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REVIEW PAPER

# HYDROGEN AS A SPARK IGNITION ENGINE FUEL

*Review is made of the positive features and the current limitations associated with the use of hydrogen as a spark ignition engine fuel. It is shown that hydrogen has excellent prospects to achieve very satisfactory performance in engine applications that may be superior in many aspects to those with conventional fuels. A number of design and operational changes needed to effect the full potential of hydrogen as an engine fuel is outlined. The question whether hydrogen can be manufactured abundantly and economically will remain the limiting factor to its widespread use as an S.I. engine fuel in the future.*

Hydrogen has long been recognized as a fuel having some unique and highly desirable properties, for application as a fuel in engines [1]. It is the only fuel that can be produced entirely from the plentiful renewable resource water, albeit through the expenditure of relatively much energy. Its combustion in oxygen produces uniquely only water but in air it also produces some oxides of nitrogen. These features make hydrogen an excellent fuel to potentially meet the ever increasingly stringent environmental controls of exhaust emissions from combustion devices, including the reduction of green house gas emissions. Hydrogen as a renewable fuel resource can be produced through the expenditure of energy to replace increasingly the depleting sources of conventional fossil fuels. Accordingly, research into all aspects of hydrogen technology, especially in recent years has been truly massive and diversified. A concise statement and discussion of the positive features of hydrogen as a fuel and the associated limitations that are impeding its wide application as an engine fuel are both necessary and needed.

Hydrogen gas has been in wide use as a fuel for quite a long time [2]. Various industrially produced fuel gas mixtures such as coal gas, water gas and synthesis gas contain varying concentrations of hydrogen in association with a wide range of other gases, were in use is a variety of applications including domestically. Additionally, enormous quantities of hydrogen are used increasingly as a raw material in a wide range of applications in the chemical industry, particularly in the upgrading of conventional fuel resources [3].

The viability of hydrogen as a fuel in general and in engine applications in particular, is critically dependent on the effective, economic and satisfactory solution of a number of remaining key limiting problems. These limitations that hinder its widespread application as an engine fuel are primarily related to its *Production, Storage, Portability, Transport and Purity*. These limitations are far more serious than those facing the current and future applications of other fuels, including natural gas.

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## Hydrogen Needs to be Manufactured

The main feature of hydrogen as a fuel is that it does not occur in its free state naturally. The gas must be manufactured from a wide variety of possible sources while requiring much energy and capital resources [4]. Hydrogen can be produced from fossil fuels such natural gas, oil and coal, mainly via their reforming with steam or through partial oxidation. These approaches are often through the application of suitable catalysts; but non–catalytic approaches are also commonly used. The hydrogen produced through these measures will be in association with a wide range of products, including carbon–bearing compounds such as carbon monoxide and dioxide. Such fuel mixtures of widely varying composition are processed usually further to increase the purity of the hydrogen produced, whether for applications in the chemical and petro–chemical industry or for combustion in conventional power and heating devices. However, for the increasingly important application of hydrogen to fuel cells, ultra high purity hydrogen is required which makes the hydrogen produced by these methods often of unacceptable quality [5].

Hydrogen can be produced in sufficiently high purity for fuel cell applications through the electrolysis of water with thermal efficiency ranging from 60% to 75%, [6]. Much of the electrical power required for hydrogen production is often supplied by hydroelectric sources. However, depending on the availability and cost, the electric energy used may be generated *via* nuclear power or thermal power stations burning fossil fuels. Then the overall efficiency of hydrogen production from fossil fuels on energy basis will be lower than 35% [7].

Also, in principle, electric power can be produced occasionally in very limited quantities from other energy sources such as those derived from solar, wind, sea waves and tides. At present, the prospects of producing hydrogen in any significant quantities *via* biological processes, chemical reactive cycles and the oxidation of metals remain mainly remote. Typically, the cost of hydrogen production ranges from about only twice to more than ten times higher than the cost of production of pipeline natural gas on energy equivalent basis.

