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Practical investigation of single cylinder spark ignition engine performance operated with various hydrocarbon fuels and hydrogen

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Abstract

Hydrogen, natural gas and liquefied petroleum gas are the most important alternative fuels for gasoline in spark ignition engines, for many reasons, such as: large world reserve of these gases, high heating value, high octane number, low emissions emitted from burning them in engines, and their low prices compared with gasoline. This practical study conducted with these fuels to operate single cylinder with variable compression ratio, speed and spark timing Ricardo E6/US, and its performance was compared with that resulted from operating the engine with gasoline. The results appeared that the HUCR (higher useful compression ratio) for gasoline is 8:1, 10.5:1 for LPG, 13:1 for natural gas and 11:1 for hydrogen. Results appeared that spark timing is highly advanced when using NG more than other used fuels, because of its low flame speed propagation, in other hand it is highly retarded when using hydrogen, because of its high flame propagation speed. The study conducted that brake power of LPG and NG are less than that for gasoline at CR=8:1, but they became closer when the engine operated at HUCR for each fuel, while it stayed very little for hydrogen due to its low heating value on volume basis. The results show that specific fuel consumption for hydrogen is less than bsfc for NG, which is less than that for LPG; gasoline has the higher bsfc on mass basis. Also, the exhaust gas temperature for hydrogen and NG is found to be less than LPG, and it is for LPG less than that for gasoline.

الخلاصـــــــة

يعد الغاز النفطي المسال والغاز الطبيعي والهيدروجين من أهم بدائل الجازولين في محركات الاشتعال بالشرارة، لعدة أسباب منها: الاحتياطي الكبير لهم في العالم، القيمة الحرارية العالية، ارتفاع الرقم الاوكتاني، انخفاض الملوثات المنبعثة من إحراقهم وأسعارها المنخفضة مقارنة بالجازولين. تمت الدراسة العملية باستخدام هذة الأنواع من الوقود لتشغيل محرك احتراق داخلي أحادي الاسطوانة يعمل بالشرارة نوع ريكاردو، ومقارنة أداء المحرك الناتج بأدائه عند استخدام الجازولين. أظهرت النتائج أن نسبة الانضغاط النافعة العليا للجازولين هي 8:1، وللغاز النفطي المسال 10.5:1، وللغاز الطبيعي 13:1، وللهيدروجين 11:1، كما بينت النتائج أن التوقيت الأمثل للشرر متقدم باستخدام الغاز الطبيعي مقارنة بالأنواع الاخرى من الوقود، بسبب سرعة انتشار اللهب البطيئة للغاز الطبيعي، كما أن التوقيت الأمثل للشرر يتأخر عند استخدام الهيدروجين، مقارنة بالانواع الاخرى من الوقود بسبب سرعة انتشار لهبة العالية. بينت الدراسة أن القدرة المكبحية للبدائل الثلاثة عند نسبة انضغاط 8:1 تكون أقل من مثيلاتها باستخدام الجازولين، ولكن تتقارب القدرة المكبحية الناتجة عن الغاز النفطي المسال والغاز الطبيعي عند عمل المحرك بنسبة الانضغاط النافعة العليا، ويبقى الهيدروجين أقل منهما بسبب انخفاض قيمتة الحرارية على أساس الحجم، كما أن الاستهلاك النوعي المكبحي للهيدروجين أقل من الغاز الطبيعي، والذي بدورة أقل من الغاز النفطي المسال، ويكون أعلى قيمة للجازولين محسوبا على أساس الكتلة، كما تقل درجات حرارة الغاز العادم للهيدروجين وللغاز الطبيعي عنها للغاز النفطي المسال، والتي بدورها أقل من تلك الناتجة باستخدام الجازولين.

Nomenclature

BDC	bottom dead centre
BMEP	brake mean effective pressure
BSFC	brake specific fuel consumption
BTE	brake thermal efficiency
CA	crank angle
CR	compression ratio
HUCR	higher useful compression ratio
LPG	liquefied petroleum gas
OST	optimum spark timing
NG	natural gas
TDC	top dead centre
SIE	spark ignition engine

Introduction

Enormous progress has been made in the past 40 years in reducing vehicle emissions all around the world. Emission control technology has progressed from rudimentary engine controls to sophisticated computer-controlled catalyst systems. Another major factor in reducing emissions, whose contribution is not as well known as that of the hardware, is the fuel [1].

When most drivers think about gasoline, it is to remember to fill up and maybe to check the price. Because gasoline almost always performs well, drivers forget what a sophisticated product it is. More thought would reveal a demanding set of performance expectations:

- An engine that starts easily when cold, warms up rapidly, and runs smoothly under all conditions.
- An engine that delivers adequate power without knocking.
- A vehicle that provides good fuel economy and generates low emissions [2].
- Gasoline that does not add to engine deposits or contaminate or corrode the fuel system [3].

Although proper vehicle design and maintenance are necessary, gasoline plays an important role in meeting these expectations.

The recent crude oil price spikes signal an apparent end of the era of cheap crude oil. Other alternatives are needed. One option is LPG, which is a by-product of both petroleum refining and natural gas processing plants. Approximately 60 percent of the LPG produced in North America comes from natural gas processing. Processing removes most of the ethane and heavier HCs as well as carbon dioxide, which may exist in the gas at the wellhead, to produce a pipeline gas with a relatively consistent heating value.

