The Iraqi Journal For Mechanical And Material Engineering, Vol.13, No.2, 2013

STUDY OF PERFORMANCE OF SI ENGINE FUELED WITH SUPPLEMENTED HYDROGEN TO NATURAL GAS

Dina Saadi Muneam Al-Zubaidi
Assist. Lecturer- Mechatronics Eng. Dept. - Al Khwarizmi Collage of Eng. –
Baghdad University

ABSTRACT

In the near future, hydrogen will be required to supplement and eventually replace rapidly diminishing hydrocarbon fuels resources for internal combustion engines. Engine variables effects like compression ratio, equivalence ratio, spark timing and speed on combustion properties, engine performance were studied in this paper, when hydrogen supplemented natural gas is used in variable compression ratio, single cylinder Ricardo E6 engine.

The results show that adding hydrogen to natural gas increase compression ratio, brake power and indicated thermal efficiency. Also this addition reduces brake specific fuel consumption, volumetric efficiency and exhaust gas temperatures. Optimum spark timing is retarded with adding hydrogen to NG.

Keyeords: NG, hydrogen, equivalence ratio, compression ratio, brake power, specific fuel consumption, indicated thermal efficiency, exhaust gas temperature.

دراسة أداء محرك أحادي الأسطوانة يعمل باضافة الهيدروجين للغاز الطبيعي

دينا سعدي منعم الزبيدي
مدرس مساعد، قسم هندسة الميكاترونيك
جامعة بغداد / كلية هندسة الخوارزمي

الخلاصة :-

ستكون إضافة الهيدروجين واحلاله محل الوقود الهيدروكاربوني السريع النضوب في محركات الأحتراق الداخلي أمرا مطلوبا" في المستقبل القريب. تمت دراسة خواص الأحتراق، أداء المحرك وتأثير متغيرات مثل نسبة الأنضغاط، النسبة المكافئة، توقيت الشرر والسرعة عند اضافة الهيدروجين للغاز الطبيعي في محرك أحادي الأسطوانة ذي نسب انضغاط متغيرة نوع ريكاردو.

بينت النتائج أن اضافة الهيدروجين الى الغاز الطبيعي تسبب زيادة نسبة الأنضغاط، القدرة المكبحية والكفاءة الحرارية البيانية. كما تسبب هذة الأضافة نقصان الأستهلاك النوعي المكبحي للوقود، الكفاءة الحجمية ودرجات حرارة الغاز العادم. يتأخر التوقيت الأمثل للشرر باضافة الهيدروجين للغاز الطبيعي.

NOMENCLATURE

[air]	molar concentration of air
bsfc	brake specific fuel consumption
BTE	brake thermal efficiency
BDC	bottom dead centre
°BTDC	degree before top dead centre
CR	compression ratio
[H]	molar concentration of hydrogen
HUCR	higher useful compression ratio
HVF	hydrogen volume fraction
LCV	fuel lower calorific value
[NG]	molar concentration of natural gas
OST	optimum spark timing
SIE	spark ignition engine
TDC	top dead centre
$\dot{m}_f$	fuel mass flow rate (kg/s)
$\dot{m}_{a,act.}$	actual air mass flow rate
$\dot{m}_{a_{theo.}}$	theoretical air mass flow rate
$\eta_{bth.}$	brake thermal efficiency
ρ_f	fuel density (kg/m^3)
$V_{s.n}$	Swept volume
Q_t	total fuel’s heat

INTRODUCTION

Pressure for more convenient and environmental acceptance fuels has resulted in an accelerated demand for supply of gaseous fuels throughout the industrialized countries of the world (Moreno, 2010). The energy demand continue to increase, threats of block off, rationing, and the relations of pollution regulations are hard evidence that source of the premium fossil fuels are finite (Das, 2000). Various investigations have been carried out to explore the possibilities of the use of alternative fuels, or new engine design. The fuels that appear to offer an attractive potential in this respect are natural gas and hydrogen (Shasby, 2004).

Natural gas is consisted of methane (CH_4) primarily, but frequently contains trace amounts of ethane, propane, nitrogen, helium, carbon dioxide, hydrogen sulfide and water vapors; natural gas is produced from gas wells or tied in with crude oil production (Chaichan, 2003).

Currently natural gas is distributed across the world through large pipelines, but can also be transported with trucks, barge or trains. Natural gas can be stored or used as compressed natural gas (CNG) or liquefied natural gas (LNG) (Suryawanshi, 2011 & Ding, 1986).