**Hydrogen, Storage, Portability and Transport**

In engine applications the storage and portability of adequate mass of hydrogen for practical applications remain one of the most difficult problems yet to be overcome. Hydrogen can be stored as a compressed gas in suitably designed high–pressure vessels. However, the very low density of hydrogen in comparison to other gaseous fuels, dictates that extremely high–pressure cylinders that are sufficiently light in weight and compact in volume need to be devised and used. The compression of the gas to such high pressures requires the expenditure of much expensive compression work and the provision of the necessary infra structure. Also, these hydrogen gas cylinders would add significantly to the total weight, cost and bulkiness of the fuel installation. Much progress has been made in recent years to reduce the effects of these limitations and the associated hazards. However, much progress is needed further to render this mode of carrying the hydrogen sufficiently attractive and on par with other conventional fuels practices.

Hydrogen also can be carried on board vehicles and engine installations in the form of various metallic hydrides that would permit the controlled release of hydrogen through the supply of heat, often from the engine exhaust gas or its cooling water. These methods are of limited usefulness as they add much cost and weight while reducing the flexibility of the fuel system and contributing to an increase in undesirable emissions [8]. Also, the carrying of hydrogen within special alloys of some uncommon metals remains an uneconomic option and has very limited near future potential.

The carrying of hydrogen as a cryogenic liquid has its serious limitations. The work and infrastructure required to liquefy hydrogen are much too expensive and energy intensive to become widely usable. The energy consumed in the liquefaction process can be upto around 30% of the heating value of the hydrogen, [3]. Also, the cryogenic tanks needed to carry the liquid hydrogen, despite the very substantial progress made in recent years in their design, safety and manufacture remain relatively expensive and bulky. In any case, the operation of engines on cryogenic hydrogen also has its many challenging problems of design, operation, safety and maintenance.

The technology for the bulk carrying and distribution of hydrogen over distances is sufficiently advanced and adequately manageable via special pipelines and marine, rail and road transport.

**Some Relevant Properties**

Some of the key overall properties of hydrogen that are relevant to its employment as an engine fuel are listed in Table 1. These are compared to the corresponding values of methane, the other promising gaseous fuel for engine applications and those of iso–octane vapor representing gasoline [9].

It is evident that hydrogen is a remarkably light gaseous fuel that requires on volume basis the least amount of air for stoichiometric combustion (2.39 versus 59.6 for iso–octane); while on mass basis it requires the highest relative mass of air. Its combustion is also associated with a substantial molar contraction of around 15%. Its heating value on mass basis is the highest; but on volume basis it is the lowest. Also since its product of combustion in air is only water, there is a significant difference between its higher and lower heating value. However, its energy release by combustion per unit mass of stoichiometric mixture is one of the highest.

Hydrogen has some remarkably high values of the key properties for transport processes, such as kinematic

*Table 1. Some Comparative Properties of Hydrogen, Methane and Iso–Octane*

| Property | Hydrogen | Methane | Iso–Octane |
|---|---|---|---|
| Density at 1 atm and 300K (kg/m$^3$) | 0.082 | 0.717 | 5.11 |
| Stoich. Composition in Air (% by volume) | 29.53 | 9.48 | 1.65 |
| Stoich. Fuel/Air Mass Ratio | 0.029 | 0.058 | 0.0664 |
| No. of Moles After Combustion to Before | 0.85 | 1.00 | 1.058 |
| HEATING VALUES | | | |
| H.H.V. (MJ/kg)<br>L.H.V. (MJ/kg) | 141.7<br>119.7 | 52.68<br>46.72 | 48.29<br>44.79 |
| H.H.V. (MJ/m$^3$)<br>L.H.V. (MJ/m$^3$) | 12.10<br>10.22 | 37.71<br>33.95 | 233. 29<br>216.38 |
| Combustion Energy per kg of stoich mixt. (MJ) | 3.37 | 2.56 | 2.79 |
| Kinematic Viscosity At 300K (mm$^2$/s) | 110 | 17.2 | 1.18 |
| Thermal Conductivity At 300K (mW/m K) | 182.0 | 34.0 | 11.2 |
| Diffusion Coefficient Into Air at NTP (cm$^2$/s) | 0.61 | 0.189 | 0.05 |