LPG is formulated to consist mainly of propane with minor amounts of propylene, butane, and other light HCs [4]. LPG is gaseous at room temperature and atmospheric pressure, but it liquefies at pressures greater than 120 psig.

This property makes it convenient to store and transport LPG as a pressurized liquid. The stored liquid fuel is easily vaporized into a gas with clean-burning combustion properties similar to those of CNG [5].

LPG and natural gas are often quite similar; the major difference is that the CNG system must be calibrated for a higher volumetric fuel flow rate at a given load [6].

Automotive fuel-grade CNG has a substantially higher octane rating than automotive LPG; therefore, to prevent combustion knock, a heavy-duty LPG engine is normally designed for lower peak combustion pressures than a similar CNG engine. This is accomplished by using a lower compression ratio or a lower turbocharger boost pressure [7].

Because of this octane limitation, an LPG engine would be expected to have somewhat lower fuel efficiency than a CNG engine operating in similar service.

Because the LPG vehicle would almost certainly have a lighter fuel storage system than a similar CNG vehicle, the LPG vehicle would perform less work, with the result that actual in-service fuel consumption (on a Btu/mi basis) probably would be quite similar to that of the CNG vehicle [8].

At atmospheric pressure, the volumetric energy density of natural gas (the amount of energy contained per unit volume) is too low to warrant use in the relatively small fuel tanks of motor vehicles. Thus, in natural gas vehicles, the gas is either compressed, or liquefied by reducing its temperature to negative 120°C at atmospheric pressure, to increase the amount of energy that can be stored in a fuel tank.

As much as any of the design elements of the engine itself, the storage and safety issues associated with compressing and liquefying the gas have presented some of the greatest challenges in the development and marketing of the technology.

However, these challenges have been duly addressed and enough operating experienced has been gained to place NGVs in the realm of the commercially viable [9].

Two motivators for the use of hydrogen as an energy carrier today are: 1) to provide a transition strategy from hydrocarbon fuels to a carbonless society and 2) to enable renewable energy sources. The first motivation requires a little discussion while the second one is self-evident [10].

Hydrogen has the highest energy content per unit weight of any known fuel (120.7 kJ/g), which means that the amount of energy produced by hydrogen per unit weight of fuel is about three times the amount of energy contained in an equal weight of gasoline, and almost seven times that of coal . It burns cleanly and with high temperatures.

For example, when burned in pure oxygen, the temperature of 2700 °C can be measured. In that case, the only by-products are heat and water. When burned with air, which is about 68% nitrogen, some oxides of nitrogen are formed [11].

Like gasoline, hydrogen takes a small amount of energy to ignite it and make it burn. However, hydrogen also diffuses faster than almost any other gas. Its buoyancy and diffusivity make it hard to contain and also difficult to ignite in open air [12].

Experimental setup

Internal combustion engine and its accessories:

The engine used in these investigations was 4 stroke single cylinder, with variable compression ratio, spark timing, a/f ratio and speed Ricardo E6, the engine connected to electrical dynamometer, and lubricated by gear pump operated separately from it, the cooling water circulated by centrifugal pump.

Gasoline supply system: This system consists of major tank (6 liter capacity), minor tank (1liter capacity), and gasoline carburetor. LPG supply systems: This system consist of LPG tank, fuel drier, solenoid valve, LPG carburetor, gaseous fuel flow measuring device (orifice plate), damping box.

CNG supply systems: This system consist of CNG tank, fuel drier, solenoid valve, CNG carburetor, gaseous fuel flow measuring device (orifice plate), damping box. Hydrogen supply system: This system consists of hydrogen cylinder, pressure regulator and gaseous fuel flow measuring device (chocked nozzles system).

Air flow measurement: Air interring the engine was measured by Alock viscous flow meter connected to flame trap.

Speed measurement: Engine speed was measured by tachometer. Power measurement: In addition of it is used to measure power; it is used as electric motor also, to rotate the engine in the starting. The dynamometer is used to measures indicated power, brake mean effective pressure and friction lost power.

Exhaust gas temperatures measurement: Exhaust gas temperatures were measured by nickel chrome/ nickel aliumel thermocouple, which was calibrated before it was used.

The engine was operated with gasoline; NG, LPG and pure hydrogen. In practice, much of the gaseous fuels available are usually mixtures of various fuels and some diluents, constituents that can vary widely in nature and concentration, depending on the type of fuel and its origin. In this work the gasoline used was Iraqi Dora refinery production with octane No. 86, the LPG fuel produced from Al Taji Gas Company; consist of ethane 0.8%, 18.47 isobutane, 47.8% propane and 32.45% butane.

NG used was produced from Iraqi Northern Gas Company; consist of 84.23% methane, 13.21% ethane, 2.15% propane, 0.15% isobutane, 0.17% n. butane and 0.03% pentane. Hydrogen produced from Al Mansur Company with 99.99% purity.

The very wide diversity in the composition of the gaseous fuels commonly available and their equally wide variety of their associated physical, chemical and combustion characteristics make the prediction and optimization of their combustion behavior in engines a more formidable task compared to conventional liquid fuels.

Continued research is needed to provide more light on their suitability as engine fuels and understand better the roles of the many factors that control their behavior so as to achieve in practice the many potential superior benefits associated with their applications as engine fuels.

