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Alternative Fuels for Spark Ignition Engines

Yousef S.H. Najjar*

Mechanical Engineering Department, Jordan University of Science and Technology, Irbid, Jordan

Abstract: In order to reduce the atmospheric pollution emitted by automobiles, control devices are being incorporated in the vehicles in many countries. This has resulted in a reduced vehicle mileage to the extent of about fifteen percent. Without the introduction of new technology, any further reduction in emission levels would be expected to extract payment in the form of further fuel economy losses. It is, therefore, worthwhile to look into the suitability of "clean" burning fuels for use in internal combustion engines and assess their potential for reducing engine exhaust emissions. So the investigation of alternative fuels becomes very necessary.

In this work three types of fuels are investigated: Alcoholic fuels, gaseous fuels and liquid fuels.

Their properties were inserted in a computer program which was specially designed to calculate the performance of a spark ignition engine over wide range of operating conditions (design and off-design). The design operating variable namely compression ratio, advance angle, engine speed and spark advance were chosen for each fuel based on the physical and chemical properties and the resulting fuel-engine interactions such as mixing, flammability and knock. The resulting performance includes power, specific fuel consumption and thermal efficiency. Their variation with equivalence ratio, engine speed and spark advance was calculated and plotted in the figures and briefly mentioned in the conclusions.

The engine variables including temperature, pressure and volume were calculated at different points of the cycle. Hence the P-V and the P-rc diagrams were drawn for the different alternative fuels. These diagrams are considered unique contribution to the characterization of alternative fuels.

INTRODUCTION

The increased use of automobiles and the rapid rate of industrial development in the world made petroleum supplies unable to keep up with demands. Moreover, petroleum fuels pollute the environment with their combustion products. Control devices were used to reduce pollution, but resulted in about 15% reduction in the vehicle mileage [1]. It is, therefore, worthwhile to look into the suitability of using "clean" burning fuels for use in spark ignition engines (S.I.E).

Using of alternative fuels maybe achieved by converting an existing engine to operate on either the original fuel and the alternative fuel "dual fueling" or, in general, a specially designed engine for the new fuel will offer better performance [2].

Two categories of fuels are investigated: alcoholic fuels and gaseous fuels. Alcohols could be produced from renewable resources and produce less exhaust pollutants. Gaseous fuels offer, cleaner combustion due to improved fuel-air mixture preparation and higher H/C ration than in conventional liquid fuels [2].

In this work the effect of different fuels on engine performance was studied using specially designed Fortran computer program for gasoline. The predicted results compared favorably with the actual engine performance at the same operating conditions. Hence, the program was further extended and modified for the other fuels.

ANALYSIS

A. Effects of Fuel on Engine and Vehicle Performance and Technology

1. Methanol and Ethanol

Methanol and ethanol have a number of similar properties and hence require similar attention when considering fueling, combustion, storage and handling [2].

Alcohols have high oxygen content hence lower stoichiometric air-fuel ratio. Consequently engine displacement volume Vd could be reduced. However, alcohols have approximately half the internal energy of combustion (Urp) of that of gasoline.

Thereby to obtain the same power output from the engine, the flow rate of alcohol needs to be doubled and consequently the relevant air, thus keeping Vd unaltered, but increasing the capacity of carburetor jets, injectors, fuel pumps and tanks.

Methanol has a latent heat of vaporization h_{fg} about four times that of gasoline. This coupled to the fact that twice the fuel quantity to be used, means that the heat required for vaporization is about eight times greater for methanol. In S.I.E. this heat must be supplied in the inlet manifold prior to entry into engine cylinders, to avoid sever wear problems within the engine.

However, correct vaporization results in decrease of inlet air temperature resulting in improved volumetric efficiency

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*Address correspondence to this author at the Mechanical Engineering Department, Jordan University of Science and Technology, Irbid, Jordan; Tel: 00962785793463; Fax: 0096227100836;
E-mail: y_najjar@hotmail.com

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and greater torque and power. Reduction in vehicles' gear ratios should be made to take advantage of the increase in torque, if fuel economy is to be improved. High h_{fg} and oxygen content may contribute to poor driveability.

The relatively high fixed boiling point of alcohols results in low vapour pressure not sufficient to start the engine, resulting in poor cold starting performance. This can be overcome with the use of heaters, more volatile fuel additive or employing a secondary "cold start" fuel.

Being a polar fluid, methanol may be incompatible with many metals and elastomers [3]. It is more corrosive than ethanol. Metals affected, such as Mg, Al, Zn and Cu should be replaced or plated with nickel for protection. The exposure of plastic and rubber components- in the fuel delivery system – to alcohol can cause swelling and softening. Hence, proper material selection is essential. Other engine and vehicle modifications include: spark plugs with higher heat rating; suitable engine oil; corrosion resistant and increased capacity fuel tank and lines; and modified bearings.