*Table 2. Some Comparative Combustion Properties of HydrogenWith Methane and Gasoline*

| Property | Hydrogen | Methane | Gasoline |
|---|---|---|---|
| Flammability Limits (% by volume) | 4–75 | 5.3–15.0 | 1.2–6.0 |
| Minimum Ignition Energy (mJ) | 0.02 | 0.28 | 0.25 |
| Laminar Flame Speed at N.T.P. (m/s) | 1.90 | 0.38 | 0.37–0.43 |
| Adiabatic Flame Temp. (K) | 2318 | 2190 | ~2470 |
| Autoignition Temperature (K) | 858 | 813 | ~500–750 |
| Quenching Gap at NTP (mm) | 0.64 | 2.03 | ~2.0 |

viscosity, thermal conductivity and diffusion coefficient, in comparison to those of the other two fuels. Such differences together with its extremely low density and low luminosity help to give hydrogen its unique diffusive and heat transfer characteristics.

Table 2 lists some combustion properties that have much influence on the potential behavior of hydrogen as a fuel in general and for engine applications in particular. The corresponding values for the other representative fuel methane are also shown for comparison. It can be seen that hydrogen has a remarkably wide flammable mixture range in air to permit extremely lean or rich mixtures support combustion. It requires also a remarkably low minimum amount of energy to effect ignition with extremely fast resulting flames in comparison to those of mixtures of methane or even iso–octane with air. However, the values of its spontaneous ignition temperatures are quite similar to those of the other two fuels and the values of its maximum adiabatic combustion temperature in air are only a little higher.

The chemical kinetics of the combustion of hydrogen in air is well understood at present and its oxidation reaction rates and the associated temporal variation of the concentrations of the reactive species can be predicted well. Mainly relatively fast and nearly thermally neutral branching chain reactions are involved. Hydrocarbon fuels oxidation on the other hand, involves normally thermally significant chain reactions that contain relatively slower endothermic reaction steps that are associated with fuel breakdown. These differences together with those in the thermodynamic and transport properties of hydrogen, contribute in a big way to the substantially different combustion characteristics of hydrogen from those of other common fuels.

## Hydrogen Fueled Engine Applications

The use of hydrogen as an engine fuel has been attempted with varying degrees of success by numerous investigators over many decades, and much information about their findings is available in the open literature [2]. However, these reported performance data do not necessarily display consistent agreement between the various investigators. There is also a tendency to focus on results obtained in specific engines and over narrowly changed operating conditions. Moreover, the increasingly greater emphasis being placed on the nature of emissions and efficiency considerations often renders much of the very early work fragmentary and mainly of historical value.

Obviously, there is a need to be aware of what has been achieved in this field while focusing both on the attractive features as well as the potential limitations and associated drawbacks that need to be overcome for hydrogen to become a widely accepted and used fuel for engine applications. Also, there is a need to indicate practical steps for operating and design measures to be developed and incorporated for hydrogen to achieve its full potential as an attractive and superior engine fuel.

The present contribution focuses primarily on hydrogen applications in conventional spark ignited piston engines. However, other applications involving other forms of work producing devices have been considered and shown to have equally their own attractive features that could have the potential even to surpass in their superiority those associated with the spark–ignited engine. For example, there is much information available and development work relating to hydrogen–fueled compression ignition engines of the dual fuel type, homogeneous charge compression ignition engines, commonly known recently as HCCI engines and engines where ignition is effected, either through surface or catalytic ignition [10,11].

## Hydrogen as an Engine Fuel

There are a number of unique features associated with hydrogen that make it remarkably well suited to engine applications. Some of these most notable features are the following:

i – Hydrogen, over wide temperature and pressure ranges, has very high flame propagation rates within the engine cylinder in comparison to other fuels. These rates remain sufficiently high even for very lean mixtures that are well away from the stoichiometric mixture region. The associated energy release is also so fast that the combustion duration, as shown typically in Figure 1 tends to be short and contributes towards producing high power output efficiencies and high rates of pressure rise following spark ignition [12].

ii – The lean operational limit mixture in a spark ignition engine when fuelled with hydrogen is very much lower than those for other common fuels, as shown typically in Figure 2 for a range of compression ratios. This permits stable lean mixture operation and control in hydrogen fueled engines [13].

iii – The operation on lean mixtures, in combination with the fast combustion energy release rates around

