# ETHANOL AS AN OCTANE ENHANCER FOR THE COMMERCIAL GASOLINE FUELS

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## ABSTRACT

Considering pollution problems today, investigations have been concentrated on lowering the concentration of toxic components in combustion products. A gasoline lead additive at a concentration of 0.6 g/l is used to provide a gasoline with an octane number of 98. In many countries methyl tertiary butyl ether (MTBE) is used instead of lead to produce gasoline with the same octane number. Presently, 15% by volume of MTBE is added to unleaded gasoline to provide a gasoline with an octane number of 98. However, the leaded gasoline is still used in many countries.

The purpose of this research is to experimentally study the possibility of using ethanol as a lead / MTBE replacement for spark ignition engines fuels. The effect of ethanol addition to unleaded gasoline on the research octane number, performance and pollutant emission of the spark ignition engine is studied. A Ricardo E6/US engine is used in this study. Results showed that the use of 15.% by volume of ethanol is a good alternative for replacing lead or MTBE in gasoline fuel and the resulted blended fuel satisfies the global specifications.

The results of the standard ASTM methods showed that with increasing the ethanol content, the research octane number of the blended fuel increases, while the Reid vapor pressure of the blended fuel initially increases to a maximum value at 10 % by volume ethanol and then decreases. The results also showed that the addition of ethanol, (from 0% to 30% by volume), increases the break power, break thermal efficiency and break specific fuel consumption, and reduces NOx, CO, and HC emissions. The higher useful compression ratio, which produced maximum break power, is directly proportional to ethanol percentage in the blended fuel.

**Keywords:** RON; Ethanol; Lead; MTBE; Alternative fuel; Pollution

**الخلاصة**

بالنظر إلى مشاكل التلوث الحالية، ازدادت البحوث للحد من تأثير هذه الظاهرة الناتجة من عمليات الاحتراق باستخدام المضافات للوقود. يتم استخدام نسبة 0.6 غرام من الرصاص لكل لتر من الكازولين لإنتاج وقود الكازولين ذو العدد الاوكتاني 98 في بعض الدول. وفي بعض الدول يستعاض عن الرصاص بمادة ( methyl tertiary butyl ether (MTBE واستخدامها مع الكازولين لزيادة عدده الاوكتاني. حاليا يتم إضافة 15%حجم من مادة ( MTBE ) إلى الكازولين للحصول على الكازولين ذو العدد الاوكتاني 98 . و مازال استخدام الرصاص مع الكازولين لرفع عدده الاوكتاني يستعمل على نطاق ضيق من بعض دول العالم.

تضمن هذا البحث دراسة عملية لاستخدام الايثانول كبديل إلى MTBE والرصاص اللذان يتم استخدامهما مع وقود الكازولين لرفع عدده الاوكتاني لتجنب ظاهرة الطرق. تم دراسة تأثير إضافة الايثانول بنسب حجميه مختلفة إلى وقود الكازولين على العدد الاوكتاني للخليط الناتج وأداء المحرك والملوثات الناتجة وبشكل مفصل. أظهرت نتائج التجارب التي أجريت على محرك الإشعال بالشرارة Ricardo E6/US إن إضافة نسبة 15% حجم من الايثانول إلى الكازولين هو خيار جيد لاستخدام الايثانول كبديل لكل من MTBE والرصاص، وعند هذه النسبة فإن الخليط الناتج يحقق المواصفات العالمية للوقود. كذلك إن إضافة الايثانول بنسبة من (0%-30%) حجم إلى الكازولين يسبب زيادة القدرة المكبحية للمحرك وكفائتة الحرارية ويقلل الاستهلاك النوعي المكبحي للوقود ويقلل جميع الملوثات وإن نسبة الانضغاط النافعة العليا تزداد طرديا مع زيادة نسبة الايثانول الحجمية.

أظهرت نتائج فحوصات ASTM إن زيادة نسبة الايثانول تؤدي إلى زيادة العدد الاوكتاني للخليط بينما يزداد ضغط البخار لحد نسبة 10% حجم ومن ثم يبدأ بالهبوط.

## INTRODUCTION

Considering pollution problems today, investigations have been concentrated on lowering the concentration of toxic components in combustion products. In many areas of the world, there has been tremendous progress in reducing and eliminating the use of lead and methyl tertiary butyl ether (MTBE) in gasoline (Hassan et al. 1989; Kiran 2002; Jonathan et al. 2004; Shing et al. 2002). There is now virtually universal acceptance of the need to eliminate lead and MTBE from gasoline. Numerous researchers (National Research Council in USA 1993) in many countries have definitively established its adverse neurological effects, especially on children. When lead is phased out of gasoline, the population's exposure to lead drops in a predictable manner (Thomas et al. 1999). Even the manufacturer of gasoline lead additives now agrees that their product needs to be phased out.

Tetraethyl lead is added to gasoline to provide high octane number. The replacements for lead must therefore have good octane characteristics. ''Octane'' is a measure of the tendency of the air/fuel mixture to resist self ignition as it is heated during the compression stroke in the engine cylinder. This pre-ignition, or ''knock'', decreases the efficiency of the engine and increases engine wear. The high temperatures and pressures during the compression stroke in the cylinder cause fuel molecules to break down into free radicals (highly reactive molecules with an unpaired electron). Tetraethyl lead scavenges the free radicals, reacting with them before they can build up the chain reaction that causes the pre-ignition. Instead of adding tetraethyl lead, one way to increase the octane value of a gasoline is to change its composition so that it is less likely to generate the free radicals that lead to knock. Molecules with stronger bonds are less likely to break down; strongly bonded hydrocarbons include low bond order hydrocarbons such as ethanol and methyl tertiary butyl ether (MTBE), and hydrocarbons with branched or ring structures (Asfaha et al. 1998; Henry et al. 1998).

The MTBE can present in the exhaust gas when MTBE-containing gasoline is used. The fate of MTBE in the environment is of great concern because a lot of complaints related to irritation effects of MTBE on eyes or lungs were reported in regions using MTBE as gasoline additive (Poulopoulos and Philippopoulos 2000). The addition of MTBE into gasoline resulted in a decrease in CO and HC emissions only at high engine loading. During low engine power, MTBE, HC and CO emissions increased with MTBE addition into fuel, and the unburned MTBE constitutes a great percentage of emitted hydrocarbons (Poulopoulos and Philippopoulos 2000).

