STUDY OF PERFORMANCE OF S.I.E. FUELED WITH SUPPLEMENTARY HYDROGEN TO GASOLINE

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ABSTRACT

This paper includes study of performance of single cylinder, 4-stroke spark ignition engine Ricardo E6, with variable compression ratio, spark timing and equivalence ratio, fueled with supplementary hydrogen to gasoline.

The speed of 25 rps and higher useful compression ratio were chosen in studying the effect of wide range of equivalence ratios and spark timing.

The results showed that HUCR for mixture of two fuels was (9:1). The brake power when operated with gasoline was higher than when it was fueled with hydrogen alone, but when mixing two fuels the brake power increased and became higher than that when working with gasoline to a certain limit (the hydrogen volumetric ratio in the mixture reached 80%), after this limit the brake power reduced by increasing hydrogen volumetric ratio.

The equivalence ratio at which the brake power reach its highest value was between (Ø=1-1.1) when mixing the two fuels. The results showed that the engine can work with very lean equivalence ratios with supplementary hydrogen, the indicated thermal efficiency increased also, and the brake specific fuel consumption reduced when hydrogen volumetric ratio increased.

الخلاصة

تضمن هذا البحث دراسة أداء محرك أحادي الاسطوانة رباعي الأشواط يعمل بالشرارة، نوع (Ricardo E6)، ذي نسبة انضغاط وتوقيت شرر ونسبة مكافئة متغيرة عند عمله بإضافة الهيدروجين للجازولين.

تركزت الدراسة على بحث تأثير متغيرات رئيسية في أداء المحرك، وهي نسبة الانضغاط والنسبة المكافئة وتوقيت الشرر والسرعة، أظهرت النتائج أن نسبة الانضغاط النافعة العليا لخليط من الوقودين هي (9 :1)، وان القدرة المكبحية كانت تزداد بزيادة نسبة الانضغاط، كما ان القدرة المكبحية في حالة الجازولين تزيد عن تلك الناتجة باستخدام الهيدروجين، ولكن عند خلط الوقودين تزداد القدرة المكبحية عن حالة استخدام الجازولين الى حد معين، (نسبة الهيدروجين الحجمية في الخليط 80%) بعدها تقل بزيادة هذه النسبة.

وان النسبة المكافئة التي تم الحصول عندها على أعلى قدرة مكبحية تتراوح بين (Ø=1.0-1.1) عند خلط الوقودين، كما بينت الدراسة ان المحرك يمكن أن يعمل عند نسب مكافئة ضعيفة جدا" بإضافة الهيدروجين،

كما ان الكفاءة الحرارية البيانية تزداد بهذه الإضافة، ويقل معدل الاستهلاك النوعي المكبحي للوقود بزيــادة النسبة الحجمية للهيدروجين المضاف.

KEY WORDS
Hydrogen, gasoline, equivalence ratio, compression ratio, spark timing, speed, brake power, specific fuel consumption, indicated thermal efficiency, exhuast gas temperature.

INTRODUCTION

There is no room for doubt that the world's convenantiol source of fossil fuel are being exhuasted at an alarming rate. The transportation sector is one of the most important areas which has been badly hit by the energy crisis, which is basicaly a fuel crisis. It is certain that the demand of indeividual transport will continue to grow despite the decline in petroleum production, because autimobiles have become an integral part of the present day life style. With the growing use of the individual transporttion system, the need for spark ignition engine is rapidly growing.

Internal combustion engines provide 85% of the energy needed by mankind, and it is supposed that in populated areas their shear of air pollution reaches up to 70%. It is supposed that for a period of 60 – 80 years thay will remain the basic converter of heat energy from the combustion of fuels in mechanical work **(Mathur and Das, 1991)**.

Compared to the fuels now in use or under considration, for future application, hydrogen offers many advantages. Its use in spark ignition engine will not only eliminate the present day proplem of dependence on petrolium fuel, but it will also reduce vehicular pollution as hydrogen is a clean burning fuel. It offers the unique advantage of being a fuel, the basic resourse of which is recycable in a short time cycle by completely normal means. It starts with the molecule of water being split and upon combustion produces water vapour as the prencipal exhuast. Water is available in plenty every where. So, looking at the future, hydrogen has a practically unlimited supply potential **(Chaichan, 1989).**

As a fuel gas, hydrogen possesses significant invironmantal advantages that compensate for preliminary reservation as asociated with the controversial issue of unproven safety. In comparission with natural gas, hydrogen possesses a higher burning velocity, greater flash back tendency, lower relative density, wider limits of flammability and lower ignition energies, selected combustion characteristics are reported in **Table (1) (Petkov and Parazev, 1987).**

There is general agreement that the hydrogen enrichment concept permets very lean combustion of hydrocarbon fuels with attendant increase in engine efficiency and reduction of engine emissions. It is an opportunity to achieve now adays standards of toxic components content in the exhaust gases of automobile engines, considerably lowering gasoline consumption.

Another advantage of this method is that it requires a smaller quantity of hydrogen to be fed to the engine which considerably lessens the problems connected with hydrogen storage in the automobile **(Frances, 1981).**

It has been well established that burning lean mixtures results in improved fuel economy and higher engine thermal efficiency. Moreover, the lean operation of gasoline fueled spark ignition engines can result in the reduction of exhaust emissions without the addition of emission control devices **(Hoen and Dowdy, 1973).**

Recently much attention has been focussed on the use of hydrogen as a supplementary fuel, to extend the engine operation in range to equivalence ratios beyound the lean operating limit of gasoline, as hydrogen exhibits a significantly lower flammability limit (around 0.1 equivalence ratio). Comparasion with other hydrocarbon fuels (around 0.6 equivalence ratio). However, no conventional engine system has been developed that can operate with gasoline at equivalence ratios leaner than 0.85 or so, while the lean limit of gasoline- air combustion is about 0.6. There are several reasons for this but perhaps the two most important are non-homogenity of the mixture and poor cylinder to cylinder distribution **(Hoen and Baisly, 1973).**

The presence of hydrogen during the ignition and initial phases of the combustion process provides a source of enthalpy release and active species of equivalence ratio where gasoline fuel alone isn't readily reacted and for these reasons hydrogen is the prime candidate for gasoline supplementation to obtain ultralean burning. **Table (2) (Bansal and Mathur, 1980)** shows a comparison of flammability limit of hydrogen with other commenly used hydrocarbon fuels.