Test program

The first tests were conducted to determine the higher useful compression ratio for each fuel. Engine performance was tested for wide range of equivalence ratios, optimum spark timing and 1500 rpm engine speed. Comparisons of engine performance produced using each fuel separately, once at gasoline HUCR, and secondly at each fuel HUCR were tested.

Discussion

Figures 1,2,3 &4 represent engine brake power resulted by fueling it with gasoline, LPG, CNG and hydrogen, for wide range of equivalence ratios, many compression ratios, optimum spark timing and 1500 rpm engine speed.

Brake power increased with equivalence ratio increase from lean side to rich one, the calibration of the air-fuel mixture affects power.

The maximum brake power lied at equivalence ratios (Ø=1.1-1.2) for hydrocarbonic fuels, while for hydrogen it lied at (Ø=0.9-1.0), in these regions the maximum thermal energy generated from burning air-fuel mixtures, using most of the oxygen in the mixture, the brake power reduced after these equivalence ratios.

There are limits or boundaries of equivalence ratio for each fuel, start from misfire limit in the lean side, and end at a quenching limit at the rich side, for gasoline these borders are convergent compared with other gaseous fuels, gasoline engine operate between Ø=0.8-1.38, for LPG these limits diverged, so LPG engine operates between Ø=0.7-1.45, NG engine operates between Ø=0.62-1.48.

Hydrogen can be distinguish by his wide equivalence ratio range, its engine can operates between Ø=0.2-2.5, but in this work hydrogen engine operates between Ø=0.34-1.25, because Ricardo SI engine combustion chamber doesn't have any modifications to increase mixing, and at rich mixtures abnormal combustion occurred, causing high brake power reduction, because of these conditions the work was completed between the mentioned ratios.

Oxygen quantity in the lean side more than the required quantity for combustion, so part of the excess air gained some of combustion's energy, which will be lost with exhaust gases, added to the little quantity of fuel in this side. In the rich side, the excess fuel hinders combustion process, causing its deterioration and reducing the resulted brake power, because of oxygen lack.

The figures show the possibility of operating the engine with leaner mixtures by increasing CR, and they show constant progress for engine brake power with all fuels, the brake power increased with CR increased to certain border, and then it reduced with continuing CR increase, because of knock occurrence which retarded the spark timing causing brake power reduction.

The equivalence ratio (at which maximum brake power occurred because of CR) moved backward with CR increased and approaching the stoichiometric ratio. It reduces for gasoline from 1.18 to 1.15, for LPG from 1.19 to 1.1, for CNG from 1.21 to 1.13, for hydrogen from 1.025 to 0.9.

The HUCR for gasoline is 8:1, 10.5:1 for LPG, 13:1 for CNG and 11:1 for hydrogen, this appears from fig 5.

The gasoline maximum brake power higher than similar readings of other alternatives, when they were compared at gasoline HUCR=8:1, as fig 6 indicates, but they approached from each others when the engine run at HUCR for each fuel, as fig 7 indicates, the brake power resulted from LPG, CNG and hydrogen reduced according to little heating value on volume basis for the three alternatives, the reduction in the volumetric efficiency for the three gases, and for CNG the drop in flame propagation speed.

The brake power approached each other when the engine run at HUCR for all the fuels, the LPG brake power reduced 3% from gasoline bp, while the reduction was about 9% for CNG, and 15 % for hydrogen.

Hydrogen gives the lower bp because of its low heating value on volume basis, to increase hydrogen fuel inside combustion chamber; cautions must be taken to prevent abnormal combustion.

The spark timing was advanced highly when the engine fueled with CNG, indicating low flame propagation speed compared with other fuels, it is a special quality for NG which speed is 0.29 m/s, as figure 8 represents, spark timing for gasoline retarded with increasing CR compared to LPG, indicating the improvement in volumetric efficiency.

Although their flame speeds are closed to each other, for gasoline 0.37m/s and 0.4 m/s for LPG, while hydrogen ST retarded more than them, the flame speed for hydrogen is very fast compared with any other known fuel, lies between 2.65-3.4 m/s.

Increasing CR will retard optimum spark timing, because of the improvements in combustion quality by increasing temperatures inside combustion chamber. The bsfc in very lean mixtures near misfire limits were very high, then it reduced to reach the minimum value near equivalence ratio Ø=0.9, after this ratio they start to increase with enriching the mixture with fuel, as figure 9 indicates, the preferable homogenous mixture produces best and complete combustion lies near this ratios.

For the other equivalence ratios the imperfect mixing with oxygen excess in combustion chamber in very lean side, and fuel excess in rich side, increase bsfc, the figure shows that bsfc for hydrogen is the minimal, followed by CNG bsfc, then LPG and the last one gasoline.

Exhaust gas temperature increased highly with increasing equivalence ratios in lean side, until the maximum bp point reached, then it reduced with mixture enrichment with fuel, but with lower average, as appears in fig 10. The exhaust gas temperature produced from gasoline are higher than the temperatures produced from other alternatives, followed by LPG , CNG and finally hydrogen had the minimum value, because the maximum burning heat for gasoline higher than similar heats for the other considered alternatives.

