Hydrogen Fueled Vehicles
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Hydrogen Cleanest of the Clean Fuels

• ...”I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together will furnish an inexhaustible source of heat and light of an intensity of which coal is not capable......water will be coal of the future”
Why Hydrogen

- Potentially an inexhaustible supply of energy can be produced from many available primary energy sources on petroleum imports produced from coal or renewable.
Sources of Hydrogen Generation

FIGURE 2. From source to utilization – hydrogen can be used both for stationary applications and for transport.
Hydrogen Availability/Production

- Hydrogen is most plentiful element in universe but does not occur as a pure gas on the earth.
- Nearly all H2 production is based on fossil fuels at present.
- Hydrogen can also be produced from renewable sources such as bio-mass, wind/solar energy.

HYDROGEN GENERATION

From Conventional Sources (Fossil Fuels)

- Natural gas, Oil, Coal
  - Steam reforming of Natural gas
  - Partial Oxidation
  - Thermal cracking of Natural Gas
  - Coal gasification

From Renewable Sources

- Bio mass-Gasification
- Electrolysis-Electricity from renewable sources like solar, wind, hydle etc.
- In India possibilities of producing hydrogen in sugar mills from Bagasse cogent power-electrolytic plant exist.
- Chloro-alkali units also have surplus hydrogen.
Mostly extracted from water

Various methods of generating hydrogen

Electrolysis

Electric power is needed

Two electrodes placed into an ion conducting electrolyte (H₂O)
- Cathode (-) produces hydrogen
- Anode (+) produces oxygen

\[ 2 \text{H}_2\text{O} \xrightarrow{(\Delta P \text{ or } \Delta T)} 2 \text{H}_2 + \text{O}_2 \]

Higher pressure or higher temperature:
Water molecules split more easily
\[ \Rightarrow \text{lesser energy required} \]
ELECTROLYSIS
Electrodes in conductive water (with an electrolyte) produce H2 at the - & O at the +

• ADVANTAGES:
  – Produces almost pure H2 (electricity through water)
  – Could be powered with cool renewables
  – Hydrogen is abundant
  – No moving parts; servicing rarely necessary
• DISADVANTAGES:
  – Currently not cost competitive
  – Fossil fuel-powered electrolysis
  – Amount of energy needed to divide H2O = amount given off when H2 burns

Solar-Powered Electrolysis
• Honda doing this in Torrance, California
• HYSOLAR: began making H2 in 1994
• Solar-Wasserstoff-Bayern in Bavaria
• CAN project
Nuclear-powered Electrolysis

- It’s a feasible alternative
- Anti-nuclear sentiment may prevent nuclear H2 production
- NRDC opposed; spent fuel

Making H2 from Natural Gas

- Stripping H2 from natural gas is called ‘reforming’
- Reforming natural gas emits CO2
- Outfitting a gas station with a machine to reform natural gas would cost $400,000 (building a conventional gas station costs $1,500,000)
Kvaerner-Process

Usage of light hydrocarbons (e.g. methane, petrol) and electrical power

\[ \text{C}_x\text{H}_{2x+2} \xrightarrow{1600^\circ \text{C, Plasma Arc}} (x+1)\text{H}_2 + x\text{C} \]

No considerable emissions
Nearly 100% efficiency

Steam Reformation

Endothermic catalytic conversion of light hydrocarbons

\[ \text{CH}_4 + \text{H}_2\text{O} \xrightarrow{\sim 850^\circ \text{C, 2.5 bar}} \text{CO} + 6\text{H}_2 \]
\[ \text{CO} + \text{H}_2\text{O} \xrightarrow{\sim 850^\circ \text{C, 2.5 bar}} \text{CO}_2 + \text{H}_2 \quad \text{Also named: Shift Reaction} \]

\( \text{CO}_2 \) is filtered by adsorption or membrane-separation

\( \text{! Nowadays up to 100,000 m}^3/\text{h generated !} \)
Getting H2 from Coal

- Coal-fired utilities can power electrolysis

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</tr>
</thead>
</table>

Gasification I

Fine grounded coal and water mixed

\[ C + 2 \text{H}_2\text{O} \xrightarrow{\text{Suspension with 50-70\% of solid matter}} \text{CO}_2 + 2 \text{H}_2 \]