However, MTBE is highly soluble in water. Low levels of its concentration make drinking water unpalatable due to its low taste and odor threshold. Moreover, MTBE is much more difficult to be degraded than other gasoline components. Therefore, it has been detected in surface water and ground water because of its widespread use. Beside, MTBE itself is found in exhaust gas and it has irritation effects on eyes or lungs (Poulopoulos and Philippopoulos 2000; He et al. 2003). When research animals inhale high levels of MTBE, they will develop cancers or experience other non-cancerous diseases. MTBE even poses a potential for carcinogenicity to humans at high doses (He et al. 2003). Therefore, it is time to find alternative oxygenates that has no such disadvantages.

Ethanol ($C_2H_5OH$) is a pure substance. It contains an oxygen atom, which can be viewed as partially oxidized hydrocarbon. Gasoline–ethanol mixtures may be prepared by the addition of a certain percentage of ethanol to the gasoline. Gasoline–ethanol mixtures, which contain up to 20% ethanol by volume, can be safely used without causing any damage to engine parts (He et al. 2003; Hsieha et al. 2002). In this system, depending on the ratio of ethanol, gasoline and water components, it is possible to distinguish the limits of a homogeneous and stable phase. A phase separation is observed in gasoline–ethanol mixtures when the amount of water present in the mixture is over a certain limit. At the phase separation, gasoline, which contains less than 20% ethanol by volume and is also aromatic in character, is said to be more stables (Al-Hasan 2003). As pointed out, in order to be able to use gasoline–ethanol mixtures as a motor fuel, the mixture must be stable and a separation of phases should not occur. In gasoline–ethanol–water systems, the phase separation depends on the ethanol and water content of the blend, the environmental temperature, and the composition of gasoline. In order to reduce the phase separation temperature, higher aliphatic alcohols are usually added to the gasoline–alcohol blends (Rajan and Fariborz 1983; Gramajo et al. 2004).

Sustaining a clean environment is an important issue in an industrialized society. The air pollution caused by automobiles and motorcycles is one of the most important environmental problems to be tackled. Since using ethanol–gasoline blended fuels can ease off the air pollution and the depletion of the petroleum fuels simultaneously, much research has been devoted to study the effect of these alternative fuels on the performance and pollutant emission of an engine (Poulopoulos et al. 2001; Yaksel and Yaksel 2004).

Alcohol fuels can be produced from renewable resources like locally grown crops and even waste products such as waste paper or grass and tree trimmings (Morris et al. 1992). Ethanol is a likely alternative automotive fuel in that it has properties, which would allow its use in present engines with minor modifications.

As a fuel for spark-ignition engines, ethanol has some advantages over gasoline, such as better anti-knock characteristics and less CO and UHC emissions. It has a high octane number than gasoline. A fuel with a higher-octane level can endure a higher compression ratio before exploding, giving the engine the ability of delivering more power and thus being more powerful and economical. Ethanol fuels burn cleaner than regular gasoline and produce less carbon monoxide and unburned hydrocarbon. Carbon monoxide is a direct human health hazard, as well as an ozone precursor. Ethanol fuel has high heat of vaporization; therefore, it reduces the peak temperature inside the cylinder and hence reduces the NOx emissions and increases the engine power (Poulopoulos et al. 2001; Al-Hasan 2003; Yaksel and Yaksel 2004).

Ethanol is completely miscible with water in all proportions, while gasoline and water are immiscible (He et al. 2003; Rajan and Fariborz 1983; Gramajo et al. 2004). This may cause the blended fuel to contain water, and further results in corrosion problems on the mechanical components, especially on the components made of copper, brass or aluminum. To minimize this problem on fuel delivery system, such materials mentioned above must be avoided (He et al. 2003; Yoshiaki and Yoshiyuki 1984). Ethanol can react with most rubber and cause a jam in the fuel pipe. Therefore, it is advised to use fluorocarbon rubber as a replacement for rubber (He et al. 2003).

Some of the combustion characteristics of ethanol such as the auto-ignition temperature and flash point are higher than those of gasoline, which make it safer for transportation and storage. The latent heat of evaporation of ethanol is about 2.5 times higher than that of gasoline, and this reduces the temperature of the intake manifold,

and increases the volumetric efficiency. The heating value of ethanol is also lower than that of gasoline. Therefore, about 1.6 times more ethanol fuel needs to achieve the same energy output. Moreover, the stoichiometric air–fuel ratio (AFR) of ethanol is about 2/3 that of gasoline, hence the required amount of air for complete combustion is lesser for ethanol (He et al. 2003; Hsieha et al. 2002; Al-Hasan 2003).
The using of ethanol–gasoline blended fuels increases the emission of formaldehyde, acetaldehyde and acetone up to 5.12–13.8 times than those from gasoline. Although the emission of aldehydes will be increased when ethanol is used as a fuel, the damage to the environment caused by the emitted aldehydes is far less than that caused by the poly-nuclear aromatics emitted from burning gasoline. Therefore, the percentage of ethanol in blended fuel can make the air quality better in comparison to gasoline (He et al. 2003; (Poulopoulos et al. 2001; Yaksel and Yaksel 2004).
A significant drawback to the use of ethanol is its high Reid vapor pressure (RVP), which is a measure of a gasoline's volatility. The RVP effect of ethanol on gasoline blends is not linear; ethanol blending at a 5–6 volume percent increases RVP by about 1.3 psi; additional ethanol blending does not further increase RVP. Gasolines with higher RVP have higher evaporative emissions, which are released during refueling and when the car is not operating. These evaporative emissions are ozone precursors, and the use of ethanol blends without compensatory blending to control RVP can result in increased ozone (smog) formation (Hsieha et al. 2002; Pumphrey et al. 2000). In the United States, the RVP of gasoline is regulated based on the region and the time of year. RVP limits are strongest in the summer and in the south, because evaporative emissions are higher in hotter weather. Baseline summer gasoline is limited to an RVP limit of 9 Psi in the northern states, and to 8 Psi in the southern states, and ethanol-gasoline blends are allowed to have a 1 Psi higher RVP. However, the state of California has a stricter RVP limit of 7.8 Psi, which both gasoline and gasoline-ethanol blends are required to meet.

## PRESENT EXPERIMENTAL STUDY

The aim of this research is to study the use of ethanol as a lead / MTBE replacement in spark ignition engines fuel. Therefore, the study is divided into two parts. The first part is to study the effect of ethanol blending on the research octane number (RON) of unleaded gasoline. The second part is to study the effect of ethanol blending on the performance and pollutant emission of the spark ignition engine operated at the optimum spark timing for best torque.
The experimental tests started with pure gasoline to set a database level for comparison purposes. Unleaded gasoline, the base fuel, with research octane number equal to 95, Table 1 was selected, and mixed with different percentages of ethanol (99.9% purity). Various blend ratios of ethanol-gasoline fuels, (5, 10, 15, 20, 25, 30, 35, 40, 45, and 50% of ethanol in gasoline), have been prepared and then sent to the fuel laboratory for ASTM standard analysis. Then, the RON, Engine performance and emission were tested.