Hydrogen exhaust gas reduction due to its low heating value on volume basis, and also due to its high burning velocity, so that it completes burning before the piston starts falling down in the power stroke, the burning gases will be cooled before the exhaust valve opens, causing these hydrogen low temperature exhaust gases levels, compared with the other fuels which continue burning at power stroke.

The highest volumetric efficiency was for gasoline, as figure 11 shows, followed by LPG, NG and finally hydrogen, this decrease is due to the larger volume of inlet air occupied by gaseous fuels, and because of the gaseous fuel nature which takes more place on air account, also it mixed with air without cooling it, as gasoline does, the volumetric efficiency reduces with enriching the mixture with fuel.

Using ideal gas state equation it can be easily shown that the volume occupied by a gaseous fuel is larger than that by gasoline in a stoichiometric air-fuel mixture.

There are several ways to improve engine volumetric efficiency while operating with gas such as increasing the number of intake valves per cylinder, valve timing and lifting optimization, using turbocharged engine and designing a modified intake manifold, however these all affect cost and reliability.

The mechanical efficiency is a function of bp produced by the engine, where friction power fasten with speed and CR, as figure 12 represents, the higher value of mechanical efficiency lies at the maximum bp equivalence ratio point, and it reduced at other equivalence ratios, its minimum values lied at very lean ratios.

The figure shows that gasoline mechanical efficiency higher than that for the other fuels, followed by LPG efficiency, CNG, and finally hydrogen, because of the higher bp for gasoline.

Indicated thermal efficiency increased from lean side to reach its maximum value near equivalence ratio Ø=0.9, then it reduced after this ratio, as figure 13 indicates, the ratios which give maximum indicated thermal efficiency is the same ratios which give minimum bsfc, figure 13 shows that the thermal efficiency for hydrogen the highest one, followed by NG efficiency, LPG and finally gasoline, because of the reduction in bsfc with increasing of bp.

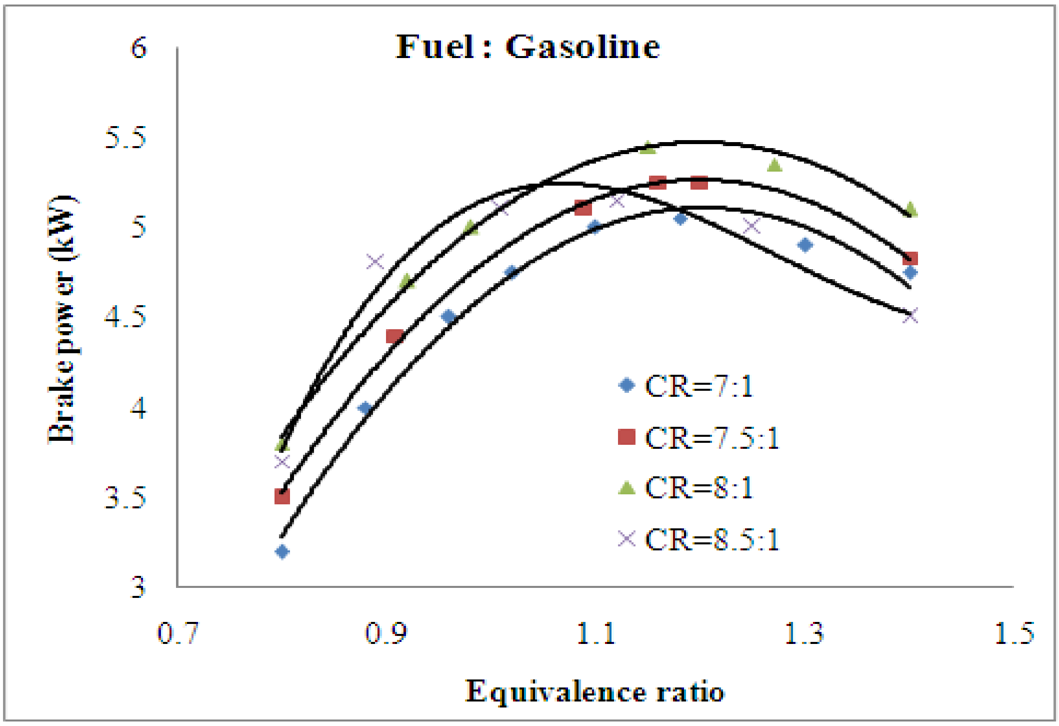

Fig.1, equivalence ratio and brake power for several compression ratios, using gasoline as fuel