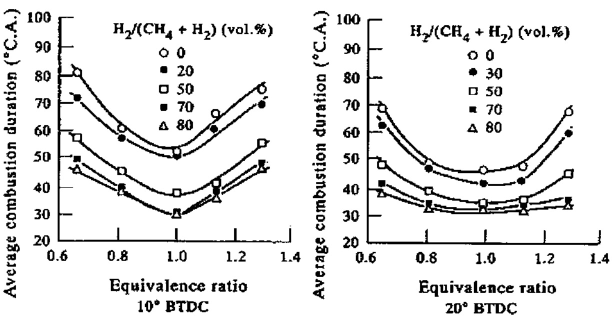


*Figure 1. Typical variations in the length of the combustion period in degrees with equivalence ratio for a range of $H_2$–$CH_4$ mixtures for two spark timings at a compression ratio of 8.5:1 and 900 rev/min, [18].*

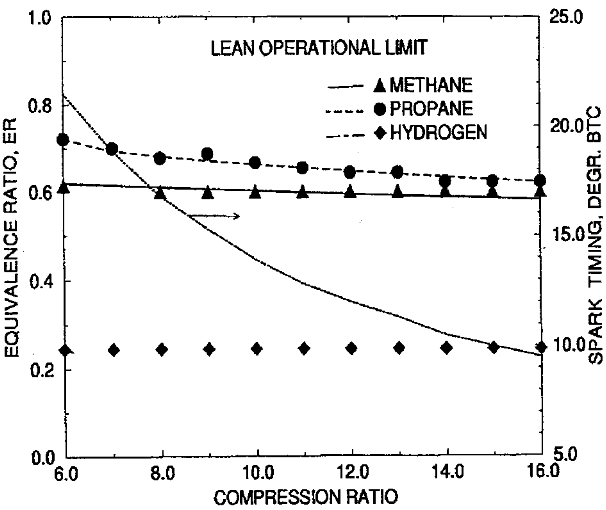


*Figure 2. Variations of the lean operational limits with changes in compression ratio for different gaseous fuels at 900 rev/min, [13].*

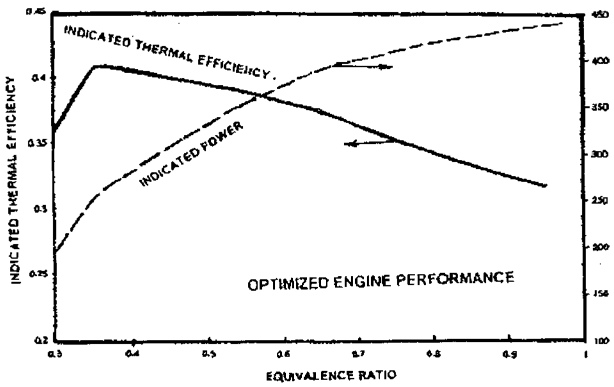


*Figure 3. Typical variations in the indicated power output and efficiency with leaning of equivalence ratio for hydrogen operation using optimum spark timing, [14].*

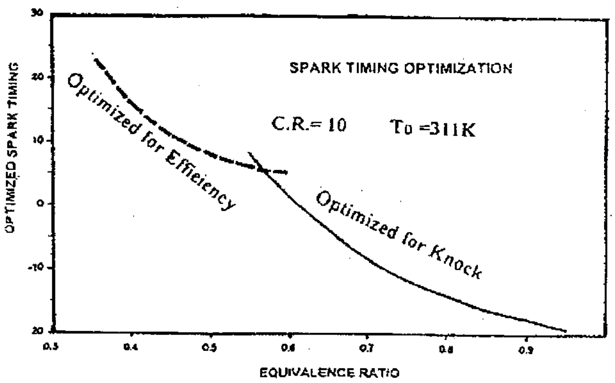


*Figure 4. Typical variations in spark timing for optimum efficiency and avoidance of knock for lean mixture operation with hydrogen, [14].*

top dead center associated with the very rapid burning of hydrogen–air mixtures results in high output efficiency values[14]. Of course, such lean mixture operation leads simultaneously to a lower power output for any engine size, as shown typically in Figure 3.

iv – One of the most important features of hydrogen engine operation is that it is associated with less undesirable exhaust emissions than for operation on other fuels. As far as the contribution of the hydrogen fuel to emissions, there are no unburned hydrocarbons, carbon monoxide, carbon dioxide, and oxides of sulfur, smoke or particulates [15]. The contribution of the lubricating oil to such emissions in well–maintained engines tends to be rather negligible. Only oxides of nitrogen and water vapor are the main products of combustion emitted. Also, with lean operation the level of NOx tends to be smaller than those encountered with operation on other fuels [16].