### Research Octane Number (RON)

The tests for research octane number of spark ignition engine fuel were done according to ASTM methods. This laboratory test method (ASTM D 2699-95a) covers the quantitative determination of the knock rating of liquid spark-ignition engine fuel in term of Research octane number. The fuel samples were tested using a standardized single cylinder, four-stroke cycle, variable compression ratio, carbureted, with cylinder bore 3.25 in, stroke 4.5 in, and engine speed $600 \pm 6$ rpm, CFR engine run in accordance with a defined set of operation conditions. The RON of a spark-ignition engine fuel is determined using a standard test engine and operating conditions to compare its knock characteristic with those of primary reference fuel blends of known octane number. Compression ratio and fuel-air ratio are adjusted to produce standard knock intensity for the fuel sample, as measured by a specific electronic detonation meter instrument system. A standard knock intensity guide table relates engine compression ratio to octane number level for this specific method is used. The fuel-air ratio for the fuel sample and each of the primary reference fuel blends is adjusted to maximize knock intensity for each fuel.

**Engine Performance and Pollutants Emission**

The engine performance and pollutants emission tests were done with Ricardo engine. Ricardo E6/US carbureted single cylinder four-stroke research engine with cylinder bore of 76.2 mm, stroke of 110 mm, connecting rod length of 241.3 mm and engine speed of 1500 rpm has been used. The engine power has been measured using an electrical dynamometer. The exhaust gas was analyzed for CO by non-dispersive infrared analyzer NDIR, for HC by flame ionization detector FID and for NOx by chemluminescet analyzer, CUSSONS equipment's. High-pressure transducer, type AVL-8QP was used to record the cylinder pressure. The transducer signal has been amplified by a CUSSONS-PIEZO channel amplifier, and then stored and presented on the display of a CRT kikusui-COS5020-ST oscilloscope. A pick-up for an angle marker has been installed and its signal is also presented on the oscilloscope display.

## RESULTS AND DISCUSSION

Figs. 1, 2 and 3 show the measurements of the research octane number by the standard ASTM method, CFR engine, for lead additives, MTBE blending and ethanol blending respectively. The increase in octane number that a given amount of lead provides depends on the baseline characteristics of the gasoline and the amount of lead that has already been added. As shown in fig. 1, the octane benefits of lead are greatest for gasoline with low initial amount of lead added, and there are decreasing benefits as more lead is added. fig. 2 shows the effect of MTBE blending on the research octane number of unleaded gasoline. It can be seen that increasing the MTBE volume ratio increases the octane number. A gasoline lead additive at concentration of 0.6 g/l is used to provide a gasoline with an octane number of 98, fig. 1. Presently, 15% by volume of MTBE is added to unleaded gasoline to provide a gasoline with an octane number of 98, fig. 2. However, the leaded gasoline is still in use.

Fig. 3 shows the effect of ethanol blending on the research octane number of unleaded gasoline. It can be seen that increasing the ethanol volume ratio increases the octane number significantly. Both gasoline lead additive and gasoline MTBE blending can be replaced by a 15% blend of ethanol in gasoline to obtain same octane number, Fig. 3. This blended ratio (15% ethanol + 85% gasoline by volume) satisfies the global specification, Table 1. Thus in bulk, to replace a ton of lead would require about 0.25 ml of ethanol.

Fig. 4 shows the variations of RVP as a function of different blend ratios of ethanol-gasoline. This indicates that with increasing the ethanol content, the RVP increases to reach a maximum at 10% ethanol addition, and then decreases. The increase in the RVP of the fuel is an indication of the increased evaporative emissions. However, the RVP of the fuel for all percentages of ethanol in gasoline were still within the limit of the global specification for fuel, Table 1.

Figs. 5 to11 show the of the effect of ethanol blending on the performance and emissions of a Ricardo E6/US spark ignition engine operated with a stoichiometric mixture and optimum spark timing for best torque at 1500 rpm engine speed. All measurements were performed under wide-open throttle conditions and were done three times repeatedly. Each parameter studied in figs. 6 to 11 are made dimensionless by relating it to its value when the engine was fueled with a pure gasoline, the base fuel, at a compression ratio of 8, 1500 rpm, stoichiometric mixture and optimum spark timing for best torque.
During these tests it is noticed that when ethanol percentage exceeds 30% the carburetor is not capable of evaporating all the fuel supplied to the engine, and part of it enters the chamber without evaporation. This causes a reduction in the break power and difficulty at the cold start. Therefore, results for only 0% - 30% of ethanol blending are chosen.
The higher useful compression ratios (HUCR), which gives maximum break power, were used for all blend ratios of ethanol–gasoline as shown in, Fig. 5. The results showed that the HUCR for a pure gasoline fuel was about 8:1 and increased as the volume percentage of ethanol fuel is increased in the fuel mixture because of the relatively high anti-knock or octane rating of ethanol fuel. Thus ethanol has the ability to raise considerably the octane rating of gasoline.
Figs. 6 and 7 show the effect of the ethanol fuel blending on the break power and thermal efficiency. The break power and thermal efficiency increase with the increase of the ethanol volume percentage ratio in the gasoline up to 30% ethanol. At this percentage, the maximum break power and maximum break thermal efficiency have been obtained due to the increase in mixture density and engine volumetric efficiency. High compression ratios were possible because of the high-octane quality and high self-ignition temperature of ethanol fuel. The increase in compression ratio improves engine ability to deliver more power, thus making it more powerful and economical. With HUCR the break power and thermal efficiency were increased.
Fig. 8 shows the effect of the ethanol fuel blending on the specific fuel consumption (sfc). The figure shows that it slightly increases as the volume percentage of ethanol fuel is increased in the mixture. This is due to the lower heating value of ethanol (29.7 MJ/kg) compared with gasoline (47.3 MJ/kg). The increase in compression ratio caused a reduction in the fuel consumption. However, the specific fuel consumption of the ethanol-gasoline mixture at a HUCR was still greater than that with pure gasoline at a compression ratio of 8 and the same operation condition.
Fig. 9 shows the effect of the ethanol fuel blending on the NOx emission. The NOx concentration is decreased as the volume percentage of ethanol fuel is increased in the mixture. This is probably a result of the higher heat of vaporization of ethanol, which reduces the peak temperature inside the cylinder. The increase in compression ratio caused an increase in NOx emission. This is due to the higher peak temperature and pressure in addition to the reduction in the time required for dissociating NO to $N_2$ and $O_2$. However, NOx concentration at HUCR for all percentages of ethanol in gasoline was still lower than with pure gasoline fuel at a compression ratio of 8 and the same operation condition.
Figs. 10 and 11 show the effect of the ethanol fuel blending on the CO and HC emissions. The concentrations of CO and HC are decreased as the volume percentage of ethanol fuel is increased in the fuel mixture. This is due to the reduction in carbon atoms concentration in the blended fuel and the high molecular diffusivity and high flammability limits which improve mixing process and hence combustion efficiency.