Much attention has been paid for hydrogen, a reproducible and clean future fuel. Compared with hydrocarbon fuels, hydrogen has the following properties:

1. Hydrogen is a remarkable light gaseous fuel that requires on volume basis the least amount of air for stoichiometric combustion (2.39 verses 59.6 for Isooctane), while on mass basis it require the highest relative mass of air (Karim, 2003).
2. Hydrogen heating value on mass basis is the highest, but on volume basis it is the lowest. Hydrogen is an energy carrier like electricity and not a fuel by itself, and has to be produced from other energy sources. Hydrogen has low mass density per unit volume. Hydrogen has

high energy density which is 2.7 times than NG or gasoline on mass basis (White, 2006 & Steefan, 2004).

3. Higher flame propagation rate, effectively reducing the period of combustion during expansion stroke and also reducing losses during combustion, particularly at higher engine speeds (Szwaja, 2007 & Chaichan, 2006).
4. Lower ignition energy, favorable to ignition in Otto cycle engines, but making pre-ignition and backfire in fresh charge more likely (Shuli, 2007).
5. Wider ignition limits with much wider changes in the air/fuel ratios of the mixture (Erjiang, 2009). The engine power output and speed can, therefore, be adjusted by supplying different air/fuel ratio mixtures, instead of changing the charge density and throttling, thus leading to decrease in pump losses and in increase in thermal efficiencies under partial load conditions (Orhan, 2004).

Many researchers studied hydrogen supplementation to NG (Thurnheer, 2009; Wang, 2009 and Das, 2005), they found that hydrogen which characterized with its wide combustion limits and high burning velocity at lean mixtures, when added to NG increased engine fuel economy, and reduced engine emissions.

The objective of the present study is to clarify the effect of hydrogen addition on the burn of natural gas combustion at various engine speeds and spark timing. Tests were conducted on a single cylinder spark ignition engine using variable premixed ratios and hydrogen fractions - NG mixtures at full load.

EXPERIMENTAL TECHNQUE

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 specifications are listed in **Table 1**. The engine is connected to electrical dynamometer, and lubricated by gear pump operated separately from it. The cooling water circulated by centrifugal pump. **Fig. 1** represents a schematic diagram for the tests rig.

NG supply systems: This system consist of NG high pressure cylinder, fuel drier, solenoid valve, NG carburetor, gaseous fuel flow measuring device (orifice plate), damping box.

Hydrogen supply system: Hydrogen was drawn from a high-pressure cylinders; this pressure was reduced to one atm through a pressure regulator. It was then passed through a control valve for regulating the amount of gas, the gas mass flow rate was metered using chocked nozzles meter, which also was used as a flame trap to arrest and control flash back if any.

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 calibrated tachometer.

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

Exhaust gas temperatures measurement: Exhaust gas temperatures were measured by calibrated thermocouple type K (nickel chrome/ nickel aliumel).

Tests were also conducted to determine the engine output and fuel economy with natural gas and with various degrees of hydrogen supplementation. Mixture equivalence ratios were varied over a wide range while hydrogen volumetric fraction (hydrogen volumetric fraction is defined as the ratio of the hydrogen volume to the total volume of hydrogen and natural gas used, that's mean $HVF= V_{H2}/(V_{H2}+V_{CH4})$ varied from 20% to 100% hydrogen. HUCR and OST were used in studying 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 supplementary fuel.

Analysis

The following equations were used in calculating engine performance parameters (Keating, 2007):

1- Brake power

$$bp = \frac{2\pi * N * T}{60 * 1000} \quad kW \qquad (1)$$

2- Fuel mass flow rate

$$\dot{m}_f = \frac{v_f \times 10^{-6}}{1000} \times \frac{\rho_f}{time} \quad {}^{kg}/_{sec} \qquad (2)$$

3- Air mass flow rate

$$\dot{m}_{a,act.} = \frac{12\sqrt{h_o * 0.85}}{3600} \times \rho_{air} \quad \frac{kg}{sec} \qquad (3)$$

$$\dot{m}_{a_{theo.}} = V_{s.n} \times \frac{N}{60 * 2} \times \rho_{air} \quad \frac{kg}{sec} \qquad (4)$$

4- Brake specific fuel consumption

$$bsfc = \frac{\dot{m}_f}{bp} \times 3600 \quad \frac{kg}{kW.hr} \qquad (5)$$

5- Total fuel heat

$$Q_t = \dot{m}_f \times LCV \quad kW \qquad (6)$$

6- Brake thermal efficiency

$$\eta_{bth.} = \frac{bp}{Q_t} \times 100 \quad \% \qquad (7)$$

7- Equivalence ratio for duel fuel (Abdul Haleem, 2007):

$$\emptyset = \frac{\dfrac{[NG]}{[air] - \dfrac{[H]}{([H]/[air])_{st}}}}{\left(\dfrac{[NG]}{[air]}\right)_{st}} \qquad (8)$$

Materials

The engine was operated with NG 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 NG used was produced from Iraqi Northern Gas Company; consist of 86.23% methane, 11.21% 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. **Table 2** gives some hydrogen and natural gas properties.