Taking advantage of the higher octane rating, the compression ratio can be increased to 12 without encountering spark knock, which results in higher thermal efficiency and power output for the same energy input as petrol. This coupled with the ability to burn lean mixtures with improved volumetric efficiency and soot free combustion means that alcohols are viable alternative to gasoline in spark ignition engines [2].

The addition of ethanol (10%) to gasoline in S. I. E. with a typical 3-way catalyst increases both Research Octane Number (RON) and the Reid vapour pressure but increases emissions of acetaldehyde and ethanol; whereas addition of methyl tertiary butyl ether (MTBE) causes only an increase in RON with less unburned HC, CO and acetaldehyde [4].

The addition of ethanol to diesel in compression ignition engine results in CO reduction due to presence of more oxygen in the combustion process. However, the power decreases with the increase of ethanol [5].

2. Gaseous Fuels

Engines fueled with gaseous fuels have certain advantages over gasoline-fueled engines, such as:

a- Less scale and gum build-up inside the combustion chamber, thus requiring less frequent engine overhaul.

b- Eliminating most of the starting difficulties associated with gasoline.

c- Proper distribution of fuel-air mixture over the cylinders, thereby reducing the cyclic variation problem.

d- Reduced evaporative emission from carburetor and fuel tank, whereas with gasoline it is a major factor that affects air pollution.

e- Reduced contamination of lubricating oil, thereby extending periods between oil and filter changes.

f- Less pollutants with less corrosive elements improves the service life of the exhaust system.

The main gaseous fuels considered in this work are: natural gas, hydrogen and synthetic fuels. Gases could be obtained from chemical industry with low thermal value of 0.54 kWh/Nm^3; gases with low methane numbers (e.g. high H_2 content) and hence low knock resistance; and gases with very high thermal value up to 34 kWh/Nm^3 (butane) [6].

3. Natural Gas (NG)

It consists mainly of about 95% methane, 3% ethane with smaller percentage of propane and butane.

Natural gas can be used as an automotive fuel either compressed in cylinders CNG or liquefied LNG. In practice LNG is rarely used as it is more expensive and difficult to handle. Due to its high octane number O.N., higher compression ratio r_c could be used to benefit from the 33% higher combustion rate, hence NG is an excellent fuel for spark ignition engines [4].

Emissions from a NG vehicle are 80% reduced (compared to gasoline) especially CO and NO_X [1], thereby dispensing with three-way catalyst needed by S.I. engines. However, refueling systems require a compressor which increases the cost to \$2000-\$4000 per vehicle.

The relative disadvantages associated with using the NG is the reduction in the engine volumetric efficiency. Moreover, NG must be stored in a high pressure tank which is heavy and reduces the payload and luggage space. An NG car with 75 litre tank is about 150 kg heavier than its gasoline counterpart [8].

Small changes in the concentration of butane produce linear significant changes in both the values of knock limited compression ratio for fixed spark timing and the knock-limited spark timing for a fixed compression ratio [9].

The use of syngas with NG extends the exhaust gas recirculation (EGR) tolerance by 45% on mass basis compared to NG only, leading to 77% reduction in NO_X over NG with EGR [10].

Considering thermal stability and heat transfer, it was found that the use of high-purity methane instead of N.G. at temperature, above 775 K, could reduce the deposit thickness by as much as a factor of three, or permit operation at correspondingly higher temperatures [11].

4. Hydrogen

Hydrogen can be considered as a true alternative fuel as it can be derived by electrolysis from non-fossil fuel source, namely water. However, hydrogen could be added to the gasoline-air mixture in the intake system, thereby extending the lean equivalence ratio Φ for smooth operation from 0.8 to 0.5, making the mixture easier to burn and reducing the pumping work at part load thereby improving mechanical efficiency [9]. Lean hydrogen mixture assists with fuel economy and in reducing unburned fuel and NO_X as exhaust emission.

Furthermore, hydrogen offers many advantages for the improvement of the combustion process. This is due to some favorable combustion properties such as: wide flammability limits, low ignition energy in air, high flame speed and high heating value. The high flame speed and wide flammability limits are of particular interest gasoline and methane have significant disadvantages with respect to these two properties. Therefore, it can be expected that the addition of hydrogen to these two fuels would improve combustion [12].

In spite of these advantages, hydrogen has some problems such as: abnormal combustion in the form of preignition, back firming and spark knock due to low ignition energy. Storage is a major difficulty where an expensive and heavy tank in the vehicle is needed to contain hydrogen compressed or liquefied [13]. A disadvantage of hydrogen fuel in the S.I. engine is the reduction of the engine's volumetric efficiency; hence the maximum power from the same engine will go down by about 20% with hydrogen.

5. Synthetic Fuels

Due to the huge reserves of coal in many countries, it has been hardly tried to utilize it in engines in different ways. However, due to its high sulphur content, the removal of SO_2 from the resulting stack gases is an expensive process. Thus considerable efforts have been directed toward the development of processes for converting coal to clean fuels, both gaseous and liquid.