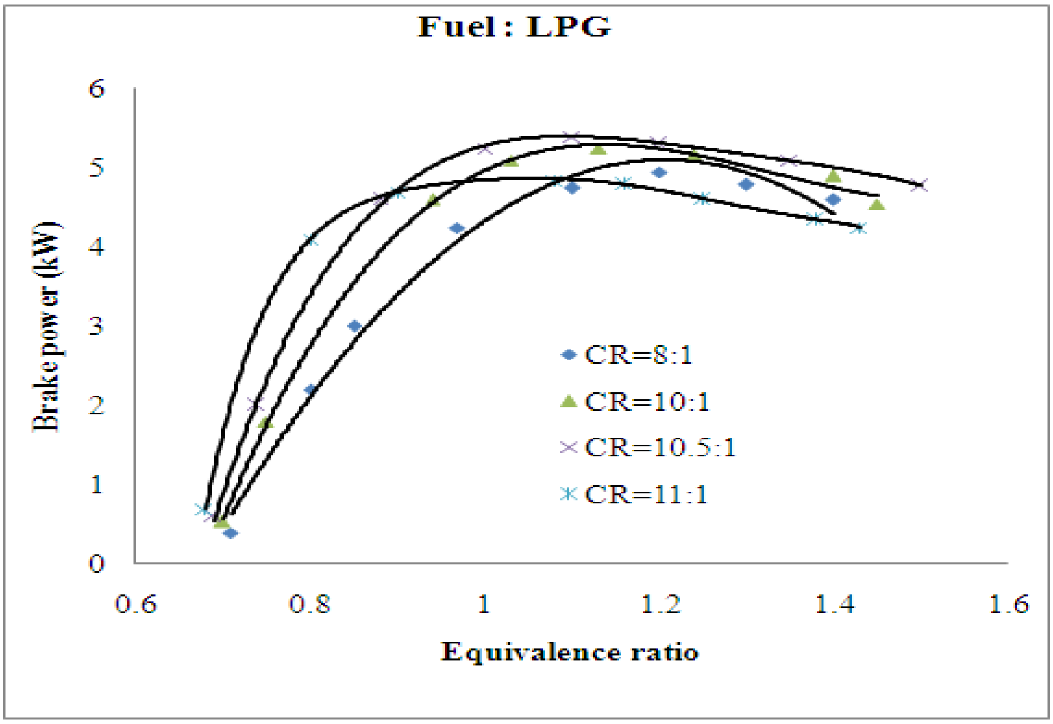

Fig.2, equivalence ratio and brake power for several compression ratios, using LPG as fuel

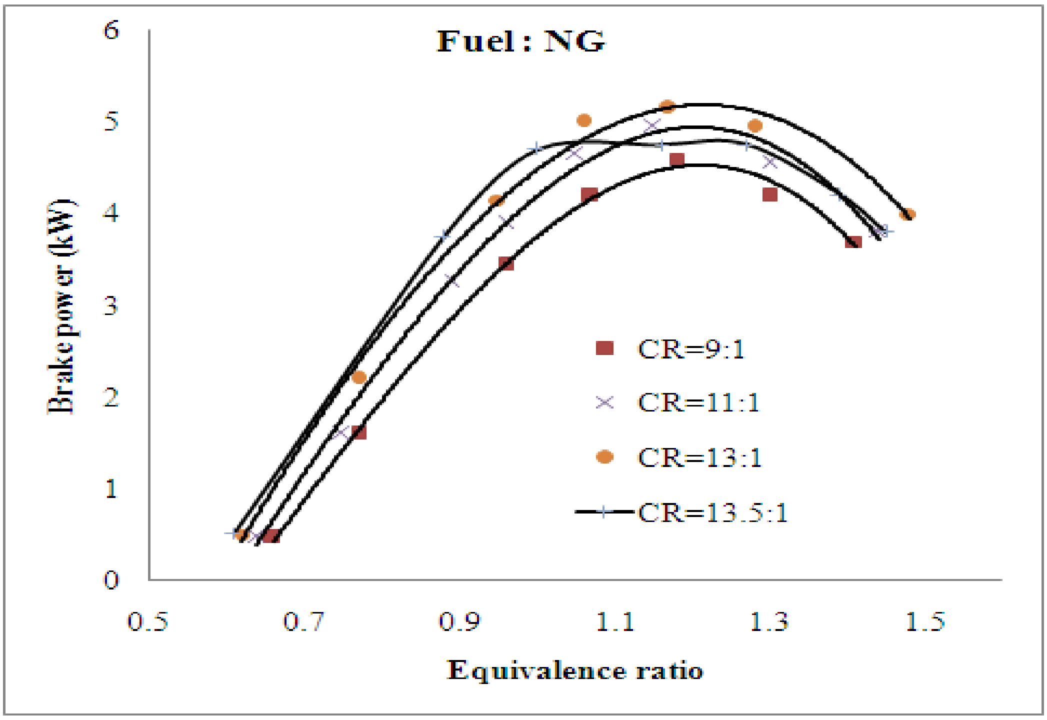

Fig.3, equivalence ratio and brake power for several compression ratios, using NG as fuel

