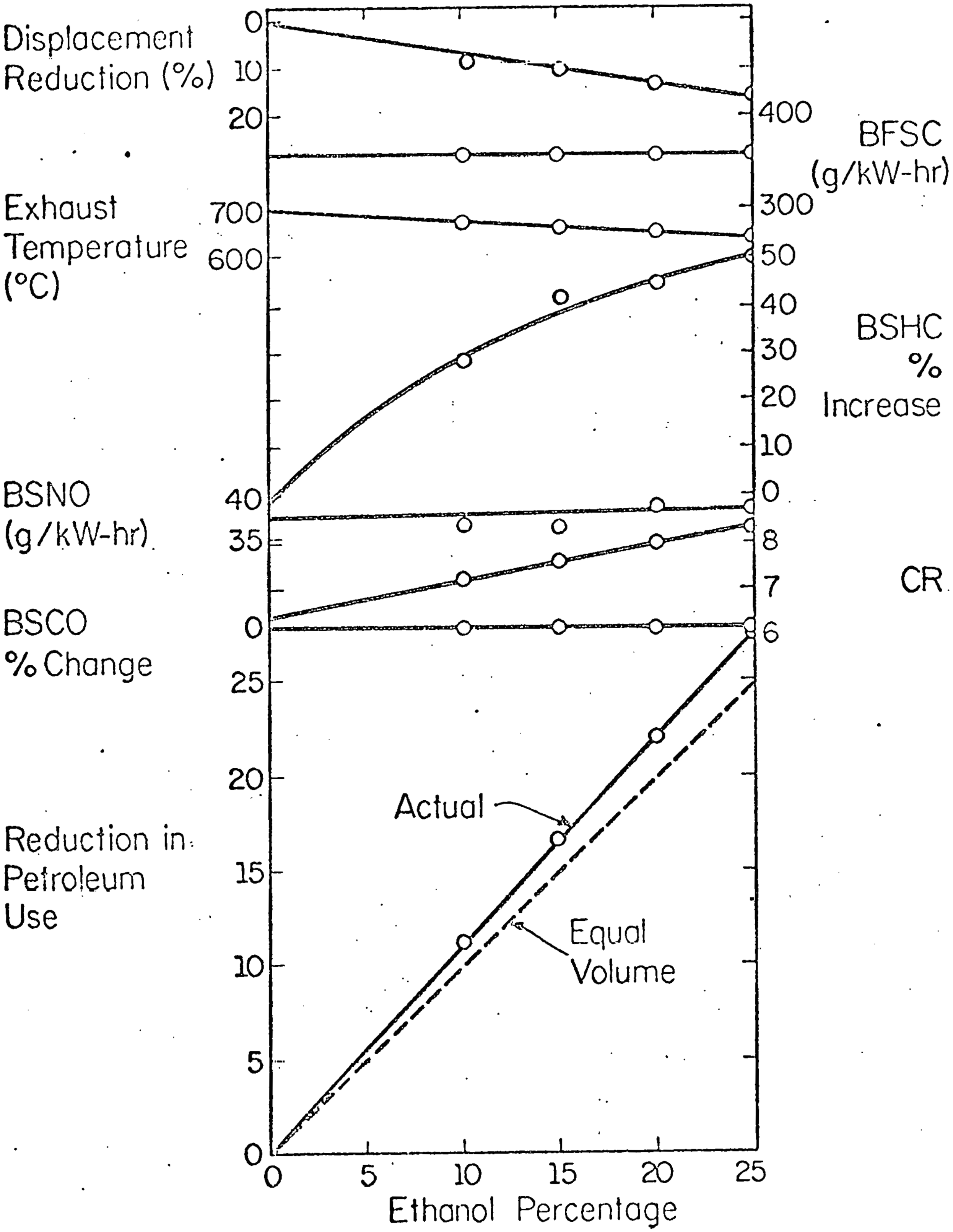

Figure 11 Effect of Ethanol Percentage on Engine Performance at an Equivalence Ratio of 0.9 and Knock Limited Compression Ratio

