

HYDROGEN INTERNAL COMBUSTION ENGINE

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Abstract— Hydrogen internal combustion engine vehicles present much of the same promise to reduced carbon dioxide emissions. Proponents envision hydrogen Internal Combustion Engine as a bridging technology from gasoline vehicles to hydrogen internal combustion engine. This paper examines the hydrogen Internal Combustion Engine technology, focusing on relevant aspects such as power, fuel economy, tank size, and the state of the technology. An economic analysis is then performed to examine the potential implications of widespread adoption of hydrogen Internal Combustion Engine vehicles. The case for hydrogen Internal combustion engine depends most on key uncertainties in the evolution of vehicle and production technology, the cost of crude oil, and the valuation of carbon dioxide emission reductions. This analysis indicates that promoting hydrogen internal combustion engine vehicles may be a sensible policy goal, but a more prudent policy would first promote gasoline-electric hybrids.

Index Terms— carbon dioxide, hydrogen, technological change, internal combustion engines, fuel cells.

I. INTRODUCTION

Fossil fuels (i.e., petroleum, natural gas and coal), which meet most of the world's energy demand today, are being depleted rapidly. Also, their combustion products are causing global problems, such as the greenhouse effect, ozone layer depletion, acid rains and pollution, which are posing great danger for our environment, and eventually, for the total life on our planet. Many engineers and scientists agree that the solution to all of these global problems would be to replace the existing fossil fuel system with the clean hydrogen energy system. Hydrogen is a very efficient and clean fuel. Its combustion will produce no greenhouse gases, no ozone layer depleting chemicals, and little or no acid rain ingredients and pollution. Hydrogen, produced from renewable energy (solar, wind, etc.) sources, would result in a permanent energy system which would never have to be changed.

Fossil fuels possess very useful properties not shared by non-conventional energy sources that have made them popular during the last century. Unfortunately, fossil fuels are not renewable. In addition; the pollutants emitted by fossil energy systems are greater and more damaging than those that might be produced by a renewable based hydrogen energy system (Winter C.J. 1987). Since the oil crisis of 1973, considerable progress has been made in the search for alternative energy sources. A long term goal of energy research has been the seek for a method to produce hydrogen fuel economically by

splitting water using sunlight as the primary energy source. Much fundamental research remains to be done. Lowering of worldwide CO₂ emission to reduce the risk of climate change (greenhouse effect) requires a major restructuring of the energy system. The use of hydrogen as an energy carrier is a long term option to reduce CO₂ emissions.

The production of hydrogen from non-polluting sources is the ideal way. The amount of solar energy reaching the Earth is enough to supply mankind with many thousand times the energy it presently requires. This energy supply is, however, neither constantly available nor distributed equally over the surface of the globe. Indeed, the places where mankind's energy consumption is highest are not the places where the Sun's irradiance is at a maximum. If the Sun's daytime energy supply also has to be used at night or its summer supply also in the winter, if the solar energy available at places with high insulation is also needed at places with low insulation and large energy demands, then it is physically impossible to meet these needs directly with the primary energy of solar irradiance. Solar hydrogen is a clean energy carrier.

Electrolytic hydrogen is made from water and becomes water again. Hydrogen obtained from solar energy is ecologically responsible along its entire energy conversion chain. At only one link of the chain can a pollutant, nitrogen oxide, arise; and this occurs only if the hydrogen is not combined with pure oxygen, but using air as an oxidant, such as in reciprocating piston engines or in the gas turbines of automobiles or aircraft. At the high reaction temperatures which arise in such places, the oxygen and nitrogen in the air can combine to form nitrogen oxide.

Energy stored in hydrogen would be available at any time and at any place on Earth, regardless of when or where the solar irradiance, the hydropower, or other renewable sources such as biomass, ocean energy or wind energy was converted. The fundamental variations in the times and places of solar energy supply and human energy demands can be overcome using hydrogen. Solar hydrogen makes solar energy as storable and transportable as oil and natural gas are by nature, but without the burden of their negative environmental impact. Solar hydrogen combines the advantages of hydrocarbons (storability and transportability) with the advantages of solar energy (ecological acceptability, renewability and low risk). Solar hydrogen has no need for the carbon atom, which makes the hydrocarbons almost infinitely storable at room temperatures, but is also the reason for their negative

ecological impact. The worldwide photo-voltaic market has grown rapidly in recent years, a growth that will continue in many areas, especially as grid-connected PV applications.

Hydrogen is a carbon-free fuel which oxidizes to water as a combustion product. The generated water becomes, together with renewable primary energy for splitting it, a source of clean and abundant energy in a carbon-free, natural cycle. In the development of all new energy options, hydrogen necessarily will play an important role because of its ability to supplement any energy stream and apply to any load. Hydrogen will act as a solar energy storage medium and transform solar energy into a transportation fuel. The economies of rich nations and the lifestyle of most of their residents depend on cars and light trucks. These vehicles contribute most of the carbon monoxide (CO), carbon dioxide (CO₂), volatile organic compounds (hydrocarbons, HC), and nitrogen oxides (NO_x) emitted in cities. It is clear that motor vehicles are important to the economy and lifestyle. Importance goes well beyond the direct consumer expenditures and indirect (support) expenditures, such as roads, suburbs, oil wells, refineries, and service stations.

The use of hydrogen as an engine fuel has been attempted on very limited basis with varying degrees of success by numerous investigators over many decades (Erren RA, Campbell WH. 1933), and much information about their findings is available in the open literature.

II. HYDROGEN AS AN ENGINE FUEL

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, tends to be short and contributes towards producing high-power output efficiencies and high rates of pressure rise following spark ignition. The lean operational limit mixture in a spark ignition engine when fuelled with hydrogen is very much lower than those for other common fuels. This permits stable lean mixture operation and control in hydrogen fueled engines. The operation on lean mixtures, in combination with the fast combustion energy release rates around top dead center associated with the very rapid burning of hydrogen-air mixtures results in high-output efficiency values.