Very profitable in typical coal mining countries (e.g., China, South Africa)
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**Gasification II**

1. Step: Pyrolysis
   Biomass (e.g. plants, wood, cultivated energy like rap) becomes thermal decomposed and change into coke, condensate and gases

   Possible key precursors: CO or C\textsubscript{4}H\textsubscript{8} or \textsubscript{2} (e.g. methane)

2. Step: Hydrogen generation

   \[
   \text{CO} + \text{H}_2\text{O(g)} \rightarrow \text{CO}_2 + \text{H}_2
   \]

   \[
   \text{CH}_4 + 2 \text{H}_2\text{O(g)} \rightarrow \text{CO}_2 + 3 \text{H}_2
   \]

**H2 Production from Bacteria**

- Some anaerobic bacteria can produce H2 at 20 times their volume per minute
- When starved of sulfur, Chlamydomonas Reinhardtii makes H2, one of ten most important discoveries in 2000 (popular science magazine)
HYDROGEN STORAGE

HYDROGEN STORAGE
ALTERNATIVES

- Storage as gas under pressure (250-350 bar)
- Cryogenic storage as liquid hydrogen (20K)
- Storage as metallic hydrides
- Carbon adsorption & carbon microsphere under development.
**Pressure Tanks**

Gas stored under high pressure (<700 bar)
Important for mobile usage, when light and small tanks required
Material: Carbon-fibre composite materials with internal aluminium liner

![Typical High Pressure Gas Tank Storage System](image)

**Liquid Storage (Cryo-Tanks)**

Hydrogen gets liquefied at −255°C
Waste steam losses very low
High storage density, perfect for cars with less available space

Big disadvantage: High amount of energy for liquefaction needed
**Adsorption Storage**

Metal hydride storage works like a sponge saturated with water
- **Sponge** = certain metal alloy
- **Water** = hydrogen

No losses, effect of cleaning hydrogen

**Very safe:**
- **exothermic**
- **endothermic**

Pure hydrogen → Filled in sponge → Even if the tank is damaged, the hydrogen stays bonded

Disadvantages:
- Quite heavy
- Very expensive

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**Usage of Hydrogen**

- **Fuel Cells**
  - Monovalent: One engine
  - Hybrid: Two engines

- **Direct Injection**
  - Bivalent: One engine, two fuels
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**Problem:**
Within the next fifty years almost all of the fossil fuels are depleted

 Alternative fuels needed

**Requirements:**
- Efficient
- Safe
- Environmentally acceptable for storage

**Solution:**

Hydrogen + Fuel cell technology = Very promising approach

**HYDROGEN FUEL CELLS**
Fuel Cells

1839 first fuel cell by the Welsh physician Sir Williams Robert Grove (1811–1896)

1950’s during Cold War electric power for spacecrafts and submarines

Last couple years interest for civil use became more important

- Increased efficiency
- Decreasing costs
- Multiple purposes

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Hydrogen Fuel Cell

- Converts hydrogen and oxygen into water and an electric current.
- Benefits
  - 40-50% efficient
  - Reduction in noise
  - No emission of greenhouse gases
  - Reduced dependence on fossil fuels
Basic Fuel Cell Structure

Consists of three layers:
1st: Anode
2nd: Electrolyte
3rd: Cathode

Problem: One fuel cell = low voltage
Solution: Stack of several fuel cells

Basic Chemical Reaction

\[ \text{H}_2 + \text{O} \rightarrow \text{H}_2\text{O} \]

In principle working like this:

\[ \text{H}_2 \xrightarrow{\text{Catalyst}} 2\text{H}^+ + 2\text{e}^- \]

Anode \[2\text{e}^-\text{Electric Current}\] Cathode

\[2\text{e}^- + \text{O}_2 \rightarrow 2\text{O}^-\]

\[\text{O}^- + 2\text{H}^+ \rightarrow \text{H}_2\text{O}\]
### Alkaline Fuel Cell (AFC)

Based on Grove's design

**Pros:**
- Quite cheap, so used for niche vehicles (e.g. London taxis)
- Pure oxygen is needed
- Smallest amounts of dirt cause destruction of FC