EXPERIMANTAL TECHNIQUE

Experiments were conducted on single cylinder, variable compression ratio Ricardo E6/US engine, to assess the effect of hydrogen supplemintation on the operation of SIE.

Tests were also conducted to determine the engine output and fuel economy with gasoline and with various degrees of hydrogen supplementation. Mixture equivalence ratios were varid over a wide range while hydrogen volumatric fraction (defined as the ratio of the hydrogen volume to the total volume of hydrogen and gasoline used, that's mean HVF= $V_{H2}/V_{H2}+V_{gasoline}$) varid from 20% to 100% hydrogen. HUCR and OST were used in studing wide range of equivalence ratios. All tests were carried out at wide open throttle and at engine speed 25 rps, except those for studying speed effect. In all experiments bottled hydrogen was used as a supplemantary fuel.

DISCUSSION

Compression ratio effect

Supplimentation of different volume fracters was studied, the different fractions were used to know which percentage was the best one to mix the two fuels, the CR was studied also to assess the HUCR. The experiments was started at CR= 6:1 untill CR=9.5:1.

Fig. (1) shows the relation between the brake power and equivalence ratio $[(A/F)_{stoichiometric}/(A/F)_{actual}]$ for different mixing volume fractions from 0 to 100% hydrogen at HUCR for each fuel, OST and 25 rps speed.

The experiment showed that brake power increased with HVF increase from 0 to 80% for compression ratios (6,7,8,8.5,9), and for volumatric fraction (0-60%) at CR=9.5, this increase in brake power was expected because hydrogen presence in combustion chamber gives significant improvment in energy release.

Also, it increase burning rate and gives better and more complete combustion. The brake power was reduced when HVR was increased above 80%, that's because a higher fraction of gasoline-air mixture was replaced with hydrogen that caused decreasing in combustion energy released, where hydrogen energy on volume basis is less than the gasoline heating value. This is obvious when hydrogen was used alone, it gave brake power less than that produced when using gasoline alone, as appear from the figure. The mixture behaviour at CR=9.5 was different from other compression ratios, because at this CR the combustion was rough and severe knock happened with increased load.

Fiq. (2) distincts realation between HVF and the highest brake power of the engine at different compression ratio in the experments done. **Fig.2** shows that HUCR for mixtures of hydrogen and gasoline is 9 while it was 8 only for gasoline-air mixture. The highest brake power happened at 80% mixture rate.

Fig. (3) shows the effect of different mixture rates and the studied CR on OST.

It appeared that ther OST retarted with HVF and compression ratio increase. This is because of high hydrogen burning velocity in comparable with gasoline, also burning velocity increase with CR increase, because the mixture temperature increased in combustion chamber.

Equivalencr ratio effect

From **Fig.1** the highest brake power when gasoline was used alone was at Ø=1.1, with hydrogen supplemintation it was approach to Ø=1.0. The hydrogen addition effect was bigger in the lean side, where the flammability limit for gasoline was at Ø=0.79 but with hydrogen addition it reached Ø=0.34 .

Fig. (4) shows the relation between brake power and HVR in mixture for five equivalence ratios at OST and 25 rps engine speed and HUCR for each fuel.

The figure shows that the brake power increased at Ø= 0.7 when HVF was increased from 0 to 80 is very large, the brake power was increased about 300 % compared with gasoline alone, the same thing can be said about Ø=0.8, where the brake power increased about 40%, this is because of three facters: precence of enough oxygen for reaction, precence of hydrogen which improves the combustion, and increase its burning velocity, and the precence of high heating value of gasoline.

The effect of addition of hydrogen at richer equivalence ratio is limited, because the intering air quantity decreased, while the intering hydrogen-gasoline mixtue removed developed volume from air. This is obvious at Ø=1.0, where brake power increased with 10% , also, at Ø=1.1 the increase was about 3.5%.

From the above it is appeared that hydrogen supplementation improves engine brake power for lean equivalence ratios in great manner.

The relation between equivalence ratio and OST is shown in **fig. (5)** for different mixing rates, at HUCR and 25 rps, where **fig. (6)** shows the effect of HVF on OST for difined equivalence ratios.

The OST retarted with hydrogen addition for all equivalence ratios, it was about 20 degree BTDC with 80% volume hydrogen , at stochiometric equivalence ratio about 10 degrees BTDC.

The effect of HVF addition to gasoline on bsfc was studied in **fig. (7)** for wide range of equivalence ratios at HUCR, 25 rps and OST.

From the figure, the bsfc decreased to a concedarable extent, especiely for lean equvilence ratios with hydrogen supplemintation, for example, at Ø=0.7 with HVF=80%, bsfc reduction was about 67%, and at Ø=1.0 for the same HVF the reduction was 17%.

Fig. (8) shows the effect of hydrogen addition on indicated thermal efficiencyat HUCR and OST, for three chosen HV fractions.

The indicated thermal efficiency increased highly with hydrogen supplementation at lean side to reach its highest value at this side, then it decreased quickly with mixture enrichment, the rise of indicated thermal efficiency in the lean side presents important and obvious improvement in combustion at this side with hydrogen adittion. The high reduction in indicated thermal efficiency at rich equivalence ratios after it reached its highest value is because of combustion difficulties in this side, so, the hydrogen supplementation in the rich side didn’t improve the combustion nor the indicated thermal efficiency.

The highest value of indicated thermal efficiency was at lean equivalence ratios, this ratio decreased with hydrogen addition to gasoline-air mixture, as an example, the highest indicated thermal efficiency was at Ø= 0.9 when using gasoline, then it became at equivalence ratios (Ø= 0.83,0.8,0.77) for supplying ratios (HVF=0.3,0.6,0.8) respectively, also, when using hydrogen it was at Ø=0.4.

Fig. (9) indicates the relation between exhuast gas temperatures and equivalence ratio, when adding different hydrogen volumatric fractions (HVF=0.3,06,0.8), engine was operated at HUCR and 25rps.