Error analysis

All measurements have some degree of errors that may come from a variety of sources. The process of evaluating these errors called error analysis or uncertainty analysis. The level of confidence associated with the measured values should be included within the complete statement of these values. All measuring devices were calibrated at The Central Organization

for Measurements and Quality Control (Baghdad), and there accuracies were defined. Thermocouples were calibrated using similar calibrated thermocouples. All flow meters (air flow meter, NG floe meter and hydrogen flow meters were calibrated using suitable calibrated orifice for measuring range. **Figures 2 & 3** represent the calibration curves. The experimental accuracies of the measuring devices that were used in present study are shown in **table 3**.
The uncertainty in the results is calculated by the equation (ASHREA, 1986):

$$e_R = \left[\left(\frac{\partial R}{\partial V_1} e_1\right)^2 + \left(\frac{\partial R}{\partial V_2} e_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial V_n} e_n\right)^2\right]^{0.5}$$

Where:
e_R : Uncertainty in the results
R : a given function of the independent variables $V_1, V_2, \ldots, V_n$ or $R=R(V_1, V_2, \ldots, V_n)$.
e_i : uncertainty interval in the nth variable.
The partial derivative $\frac{\partial R}{\partial V_1}$ is a measure of the sensitvity of the result to a single variable.
The uncertainty for present tests was:

$$e_R = [(0.9)^2 + (1.12)^2 + (0.64)^2 + (1.1)^2 + (0.87)^2 + (0.91)^2]^{0.5} = \pm 2.295\%$$

Tests procedure

The first set of tests was conducted to define the engine higher useful compression ratio when it was run with NG for wide range of equivalence ratios, 25 rps engine speed and optimum spark timing. At this compression ratio engine performance was studied to find the effects of engine speed, compression ratio, spark timing and equivalence ratio. The second set of tests was conducted with adding gaseous hydrogen to NG to study the influence of this addition on the former parameters and there effects on engine performance.

RESULTS AND DISCUSSION

1. CR effect

Various hydrogen volumetric fractions [HVF= $V_{H2}/(V_{H2}+V_{NG})$] supplemented to natural gas was studied (HVF=0.2, 0.4, 0.6, 0.8), to explore the best mixture ratio for two gases with compression ratio changed starting from 8:1, to find the higher useful compression ratio (HUCR) for each mixture.
Fig. 4 shows the relations between hydrogen volume fractions and the maximum brake power at every CR studied. From this figure it appeared that the maximum brake power existed at CR = 14:1. Then this compression ratio is considered as higher useful compression ratio at HVF= 60%.
Fig. 5 gives the relationship between brake power and equivalence ratio for different HVF and optimum spark timing (OST), HUCR and 25 rps speed. Brake power increased with HVF increase from 0 to 60%, this increment in brake power was expected, because hydrogen presence in combustion chamber gives improvement in energy released, and increased burning rate giving better combustion. The brake power decreased with increasing HVF to 70 and 80%,

because a large part by volume of natural gas was substituted with hydrogen causing the heat released from the combustion to be decreased, in other words the volumetric efficiency deteriorated at these HVF. Hydrogen heating value on volume basis is less than that for natural gas. This appears clearly when using hydrogen alone, where it gives less brake power than that released when natural gas is used.

Fig. 6 indicates HVF and CR effects on optimum spark timing. HVF increase in fuel resulted in retarding OST. Also, CR increase gives the same effect on engine spark timing. This is expected, in view of the fact that hydrogen characterized with its high burning velocity compared to NG. Also, burning velocity increased with CR increase, due to increments in mixture temperatures inside combustion chamber. Due to these two factors OST was retarded on an average of 16°BTDC.

2. Equivalence ratio effect

Fig. 5 shows the effect of hydrogen supplementation on equivalence ratio limits, the range of combustion operating limits became wider with this supplementation. Hydrogen addition made the engine run with much more leaner mixture. The lean misfire limit for NG was at (Ø=0.63) while with hydrogen addition this limit reduced to (Ø=0.49) at HVF=80%.