Gasification processes have been developed which could produce synthetic fuel with approximate formula $(CH_2O)_n$. A typical volumetric analysis of the fuel is: 0.3% CH_4, 29.6% H_2, 41% CO, 10% CO_2, 17% H_2O and 0.8% N_2. Hence, CH_4 and N_2 can be neglected, H_2O can be removed by using vapour trap and CO_2 extracted for other uses. This results in a fuel which consists of CO and H_2. Advanced gasifiers are being developed which produce H_2 and CO in roughly equal amounts [15].

Although synthetic fuel-air mixtures are slower burning than gasoline-air mixtures, the first should be used with low compression ratio r_c engine to avoid knock. However, it was found that with synthetic fuels the engine r_c can be increased to 14 instead of 8 the typical value for gasoline [3]. This is thought to be due to the relatively lower heating value, hence lower heat release per unit mixture with consequent reduced temperature and lower tendency to knock.

Biodiesel is being recently developed to be used as a fuel in compression ignition engines CIE [16, 17]. The combustion related properties of vegetable oils are some what similar to diesel oil. Neat vegetable oils or their blends with diesel, however pose various long-term problems in C.I.E. e.g.: poor atomization characteristics, ring sticking, injector coking, injector deposits, injector pump failure and lube oil dilution by crank-case polymerization. These undesirable features of vegetable oils are due to their inherent properties like high viscosity, low volatility and polyunsaturated character [16]. Using 20% biodiesel-fuelled engine, the physical wear of various vital parts, injector coking, carbon deposits on piston and ring sticking were found to be substantially lower. The lube oil analysis showed lower wear and thus improved life for biodiesel operated engines [16, 17].

B. Fuel Performance in Internal Combustion Engines

It is essential to explore the fuel performance relative to different engine designs. This covers a range of parameters that are fundamental to basic vehicle operation and those related to engine performance. These parameters and their relationship to key fuel properties are discussed below [12]:

Fuel handling and delivery to the injection point into the engine is related to fuel properties such as viscosity, cloud point, pour point and vapour pressure.

Initiation of combustion is related to spontaneous ignition temperature Tsp, vapour pressure, viscosity, volatility, stoichiometric F/A ratio (F/A)st and flame speed [18] combustion stability is affected by laminar flame speed S_L, flammability limits, viscosity and Tsp.

Materials compatibility is associated with the ability of fuel-wetted metallic and elastomeric materials to withstand corrosion and dimensional instability. Key fuel properties are sulfur content, acidity and aromatic content.

Wear life of fuel pump, fuel system and injectors is related to lubricant and particulate content. High -temperature corrosion of combustion chamber, igniter and injectors are related to vanadium, Ni, K, S and Na contents. Ceramics are less sensitive to these contaminants.

Low-temperature corrosion due to contact with cool exhaust gases is related to sulfur content.

Exhaust emissions are affected by the percent content of aromatics, carbon, sulfur, particulate, nitrogen, hydrogen, oxygen and ash. Other properties are (F/A)st and maximum flame temperature.

Power output is related to (A/F)st, internal energy of combustion Urp, and maximum flame temperature:

> Fuel consumption depends on engine thermal efficiency, power and F/A besides Urp.
>
> Reliability and durability is affected by ash and particulates, gum content, metals content, lubricity, fuel stability and carbon residue.
>
> Safety in fuel tank and engine, to avoid fire when the engine is shut down, is affected by flammability limits, vapour pressure, flash point, Tsp and electrical conductivity.

DISCUSSION OF RESULTS

Alternative Fuels-Engine Relationship

A computer program initiated by Campell using C_8H_{18} as fuel [19], was utilized then further modified to compare the performance of spark ignition engine S.I.E., using gasoline taking into consideration the four following modifications on the fuel air cycle, namely : progressive combustion, valve timing, heat transfer and friction [19]. The operating variables namely r_c, SA and rpm were varied as shown in Table **1** with gasoline, whereas the corresponding experimental results are shown in Table **2**. The experimental device was a single cylinder variable compression engine with

B= 0.095m, S=0.082m, L=0.155m, AO= 7.068mm^2

IVO=36˚ABDC, EVO=36˚BBDC, VDISP=0.58123 X 10^{-3} m^3

The average operating conditions were assumed

PM=P_1=101.4 k Pa

Tg=1500 K

Tw=400 K

R=8.314 kJ/ kmol K

Table 1. Operating Variables with Gasoline D.P

CR	6.00	7.00	8.00	10.00
SA	0.00	5.00	10.0	20.00
rpm	1250	1500	2000	2250

Table 2. Experimental Results for Different Speeds with Gasoline

Engine Speed (rpm)	1250	1500	2000	2250
Power (kW)	5.3	6.8	8.7	8.4
s.f.c. (g/kWh)	374.4	323	306	381

The detailed predicted results for different modifications along with the experimental results are shown in Table **3**. The comparison is favorable with average variation of (4.6%) in power and (-2.87%) in sfc.