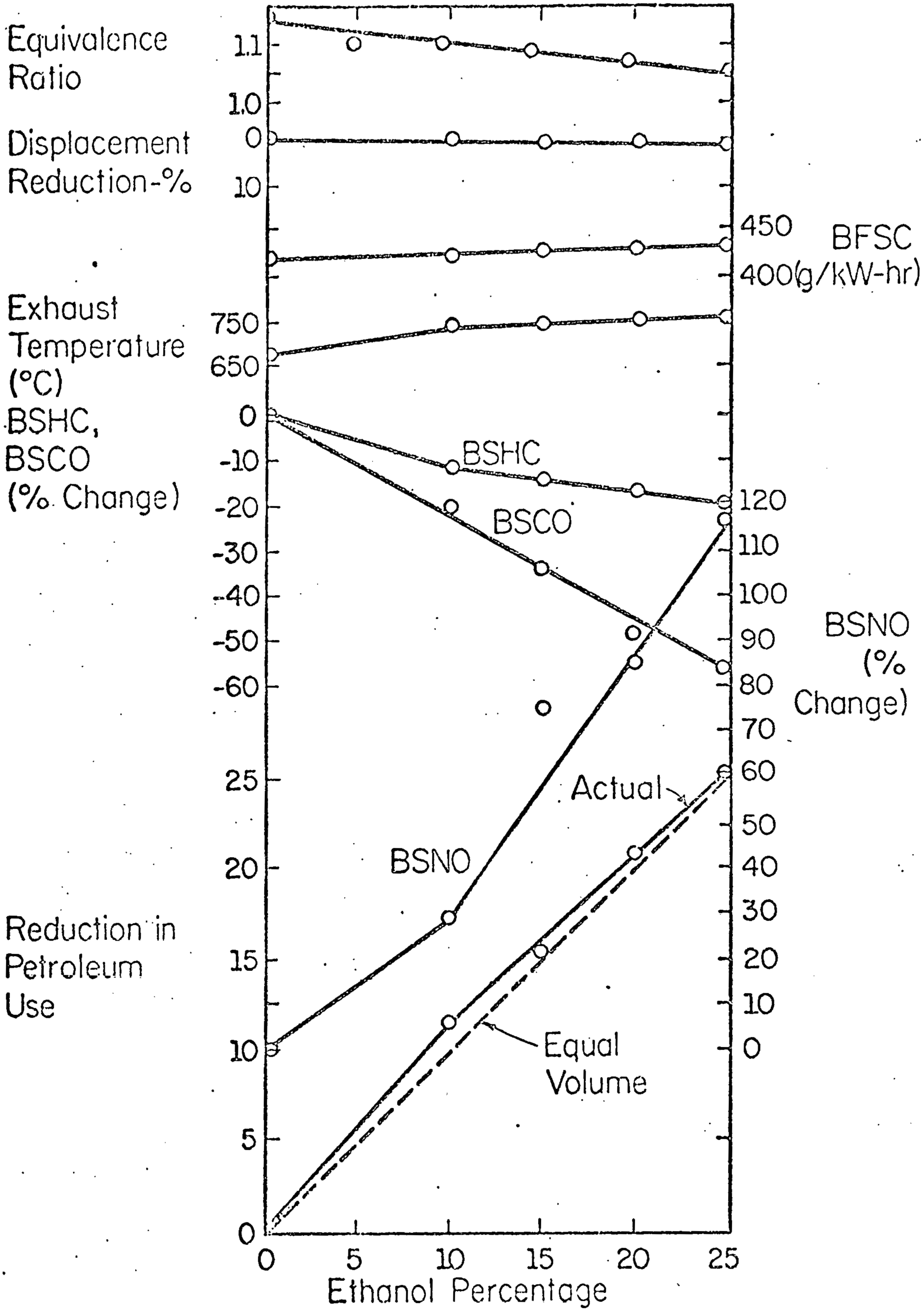

Figure 12 Effect of Ethanol Percentage on Engine Performance with Constant Fuel Air Ratio at a Compression Ratio of 6.1

Table 1 Engine Specifications and Test Conditions

Bore	82.55 mm
Stroke	114.3 mm
Compression Ratio	Variable
Speed	1,800 rpm
Intake Pressure	101 KPa
Intake Air Temperature	45 C
Spark Advance	Variable, set for maximum power
Fuels	85 octane, mixture of 85% ASTM isooctane, 15% ASTM n-heptane (primary reference fuels)
*Fuel-air Equivalence Ratio	Variable, 0.85 to 1.4

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*The fuel-air equivalence ratio is defined as the fuel-air ratio supplied to the engine divided by the stoichiometric fuel-air ratio for the fuel used.

Table 2 Fuel Properties

	Ethanol	Isooctane	Normal Heptane
Vapor* Pressure (KPa) C 38 C	30.68	11.68	11.17
Molecular** Weight	46.06	114.22	100.2
Specific** Gravity	0.7893	0.6919	0.6838
Heating Value* (KJ/kg)			
Higher	29,721	47,805	48,065
Lower	26,986	44,338	44,552
Research* Octane No.	106	100	0
Motoring* Octane No.	89	100	0
Heat of Vaporization** (KJ/kg) 25 C	920	272	316

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*Obert, 1973.

**CRC, 1976.

Table 3 Reduction in Petroleum Use due to Leaning Mixtures

Equivalence Ratio	1.15	1.101	1.096	1.076	1.058
Reduction in Petroleum Use with 85 ON Fuel	-	4.11	4.82	6.01	7.19
Reduction in Petroleum Use with Blends	-	11.7	15.5	21.0	25.4
Net Savings due to Blend	-	7.6	10.7	15.0	18.2
Volume Percent Ethanol to Give Equal Equivalence Ratio	-	10	15	20	25