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 unburnt hydrocarbons, carbon monoxide, carbon dioxide, and oxides of sulfur, smoke or particulates. 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 NO_x tends to be significantly smaller than those encountered with operation on other fuels. The fast burning characteristics of hydrogen permit much more

satisfactory high-speed engine operation. This would allow an increase in power output with a reduced penalty for lean mixture operation.

A. Properties of Hydrogen

Hydrogen is an odorless, colorless gas with molecular weight of 2.016 (hydrogen is the lightest element). Its density is about 14 times less than air (0.08376 kg/m³ at standard temperature and pressure). Hydrogen is liquid at temperatures below 20.3 K (at atmospheric pressure). Hydrogen has the highest energy content per unit mass of all fuels – higher heating value is 141.9 MJ/kg, almost three times higher than gasoline. Some important properties of hydrogen are compiled in Table I.

TABLE I. PHYSICAL PROPERTIES OF HYDROGEN, METHANE AND GASOLINE

Properties	Hydrogen	Methane	Gasoline
Density at 1 atm & 300K (kg/m ³)	0.082	0.717	5.11
Stoichiometric Compression in air (%by volume)	29.53	9.48	1.65
Number of moles after combustion to before	0.85	1.00	1.058
LHV(MJ/kg)	119.7	46.72	44.79
Combustion energy per kg of stoichiometric mixture (MJ)	3.37	2.56	2.79

The specific physical characteristics of hydrogen are quite different from those common fuels. Some of those properties make hydrogen potentially less hazardous, while other hydrogen characteristics could theoretically make it more dangerous in certain situations. In Table II combustion characteristics are shown for certain fuels.

TABLE II. COMBUSTION PROPERTIES OF HYDROGEN, METHANE AND GASOLINE

Properties	Hydrogen	Methane	Gasoline
Flammability limits (% byvolume)	4-75	5.3-15.0	1.2-6.0
Minimum ignition energy (mJ)	0.02	0.28	0.25
Laminar flame speed at NTP (m/s)	1.90	0.38	0.37-0.43
Autoignition temperature (K)	858	813	500-750

B. Hydrogen Safety Issues

Like any other fuel or energy carrier hydrogen poses risks if not properly handled or controlled. The risk of hydrogen,

therefore, must be considered relative to the common fuels such as gasoline, propane or natural gas. Since hydrogen has the smallest molecule it has a greater tendency to escape through small openings than other liquid or gaseous fuels. Based on properties of hydrogen such as density, viscosity and diffusion coefficient in air, the propensity of hydrogen to leak through holes or joints of low pressure fuel lines may be only 1.26 (laminar flow) to 2.8 (turbulent flow) times faster than a natural gas leak through the same hole (and not 3.8 times faster as frequently assumed based solely on diffusion coefficients). Since natural gas has over three times the energy density per unit volume the natural gas leak would result in more energy release than a hydrogen leak. For very large leaks from high pressure storage tanks, the leak rate is limited by sonic velocity. Due to higher sonic velocity (1308 m/s) hydrogen would initially escape much faster than natural gas (sonic velocity of natural gas is 449 m/s). Again, since natural gas has more than three times the energy density than hydrogen, a natural gas leak will always contain more energy.

If a leak should occur for whatever reason, hydrogen will disperse much faster than any other fuel, thus reducing the hazard levels. Hydrogen is both more buoyant and more diffusive than either gasoline, propane or natural gas. Hydrogen/air mixture can burn in relatively wide volume ratios, between 4% and 75% of hydrogen in air. Other fuels have much lower flammability ranges, natural gas 5.3-15%, propane 2.1-10%, and gasoline 1.2-6%. However, the range has a little practical value. In many actual leak situations the key parameter that determines if a leak would ignite is the lower flammability limit, and hydrogen's lower flammability limit is 4 times higher than that of gasoline, 1.9 times higher than that of propane and slightly lower than that of natural gas.

Hydrogen has a very low ignition energy (0.02 mJ), about one order of magnitude lower than other fuels. The ignition energy is a function of fuel/air ratio, and for hydrogen it reaches minimum at about 25%-30% hydrogen content in air... Hydrogen has a flame velocity 6 times faster than that of natural gas or gasoline. A hydrogen flame would therefore be more likely to progress to a detonation than other fuels. However, the likelihood of a detonation depends in a complex manner on the exact fuel/air ratio, the temperature and particularly the geometry of the confined space.

Hydrogen detonation in the open atmosphere is highly unlikely. The lower deniability fuel/air ratio for hydrogen is 13%-18%, which is two times higher than that of natural gas and 12 times higher than that of gasoline. Since the lower flammability limit is 4% an explosion is possible only under the most unusual scenarios, which is, hydrogen would first have to accumulate and reach 13% concentration in a closed space without ignition, and only then an ignition source would have to be triggered. Should an explosion occur, hydrogen has the lowest explosive energy per unit stored energy in the fuel, and a given volume of hydrogen would have 22 times less explosive energy than the same volume filled with gasoline vapor.

Hydrogen flame is nearly invisible, which may be dangerous, because people in the vicinity of a hydrogen flame may not even know there is a fire. This may be remedied by adding some chemicals that will provide the necessary luminosity. The low emissivity of hydrogen flames means that nearby materials and people will be much less likely to ignite and/or hurt by radiant heat transfer. The fumes and soot from a gasoline fire pose a risk to anyone inhaling the smoke, while hydrogen fires produce only water vapor (unless secondary materials begin to burn). Liquid hydrogen presents another set of safety issues, such as risk of cold burns, and the increased duration of leaked cryogenic fuel. A large spill of liquid hydrogen has some characteristics of a gasoline spill, however it will dissipate much faster. Another potential danger is a violent explosion of a boiling liquid expanding vapor in case of a pressure relief valve failure.