Table 3. Power and sfc at Different rpm for Different Modifications at Design Point

Experimental		**Friction**		**Heat Transfer**		**Valve Timing**		**Prog. Combustion**		**Ideal**		**Modification**
s.f.c	**Power**	**s.f.c**	**Power**	**s.f.c**	**Power**	**s.f.c**	**Power**	**s.f.c**	**Power**	**s.f.c**	**Power**	**rpm**
374.40	5.30	400.2	5.04	348.53	5.79	325.18	6.20	288.98	6.98	250.25	8.06	1250
323.00	6.80	331.10	6.65	289.76	7.60	269.50	8.20	244.098	9.02	220.88	9.97	1500
306.00	8.70	297.20	9.10	257.02	10.52	239.88	11.3	211.08	12.24	199.4	13.54	2000
381.00	8.40	348.8	9.22	294.52	10.92	275.2	11.7	256.49	12.55	218.09	14.55	2250

Table 4. Operating Particulars of the Different Fuels

Property	**Com. R**	**RON**	**$\phi_{mis\ fire}$**	**ϕ_{pl}**	**ϕ_{fl}**	**$(O_2 / F)_s$**	**H.V,MJ/kg**	**MM, kg/kmol**	**r_c**
$C_{7.12}H_{14.56}$	-	95	0.8	0.9	1.2	10.76	43.7	100	8
CH_3OH	Higher	105		0.8	1.3	1.5	20	32	12
$C_{1.1}H_{4.2}$	Higher	120	0.5	0.6	1.1	2.15	50	17.4	14
$C_{0.58}H_{0.84}O_{0.58}$	Lower	-	0.5	-	1.1	0.5	15.5	17	14
2 % H_2 + Gasoline	Higher	98	0.5	0.7	1.3	11.04	49.68	100	8

This success in using the modified model to predict performance with gasoline, encouraged its use with other fuels which are considered as candidate alternative fuels for the S.I.E., such as methanol CH_3OH, natural gas NG, synthetic gas from coal, and mixture of gasoline and hydrogen. The operating particulars of these fuels along with gasoline are shown in Table **4**. Thus, further modifications in the modified computer program are carried out to take these particulars into consideration.

In addition to the basic three operating variables namely N, Φ and SA which were used with gasoline, the compression ratio r_c is now added to represent the effect of fuel on knock requirements of the engine. Table **5** shows the values of these variables at the design point with six fuels. Table **6** gives the overall picture of operation and performance at the design point for the different fuels.

The following figures show the off-design performance of the engine. Fig. (**1**) shows the variation of brake power P_b with equivalence ratio Φ, for different fuels. All the fuels manifest maximum P_b at stoichiometric fuel air mixture Φ =1 consistent with maximum temperature.

Fig. (**2**) shows minimum brake specific fuel consumption bsfc around the stoichiometric Φ where maximum temperature results in maximum combustion rate hence heat release rate which is directly related to fuel consumption.

Fig. (**3**) shows the maximum brake thermal efficiency ŋ at stoichiometric Φ, consistent with the reverse relation between bsfc and ŋ.

An important operating parameter is the engine speed N. Fig. (**4**) shows the variation of P_b with N. It increases steadily until 2500 rpm is reached for all fuels. Methanol CH_3OH produces the highest P_b for the same heat input, whereas natural gas and the synthetic fuel gives the lowest power due to the drop of volumetric efficiency.

Fig. (**5**) shows the maximum ŋ at 1500 rpm, a condition of part load but relatively low friction power.

Table 5. Design Points for the Fuels

Fuel	**Iso-Octane**	**Gasoline**	**Methanol**	**CNG**	**Syn. Fuel**	**H2 + Gasoline**
CR	9	9	12	14	14	9
rpm	2500	2500	2500	2500	2500	2500
ϕ	1.2	1.2	1.3	1.1	1.1	1.3
SA	20	20	20	15	20	20

Table 6. **Operating Variables and Results of Different Fuels at Design Point**

Fuel	C8H18	C7.12H14.56	CH3OH	C1.1H4.2	C.58H.84O.58	Gasol. + H2
Φ	1.2	1.2	1.3	1.1	1.1	1.3
N (rpm)	2500	2500	2500	2500	2500	2500
SA °	20	20	20	15	20	20
Brake Power (kW)	12.31	12.16	15.42	11.08	11.10	12.5
Torque (N.m)	48.40	47.75	60.85	42.32	42.40	51.22
BSFC (g/kWh)	302.59	311.08	575.39	254.03	811.96	335.78
η %	26.61	26.48	26.88	30.33	28.60	23.70