v – The fast burning characteristics of hydrogen permit much more satisfactory high–speed engine operation [17]. This would allow an increase in power output with a reduced penalty for lean mixture operation. Also, the extremely low boiling temperature of hydrogen leads to fewer problems encountered with cold weather operation.

vi – Varying the spark timing in hydrogen engine operation represents an unusually effective means for improving engine performance and avoidance of the incidence of knock, Figure 4. Also, the heat transfer characteristics of hydrogen combustion in engines are significantly different from those in engines operating on other fuels. The radiative component of heat transfer tends to be small yet the convective component can be higher especially for lean mixture operation.

vii – The sensitivity of the oxidation reactions of hydrogen to catalytic action with proper control can be made to serve positively towards enhancing engine performance.

### Some Other Positive Features of Hydrogen for Engine Applications

In addition to the above unique features associated almost exclusively with hydrogen, a number of others can be cited in support of hydrogen applications in engines. The following is a listing of some of the main of these features:

– Less cyclic variations are encountered with hydrogen than with other fuels, even for very lean mixture operation. This leads to a reduction in emissions, improved efficiency, and quieter and smoother operation.

– Hydrogen can have a high effective octane number mainly because of its high burning rates and its slow preignition reactivity.

– Hydrogen has been shown to be an excellent additive in relatively small concentrations, to some common fuels such as methane [18].

– Its gaseous state permits excellent cold starting and engine operation.

– Hydrogen engines are more amenable to high–speed engine operation mainly due to the associated fast burning rates.

– Less spark advance is usually needed, which contributes to better efficiencies and improved power output as the bulk of the heat release by combustion can be completed just after the TDC region.

– Hydrogen engine operation can be associated with less heat loss than with other fuels

– Moderately high compression ratio operation is possible with lean mixtures of hydrogen in air, which permits higher efficiencies and increased power output as shown in Figure 5.

– Hydrogen engines are very suitable for cogeneration applications since the energy transfer due to condensing some water vapor can add up significantly to the thermal load output and the corresponding energy efficiency.

– Hydrogen unlike most other commercial fuels is a pure fuel of well–known properties and characteristics, which permits continued and better optimization of engine performance.

– The reaction rates of hydrogen are sensitive to the presence of a wide range of catalysts. This feature

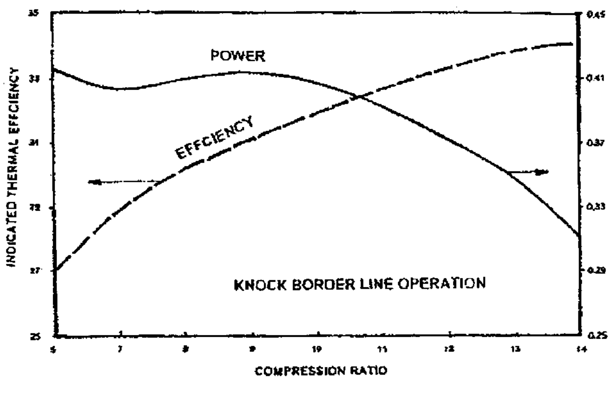


*Figure 5. Typical variations in indicated power output and efficiency with changes in compression ratio when using optimum spark timing for border line knock,* [14].

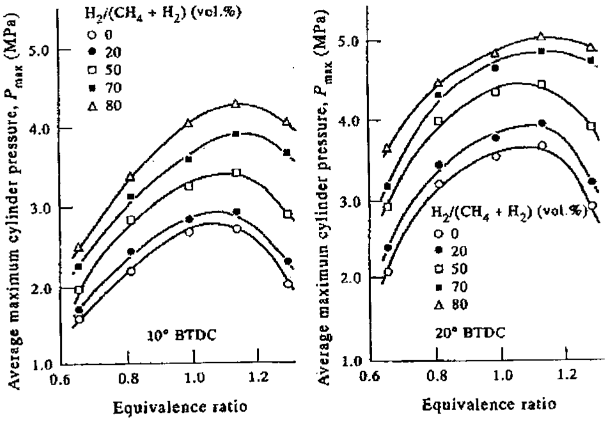


*Figure 6. Typical variations in the maximum cylinder pressure with changes in equivalence ratio when operating on a range of fuel mixtures of hydrogen and methane for two spark timings,* [18].

helps to improve its combustion and the treatment of its exhaust emissions.