Hydrogen supplimantation decreases exhaust gas temperature for all equivalence ratios, and we got the minimum exhust gas for the whole range of equivalence ratios temperature when hydrogen was used. This was explained by (Al-Alousi, 1982), that the hydrogen heating value on volume basis is low, so it cuases this reduction in temperature, also it can be explained in another way, where the burning velocity for hydrogen is fast, and the mixture combusted in very high speed, especialy when engine operated at OST, so when expansion stroke takes place the whole mixture will be burned and became combusted gases, and it will be cooled in this stroke, and when exhuast valve opened these gases will get out cooler than any hydrocarbon fuels may be used, also the heat transfer from cylinder wall increased because of the reduction of unburned gases in the inner film thickness, which are near the cylinder walls as sugested by (Chaichan, 1989).

SPEED EFFECT

Fig. (10) represents the relation between the highest engine brake power and HVF in mixture, to obtain different speed effects at HUCR and OST.

It is appeared that the effect of engine speed is invariable when using any fuel alone. The brake power increased with speed increase, for all experiment speeds, although the increase rate is different this increase was too large when engine speed accelerate from low to meduim speeds, then this rate lessened when engine run from meduim to high speeds. This is because of the inlarged friction power with engine speed.

Fig. (11) shows the effect of supplementary hydrogen on OST when the engine run at different speeds. Hydrogen supplementation caused retarding OST about 20 degrees BTDC, for all experiment speeds. Also, the speed increase cuased advancing of OST, as it is familiar when working with any fuel alone, and the optimum spark timing at any speed and equivalence ratio is the resultant of these two parameters.

SPARK TIMING EFFECT

Figs. (12 to 14) represent the relation between engine brake power and equivalence ratio for three different spark timings (10,15,20) degree BTDC, with hydrogen addition to gasoline in three different volumatric percentage (HVF=.3,.6,.8), the engine operated at HUCR and 25 rps.

Spark timing 10 degrees BTDC is very late for gasoline as appears from **Fig. (12)**, where engine brake power went down, but with hydrogen supplementation the brake power became larger in very obvious manner, especiely for equivalence ratios from Ø=0.7 to Ø=1.1, where this timing is neer the OST.

Spark timing 15 degrees BTDC is a better timing for gasoline, so the brake power increased for all equivalence ratios as appears in **Fiq. (13)**, also brake power increased clearly with hydrogen added to mixturs at 30% volumatric fraction for equivalence ratios from Ø=0.7 to Ø=1.3. The brake power increased also with hydrogen supplied to system at 60% by volume, but a smaller increase for the same equivalence ratios mitioned above, that is because the timing is advanced compared with OST for these equivalence ratios, but when hydrogen was supplied to system in 80% volume, the brake power increased in lean side, and decreased for equivalence ratios between (Ø=0.75-1.3), and the curves take another figures. This was expected because this timing is highly advanced timing from OST for these equivalence ratois.

Brake power figures take another style from their relatives in **Fig. (14)**. Gasoline brake power became better, that's because the timing (20 degrees BTDC) close to OST, and the equivalence ratios which gave the highest brake power were between Ø=1.0-1.15. Brake power decreased with hydrogen addition in 30, 60% by volume for range of (Ø=0.85-1.35), and engine operation was not available for HVF=80, at this fraction and for this spark timing, because it considerd very advanced from OST for these equivalence ratios, so it caused reduction in brake power for HVF= 0.3-0.6, and caused the phenomenant of the high pressure rate before top dead centre to occur, which cause negative work on engine.

CONCLUSIONS

1-The HUCR for a mixture of gasoline and hydrogen is 9:1.

2-The OST retards with hydrogen supplementation for all equivalence ratios.

3-The OST retards with CR increase for all kind of fuels.

4-The OST advanced with speed increase for all kinds of fuels.

5-With hydrogen supplied in volumatric fractions to gasoline-air mixture the brake power increased to extend limit (HVF=80%) then it started to fall down if HVF continue increasing above this percentage.
6-With hydrogen supplementation engine can operate with very lean equivalence ratios, can't be reached with gsoline operation.
7-Indicated thermal efficiency increased with hydrogen supplementation, it's highest value when using hydrogen alone, at very lean equivalence ratio.
8-Exhaust gas temperature reduced with hydrogen supplementation.
9-Brake specific fuel consumption reduced with hydrogen supplimantation to gasoline.

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NOMENCLATURE

TDC	top dead centre
BDC	bottom dead centre
BMEP	brake mean effictive pressure
BSFC	brake specific fuel consumption
BTE	brake thermal efficiency
CA	crank angle
CR	compression ratio
HUCR	higher usful compression ratio
OST	optimum spark timing
SIE	spark ignition engine

Table (1)
Combustion characteristics for gasous hydrogen

Ignition energies (at 1 atm and 298 K)	
$E_{\text{min at stoicheometric}}$	0.019MJ
Critical E_{min}	0.0185MJ
Auto-ignition temperature (at 1 atm and room temperature)	847-864 K
Quinching distance (at 1 atm and 298K)	
Critical port at stoichiometric	0.64mm
Slotted point at stoichiometric	0.81mm
Limit of flammability (at 1 atm and 298K)	
Lower limit	4.0%
Upper limit in air	75.0%
Upper limit in oxygen	94.0%
Limit of detonability (at 1 atm and room temperature)	
In air	18.3-59.0%
In oxygen	15.0-90.0%
Detonation velocity (at 1 atm and 291K)	
In air	2055 m/s
In oxygen	2819 m/s
Maximum flame temperature (at 1 atm and room temp)	
In air	2318 K
In oxygen	2933 K

Table (2)
Lean flammability limits for gases and vapors in air

Compound	formula	Lean flammibality limit	
		Vol%	Ø
Paraffins			
Methane	CH_4	5.3	0.53
Propane	C_3H_8	2.2	0.54
Pentane	C_5H_{12}	1.5	0.58
octane	C_8H_{18}	1.0	0.60
Aromatics			
Benzene	C_6H_6	1.4	0.51
Alcohols			
Meathanol	CH_3OH	7.3	0.56
Inorganic			
$CO+H_2O$ vapor at 18°C	$CO+H_2O$	12.5	0.54
Hydrogen	H_2	4.0	0.10
Indoline 30 gasoline	$C_7H_{13.02}$		0.57