**Contras:**
- Requires atmospheric oxygen
- Sensitivity to carbon monoxide (CO)
- Reduces performance by blocking anode catalyst

**Cathode:** $O_2$

**Anode:** $H_2$

**Electrolyte:** KOH (Potash Solution)

**Function:**

\[
2O^– + 2H_2O \rightarrow 4OH^– \\
OH^– + H^+ \rightarrow H_2O
\]

### Proton Exchange Membrane Fuel Cell (PEMFC)

**Pros:**
- Very light
- Very efficient
- Requires atmospheric oxygen

**Contras:**
- Sensitivity to carbon monoxide (CO)
- Reduces performance by blocking anode catalyst

**Cathode:** $O_2$

**Anode:** $H_2$

**Electrolyte:** Solid proton exchange membrane made from sulphonated polymers

**Function:**
- Simpler as AFC because the $H^+$ ions move through the electrolyte
- No water required
Phosphoric Acid Fuel Cell (PAFC)

Pro: High operating temperature of 140°C
- Cogeneration of heat and power (e.g. residential power plants)
- Requires atmospheric oxygen

Contra: Below 42°C phosphoric acid (used as catalyst) effloresces irreversible
- Fuel cell unusable

Cathode: $O_2$
Anode: $H_2$
Electrolyte: Solid proton exchange membrane made from sulphonated polymers

Function: Simpler as AFC because the $H^+$ ions move through the electrolyte
- No water required

Hydrogen Fuel Cell (cont...)

- Hurdles to overcome
  - Storage tank size
  - Operation in cold weather
  - Consumer cost
  - Scarcity of fuel stations
  - Safety
  - Environmental problems
Storage Tank Size

- Low density of hydrogen means a larger tank size to achieve driving range similar to petrol.
- Reduction of trunk space

Operation in cold weather

- Fuel cells contain water for
  - Humidifying the cell
  - As byproduct of reaction
- Fuel cells need to reach a critical temperature for full performance
Consumer Cost

- Market price of fuel cell vehicles must be comparable to that of petrol
- Price of the fuel must also be comparable

Scarcity of fuel stations

- Refueling stations must exist before consumers will buy the vehicles
- Meetings between the nations’ top car manufacturers, fuel distributors, and airlines are currently underway
Safety

- Public must be educated in the use of hydrogen as a fuel
- Preliminary experiments:
  - Leak simulation (Dr. Swain)
  - Results
    - Petrol car is destroyed
    - Hydrogen car never reached above 67°F

Hydrogen Leaks

- Cal Tech estimates 10-20% hydrogen leak from cars and refueling stations.
- Results
  - Cooling of upper stratosphere
  - Disturbing of ozone chemistry
- President of International Association of Hydrogen for energy believes percentage of leaked gas would be “much less than they are considering.”
FUEL CELL VEHICLES

FUEL CELL VEHICLE CONFIGURATION
Hydrogen Car Models

- GM Hy-Wire
- BMW 750hL
- Toyota FCHV
- Toyota FINE-S

GM Hy-Wire

- Features
  - Hydrogen fuel cell
  - Drive-By-Wire technology
  - Ability to switch the X-drive from the left side to the right
GM Hy-Wire (cont...)

- Technical Specifications
  - Motor Max Power: 60 kW
  - Motor Max Torque: 215 Nm
  - Max RPM: 12000
  - Max Torque: 1864 Nm

BMW 750hL

- Interesting Features
  - Capable of running petrol or hydrogen
  - Capable of running the air conditioner even when engine is off
BMW 750hL (cont...)