Hydrogen onboard a vehicle may pose a safety hazard. The hazards should be considered in situations when vehicle is inoperable, when vehicle is in normal operation and in collisions. Potential hazards are due to fire, explosion of toxicity. The latter can be ignored since neither hydrogen nor its fumes in case of fire are toxic. Hydrogen as a source of fire or explosion may come from the fuel storage, or from the fuel supply lines. The largest amount of hydrogen at any given time is present in the tank. Several tank failure modes may be considered in both normal operation and collision, such as: catastrophic rupture, due to manufacturing defect in tank, a defect caused by abusive handling of the tank or stress fracture, puncture by a sharp object, external fire combined with failure of pressure relief device to open; massive leak, due to faulty pressure relief device tripping without cause or chemically induced fault in tank wall; puncture by a sharp object, operation of pressure relief device in a case of fire (which is the purpose of the device); slow leak due to stress cracks in tank liner, faulty pressure relief device, or faulty coupling from tank to the feed line, or impact-induced openings in fuel line connection.

Most of the above discussed failure modes may be either avoided or their occurrence and consequences minimized by: leak prevention through a proper system design, selection of adequate equipment, allowing for tolerance of shocks and vibrations, locating a pressure relief device vent, protecting the high pressure lines, installing a normally closed solenoid valve on each tank feed line; leak detection by either a leak detector or by adding an odorant to the hydrogen fuel (this may be a problem for fuel cells); ignition prevention, through automatically disconnecting battery bank, thus eliminating source of electrical sparks which are the cause of 85% gasoline fires after a collision, by designing the fuel supply lines so that they are physically separated from all electrical devices, batteries, motors and wires to the maximum extent possible, and by designing the system for both active and passive ventilation (such as an opening to allow the hydrogen to escape upward).

C. Features of Hydrogen for Engine Applications

In addition to the previous unique features associated almost exclusively with hydrogen, a number of others can be cited in support of hydrogen applications in engines. To list 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 pre-ignition reactivity.

Hydrogen has been shown to be an excellent additive in relatively small concentrations, to some common fuels such as methane. Its gaseous state permits excellent cold starting and engine operation. Hydrogen remains in gaseous state until it reaches its condensation point around 20 K. Hydrogen engines are more appropriate for 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.

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 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 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. Internal combustion engines can burn hydrogen in a wider range of fuel-air mixtures than with gasoline. Hydrogen with wider flammability limits and higher flame speed makes it more efficient in stop and start driving. 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 gas is highly diffusive and buoyant which make fuel leaks disperse quickly, reducing explosion hazards associated with hydrogen engine operation.

III. GENERATION OF HYDROGEN GAS

Photo-electrochemical (PEC) production of hydrogen is a promising renewable energy technology for generation of hydrogen for uses in the future hydrogen economy. PEC systems use solar photons to generate a voltage in an electrolysis cell sufficient to electrolyze water, producing H₂ and O₂ gases. A major advantage of PEC systems is that they involve relatively simple processes steps as compared to many other H₂ production systems. Additionally, they possess a wide operating temperature ranges, with no intrinsic upper temperature limit and a lower temperature of slightly below 0°C without a warm-up period, and well below 0°C with a warm-up period dependent on outside temperature. The primary challenges for PEC are to develop materials with sufficient photo-voltage to electrolyze water, to minimize internal resistance losses, to have long lifetime (particularly corrosion life), to maximize photon utilization efficiencies, and to reduce plant capital cost.

A fixed PEC planar array tilted toward the sun at local latitude angle, using multi-junction PV/PEC cells immersed in an electrolyte reservoir. This inclination allows the array, in general, to maximize overall capture of direct solar flux throughout the year and results in a much more leveled output between summer and winter. The system captures the solar direct component determined by panel tilt angle and the solar zenith and azimuth angles, and also captures much of the diffuse radiation component. The yearly mean of the average daily radiation energy input (after window refraction and inter-array shading losses) is 6.19kW-hr/m² per 24 hour period.

The photocell PEC system utilizes a PV cell generating sufficient voltage to electrolyze water, with modifications to allow it to survive in an electrolyte. The cell generates electrons from incident photons and has either integral electrode immersed in the electrolyte as shown in Photocell Systems electrically connected spaced apart electrodes immersed in the electrolyte. For the PEC cell, the PV materials absorb photons to generate electrons for electrolysis at a total voltage on the order of 1.6-2.0V and conduct the electrons between the oxygen gas generating anode and the hydrogen gas generating cathode. In experimental systems, the required voltage is higher due to losses in ion and electron transport and other losses. The electrolysis gases are separated by their physically separate reaction sites to create separate outlets for pure H₂ and pure O₂. In a common embodiment, the cell front face illuminated by solar radiation is a conductive window that functions as the electrolysis anode. Multi-junction PV active layers are used to use multiple sub-threshold photons to reach desired overall voltage and increase solar spectrum utilization.

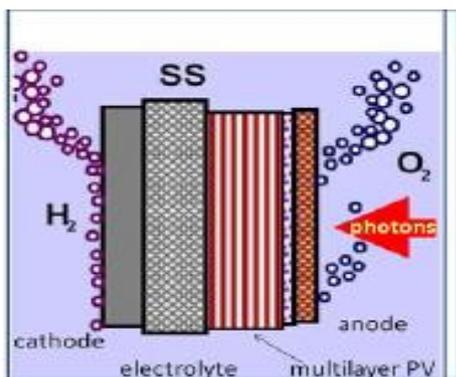


Fig. 1. Electro chemical water splitting

There are multiple PEC cell configurations which can be used, some using membrane separation of the gases and others relying solely on buoyancy separation. For this costing study, we have based our cell design on the simplest generic design assuming an open electrolyte compartment and buoyant separation of gases. Costing of the PV/PEC active components relies heavily on the cost estimates, projections, and achievements in the solar cell industry. To estimate cell cost, we have assumed the PV cell advances of-

- Minimized thickness of individual PV layers.
- Use of low cost printing techniques for material deposition.
- Use of lower cost PV materials, when possible.
- Low cost conductive coatings to protect against corrosion.