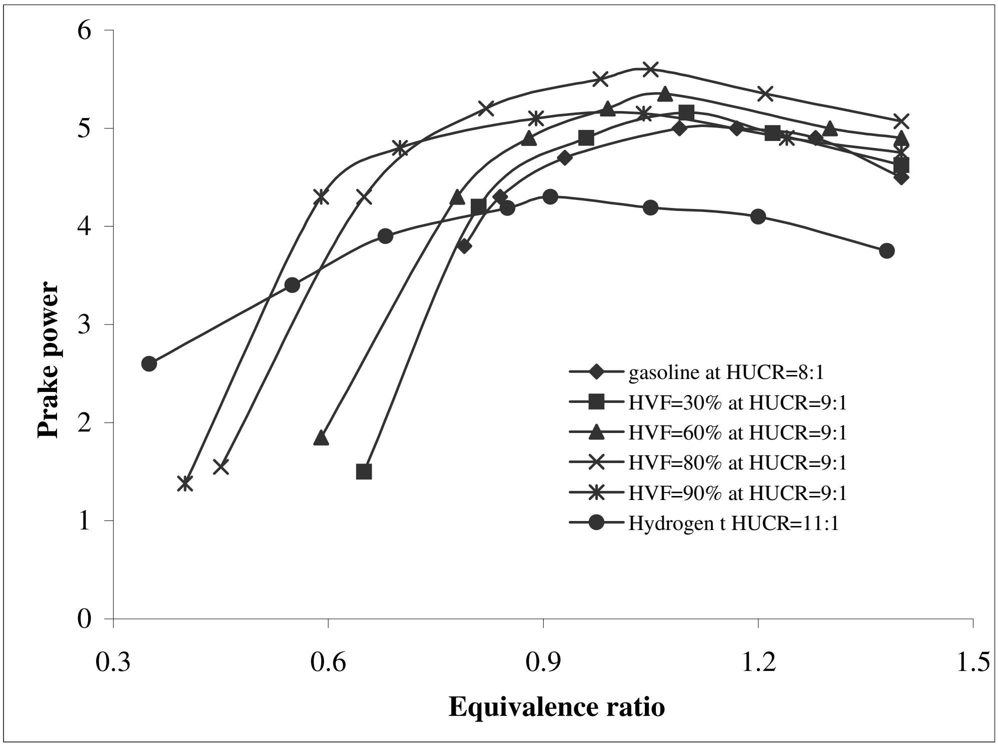


Fig. (1). The relation between the brake power and equivalence ratio for different mixing volume fractions from 0 to 100% hydrogen at OST and 25 rps speed

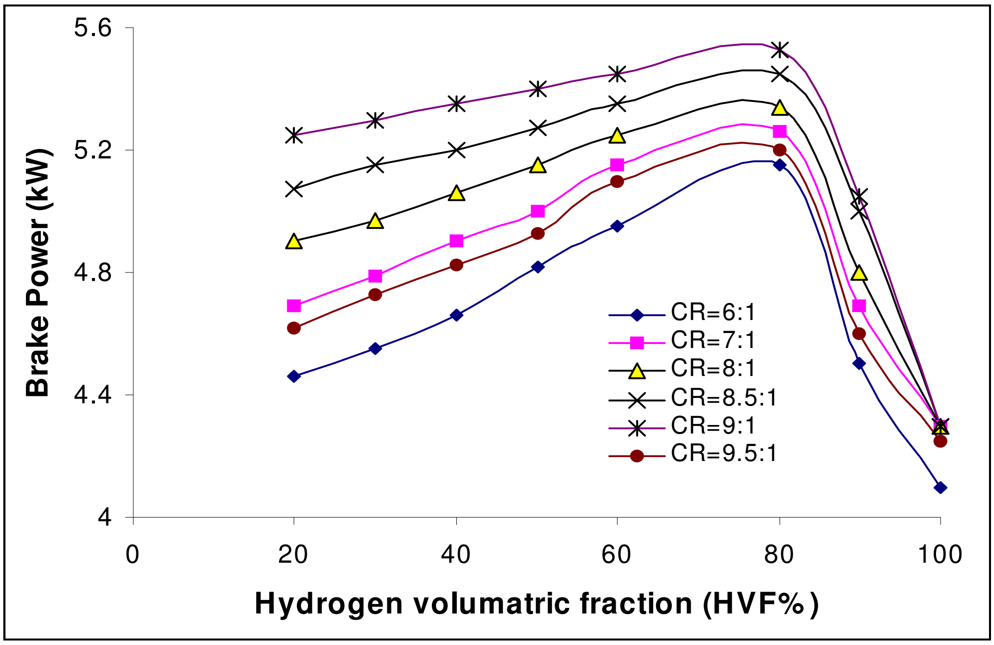


Fig. (2). The realation between HVF and the highest brake power of the engine at every compression ratio in the experments done