- Technical Specifications
  - 0 to 100 km/h in 9.6 seconds
  - Maximum speed of 226 km/h
  - Range of 350 km

- Safety Tests
  - Destruction of tanks under high pressure
  - Fire tests where tank was consumed in excess of 1000°C
  - Tank deformation tests
  - Side collision tests

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**Toyota FCHV**

<table>
<thead>
<tr>
<th>Max Speed</th>
<th>Over 250 km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seating Capacity</td>
<td>5</td>
</tr>
<tr>
<td>Output</td>
<td>90 kW</td>
</tr>
<tr>
<td>Cruising Distance</td>
<td>Over 250 km</td>
</tr>
<tr>
<td>Fuel Cell Stack Type</td>
<td>PEM</td>
</tr>
<tr>
<td>Motor Type</td>
<td>Permanent Magnet</td>
</tr>
</tbody>
</table>
Toyota FINE-S

- Concept Car
- Seats up to 4
- Futuristic look
- Featured at the 2003 Detroit Auto Show

Hydrogen Internal Combustion Engines ("HICEs")
Why HICE,s

- HICEs are a viable alternative for bridging the gap to the H2 fuel cell economy
- HICEs may be a viable long-term possibility as the ICE has undergone 100 years of refinement
- To lessen greenhouse gases and foreign oil dependence, the government should encourage the transition to the H2 economy with large investments in R&D, subsidies and tax incentives,
EARLY HISTORY OF H2

- **1800**: Electrolysis
- **1820**: Reverend W. Cecil proposes HICE
- **1874**: Jules Verne
- **1860-70’s**: N.A. Otto uses ICEs and mixed H fuel
- **1930-40’s**: Rudolf Erren develops HICEs
- **1950**: Francis T. Bacon
BIGGEST SETBACK

Safety of hydrogen

- Non-toxic
- Only water remains after evaporation
- High self-ignition temp. 550°C
- Burns upwards (lighter than air)
- Mixture with oxygen explosive

Burning Hindenbourg 1937

Military Research into H Vehicles

• 1943: Air Force investigates LH2 fuel

• 1956: Lockheed

  A B-57B airplane that flew with one engine fueled by liquid hydrogen

• 1960’s: ‘Nuclear Powered Energy Depot’
The Modern Era of HICEs

- **1972**: Urban Vehicle Design Competition – UCLA Gremlin wins
- **1972-3**: International H2indenburg society
- **1980’s**: H-fueled airplanes (NASA continues to study FC airplanes)

MODERN H2 VEHICLES

- **1993**: Ballard FC bus developed
- **1995+**
  - CTA FC buses
  - Royal Dutch/ Shell
  - FC prototype cars
  - BMW HICE vehicles
  - H refueling stations open

Ballard phase 3 FC buses, in Vancouver and Chicago
Companies making HICE prototypes

- Daimler-Benz: *hydride HICEs, 1984-8*
- GM *has created a HICE prototypes*
- Mazda, Cadillac: *HICEs and hydride HICEs*

Ford & BMW HICEs

- BMW: *1999 fifth generation prototype, LH2 commercially available*
- *Ford: 1999 announced P2000 HICE (H2, LH2)*
How HICEs Work

- $2\text{H}_2 + \text{O}_2 = 2\text{H}_2\text{O} + \text{heat}$
- H behaves like octane
- Compressed H2 takes up more room than gas
- Unlike gasoline, which needs strict air-fuel ratio
- More explosive than gas, timing critical
- Injected fuel delivery

MODE OF OPERATION IN I.C. ENGINES

- Neat Hydrogen
- Hydrogen Supplementation (Petrol+ Hydrogen)
- Hydrogen+CNG
- Dual Fuelling (Diesel +Hydrogen)
Hydrogen Storage

STORAGE OF HYDROGEN ONBOARD

- Metal hydrides- special alloys incorporate hydrogen atom in their crystalline structure
- Hydrogen is released when heat is applied to alloys
- A tank with 120kg metal hydride could store 6kg of H₂ which can have vehicle range of about 480 km in a car.
- 3 wheeler can given upto 150km with 500gm hydrogen.
H Onboard Storage Issues

- Hydride
- gas compression,
- cryogenic cooling
- No consensus
  Infrastructure cost vs. onboard extraction

Hydride Storage

- 1960’s R&D in the U.S. & Netherlands
- Metal alloys, absorb H2 at higher temp./pressures
- Heat released when H2 absorbed, same heat required to release H2
- D-B used radiator heat to de-bond H2
Hydride Viability