Planar PEC arrays are similar to planar solar cell PV arrays, except that the cell electrodes are in direct contact with the PEC electrolyte and output is H₂ PEC Panel and O₂ "Thin film PV manufacturing: materials costs and their optimization", Solar Energy Materials & Solar Cells, 2000, Elsevier gas rather than an external electric current. Each panel is made up of multiple cells, with the cell area being as large as can be readily manufactured. The arrays are fixed in place and inclined toward the sun at a tilt angle from horizontal equal to the local latitude.

A. PEC Electrolysis

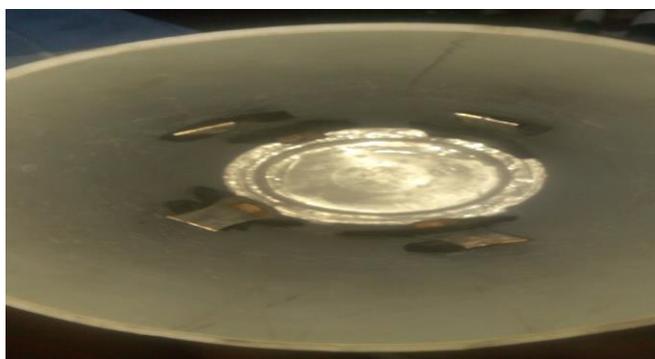


Fig. 2. Copper electrode submerged in KOH

PEC systems, as defined in this analysis, use solar photon energy to generate sufficient energy to electrolyze water to produce hydrogen and oxygen. The advantage of PEC direct conversion over separate photovoltaic (PV) generation plus conventional electrolysis is the elimination of the electrical current collection network and concomitant current transmission losses. However, the PEC technology must overcome the increased electrochemical issues in order to be viable. The photoactive element within a PEC device is a photovoltaic component that converts photon energy to a current as long as the photon energy level exceeds the band gap of the PV junction materials. The electrolysis reaction (i.e., water splitting reaction) is represented by the equation,



Thus the minimum electrochemical voltage to carry out the reaction is 1.23 Volts. However, with the normal losses in carrying out direct electrolysis of water, in practice >1.6 Volts is generally required to initiate the reaction. Since these low energy photons would otherwise be "lost" to the reaction, multilayer PV components are used to allow multiple photons to produce a total combined voltage which is above the electrolysis threshold. In this manner solar flux utilization is maximized for hydrogen production and has been demonstrated in the 12.4% efficient PEC cell. Both dual layer and triple layer solar cells have been developed and are commonly produced by the PV industry with new low cost manufacturing embodiments. We postulate that analogous multi-layer devices can be used to generate the requisite PEC electrolysis voltages.

For direct PEC decomposition of water to occur, several requirements must be simultaneously met by the PEC components:

PV total band-gap significantly larger than the H₂/O₂

PV band-gap matching with the H redox potential of 1.23V: generally with a goal of 1.5-2.0 V, and, in practice, as high as 3.0V when there are significant resistive losses 2/O₂

Fast charge transfer across the electrode/electrolyte interface to prevent corrosion and reduce energy losses redox potential

Electrode surfaces stable against corrosion.

For photon energies greater than the band-gap voltage, the photoelectrons transfer more energy than needed for electrolysis and the extra energy is absorbed as heat. After satisfying these four threshold requirements for basic functionality, the subsequent measures of PEC cell economic viability for H₂ production are photon utilization efficiency and cost.

B. PEC Efficiency

Overall photo-electrolysis performance is measured by solar to hydrogen (STH) conversion efficiency, η .

The hydrogen production rate is based on the following formula:

$$\text{H}_2 \text{ generation rate/area} = I_s \eta / \text{LHV of H}_2 \text{ (in kg H}_2 \text{/hr/m}^2 \text{)}$$

Where,

I_s = solar intensity (1000 kW/m^2 at 1 sun)
 η = photon conversion efficiency
LHV of H_2 = lower heating value of hydrogen
= 33.3 kWh/kg

A single layer PEC cell with sufficient band-gap energy for electrolysis, $\sim 1.8 \text{ eV}$, would be unable to electrolyze water over a significant part of the solar spectrum. Therefore, for best efficiency, a PEC cell would utilize a multi-layer PV component to generate the requisite electrolysis voltage from two low energy photons.



Fig.3. Photo electro chemical cell

IV. ENGINE MODIFICATION

SI engines are easily adaptable to gaseous fuels like propane, methane, and hydrogen. Slight modifications for the introduction of the fuel in appropriate amount are applied.

A fuel supply system that can be tuned according to the engine's need is just good enough to make the engine work. In case of hydrogen there are certain additional issues concerning safety and backfire-safe operation throughout the whole operating region. The storage of the fuel is another aspect that affects the range of the vehicle operating on hydrogen. Due to its low energy per volume content, the compressed gas storage cannot compete with liquid gasoline. Compared to gasoline, hydrogen's low energy per unit volume produces less energy in the cylinder. An engine running on hydrogen produces less power than with gasoline. Supercharging may help remedy this by compressing the incoming fuel/air mixture before it enters the cylinder. This increases the amount of energy per volume of fuel. Additional weight and complexity is added to the engine by such modifications. But the power gain and backfire resisting property (by cooling the cylinder with more air) compensates for the mentioned drawbacks.

Addition of spray nozzles for water is essential to provide backfire free operation. Although very simple in structure, it is important to supply the right amount of water according to load, engine speed and temperature. If cryogenic hydrogen is to be supplied, material selection for the injectors, fuel supply line, tank and metering devices must be made accordingly. Since much progress has been made in the safe handling and storage of liquid hydrogen in space industry, the remaining

focus needs to be done on applying this know-how to small vehicle systems.