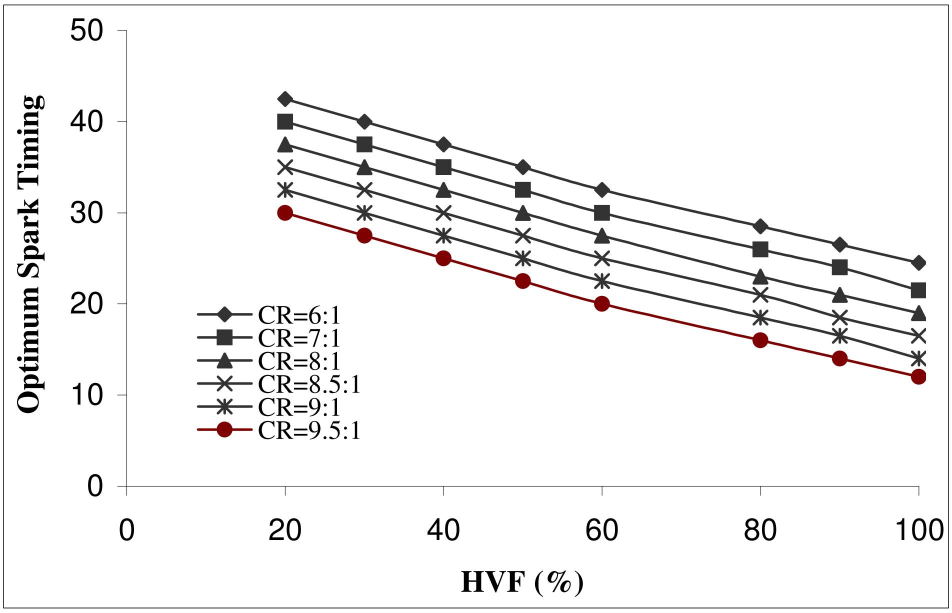
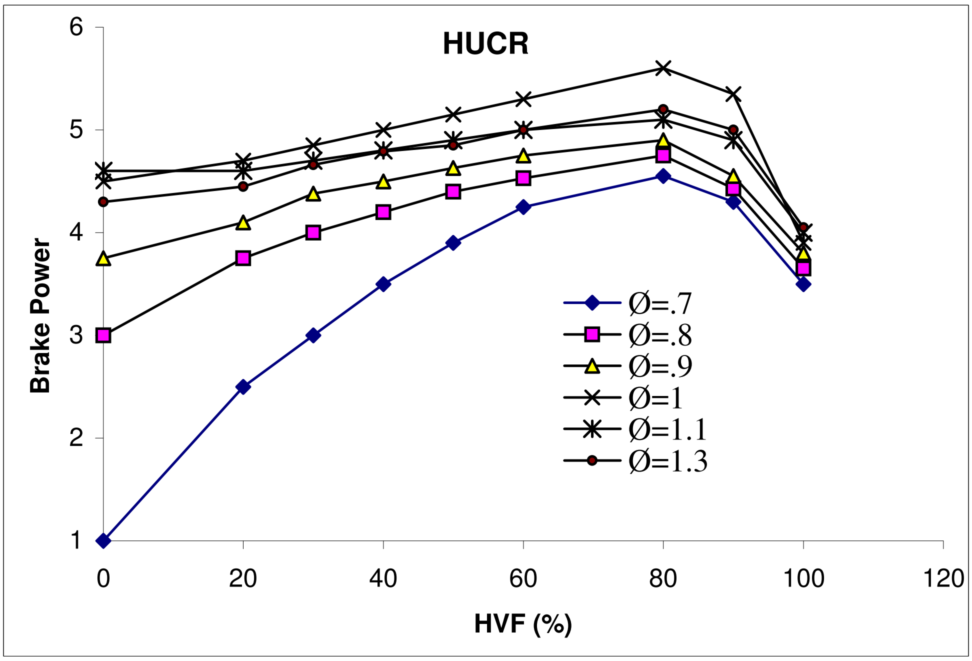


Fig. (3).The effect of different mixture rates and the satudied CR on OST



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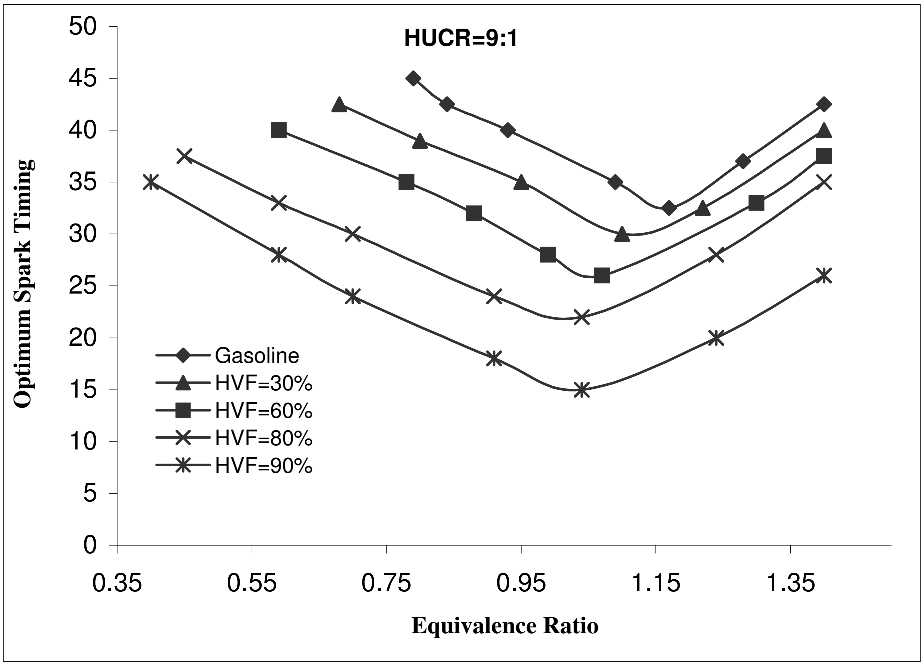

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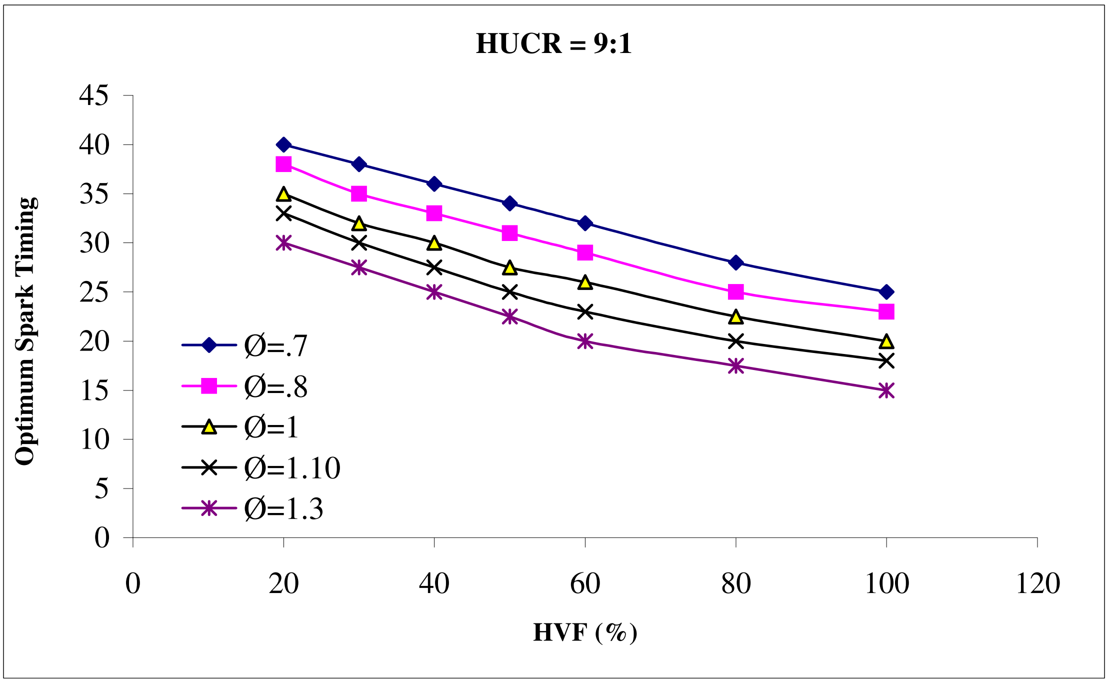