NG is known with its low burning velocity. The addition of hydrogen improves and increases this velocity several times as **Fig. 6** illustrates. The principal effect of hydrogen addition occurs during the induction or ignition delay period. This period is initiated by a spark discharge, and the duration of the period characteristic of the time required establishing a combustion volume. This time depends on the rate of chemical processes in the expanding flame kernel. On this basis, it would be expected that the principal effect of added hydrogen would be to accelerate the delay stage of the combustion process by the rapid chain branching oxidation characteristics of hydrogen. In comparison with the much slower partially degenerate chain reactions characteristic of hydrocarbon oxidation like NG, this process known to be fast. This is apparently in **Fig. 7**, which gives the relationship between maximum brake power at HVF in fuel for five chosen equivalence ratios at OST, 25 rps speed and HUCR.

Fig. 7 shows that the effect of added hydrogen on engine maximum brake power is much more pronounced in lean mixtures, this is appeared when HVF increased from 0 to 60% for (Ø=0.7), where brake power increased about 250% compared with NG value. This is because of three parameters: oxygen availability for reaction, hydrogen existence which increases burning velocity and the high heating vale of natural gas. This result is very important and encourages operating engine with this mixture, because at this lean equivalence ratio all engine emissions are at their least values.

At Ø=0.8 the brake power increased about 97.5% compared with NG. But at equivalence ratios richer than Ø=0.8, hydrogen addition effect is limited. Due to reduction in entering air quantity which was replaced with hydrogen and NG volumes instead of it. This means that the energy produced from the reaction will be limited. From the figure it appears that the increase in brake power at Ø=1.0 was about 7.5% and at Ø=1.1 was about 5.0%, and at Ø=1.3 it was about 2%.

Fig. 8 indicates the hydrogen addition effect on brake specific fuel consumption (bsfc), for wide range of equivalence ratios at HUCR, OST and 25 rps speed. Bsfc decreased for lean equivalence ratios in a high rate with hydrogen addition, for example, at Ø= 0.7 and HVF= 60%, bsfc decreased about 60% compared to NG. At Ø=1.0 and the same HVF the reduction reached about 15%.

Fig. 9 indicates the hydrogen addition effects on maximum indicated thermal efficiency and volumetric efficiency at HUCR, 25 rps speed and OST. The maximum indicated thermal efficiency increased with hydrogen addition by high rates. The high increments of indicated thermal efficiency conduct the improvement of burning in this side with supplemented hydrogen.

Fig. 9 indicates the reduction in maximum volumetric efficiency with hydrogen addition, where hydrogen introduction in combustion chamber was on air account. It can be consider that a part of the increment in bsfc and the reduction in bp at high equivalence ratios referred to this deterioration in volumetric efficiency.

Fig. 10 presents the relation between HVF and exhaust gas temperature at HUCR, OST and 25rps. Exhaust gas temperature decreased with hydrogen addition, because the burning velocity with hydrogen existence in mixture was rapid and complete, especially when the engine run at OST, so when expansion stroke occurred all the mixture would be burned and became burned gases, and it will be cooled in this stroke. When exhaust valve opened exhaust gas will get out in low temperatures and much lower than when engine run with any other hydrocarbon fuels.

3. Speed effect

Fig. 11 indicates the relation between maximum engine brake power and HVF in mixture for wide range of equivalence ratios to represent speed effect at HUCR and OST. Maximum brake power increased with HVF for all studied speeds but the increase rate was different. The increment rate for low speed (20 rps) to medium one (25 rps) was about (19.18%), and then this rate decreased when the engine was run in high speeds (35 rps) where the increment in bp was about (3.58%), because of increased friction power with speed increased.

Fig. 12 represents effect of hydrogen addition on OST for different speeds. Hydrogen addition appears to retard the OST about 15° BTDC for all studied speeds. Also, speed increase cause OST to be advanced, so the OST resulted was the resultant of these two opposite effects.

4. Spark timing effect

Fig. 13 indicates the relation between brake power and equivalence ratio at 10°BTDC, HUCR and 25 rps. Spark timing 10°BTDC is very retarded timing for natural gas which is characterized with its low burning velocity, and brake power resulted was very low. Hydrogen addition increased brake power, for all HVF until Ø=1.2 and then decreases.