A. Pre-ignition and Backfire

Hydrogen burns quickly and has a low ignition temperature. This may cause the fuel to be ignited by hot spots in the cylinder before the intake valve closes. It may also cause backfire, pre-ignition, or knock. These problems are particularly more with high fuel-air mixtures. Uncontrolled pre-ignition resists the upward compression stroke of the piston, thereby reducing power. Remedies for backfire include: timed port injection, delayed injection to make sure the fuel detonates only after the intake valve is closed; water injection, 1.75 water to hydrogen, by weight (Peavey 2003). An appropriately designed timed manifold injection system can overcome the problems of backfiring in a hydrogen engine.

B. Fuel Mixing

Keeping the air and fuel separate until combustion is an important strategy for controlling the difficulties arising from the fast-burning properties of hydrogen. The low flammability limits and low energy required for ignition of hydrogen cause pre-ignition and backfire when using hydrogen fuel. Ignition occurs when a fuel-air mixture ignites in the combustion chamber before the intake valve closes. Pre-ignition can cause backfire when ignited fuel-air mixture explodes back into the intake system. It is most present at higher loads and at higher fuel-air mixtures near open throttle. Pre-ignition is not a necessary precursor to backfiring and probably not occurs under normal circumstances at moderate compression and equivalence ratios. Because of the low volumetric energy content of hydrogen, higher compression ratios or higher fuel delivery pressures are needed to avoid reduced power. Supercharging spark ignition engines compresses the fuel-air mixture before being inducted into the cylinder. Direct fuel injection involves mixing the fuel with air inside the combustion chamber. The fuel and air are kept separate until then. If the fuel and air are mixed before entering the combustion chamber; the arrangement is called external mixing. A carburetor usually accomplishes this.

C. Mixture Formation and Engine Operation

The extreme physical properties of hydrogen at ambient and cryogenic conditions are of beneficial influence on combustion as well as on mixture formation. In contrast to conventional fuels, the hydrogen fraction in a stoichiometric mixture at ambient temperature is about 30% of the mixture volume. The volumetric heat value of the hydrogen-air mixture (2890 J/l) results in a corresponding power loss at the engine compared to conventional fuel (3900 J/l). The wide flammability range of H_2 -air mixtures enables very lean operation with substantially reduced NO_x emissions much more easily than with conventional fuels. Also, hydrogen offers a considerable reduction of air throttle and cylinder charge intake flow losses. In this point hydrogen differs considerably from other gaseous fuels such as natural gas or propane.

D. Mixture Formation With Hydrogen At Ambient Conditions

Substantial reduction of NO_x emissions is demonstrated with lean mixture concepts without using catalysts at the exhaust. To achieve satisfactory engine operation several additional measures are necessary to prevent uncontrolled pre-ignition and backfiring into the intake manifold. Supercharging is an additional measure to compensate for the loss of power output, which is related to the lean mixture concepts.

As a consequence of low energy content in the exhaust gas due to larger partial load efficiency and lower volumetric heat value, exhaust gas turbo-charging is less suitable with hydrogen operation than with conventional fuel despite un-throttled air supply. Due to lower exhaust gas temperature with hydrogen operation (approximately 650 °C) under partial load, there is not enough energy available from the exhaust gas for charging up and improving torque. This “turbocharger hole” can be effectively bridged with an additional centrifugal compressor driven directly by the engine via a high speed transmission gear. Although the recognized turbocharger deficiency can be diminished through the reduction in flow orifice of the turbine’s case, this results in increased choking of the exhaust gas and in additional problems with uncontrolled pre-ignition. The problems with the hot residual gas could basically be reduced through an increase of the compression ratio (to 10:1 and 11:1). This measure, however, is contradictory to supercharging.

V. RESULT AND DISCUSSION

For the purpose of detailed analysis, as many as possible operating points were recorded. Much experimentation has been done to avoid backfire. Firstly the mixer was placed above the throttle valve, level with the air filter housing. In this arrangement the engine’s tendency to backfire was considerably high. For this reason it was placed between the carburetor body and inlet manifold afterwards. At idling and no load speeds, no backfire occurred. When load was applied, a practical limit of about 20 Nm prevented further loading no matter how much water was given as a fine mist into the inlet manifold. At speeds below 2600 rpm serious backfire caused sudden loss of power and therefore the operating range for hydrogen was set between 2600 rpm and 3800 rpm (the upper limit is due to the rated speed of the dynamometer).

Sample calculation for power, thermal efficiency and mean effective pressure is as follows: For 3000 rpm,

Gasoline T=22 Nm

$$P \text{ (kW)} = 2\pi \omega \text{ (rev/s)} \times T \text{ (Nm)} \times 10^{-3}$$

$$P = 2\pi \times (3000 \times 1 / 60) \times 22 \times 10^{-3}$$

$$P = 6.9 \text{ kW}$$

Hydrogen T = 19 Nm

$$P \text{ (kW)} = 2\pi \omega \text{ (rev/s)} \times T \text{ (Nm)} \times 10^{-3}$$

$$P = 2\pi \times (3000 \times 1 / 60) \times 19 \times 10^{-3}$$

$$P = 6.0 \text{ kW}$$

Gasoline P_b = 6.9 kW

$$\eta_{bth} = \frac{P_b \text{ (kW)}}{\dot{m}_f \text{ (kg/s)} \times Q_{LHV} \text{ (kJ/kg)}}$$

$$t = \text{time for 100 ml of fuel, } t = 74 \text{ s}$$

$$Q_{LHV} = 44000 \text{ kJ/kg}$$

$$\dot{m}_f = 760 \text{ kg/m}^3 \times 10^{-6} \text{ m}^3/\text{ml} \times 100 \text{ ml} / 74 \text{ s}$$