Fig. (6). The effect of HVF on OST for difined equivalence ratios

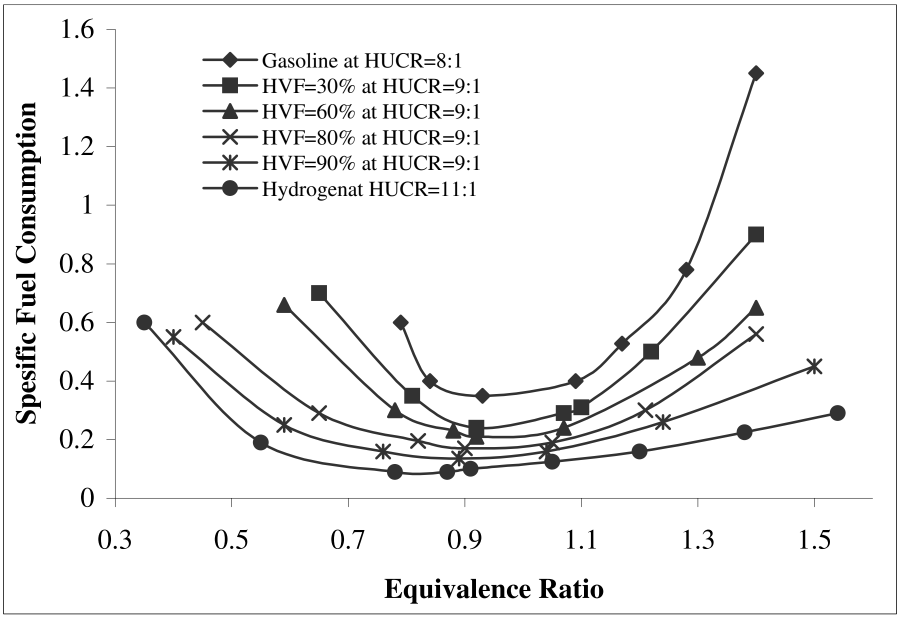
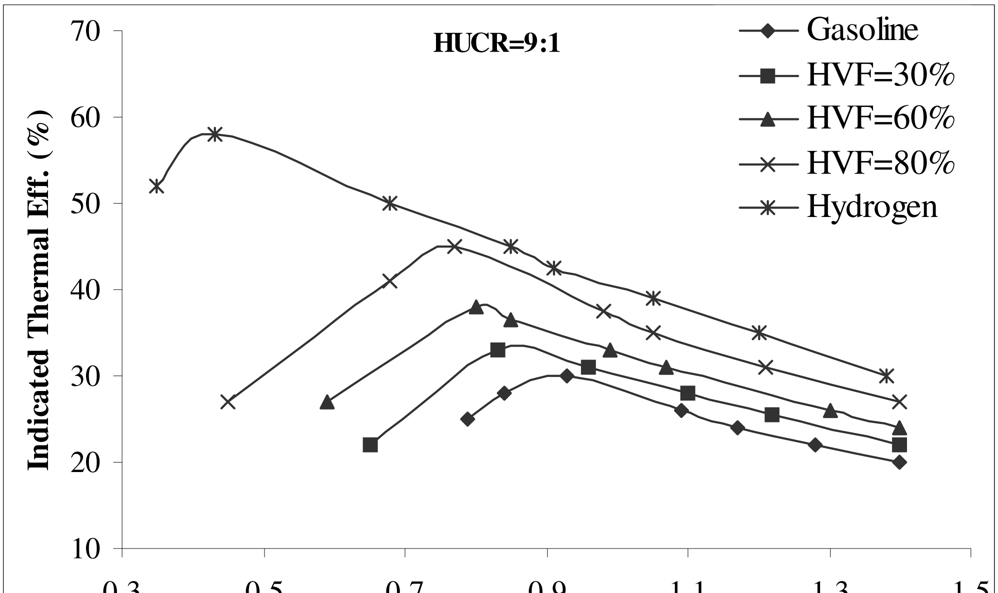


Fig. (7). The effect of HVF addition to gasoline on bsfc was studied for wide range of equivalence ratios at HUCR, 25 rps and OST



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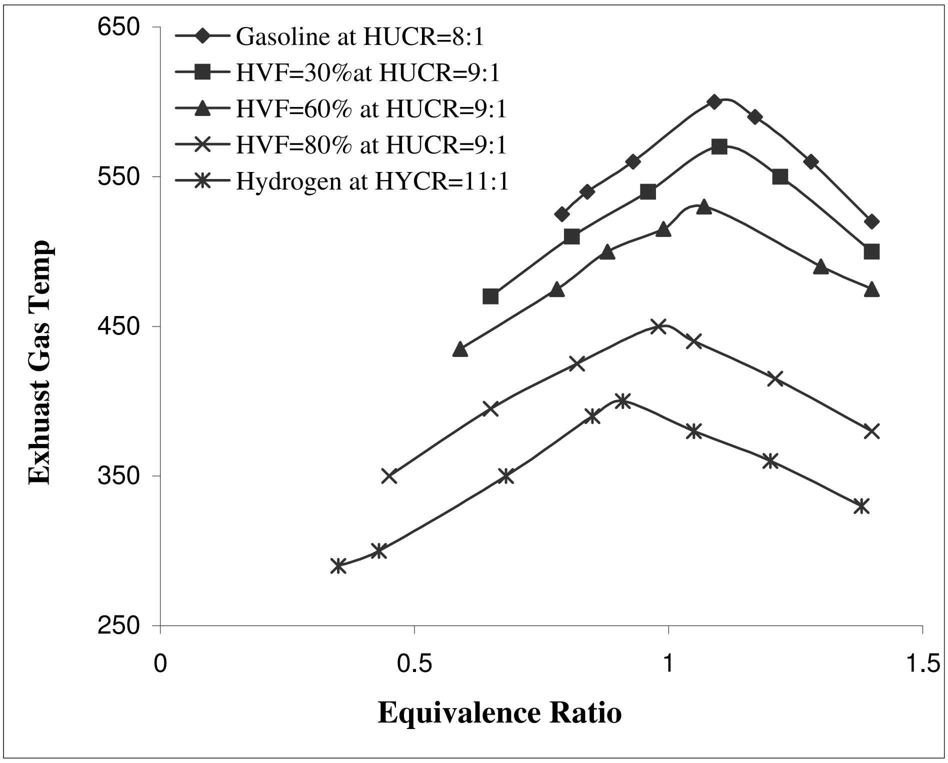