Spark timing 20° BTDC is a preferable timing for natural gas, as brake power increased for all HVF as appears in **Fig. 14**. Also, break power increased with hydrogen addition for all equivalence ratios compared to NG, because this timing appears to be near the OST for these ratios. Brake power reduced for rich equivalence ratios (more than Ø=1.2), where this ST can be considered retarded from OST for these ratios. The increments in brake power for the tested equivalence ratio range were 13.5%, 28.82% and 40.9% for 20, 40 and 60% hydrogen addition respectively compared to NG.

In **Fig. 15** the brake power curves take another shape, compared with curves in figures 11 and 12. The natural gas brake power increased at 30° BTDC spark timing, because this timing near the OST for equivalence ratios where maximum brake power happened (Ø=0.95-1.15). The brake power decreased with hydrogen addition about (20-40%) for equivalence ratios (Ø=0.9-1.35) compared with former spark timing (20° BTDC). It was difficult to run the engine with HVF=60% at these equivalence ratios. This spark timing which appeared very advanced from OST for NG-hydrogen mixtures, so it reduced the brake power for HVF= 20 and 40%, and cause the high pressure to happen before top dead centre causing negative work on engine. This figure shows an obvious increments in brake power in lean equivalence ratio less than Ø=0.7.

CONCLUSIONS

1- The HUCR with hydrogen supplementation was increased to 14:1 compared with 13:1 for pure NG.
2- The optimum spark timing retarded with hydrogen addition.
3- The OST retarded with CR increase.
4- Brake power increased with hydrogen addition to natural gas for certain limit HVF=60%), then it decreased with HVF increase.
5- The engine run at wider burning limits with hydrogen addition.
6- The volumetric efficiency decreased with hydrogen supplementation.
7- The indicated thermal efficiency increased with hydrogen addition to natural gas. The maximum value of this efficiency was at very lean equivalence ratio.
8- Exhaust gas temperature reduced with hydrogen addition, the maximum value was near the stoichiometric equivalence ratio.
9- Bsfc reduced with hydrogen supplementation to natural gas.

Table 1: Ricardo E6 engine geometry and operating parameters.

Model	Ricardo E6
Displaced Volume	504 cm3
Bore	76.2mm
Stroke	111.1mm
Exhaust Valve Open	43° BBDC (at 5 mm lift)
Exhaust Valve Close	6° ATDC (at 5 mm lift)
Inlet Valve Open	8° BTDC (at 5 mm lift)
Inlet Valve Close	36° ABDC (at 5 mm lift)
Speed	1000-3500 RPM

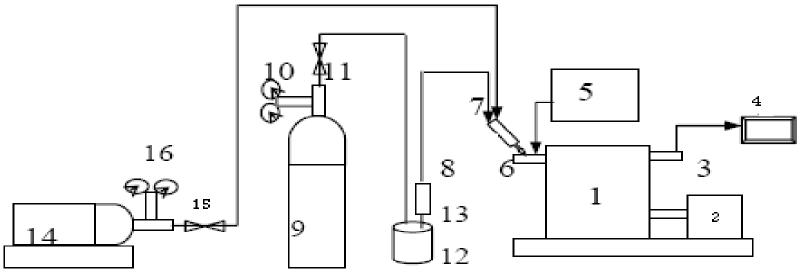
Table 2, some hydrogen and NG properties

Property	Hydrogen	Natural gas
Limit of flammability in air (vol %)	4-75	5.3-15
Laminar burning velocity in air* (cm/s)	200-230	37-43
Minimum energy for ignition in air (mJ)	0.02	0.29
Auto ignition temperature (K)	858	813
Quenching gap in air (mm)	0.64	2.03
Diffusion coefficient in air * (cm2/s)	0.61	0.16
Density* (kg/m3)	0.0838	0.7174
Flame temperature in air at Ø=1* (K)	2318	2148
Lower heating value (MJ/kg)	120	53
Research octane number	>130	>120
Normal boiling point (K)	20.3	111.6

- **273 K 1013kpa**

Table 3, Experimental Accuracies

Measurements	Accuracies in this study
Thermocouples	± 0.9 %
Engine speed tachometer	± 1.12%
NG flow meter	± 0.64 %
Air flow meter	± 1.1 %
hydrogen fuel flow meter	± 0.87%
dynamometer	± 0.91%



1. Single cylinder engine
2. Dynamometer
3. Engine exhausts manifold
4. Exhaust gas cooler
5. Air drum
6. Engine intake manifold
7. Solenoid valve
8. Gas carburetor
9. Hydrogen cylinder
10. Pressure gauge
11. Non return valve
12. Flame trap
13. Choked nozzles system
14. NG cylinder
15. NG flow meter (orifice plate)
16. Pressure gauge and pressure regulator