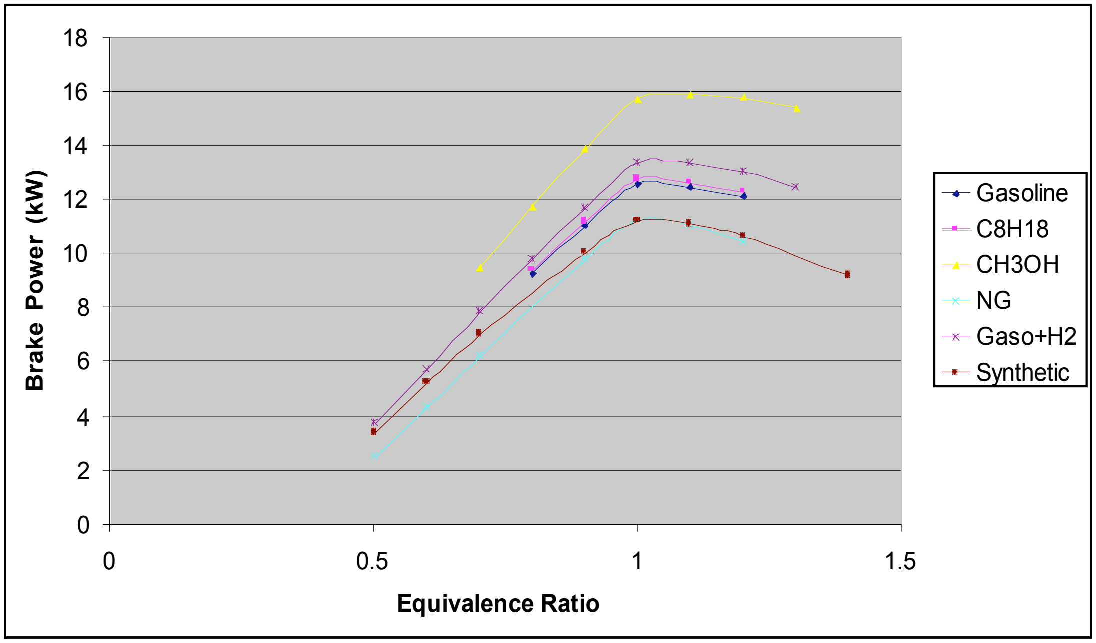

Fig. (1). Variation of brake power with equivalence ratio for different fuels.

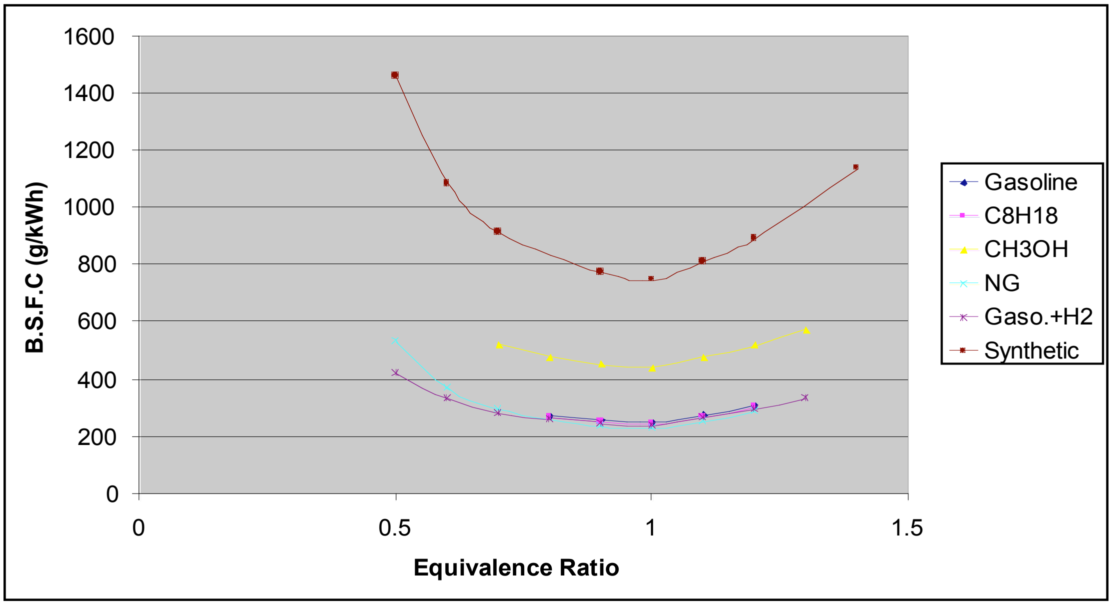

Fig. (2). Variation of brake specific fuel consumption with equivalence ratio for different fuels.