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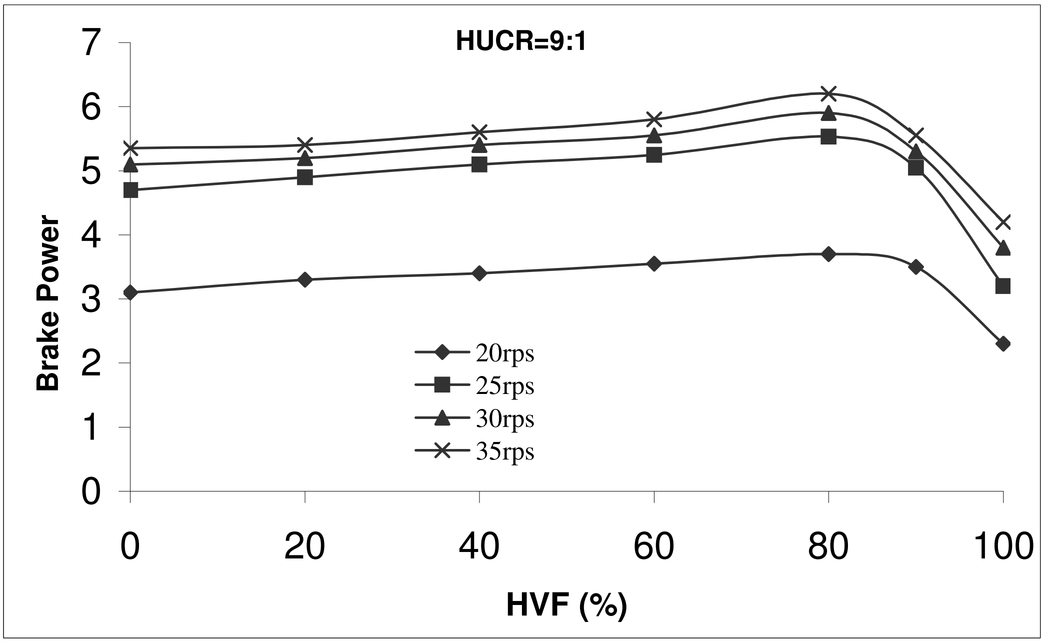

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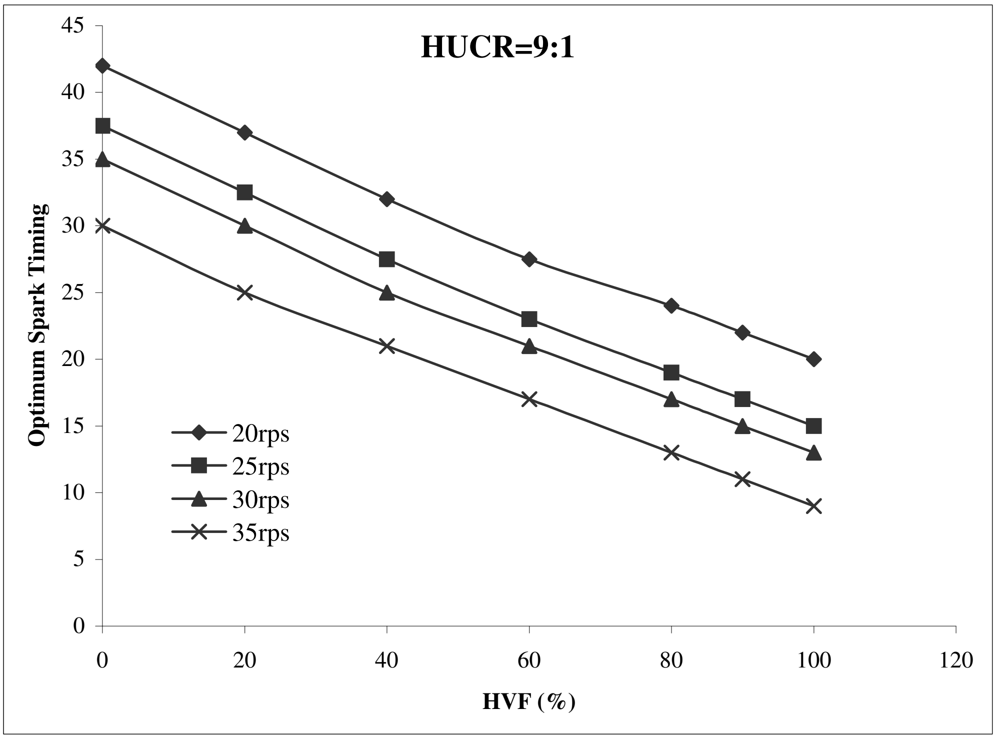

Fig. (11). The effect of supplementary hydrogen on OST, when the engine run at different speeds