Fig. 1, a schematic diagram for the tests system

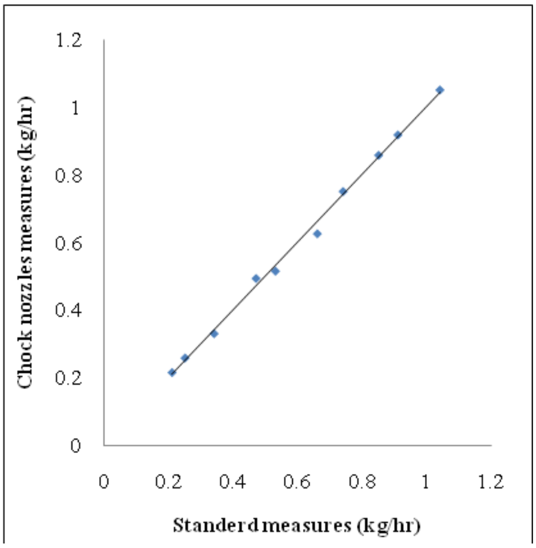


Fig.2 Chock nozzles calibration curve

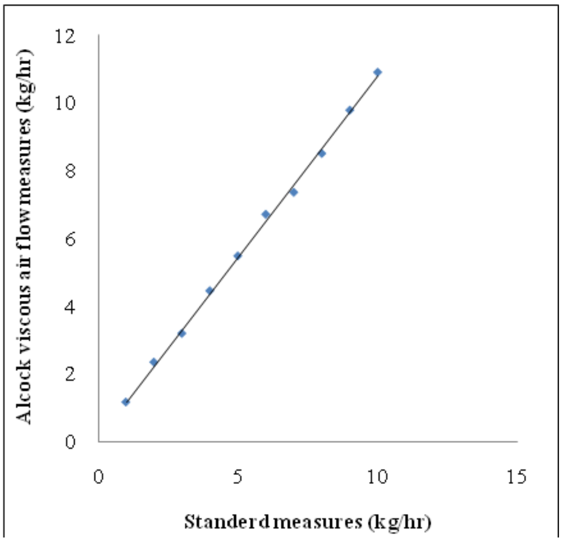
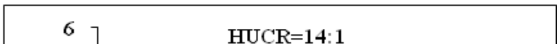


Fig.3 Alcock viscous air flow meter calibration curve



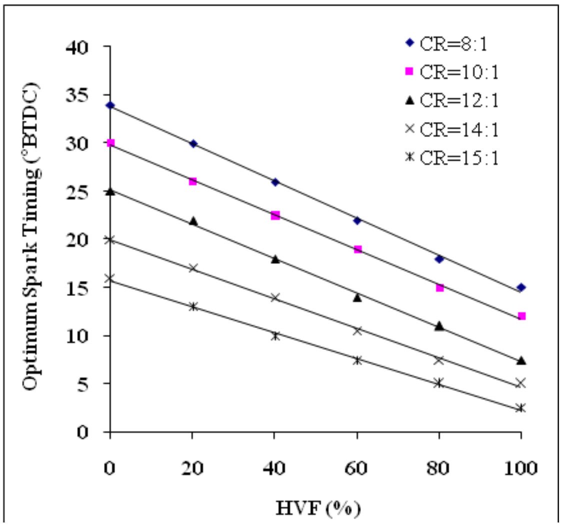


Fig. 6, Relation between HVF in mixture and OST for different compression ratios and 25 rps

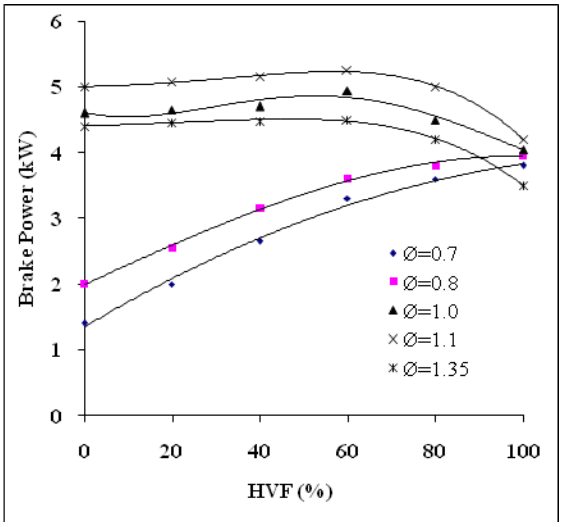


Fig. 7, Relation between HVF in mixture and brake power at higher useful compression ratio, OST and 25 rps for different equivalence ratios