The increase in compression ratio caused a reduction in both of CO and HC emissions due to the improvement of the combustion process.

**CONCLUSIONS**

The following conclusions can drawn from the present research:

1- Ethanol can be used as a supplementary fuel up to 30% of gasoline in modern spark ignition engines without major changes. It can help to save our environment from toxic pollutants and to save a considerable part of the available oil.
2- The addition of ethanol to gasoline fuel initially increases the Reid vapor pressure of the blended fuel until 10% ethanol addition, then the Reid vapor pressure decreases with further addition of ethanol. This increases the evaporative emissions for ethanol-gasoline blended fuels. However, the RVP of the fuel for all percentages of ethanol in gasoline was still in the limits of the global specification.
3- The addition of ethanol to gasoline fuel enhances octane number of the blended fuels. An addition of 15% by volume of ethanol to gasoline produces the same effect as the addition of 0.6 g/l of lead or 15% by volume MTBE. All specifications of the resulted fuel mixture satisfy the global specification.
4- The higher useful compression ratio, which produced maximum break power, is directly proportional to ethanol percentage added.
5- The break power and the break thermal efficiency increases as the volume percentage of ethanol is increased in the fuel mixture at fixed compression ratio. Increasing the compression ratio caused an increase in both power and thermal efficiency of the engine. High compression ratios were possible because of the high-octane quality of ethanol.
6- The specific fuel consumption increases as the volume percentage of ethanol is increased in the mixture at fixed compression ratio, but increasing the compression ratio improves the specific fuel consumption.
7- The concentration of NOx, CO and HC are decreased as the volume percentage of ethanol is increased in the fuel mixture at fixed compression ratio. Increasing the compression ratio caused an increase in NOx and a decrease in both CO and HC emission. However, NOx concentration at HUCR for all percentages of ethanol in gasoline was still lower than that with pure gasoline fuel at a compression ratio of 8.

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**Table 1. Properties of the unleaded gasoline fuel (base fuel) and 15 vol.% ethanol addition.**

| Property item | Global specification | Gasoline | E15* | Test method |
|---|---|---|---|---|
| Density (kg/l @ 15.5 °C | min 0.720 – 0.78 max | 0.7729 | 0.776 | ASTM D1298 |
| RON | 98 | 95 | 98.5 | ASTM D2699 |
| RVP (kPa @ 37.8 °C) | min 48–70**/90*** max | 53.4 | 58.9 | ASTM D323 |
| Total Sulfur (wt%) | max 0.04 | 0.0074 | 0.0067 | ASTM D4292 |
| Existent Gum (mg/100 ml) | max 5 | 0.8 | 0.8 | ASTM D381 |
| Corrosivity (3 h @ 50 °C) | max 1a | 1a | 1a | ASTM D130 |
| Oxidation Stability Induction Period | min 360 | > 360 | > 360 | ASTM D525 |
| Distillation: | | | | ASTM D86 |
| Vol.% recovered @ 70 °C | min 15 – 45 max | 21 | 19 | |
| Vol.% recovered @ 100 °C | min 40 – max 65 | 48 | 45 | |
| Vol.% recovered @ 150 °C | min 75 | 90 | 83 | |
| Final Boiling Point (°C) | max 210 | 168 | 164 | |
| Residue + Loss (vol.%) | max 2 | 1 | 0.7 | |

* 15% ethanol + 85% gasoline by volume
** Summer Specification
*** Winter Specification

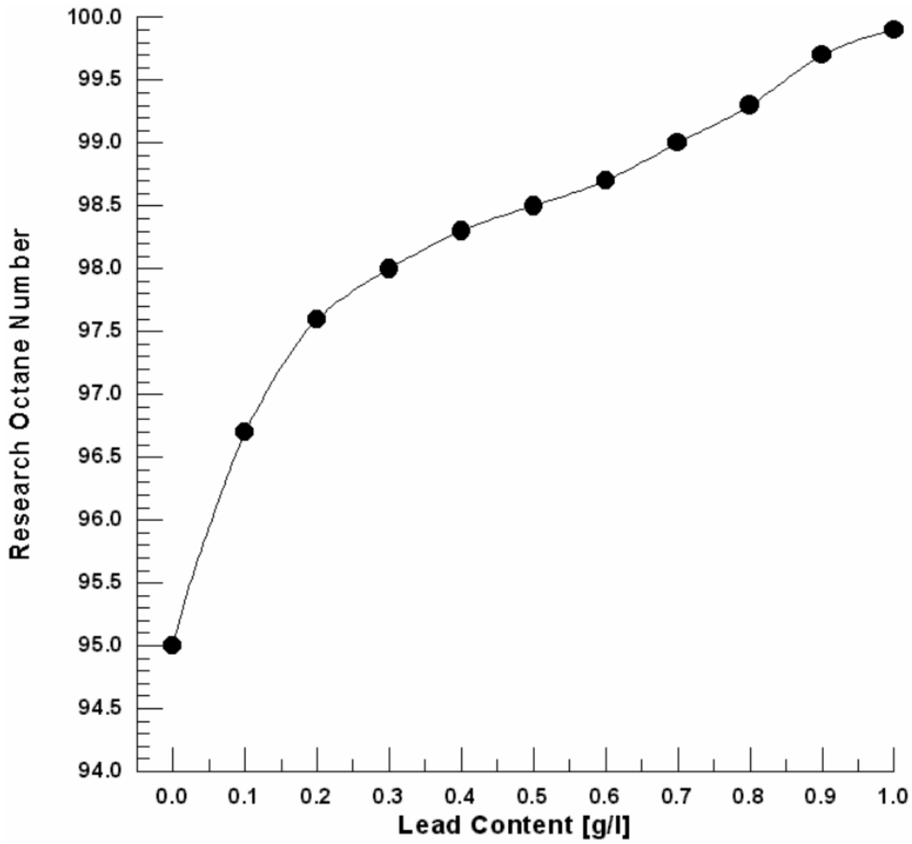


Fig.1. Contribution of lead additives to gasoline octane (RON) for gasoline's (CFR engine).