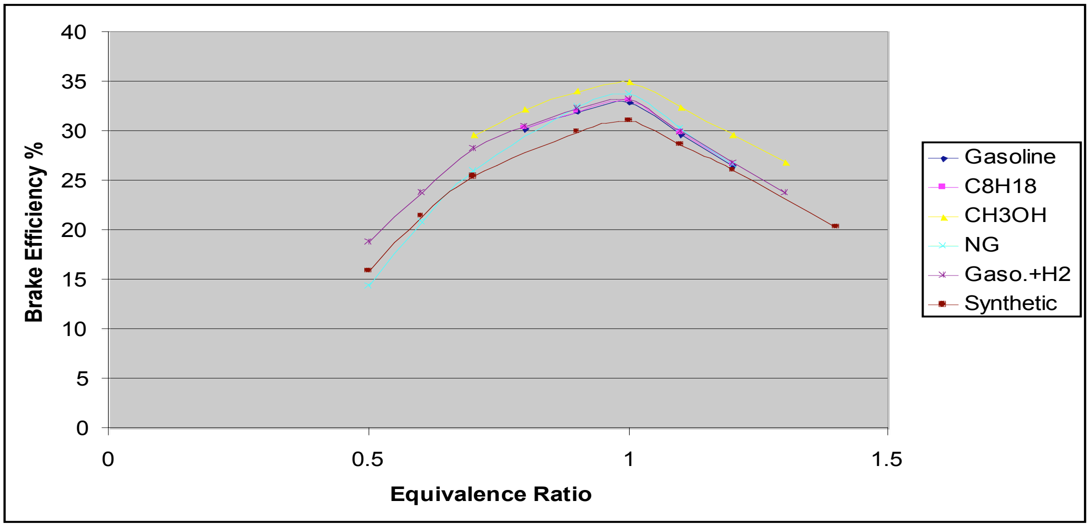

Fig. (3). Variation of brake efficiency with equivalence ratio for different fuels.

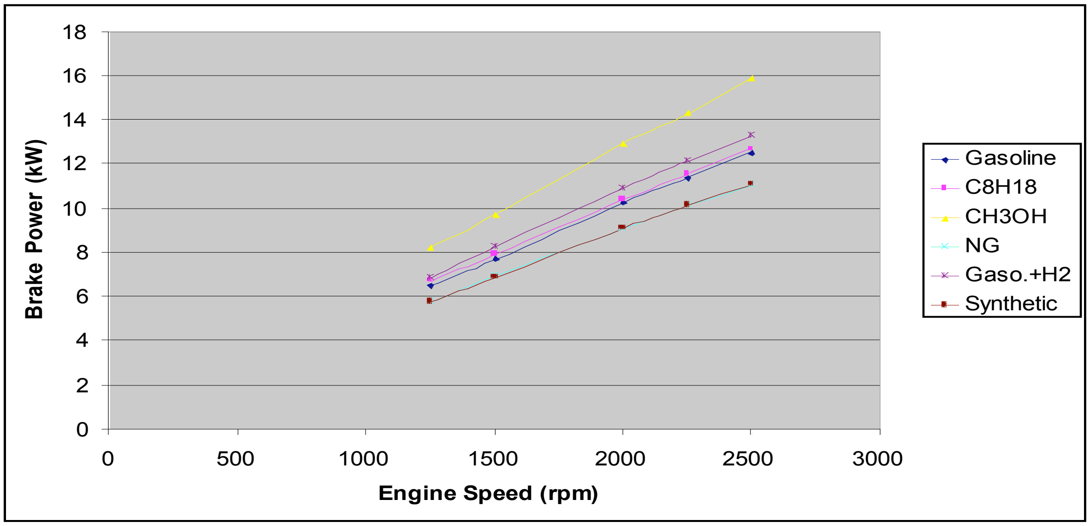

Fig. (4). Variation of brake power with engine speed for different fuels.

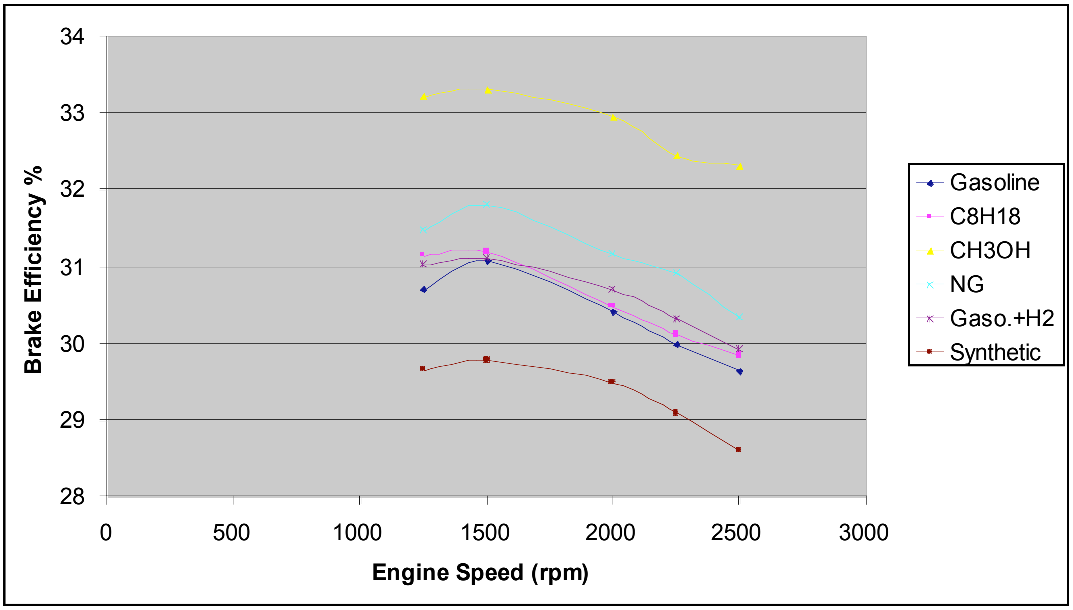

Fig. (5). Variation of brake efficiency with engine speed for different fuels.