$$\dot{m}_f = 1.027 \times 10^{-3} \text{ kg/s}$$

$$\eta_{bth} = 15.3 \%$$

Hydrogen P_b = 6.0 kW

$$\eta_{bth} = \frac{P_b \text{ (kW)}}{\dot{m}_f \text{ (kg/s)} \times Q_{LHV} \text{ (kJ/kg)}}$$

$$Q_{LHV} = 120000 \text{ kJ/kg}$$

$$\dot{m}_f = 0.084 \text{ kg/m}^3 \times 10^{-3} \text{ l/m}^3 \times 139 \text{ l/min} \times 1/60 \text{ min/s}$$

$$\dot{m}_f = 1.946 \times 10^{-4} \text{ kg/s}$$

Gasoline P_b = 6.9 kW

$$V_d = 1.197 \text{ dm}^3, n_r = 2 \text{ (4-stroke engine)}$$

$$mep \text{ (kPa)} = \frac{P_b \text{ (kW)} \times n_r \times 10^3}{V_d \text{ (dm}^3) \times \omega \text{ (rev/s)}}$$

$$\omega = 3000 \text{ rev/min} \times 1/60 \text{ min/s}$$

$$\omega = 50 \text{ rev/s}$$

$$mep = 231 \text{ kPa}$$

Hydrogen

$$P_b = 6.0 \text{ kW}$$

$$V_d = 1.197 \text{ dm}^3, n_r = 2 \text{ (4-stroke engine)}$$

$$mep(kPa) = \frac{P_b(kW) \times n_r \times 10^3}{V_d(dm^3) \times \omega(rev/s)}$$

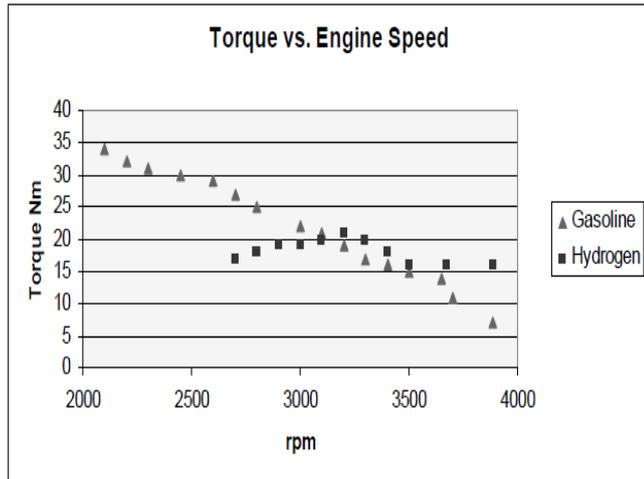
$$\omega = 3000 \text{ rev/min} \times 1/60 \text{ min/s}$$

$$\omega = 50 \text{ rev/s}$$

$$mep = 199 \text{ kPa}$$

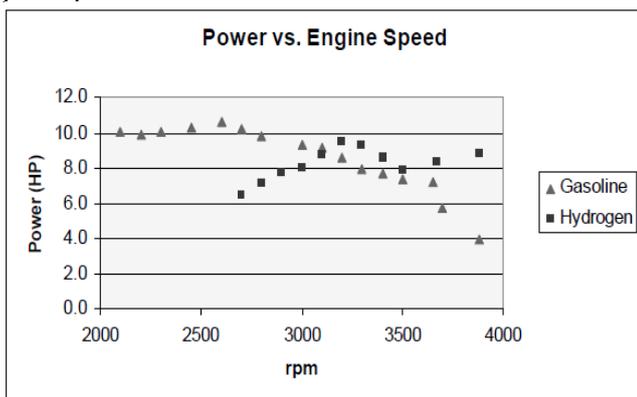
to its low energy content per unit volume, an externally mixed hydrogen engine has less power than a conventional gasoline fueled engine. This drawback can be overcome by supercharging. In this way more air can be charged in the cylinder and more fuel as well. It also helps to cool down the cylinder avoiding pre-ignition. Hydrogen has a wide flammability range (4-75 %). Certain non-homogeneity in the fuel air mixture has no considerable effect on its combustion. The mixture burns completely and thermal efficiency tends to be higher. With external mixture formation non-homogeneity is lower than internal mixture formation. This is also the reason for the high backfire tendency when external mixing is applied. There is fuel air mixture ready to burn flowing into the cylinder through the manifold. At any time this mixture can be ignited by a hot spot within the cylinder.

A. Comparative graphs



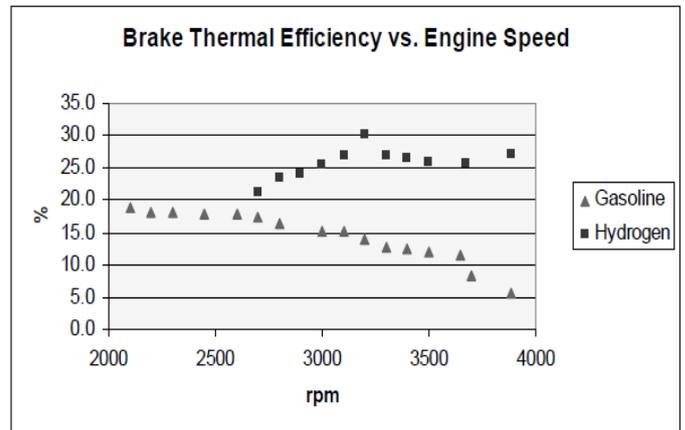
Graph 1. Torque vs Engine Speed

Graph 1 shows Torque comparison between gasoline and hydrogen, the variation of brake torque, which is read directly from the dynamometer. At a speed of about 3100 rpm hydrogen achieves the torque values for gasoline and exceeds them at greater speeds. Since hydrogen has fast burning characteristics, it is expected to show better results at high speed operation.