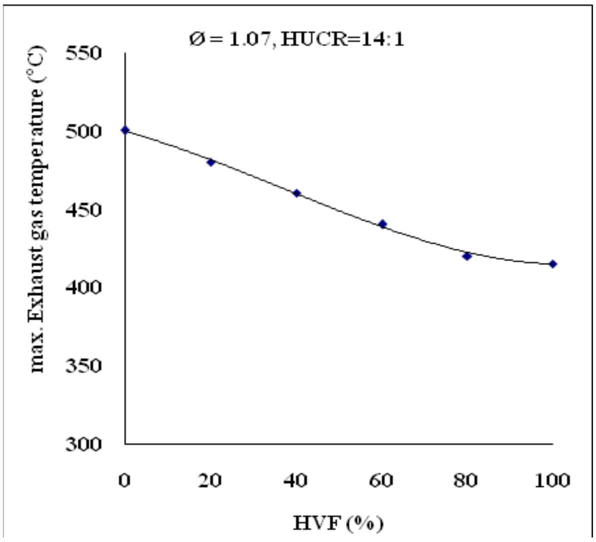


Fig. 10, Relation between HVF in mixture and high exhaust gas temperature at higher useful compression ratio, OST and 25 rps

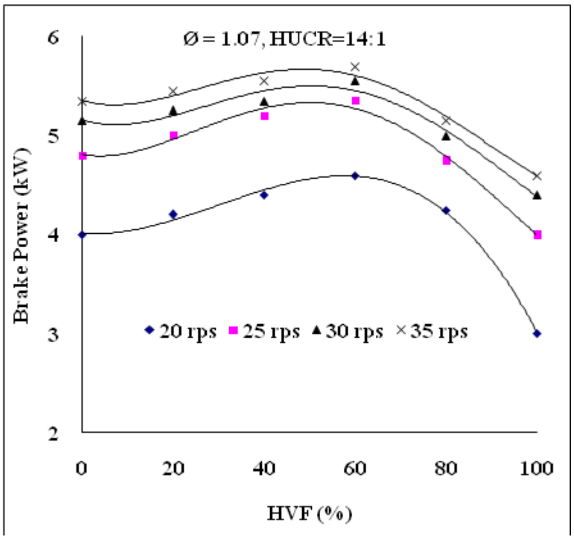


Fig. 11, Relation between HVF in mixture and brake power for different engine velocities at higher useful compression ratio and OST

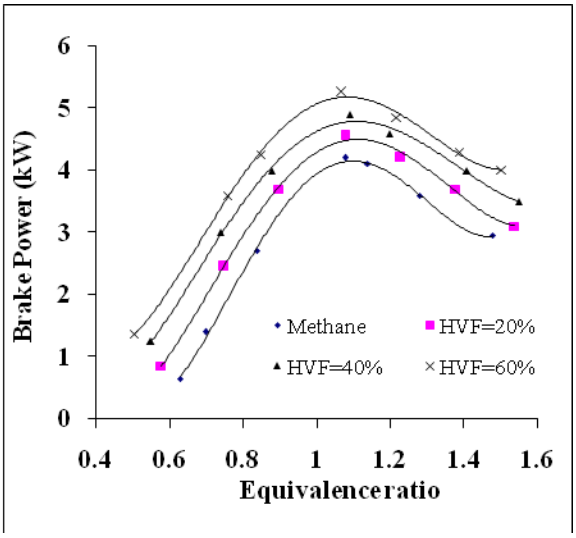


Fig. 14, Relation between equivalence ratio and brake power at spark timing=20°BTDC at higher useful compression ratio, and 25 rps for different HVF's