Table **7** shows the resulting values of pressure, volume and temperature at the different points of the cycle for all the fuels. Hence, it becomes possible to draw Fig (**6**) which shows a nice comparison of the different fuels on the P-V diagram at their design points. However, they are not very different at BDC due to using the same engine for all the fuels.

Therefore, Fig. (**7**) was drawn to show the P-rc diagrams for the different fuels which have different design compression ratio depending on fuel properties. Now the differences are more obvious at BDC.

CONCLUSIONS

1. Iso-octane produces more brake power than gasoline by 1.2%, It shows an increase in brake thermal efficiency η by 0.5% and reduction in brake specific fuel consumption bsfc by 2.7%, which means that they are almost equivalent.
2. For the same energy input, Methanol produces more brake power than gasoline by 21%, It shows an increase in η by 11% and an increase in bsfc by 46%.
3. Natural gas produces less brake power than gasoline by 10%, It shows an increase in η by 13% and reduction in bsfc by 18%.
4. Gasoline-Hydrogen mixture produces brake power more than gasoline by 7%, It shows an increase in η by 2% and reduction in bsfc by 5%.
5. Synthetic fuel produces less brake power than gasoline by 12%, It shows a decrease in η by 2% and an increase in bsfc by 65%.
6. Spark advance from 0-15º BTDC increases the brake power by 5% and the η by 5%, and decreases bsfc by 4%. Spark advance from 15-25º BTDC increases the brake power by 2% and the η by 1.5%, and decreases bsfc by 1.8%.
7. The ratio of brake power to the engine speed increases by 15%. At low engine speed the η increases by 2% and the bsfc decreases by 1%. At high engine speed the η decreases by 1% and the bsfc increases by 2%.

Table 7. Pressure, Volume and Temperature with Different Fuels Throughout the Cycle

C_8H_{18}			$C_{7.12}H_{14.56}$			CH_3OH			$C_{1.1}H_{4.2}$			$C_{.58}H_{.84}O_{.58}$			Gasoline + H2		
P (kPa)	V*10³ (m³)	T (K)	P (kPa)	V*10³ (m³)	T (K)	P (kPa)	V*10³ (m³)	T (K)	P (kPa)	V*10³ (m³)	T (K)	P (kPa)	V*10³ (m³)	T (K)	P (kPa)	V*10³ (m³)	T (K)
101.4	0.648	280	101.4	0.654	279	101.4	0.634	281	101.4	0.643	303	101.4	0.626	303	101.4	0.654	277
1810.3	0.093	645	1804.6	0.095	640	2664.8	0.075	660	2013.5	0.088	731	3682.2	0.067	843	1803.7	0.094	593
9150.6	0.071	2963	9124.4	0.073	2941	14087	0.053	3086	10574	0.067	3256	12877	0.045	3443	9490.6	0.073	2813
3792.7	0.146	2484	3788.3	0.147	2471	3953.3	0.592	2405	3568.4	0.155	2623	4014.7	0.113	2712	3368.6	0.167	2289
641.25	0.612	1735	636.87	0.613	1728	700.92	0.634	1720	687.12	0.593	1790	534.45	0.584	1865	657.84	0.615	1642