**Advantages:**
- **Storage:** the H takes up no extra room
- **Efficiency:** hydrides carry more energy per volume than LH2 ('compressed' >1000x) & carry 2.2X more than compressed H2 at 5,000 psi
- **Safety:** no onboard tank of H2 or LH2

**Disadvantages:**
- **Weight:** a 100-liter titanium-iron tank has 1.2-1.5X energy as 100 liters of LH2 but weighs 25X

FC & iron-titanium-magnesium hydride
Compressed Gas Onboard Storage

Compressed H2 storage has been used in:
- Mercedes NECAR-2
- Ford FC concept car
- Daimler-Chrysler FC buses
- Neoplan vehicles

Compressed Onboard Storage

ADVANTAGES:
- Easiest form of H storage

DISADVANTAGES:
- Backfire, engine knock are problematic
- Despite extreme pressure, compressed tanks occupy so much space that they are only practical for buses or vans

"Compressed hydrogen storage for bus
(Courtesy of Daimler Chrysler)"
Cryogenic Liquid Hydrogen (LH2) Onboard Storage

- Cryogenically-cooled LH2 is BMW’s preference
- The Musashi Institute of Technology has also investigated this
- Requires an extremely pressurized tank to keep the LH2 in liquid form

A BMW, “in operation since 1990, equipped with an aluminum alloy tank that carries 120 liters of LH2 with a capacity of about 120 liters of LH2

Viability of onboard LH2 storage

**ADVANTAGES:**
- Lowest cost/unit energy
- Lowest weight/unit energy
- Easier supply logistics
- Fast refueling

**DISADVANTAGES:**
- Loss of fuel when not operational
- Large tank needed
- Cryogenic engineering obstacles
- Energy to cool LH2
Hydrogen Refueling Stations

2003:
- Shell plans a H2 refueling station in Luxembourg; others in California, Iceland, Japan, Holland, Norway
- California, Arizona, Nevada, Illinois H2 refueling stations
- Washington, D.C. demo refueling project planned
- EC International Hydrofueler Project
- Reykjavik, Iceland H2 bus refueling station opens
- 1999: Hamburg, Munich, Dearborn

ARE FUEL CELLS BETTER?

- Fuel cells are more efficient than HICEs but less efficient when operated on methane
- Barriers exist to FCs as ‘dual fuel’ vehicles, and thus may be less feasible than HICEs in the near future unless H2 onboard conversion materializes

- FCs cars are the best for zero emissions
- FC cars average 60 more mpg than BMW’s HICEs
- FCs cars are far more costly than HICE vehicles
What if FCs are the future?
• BMW’s future could be adversely affected
• Unlikely soon:
  – FC engines 3x as heavy as ICEs
  – No transport FC mass production
  – Most H2 vehicles produced are HICEs
• HICEs offer a good opportunity to improve the H2 infrastructure as HICEs are “comparatively easy to produce”
• HICEs can bridge the gap to H2-fueled transport that eventually incorporates fuel cells

Hydrogen in IC engines

Fuel cell is a very costly technology—about 10 times than IC engines.
• It will take atleast 10 year to become affordable.

H2 can be used in existing I.C engines
• IC engine is a 100 years established technology and will require some modifications in tooling to make it adaptable for using hydrogen as a fuel.

H2 is clean burning fuel in IC engine
• It gives only Nox emission which can be minimised to negligible.
• No after treatment needed, hence no deterioration of emissions

H2 can be used as admixture to CNG
• H2 has a very high burning rate while CNG has slower burning rate
• It can improve fuel economy & emission of CNG engine

H2 can be used competitive with CNG
• With the infrastructure existing for CNG usage, H2 can replace CNG except of additional cost for reforming facility
## COMPARTIVE PROPERTIES

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>HYDROGEN</th>
<th>METHANE</th>
<th>GASOLINE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular weight</td>
<td>2.016</td>
<td>16.043</td>
<td>107.0</td>
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<tr>
<td>Density of gas at NTP (GM-1)</td>
<td>83.764</td>
<td>651.19</td>
<td>4400</td>
</tr>
<tr>
<td>Heat of combustion (low) (kJ g⁻¹)</td>
<td>119.93</td>
<td>50.02</td>
<td>44.5</td>
</tr>
<tr>
<td>Heat of combustion (high) (kJ g⁻¹)</td>
<td>141.86</td>
<td>55.53</td>
<td>48</td>
</tr>
<tr>
<td>Specific heat ratio (v) of NTP gas</td>
<td>1.383</td>
<td>1.308</td>
<td>1.05</td>
</tr>
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</table>