– The thermodynamic and heat transfer characteristics of hydrogen tend to produce high compression temperatures, as shown in Figure 6 that contribute to improvements in engine efficiency and lean mixture operation.

– Hydrogen high burning rates make the hydrogen fueled engine performance less sensitive to changes to the shape of the combustion chamber, level of turbulence and the intake charge swirling effect.

– Hydrogen can tolerate better the presence of diluents. This would allow a better exploitation of low heating value fuel mixtures.

– Hydrogen can be employed quite effectively with oxygen–enriched air such as resulting from the electrolysis of water.

– The spark ignition engine is quite tolerant to not so pure fuel, unlike the fuel cell.

– The gas is highly diffusive and buoyant which make fuel leaks quickly dispersant, reducing the fire and explosion hazards associated with hydrogen engine operation.

### Some Limitations Associated With Hydrogen Engine Applications

– Hydrogen as a compressed gas at 200 atmospheres and atmospheric temperature has merely around 5% of the energy of gasoline of the same volume. This is a major shortcoming particularly for transport applications.

– Engines fueled with hydrogen suffer from reduced power output, due mainly to the very low heating value of hydrogen on volume basis and resorting to lean mixture operation.

– The mass of the intake air is reduced for any engine size because of the relatively high stoichiometric hydrogen to air ratio.

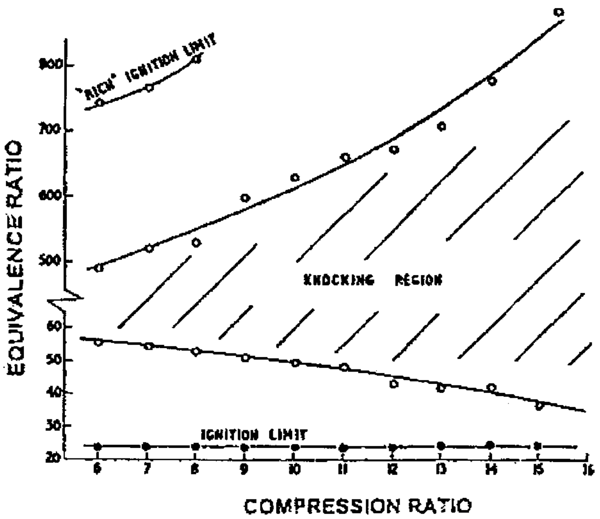


*Figure 7. Variations of operational limits for ignition and knock with compression ratio changes for hydrogen operation at ambient intake conditions,* [20].

– There are serious potential operational problems associated with the uncontrolled preignition and backfiring into the intake manifold of hydrogen engines [19].

– Hydrogen engines are prone to produce excessively high cylinder pressure and the onset of knock as shown in Figures 6 and 7. The equivalent octane number of hydrogen is rather low in comparison to gasoline and methane [20].

– The high burning rates of hydrogen produce high pressures and temperatures during combustion in engines when operating near stoichiometric mixtures. This may lead to high exhaust emissions of oxides of nitrogen.

– There are serious limitations to the application of cold exhaust gas recirculation for exhaust emissions control.

– Hydrogen engines may display some serious limitations to turbo charging.

– There are always some potential for increased safety problems with hydrogen operation [21].

– Hydrogen engine operation may be associated with increased noise and vibrations due mainly to the high rates of pressure rise resulting from fast burning. Great care is needed to avoid materials compatibility problems with hydrogen.

– In certain applications such as in very cold climates the exhaust emission of steam can be undesirable feature leading to poor visibility and increased icing problems.

– The sensitivity of hydrogen–air mixtures to catalytic action can be occasionally undesirable as it may contribute to reduced safety and poorer control of the combustion process.

– Hydrogen requires a very low ignition energy, which leads to uncontrolled preignition problems.

– There is an increased potential for undesirable corrosion and lubricating oil contamination due to exhaust water vapor condensation.