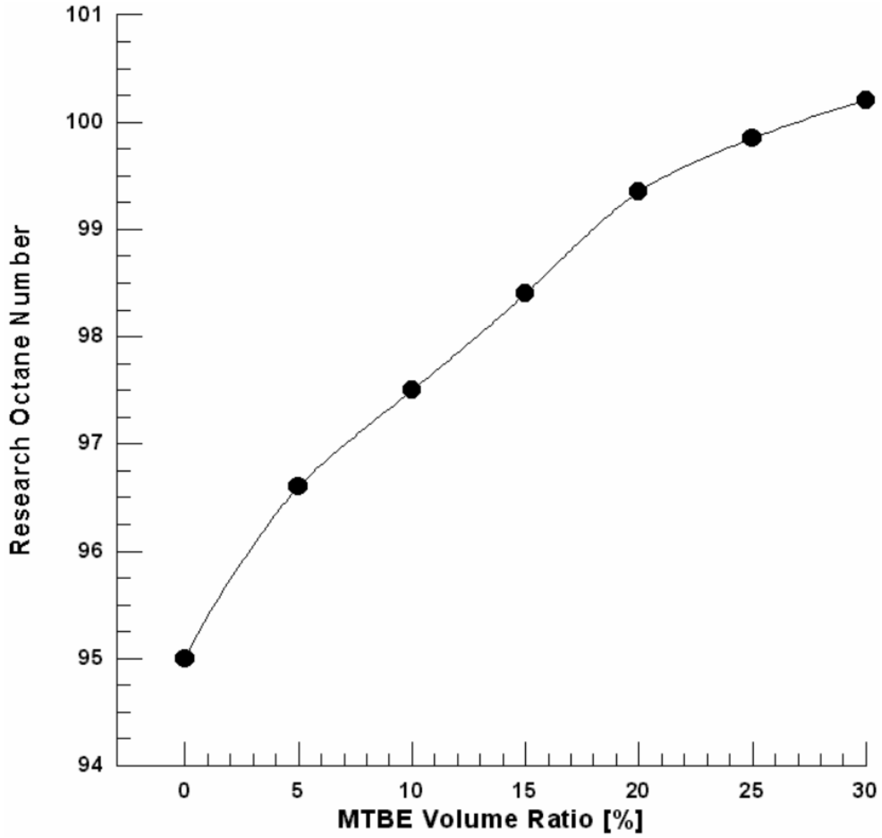


**Fig.2. Contribution of MTBE additives to gasoline octane (RON) for gasoline's (CFR engine).**

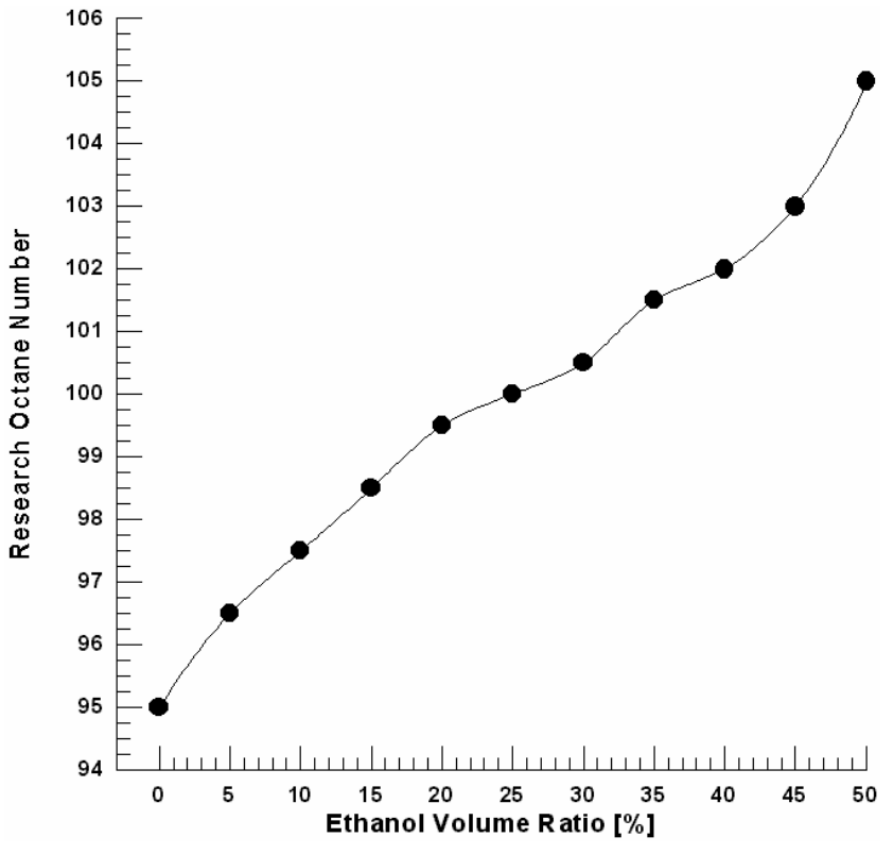


**Fig.3. Contribution of ethanol additives to gasoline octane (RON) for gasoline's (CFR engine).**

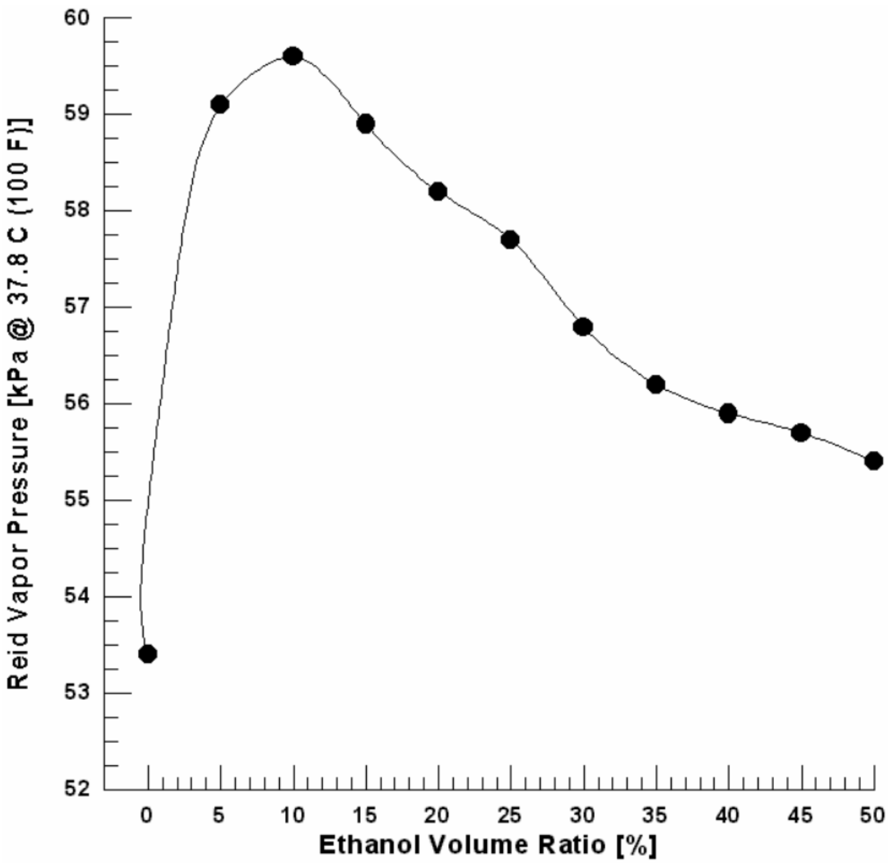