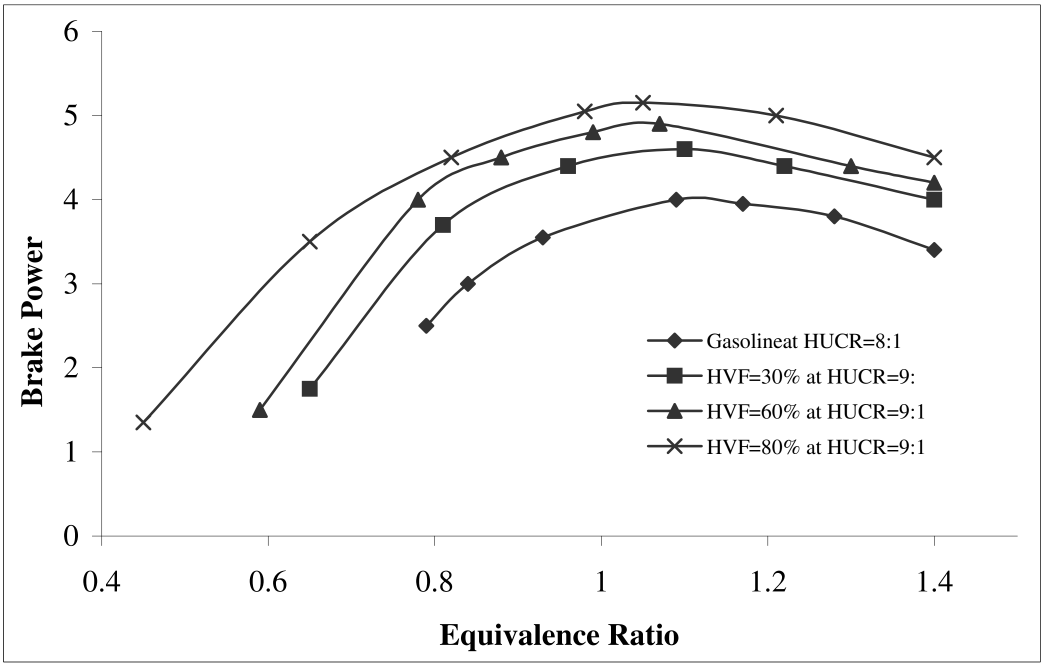

Fig. (12). The relation between engine brake power and equivalence ratio for spark timing 10 degrees BTDC

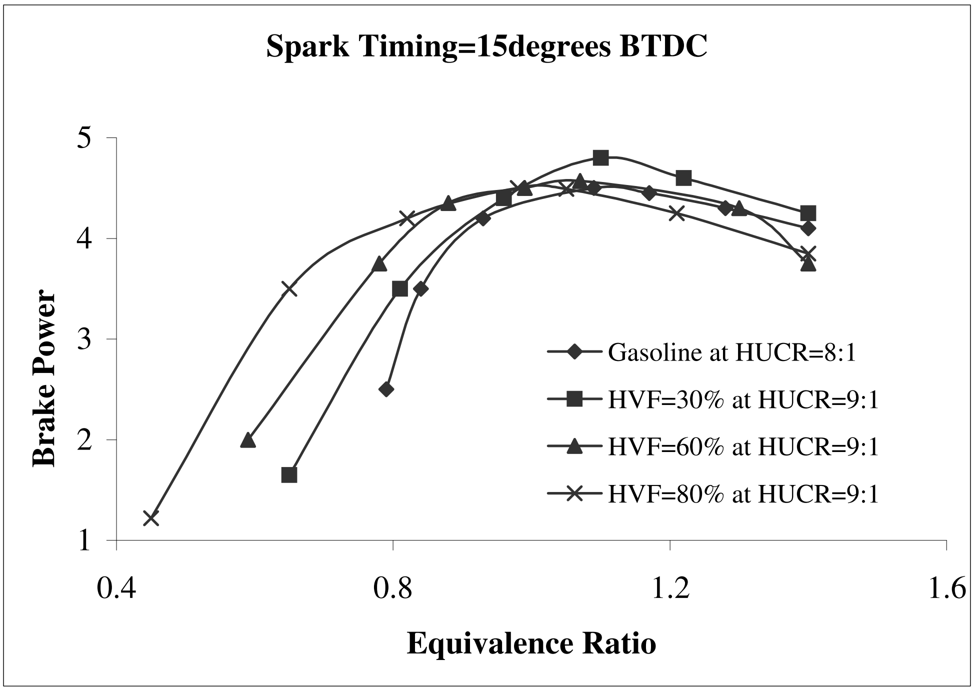

Fig. (13). The relation between engine brake power and equivalence ratio for spark timing 15 degrees BTDC

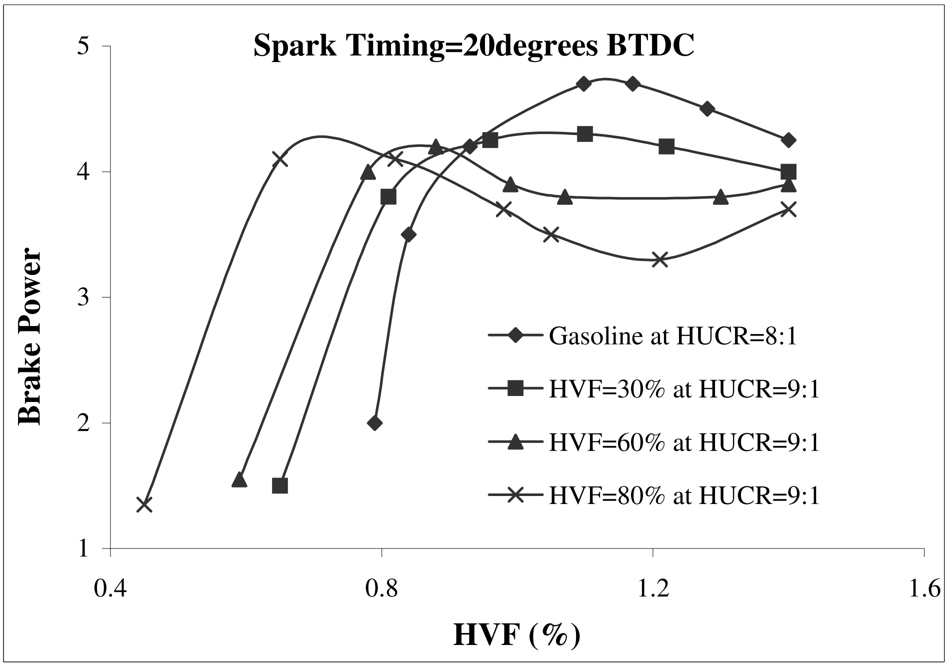

Fig. (14), The relation between engine brake power and equivalence ratio for spark timing 20 degrees BTDC