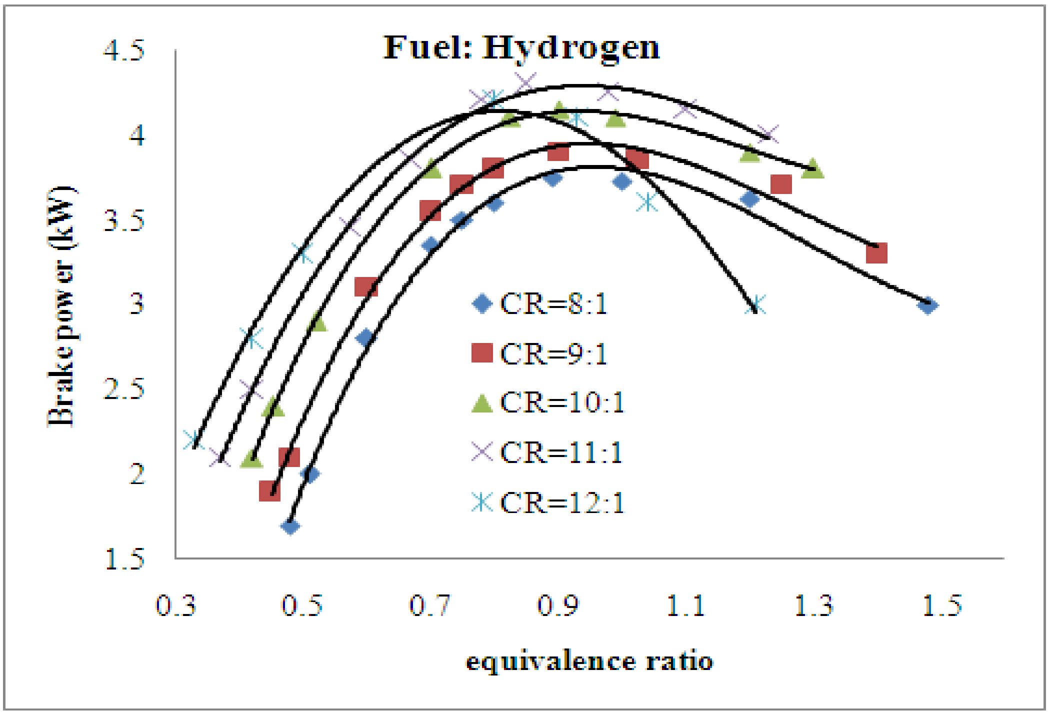

Fig.4, equivalence ratio and brake power for several compression ratios, using hydrogen as fuel

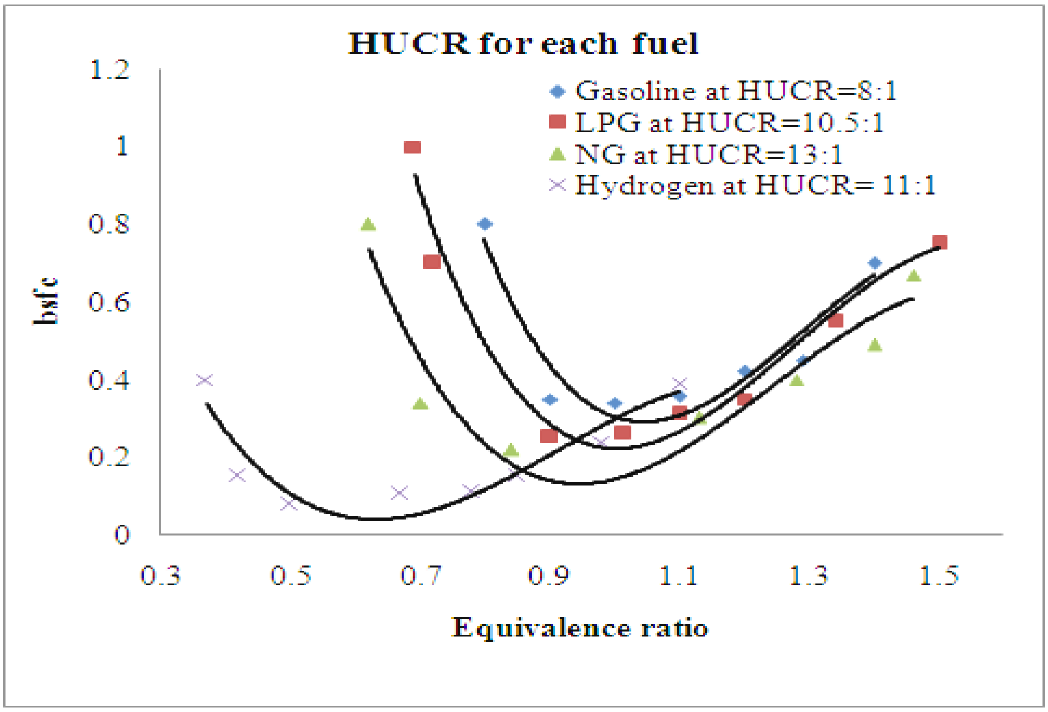

Fig. 9, Equivalence ratio and brake specific fuel consumption relationship at HUCR for each fuel