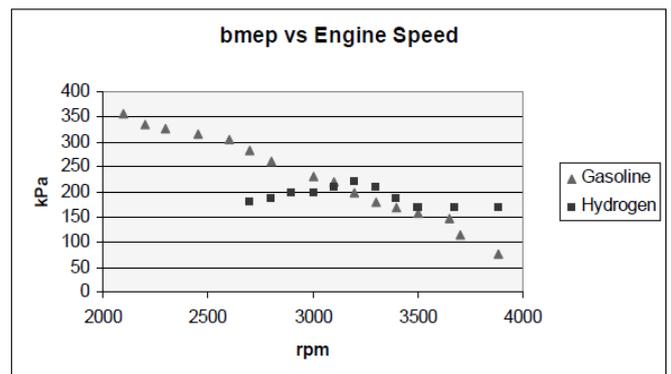
Graph 2. Power vs Engine Speed

Graph.2 shows brake power comparison for both fuels. At low speeds hydrogen suffers power but competes well within the second operating speed range (3000 rpm – 4000 rpm). Due



Graph 3. Brake Thermal Efficiency vs Engine Speed

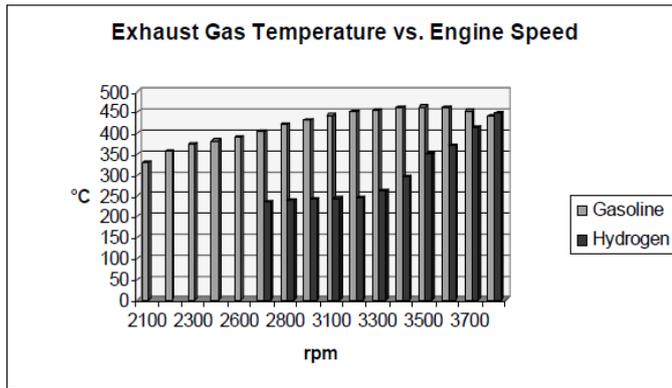
Comparison of brake thermal efficiency of gasoline and hydrogen operation is shown in Graph 3. Obviously hydrogen has a higher brake thermal efficiency. It is known for gasoline engines that they show their effective efficiency at greater part loads whereas hydrogen can operate even at low part loads with better efficiency.



Graph 4. bmep vs Engine Speed

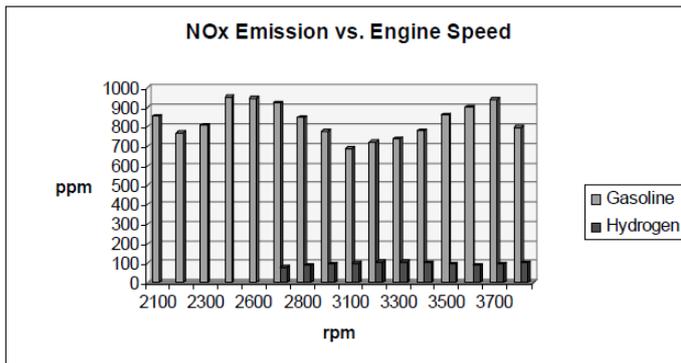
The brake mean effective pressure is another performance parameter, plotted against engine speed in Graph 4. At a speeds below 3000 rpm the gasoline engine is more effective.

Hydrogen operation shows a slightly better effectiveness at speeds above 3200 rpm.



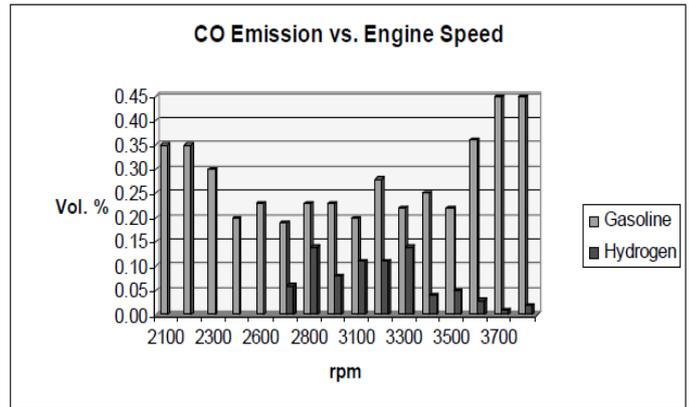
Graph 5. Exhaust Gas Temperature vs Engine Speed

Graph 5 represent temperature analysis of the exhaust gas against engine speed. As soon as the hydrogen engine gets into the high speed range, the exhaust temperature starts to increase significantly. The cooling effect of water that is added with hydrogen is observed. But fast burning that occurs at increased speed during hydrogen operation results in temperature rise.



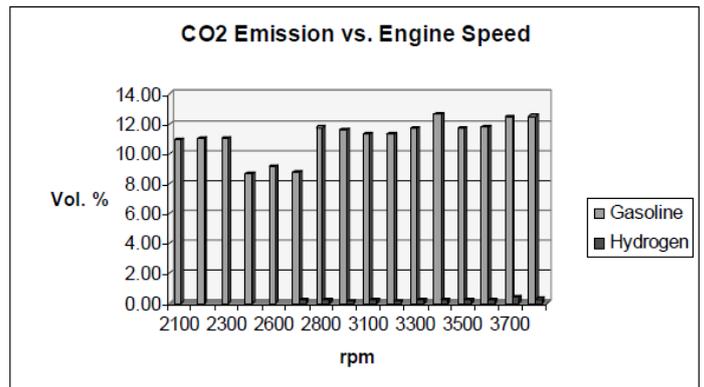
Graph 6. NOx Emission vs Engine Speed

Graph 6. clearly shows very less NOx emission take place when we using hydrogen as fuel instead of gasoline fuels. Significant decrease in NOx emissions is observed with hydrogen operation.