Fig.4. Effect of ethanol blending on the Reid vapor pressure value.

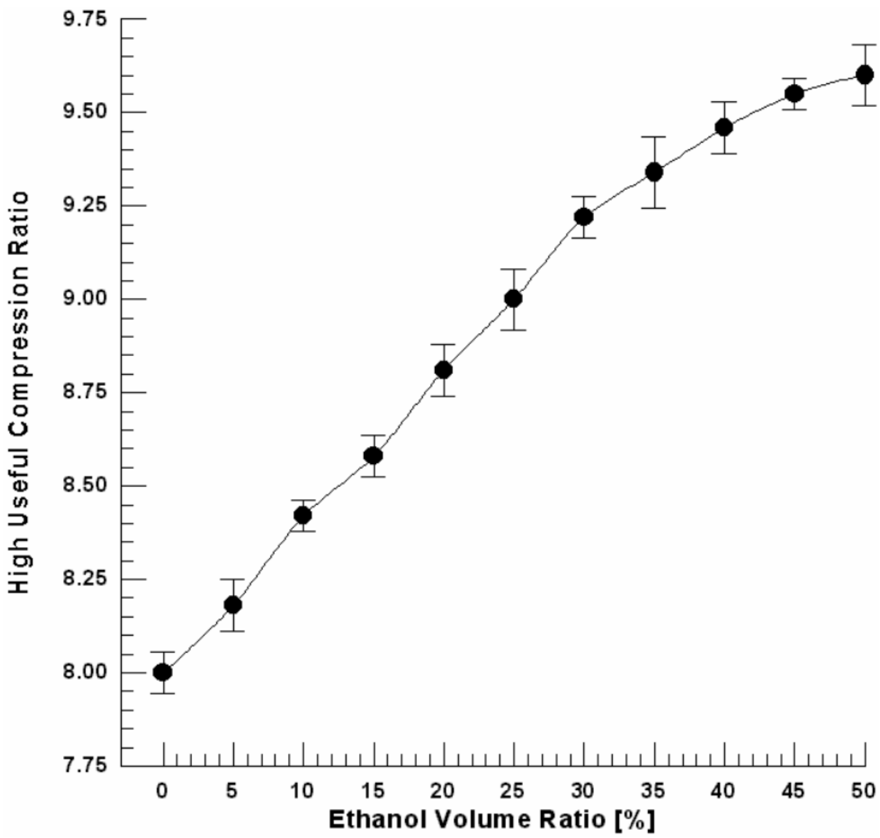


Fig.5. Effect of ethanol blending on the high useful compression ratio of the Ricardo E6 SI engine.

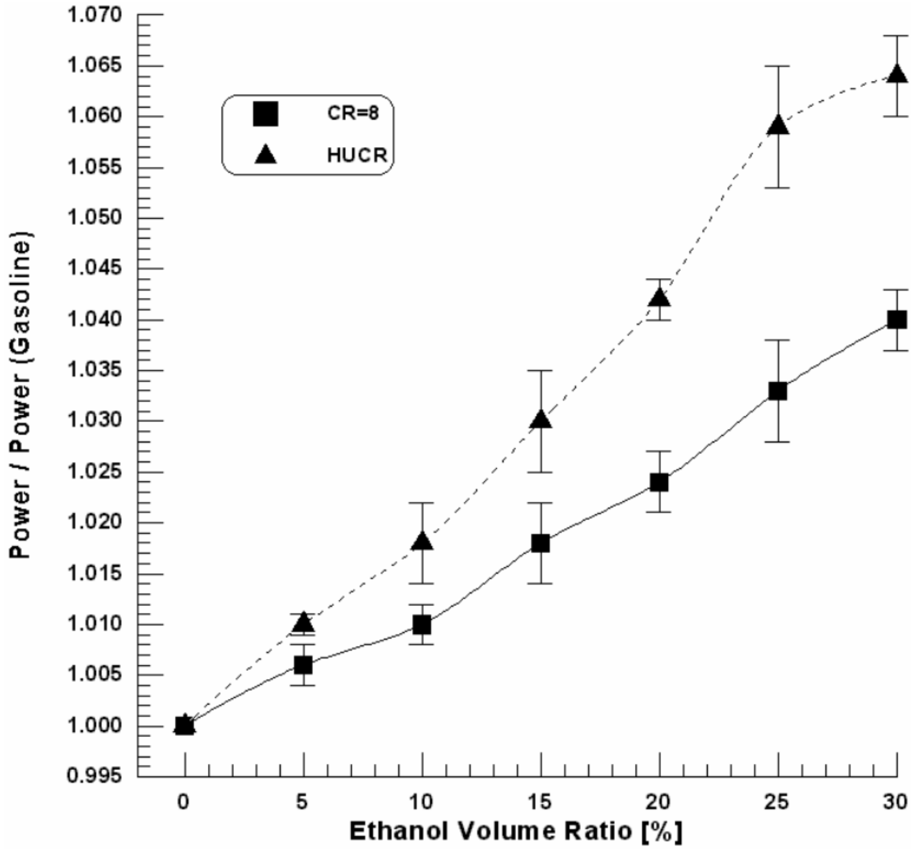

Fig.6. Effect of ethanol blending on the brake power of the Ricardo E6 SI engine.