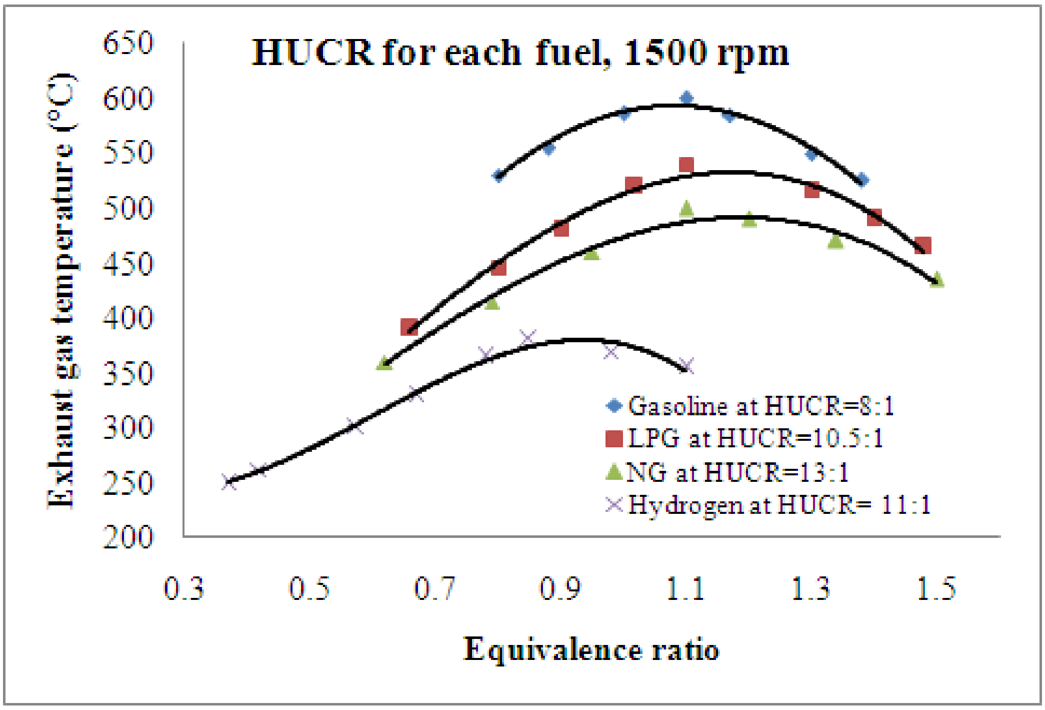

Fig. 10, Equivalence ratio and exhaust gas temperature relationship at HUCR for each fuel

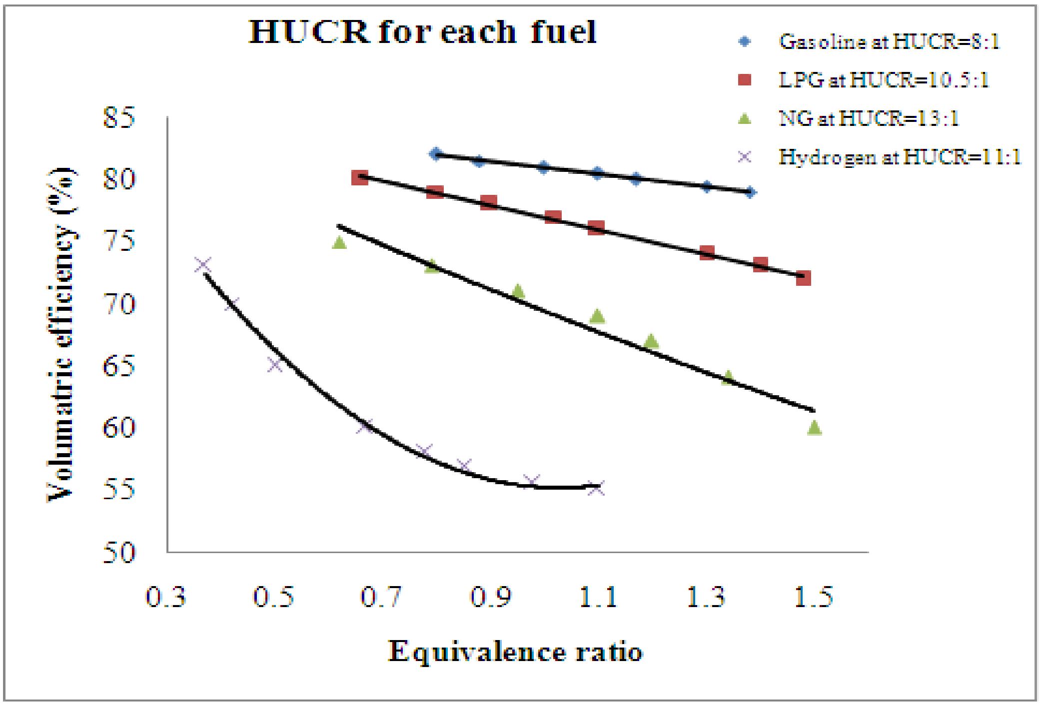

Fig. 11, Equivalence ratio and volumetric efficiency relationship at HUCR for each fuel