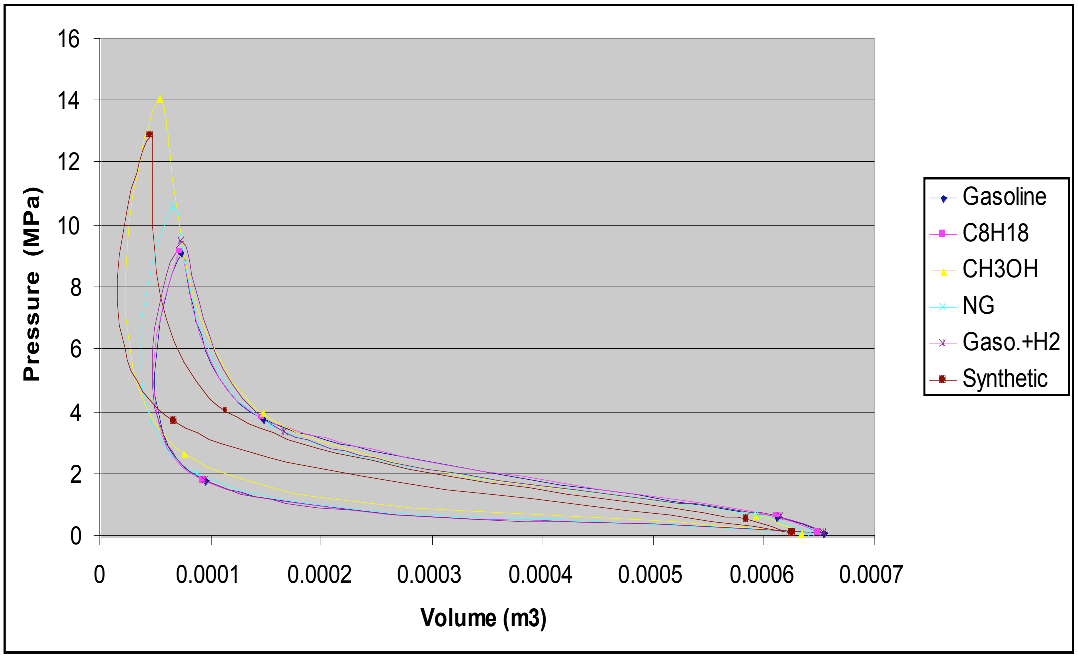

Fig. (6). Pressure volume diagram for different fuels at their design point.

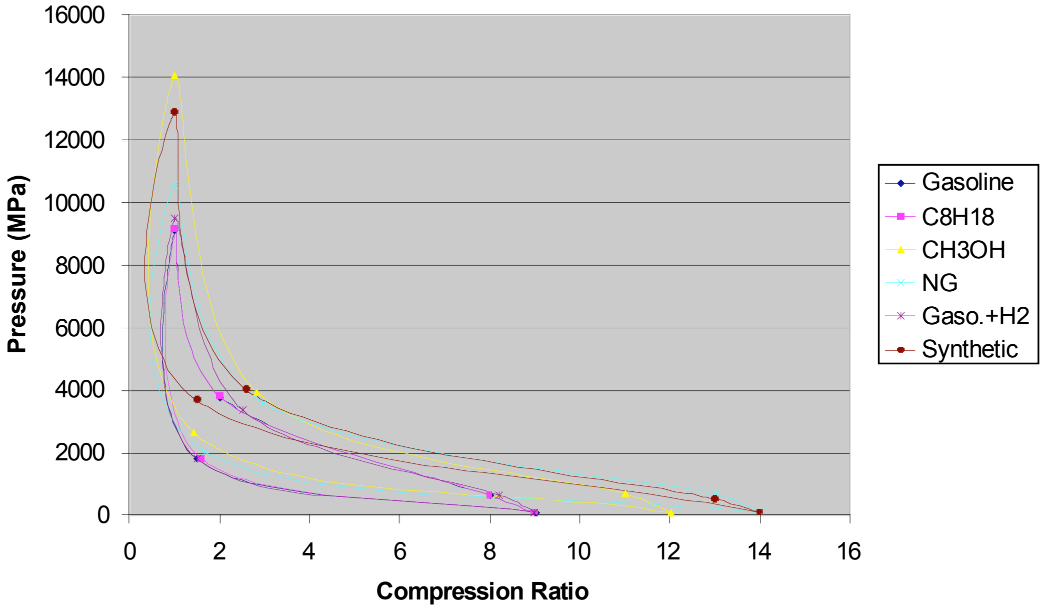

Fig. (7). Pressure *vs* compression ratio for different fuels.

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ABBREVIATIONS

ABDC = After bottom dead center degrees
AO = Wide open valve area for both valves m3
B = Bore m
P$_b$ = Brake power kW
bsfc = Brake specific fuel consumption g/kW.h
BBD = Before bottom dead center degrees
CIE = Compression ignition engine
CO = Carbon monoxide
EVO = Exhaust valve open degrees
EGR = Exhaust gas recirculation
F/A$_{act}$ = Actual fuel air ratio
(F/A)$_{st}$ = Stiochiometric fuel air ratio
H/C = Hydrogen – carbon ration
h$_{fg}$ = Heat of vaporization kJ/kg
IVO = Inlet valve open degree
L = Length of the connecting rod m
N = Engine speed rpm
NG = Natural gas
p = Pressure M Pa
RON = Research octane number
r$_c$ = Compression ratio
S = Stroke m
SO$_2$ = Sulphur dioxide
SA = Spark advance degrees
SIE = Spark ignition engine
TM = Intake manifold temperature K
T1 = Temperature at the start of the compression stroke
Tsp = Spontaneous ignition temperature K
Urp = Internal energy of reaction of the fuel kJ/kg
V = Volume m^3
VBDC = Volume at the bottom dead center m^3
Vd = Displacement volume m^3
VTDC = Clearance volume m^3

GREEK LETTERS

$ŋ_b$ = Brake thermal efficiency
$ŋ_v$ = Volumetric efficiency
Φ = Equivalence ratio

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