– There can be an increased potential for operational durability problems with lubricants.

– Heat transfer losses can be high, yet under some conditions they can be quite low.

– A hydrogen engine needs to be some 40% to 60% larger in size than for gasoline operation for the same output. This could impose some reduction to engine speed, increased mechanical and motoring losses and reduced tolerance to knocking. Also, some engine design modifications are needed.

## Some Measures for Improving the Operational Features of SI Hydrogen Engines

A number of possible changes to the design and operational features of a hydrogen fueled S.I. engine can be suggested to affect the full potential of hydrogen in engine applications. These measures can include the following:

i – Employ lean mixture operation with wide–open throttle. Means are to be provided to apply optimal variable partial throttling at extremely lean mixtures to effect better engine performance.

ii – There is a need with hydrogen as a fuel for uniquely optimized variations in the spark timing throughout so as to improve engine performance while avoiding knock, as shown in Figure 4. The variation in spark timing with hydrogen is more effective in controlling the combustion process than with other fuels.

iii – Optimum spark ignition characteristics in terms energy, spark plug gap size and material, plug geometry, electrical insulation etc. need to be employed

iv – Higher engine rotational speeds can be used to increase the power output of an engine operating on hydrogen while maintaining high efficiency and knock free operation

v – It is preferable to have timed injection of the hydrogen whether within the manifold or directly into the cylinder optimized for injection duration, timing and pressure. This is important especially for the avoidance of preignition and backfiring. Provision of some water injection when needed can be also made [22].

vi – Higher compression ratios can be applied satisfactorily to increase the power output and efficiency, mainly because of the relatively fast burning characteristics of the very lean hydrogen–air mixtures.

vii – Carefully controlled cooling of exhaust gas recirculation can be applied for knock avoidance and control. For lean mixture operation with hydrogen suitably heated exhaust gas recirculation can be used.

viii – Direct hydrogen gas injection into the cylinder can be applied to produce suitably stratified mixtures for better performance and reduced exhaust emission.

ix – In order to produce a power output comparable with that obtained with other fuels, larger size engines are needed. This will increase somewhat the frictional and motoring losses of the engine. Accordingly, greater care is needed to reduce these losses so that to retain the high efficiency of hydrogen operation.

x – The volumetric efficiency needs to be maximized so as to enhance the power output.

xi – Uniquely compatible and specially designed turbochargers need to be used for hydrogen engine applications.

xii – There is a need to give a greater attention to heat transfer. Also, hotter water jacket temperatures than normally employed for gasoline operation are needed for lean operation. Cooler temperatures need to be employed, however, for high loads with hydrogen.

xiii – Resort to catalytically reduce exhaust NOx emissions and any unconsumed hydrogen. Both of these components of the exhaust gas tend to be very low in concentration, especially for lean mixture operation. There are also excellent prospects to enhance the combustion process within the engine cylinder through the suitable provision of catalytic surfaces.

xiv – Further improvement in performance can be obtained by having the design features of the combustion chamber and its surfaces suitably optimized for hydrogen operation.

xv – Variable valve timing needs to be incorporated and optimized to effect higher volumetric efficiency and better control of exhaust gas recirculation.

xvi – Hydrogen compatible lubricants and materials need to be ensured throughout.

xvii – Appropriate safety precautions must be maintained under all possible operating conditions and scenarios.

When these measures are implemented in the design and operation of hydrogen fuelled spark ignition engines then most of the apparent limitations associated with hydrogen as an engine fuel will disappear. Moreover, hydrogen engine operation can be shown to possess operational characteristics that are superior to those associated with other more conventional fuels.

## Conclusion

• There are excellent prospects to achieve very satisfactory S.I. Engine operation with hydrogen as the fuel

• The question of whether hydrogen can be obtained abundantly and economically remains yet to be answered satisfactorily.

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## REFERENCES

[1] R.O. King, M. Rand, "The Hydrogen Engine", Canad. J. of Techn. **33** (1955) 445–469.

[2] R. A. Erren, W.H. Campbell, "Hydrogen a Commercial Fuel for Internal Combustion Engines and Other Purposes", J.of Inst. of Fuel **6** (1933) 277–290.