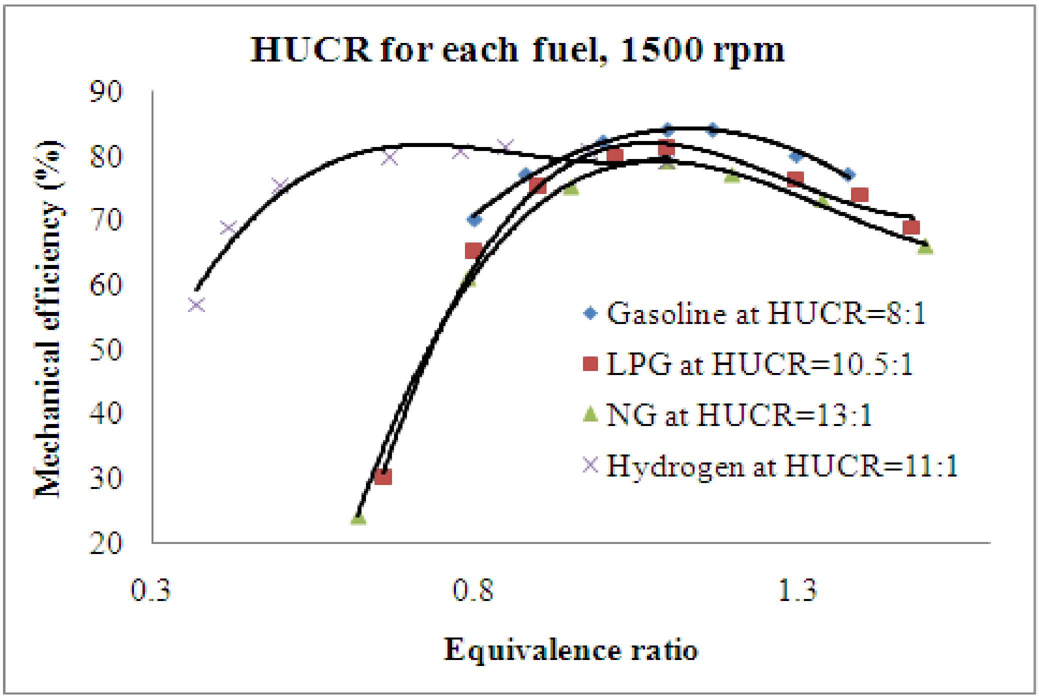

Fig. 12, Equivalence ratio and mechanical efficiency relationship at HUCR for each fuel

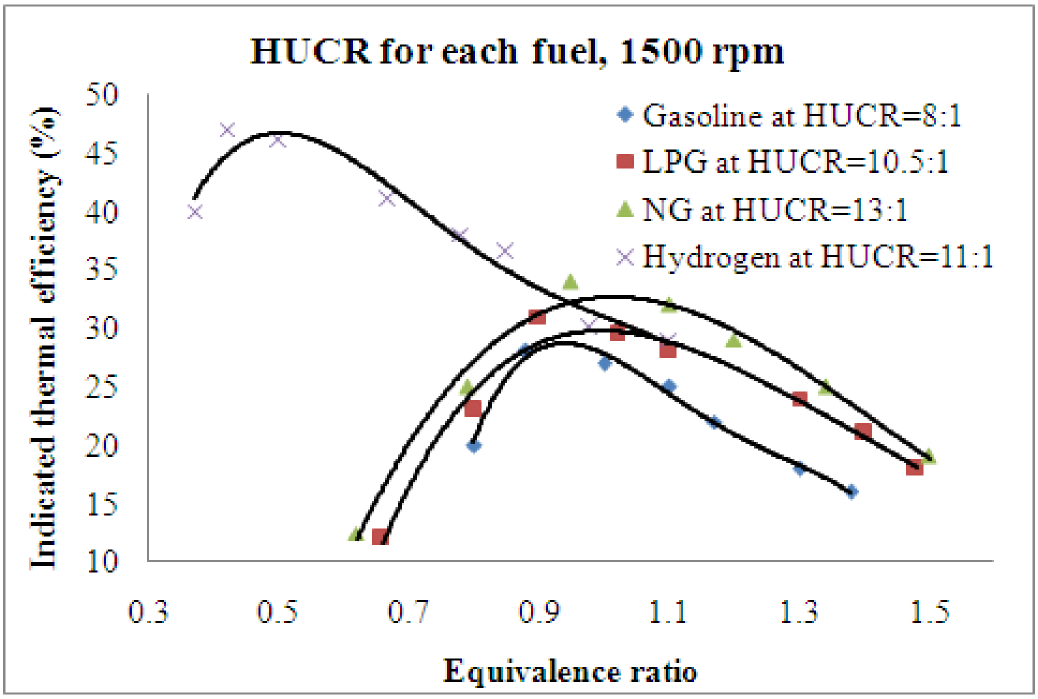

Fig. 13, Equivalence ratio and mechanical efficiency relationship at HUCR for each fuel

Conclusions

The aim of this work was to compare engine performance when it was fueled with four different fuels, gasoline as the reference fuel, LPG, NG and hydrogen as international expected alternatives, the results show that:

1. Engine brake power increase with increasing compression ratio to a certain limit (HUCR of the fuel), after this ratio knock occurs and bp reduced.

2. HUCR for gasoline was 8:1, 10.5:1 for LPG, 13:1 for NG and 11:1 for hydrogen.

3. Gasoline bp precedes the other fuels brake powers, when the engine operated at gasoline HUCR=8:1, but alternative fuels brake powers converged to gasoline bp, when the engine operated with each fuel HUCR.

4. The equivalence ratio range becomes wider with gaseous fuels, and it expands highly for hydrogen, so the engine can operates with extremely low equivalence ratios less than Ø=0.6, which can't be reached with the other tested fuels.

5. The work with lean equivalence ratio increases the engine indicated thermal efficiency.

6. Hydrogen operation with rich mixtures suffers from abnormal combustion conditions, like pre-ignition and backfire, and the engine must have some modifications to prevent these phenomenons.

7. Spark timing must be advance highly when using NG as fuel, because of it low flame speed.

8. Spark timing must be retarded highly when using hydrogen as fuel, because of its high flame speed.

9. Bsfc reduced by using alternative fuels, the minimum values were hydrogen share, the maximum values were gasoline share.

10. Volumetric efficiency reduced by using alternative gaseous fuels, the minimum values were hydrogen share, NG followed the LPG; the maximum values were gasoline share.

11. Indicated thermal efficiency depends on bsfc and bp, so hydrogen has the highest values, followed by NG then LPG, and finally gasoline.

12. Exhaust gas temperatures reduced by using alternative fuels, the minimum values were hydrogen share. The maximum values were gasoline share.

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