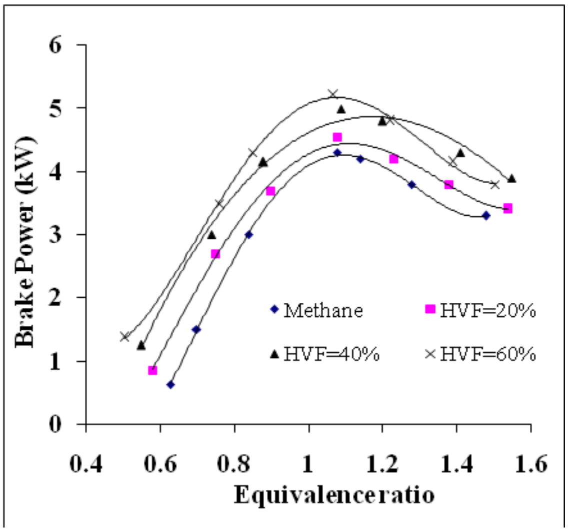


Fig. 15, Relation between equivalence ratio and brake power at spark timing=30°BTDC at higher useful compression ratio, and 25 rps for different HVF's

REFERANCES

Abdul Haleem S M, Theoretical and experimental investigation of engine performance and emissions of a four strokes spark ignition engine operated with hydrogen blended gasoline, Ph D thesis, College of Engineering, Al-Mustansiriya University, Baghdad, Iraq, 2007.

ASHREA Guide Line. Guide engineering analysis of experimental data, Guideline 2-1986.

Chaichan M T and AL-Sheikh S A, Study of performance of SIE fueled with methane. AL-Jufra J. Sci. Tech., vol.1, 2003.

Chaichan M T, Study of performance of SIE fueled with supplemented hydrogen to gasoline, Engineering J. Baghdad Un., vol. 12, No. 4, pp: 983-996, 2006.

Das L M, Gulati R, Gupta P K, A comparative evaluation of the performance characteristics of a spark ignition engine using hydrogen and compressed natural gas as alternative fuels, International Journal of Hydrogen Energy, vol. 25, pp:783-793, 2000.

Das L M & Polly M, Experimental Evaluation of a Hydrogen added natural gas (HANG) operated S.I engine, SAE paper No. 2005-26-029, 2005.

Ding L J, Qing L Y and Shen D T, Improvement of the combustion of hydrogen fueled engine. Int. J. Hydrogen Energy, vol.11, 1986.

Erjiang H, Zuohua H, Bing L, Jianjun Z, Xiaolei G & Bin H, Experimental investigation on performance and emissions of a spark-ignition engine fuelled with natural gas–hydrogen blends combined with EGR, International Journal of Hydrogen Energy, vol. 33, pp: 528 – 539, 2009.

Karim G A, Hydrogen as a spark Ignition Engine fuel, International Journal of Hydrogen energy, vol. 28, pp: 569-577, 2003.

Keating E L, Applied combustion, 2nd eddition, Taylor & Francis Group, LLC, 2007.

Moreno F, Muñoz M, Magén O, Monné C. & Arroyo J, Modifications of a spark ignition engine to operate with hydrogen and methane blends, International Conference on Renewable Energies and Power Quality (ICREPQ'10), Granada (Spain), 23th to 25th March, 2010.

Orhan A S, et al., Internal Combustion Engine Fueled by Natural Gas – Hydrogen Mixtures, International Journal of Hydrogen Energy, vol. 29, pp: 1527-1539, 2004.

Shasby BM, Alternative fuels: Incompletely addressing the problem of the automobile. M Sc thesis, Alexandria, USA, 2004.

Shuli Z, Experimental study on thermal efficiency and emission characteristics of a lean burn hydrogen enriched natural gas engine. International Journal of Hydrogen Energy, vol. 32, pp: 5067 – 5075, 2007.

Steefan V, Roger S and Sebastian V, A high speed single cylinder hydrogen fueled internal combustion engine. Fista World Automotive Congress, Barcelona, Spain, 2004.

Suryawanshi J G & Nitnaware P T, An investigation on SI engines using hydrogen and CNG blends, IJRRAS, vol. 7, No. 3, pp: 295-303, 2011.

Szwaja S, Bhandary K R & Naber J D, Comparisons of hydrogen and gasoline combustion knocks in a spark ignition engine. International Journal of Hydrogen Energy, vol. 32, pp: 5076 – 5087, 2007.

Thurnheer T & Dimopoulos P, SI engine fuelled with gasoline, methane and methane/hydrogen blends: Heat release and loss analysis, International Journal of Hydrogen Energy, vol. 34, pp: 2494-2503, 2009.

Wang Y & Zhanga X, Experimental and modeling study of performance and emissions of SI engine fueled by natural gas–hydrogen mixtures, International Journal of Hydrogen Energy, vol. 48, pp: 1-4, 2009.

White C M, Steeper R R & Lutz A E, The hydrogen fuelled internal combustion engine: a technical review. International Journal of Hydrogen Energy, vol. 31, pp: 1292-1305, 2006.