[3] K.E. Cox, K.D. Williamson, "Hydrogen: Its Technology and Implications", Vol I to V, CRC Press, 1977.

[4] T.T. Maxwell, J.C. Jones, "Alternative Fuels –Missions, Economics and Performance", S.A.E. Publishers, 1995.

[5] A.J. Appleby, "Fuel Cells and Hydrogen Fuel", Int. J. of Hydrogen Energy **19** (1994) 175–180.

[6] C.A. Kukkonen, M. Shelef, "Hydrogen as an Alternative Fuel: 1993 Update", SAE paper #940766, 1994

[7] M. Steinberg, H.C. Cheng, "Modern and Prospective Technologies for Hydrogen Production from fossil Fuels", Int. J. Hydrogen Energy **14** (1989) 797–803.

[8] E.P. Silva, W.L.R. Gallo, J. Szajner, E.G. Amaral, C.R. Bezerra, "State of the Art in the Use of Hydrogen as an Automotive Fuel", SAE paper # 931706E, 1993.

[9] J.W. Rose, J.R. Cooper, "Technical Data on Fuels", Scottish Academic Press, 1977.

[10] G.A. Karim, S.R. Klat, "Hydrogen as a Fuel in Compression Ignition Engines", J. of Mech. Eng. – ASME, April 1976, pp.3439.

[11] M. Ikegami, K. Miwa, M. Shioji, "A Study of Hydrogen Fuelled Compression Ignition Engines", Int. J. of Hydrogen Energy, **7** (1982) 341–353.

[12] Y. Al–Alousi, "Examination of the Combustion Processes and Performance of a Spark ignition Engine Using a Data Aquisition System", Ph.D. thesis of University of Calgary, Mechanical Engineering, November 1982.

[13] B. Shrestha, G.A. Karim, I. Wierzba, "Examination of Operational Limits in Gas Fueled Spark Ignition Engines", S.A.E. paper No. 2000–01–1944. – SP–1549.

[14] H. Li, G.A. Karim, "Experimental and Predictive Performance of a S.I. Engine", to be published.

[15] L.M. Das, "Exhaust Emission Characterization of Hydrogen Operated Engine System", Int. J. of Hydrogen Energy **15** (1990) 833.

[16] M. Shioji, N. Inoue, "Performance and NOx formation in a Hydrogen Premixed–Charge Engine", Proceedings of 12th World Hydrogen Confrence, 1998, 1469–1478.

[17] M. Shioji, T. Ishayama, "Feasibility of the High Speed Hydrogen Engine", Int. Symposium on Hydrogen Energy", Osaka, Japan, Jan. 2002, pp.1–9.

[18] G.A. Karim, I. Wierzba, Y. Al–Alousi, "Methane–Hydrogen Mixtures as Fuel", Int. J. of Hydrogen Energy **21** (1996) 625–634.

[19] R. Sierens, E. Rosseel, "Backfire Mechanism in a Carburetted Hydrogen Fuelled Compression Ignition Engine", Proceedings of 12th World Hydrogen Conference, 1998, pp.341–353.

[20] G.A. Karim, S. R. Klat, "The Knock and Autoignition Characteristics of Some Gaseous Fuels and Their Mixtures", J. of the Institute of Fuel, March 1966, pp.109–119.

[21] J. Hord, "Is Hydrogen a Safe Fuel", Int. J. of Hydrogen Energy, **3** (1978) 157–176.

[22] J.M. Norbeck, et al., "Hydrogen Fuel for Surface Transportation", Published by S.A.E., 1996.

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Dr. Karim has carried out consulting and advisory assignments on fuel, safety, engines, and combustion topics for industrial concerns, official agencies, etc. all over the world and has served on numerous occasions as an expert witness in litigation in matters relating to combustion, and fuel problems and devices. Moreover, he has been recruited as advisor, evaluator of research and academic programs for a number of universities and research institutions in various countries.

Dr. Karim has supervised numerous Ph.D. and M.Sc. students, mainly in combustion and engines related problems. Relatively early in his career, 1972, London University, England awarded him the distinguished degree of Doctor of Science in Combustion Engineering. More recently he was elected to be a Fellow of the Society of Automotive Engineers, S.A.E. He was also selected to be the Honda Lecturer of the Am.Soc. of Mech. Eng. Int. for the year 2000.