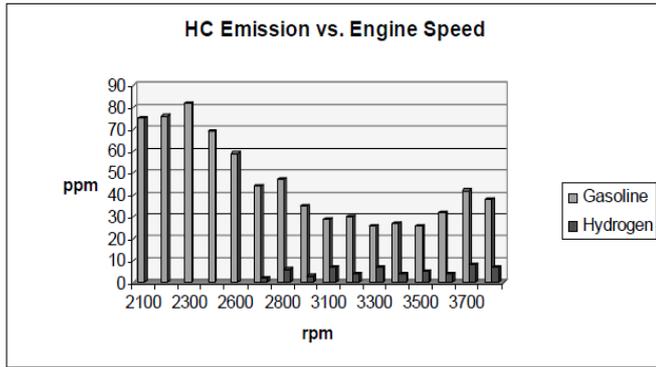
Graph 7. CO Emission vs Engine Speed

Although more air than required for complete combustion is present in the cylinder (fuel lean operation), the engine is not capable of burning the total amount of fuel. Carbon monoxide emissions are due to incomplete combustion of fossil fuels. It is expected that the hydrogen engine has zero carbon monoxide emissions since hydrogen is a carbon-free fuel. Some amount of carbon monoxide is still present even with hydrogen. This is due to the burning of the lubricating oil film inside the cylinder. As speed increases, these emissions tend to diminish.



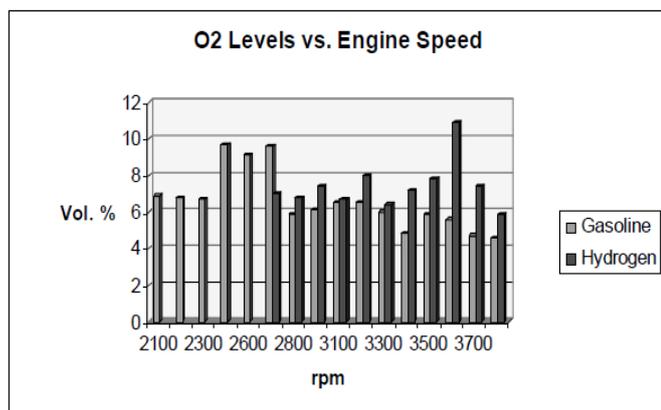
Graph 8. CO₂ Emission vs Engine Speed

A similar presentation of results for carbon dioxide emissions is contained in graph 8. For hydrogen there is practically no emission, only very slight values again due to combustion of the lubricating oil film. During combustion the temperature inside the cylinder is extremely high. As the piston expands, this heat evaporates a certain amount of the oil, which results in production of CO₂.



Graph 9. HC Emission vs Engine Speed

Contribution of the evaporated and incompletely burned oil to the overall emission can be guessed. Gasoline is a long-chain hydrocarbon and when not completely burned, breaks up into short chain hydrocarbons. Hydrogen is a gaseous fuel and does not dissolve the oil film on the cylinder walls. This is another advantage of it against conventional fuels. Better lubricating characteristics and longer engine life is obtained. At low speed the gasoline engine is choked and therefore more un burnt hydrocarbons are present in the exhaust gases. The only hydrocarbon emission from the hydrogen engine is due to the above mentioned oil film evaporation.



Graph 10. O₂ Level vs Engine Speed

Since the tests were performed at part load, fuel lean operation was needed. Especially to cool down the cylinder and operate the engine safely without backfire, in hydrogen operating case, mixture was leaned by following the oxygen content in the exhaust gas. Figure 8.10.shows the oxygen levels in the exhaust gas. During hydrogen operation, the engine was kept on extremely lean side.

VI. CONCLUSION

A conventional 4 cylinder SI engine was adapted to operate on gaseous hydrogen. Compressed gas at 200 bar in steel bottles was introduced to the engine by external mixing. The first stage regulator drops the pressure to 3 bar to a copper gas supply line where a flow meter is installed. The second stage

regulator supplies hydrogen to the mixing apparatus installed on the inlet manifold. Spray nozzles for water induction are placed approximately 4 cm away from the inlet valves. Ignition timing was set to 10° before TDC and fixed.

First tests were performed with the mixer installed on top of the carburetor body. This is the usual configuration in propane mixing. Serious backfire was observed with this installation. Another mixer was then put between the carburetor body and inlet manifold. Backfire was prevented in this option. Under no-load condition, the engine operated flawless with a smooth idling. When load is applied and engine speed is below 2600 rpm, serious backfire occurred and caused a sudden drop in engine power. Water mist from the spray nozzles greatly enhances the backfire-safe operation. Specific features of the use of hydrogen as an engine fuel were analyzed. Results of the tests demonstrated that there will be power loss for the low speed operation whereas high speed characteristics could compete with gasoline performance. The increase in thermal efficiency was obvious. It has been proved that hydrogen is a very bright candidate as an engine fuel. NO_x emissions were about 10 times lower than with gasoline operation. CO and HC emissions were almost negligible as expected. Traces of these emissions were present because of the evaporating and burning lubricating oil film on the cylinder walls.

Combustion properties of hydrogen favor fast burning conditions such as in a high speed engine. Design changes that would allow the engine to greater speeds would have a beneficial effect. Appropriate changes in the combustion chamber together with better cooling of the valve mechanism, would increase the possibility of using hydrogen across a wider operating range. Sequential injection of gaseous hydrogen instead of carburetion could greatly solve the backfire problem. Better performance could be obtained. Even further, liquid hydrogen either internally mixed or injected into the manifold could be a measure against backfire due to its extraordinary cooling effect (20 K temperature). An electronic control unit that measures the speed, and varies the injection timing together with ignition timing installed on a supercharged, intercooled, high compression ratio, short stroke and high speed engine seems to be the most appropriate way to get the best from hydrogen's unique properties. Hydrogen has the potential to achieve problem-free operation in IC engines. The future advances depend on whether hydrogen can be obtained abundantly and economically.

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