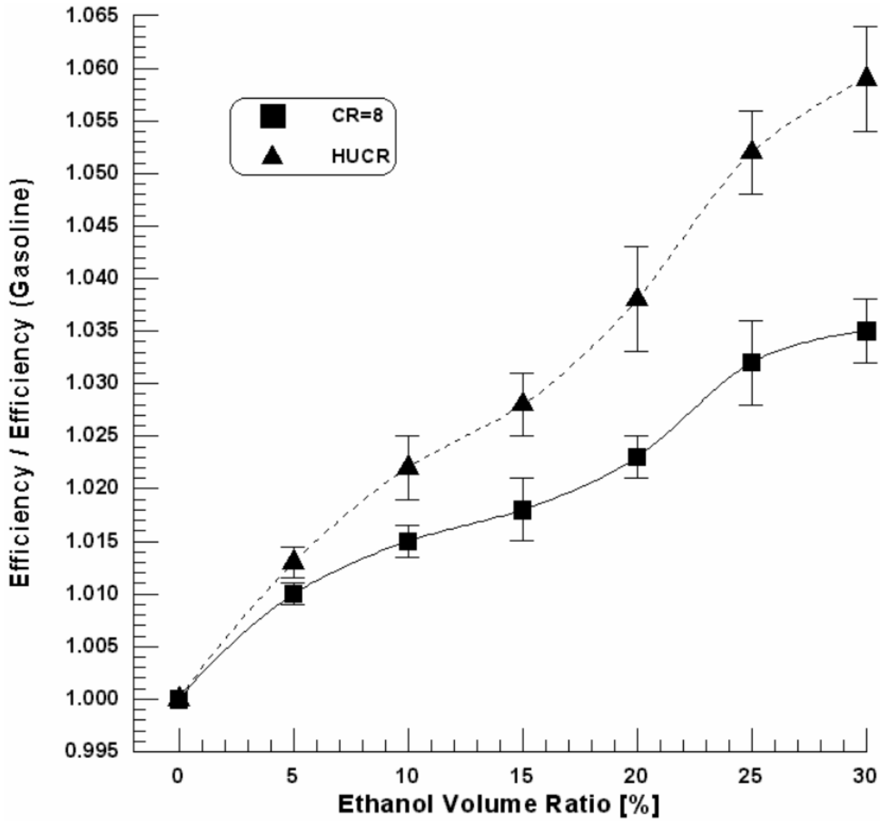

Fig.7. Effect of ethanol blending on the brake thermal efficiency of the Ricardo E6 SI engine.

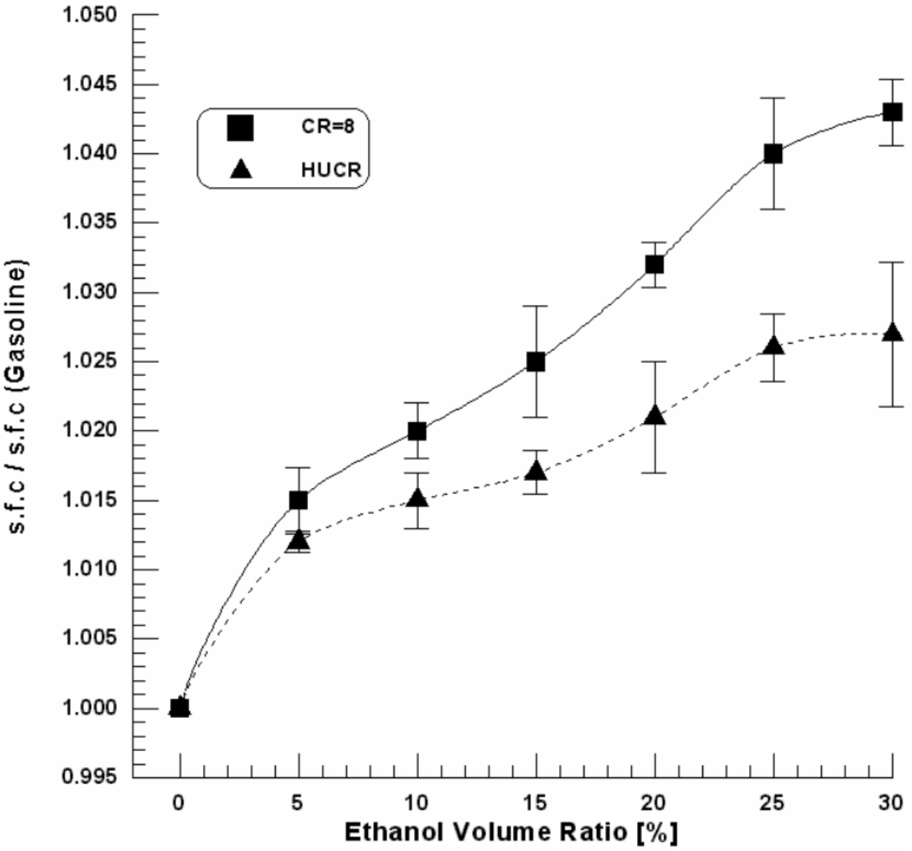

Fig.8. Effect of ethanol blending on the brake specific fuel consumption of the Ricardo E6 SI engine.

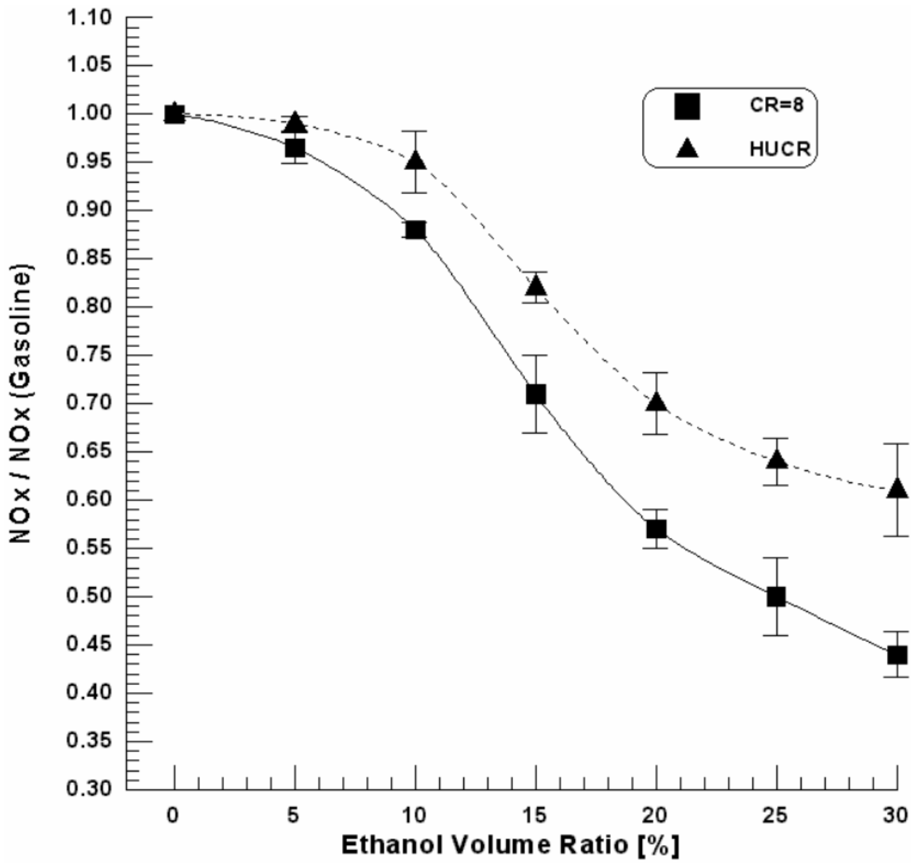

Fig.9. Effect of ethanol blending on the NOx of the Ricardo E6 SI engine.

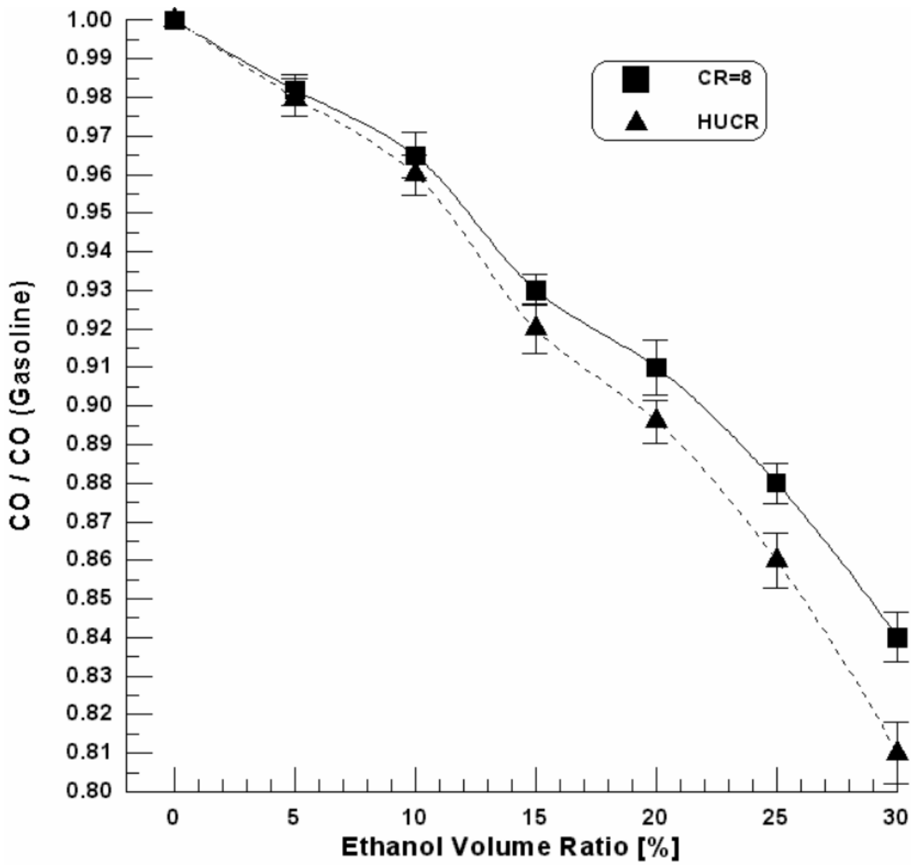


Fig.10. Effect of ethanol blending on the CO of the Ricardo E6 SI engine.

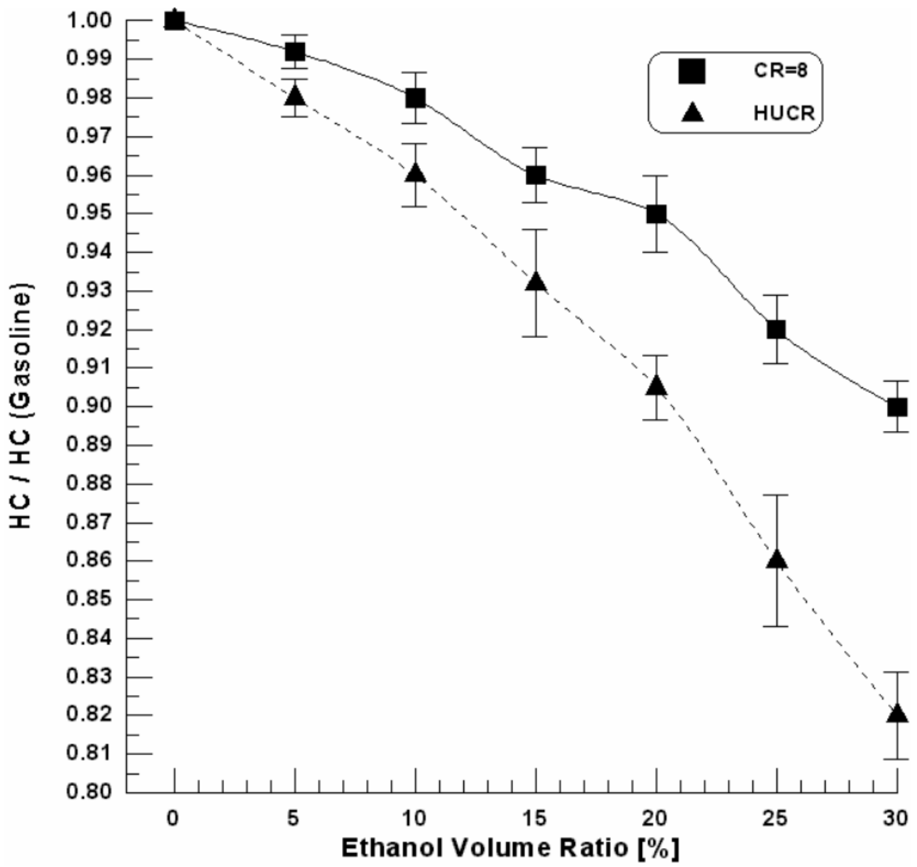


Fig.11. Effect of ethanol blending on the HC of the Ricardo E6 SI engine.