## COMPARTIVE PROPERTIES

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<th>METHANE</th>
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</thead>
<tbody>
<tr>
<td>Burning velocity in NTP air, cm</td>
<td>265-325</td>
<td>37-45</td>
<td>37-43</td>
</tr>
<tr>
<td>Quenching gap in NTP air, cm⁻¹</td>
<td>0.064</td>
<td>0.203</td>
<td>0.2</td>
</tr>
<tr>
<td>Percentage of thermal energy radiated from flame to surround</td>
<td>17-25</td>
<td>23-32</td>
<td>30-42</td>
</tr>
<tr>
<td>Diffusivity in air, cm²s</td>
<td>0.63</td>
<td>0.2</td>
<td>0.08</td>
</tr>
<tr>
<td>Normalized flame emissivity 2000K, 1 atm</td>
<td>1.00</td>
<td>1.7</td>
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</table>
COMPARTIVE PROPERTIES

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<th>METHANE</th>
<th>GASOLINE</th>
</tr>
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<tbody>
<tr>
<td>Limit of flammability in air vol %</td>
<td>4.0-75.0</td>
<td>5.3-15.0</td>
<td>1.0-7.6</td>
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<tr>
<td>Stoichiometric composition in air vol %</td>
<td>29.53</td>
<td>9.478</td>
<td>1.76</td>
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<tr>
<td>Minimum energy for ignition in air . MJ</td>
<td>0.02</td>
<td>0.29</td>
<td>0.24</td>
</tr>
<tr>
<td>Autoignition temperature K</td>
<td>858</td>
<td>813</td>
<td>501-744</td>
</tr>
<tr>
<td>Flame temperature K</td>
<td>2318</td>
<td>2148</td>
<td>2470</td>
</tr>
</tbody>
</table>

Hydrogen vehicles Based on IC engine

- Energy content of 9.5 kg of H₂ is equivalent to 25kg of petrol.
- Storing of 9.5kg of H₂ require a 55kg tank v/s 25kg of petrol of 17 kg tank.
- H₂ fuel typically takes 4 times space than petrol for same energy.
INDIA’S ADVANTAGES FROM HYDROGEN

- Potential to build a “National Hydrogen Industry” at aggressive pace using exiting oil & natural gas infrastructure produce at refineries or locally supply through existing distribution & retail network.

ENERGY SECURITY
- Hydrogen vehicles & gensets can replace diesel, gasoline & kerosene, fueled polluted power units.

ENVIRONMENT PROTECTION
- Allow India to “leap frog” in technological advancement.

ECONOMIC ADVANCEMENT
- Will enable smooth transition to use of more efficient energy conversion fuel cells.

REMEDIES OF BACKFIRE

- Limiting the equivalence ratio
- Adopting exhaust gas recirculation (EGR)
- Avoiding hot spots on sharp edges and protrusions and using spark pluges with narrow gap settings.
- Water induction.
- Fuel injection
CURATIVE/PREVENTIVE STEP

- Fuel injection – optimum performance & low emmision (Manifold Injection/ Incylinder Injection)
- Exhaust gas recirculation- avoid back fire & limits Nox
- Ultra lean operation(\(\phi=0.28\) achieved)
- Water injection- back fire control
- Timed manifold injection has been experimentally found to be most effective

INJECTOR ACTUATION MECHANISMS

- Hydraulically operated
- Cam actuated
- Solenoid-actuated electronically- controlled

Positive Features of Injection System-
- Eliminate pre ignition backfire and rapid rate of pressure rise
- Reduces Nox emissions drastically – no other pollutant in hydrogen engine exhaust.
FUEL INDUCTION TECHNIQUES

- Carburetion
- Continuous manifold injection (CMI)
- Timed manifold injection (TMI)
- Low pressure direct cylinder injection (LPDI)
- High pressure direct cylinder injection (HPDI)

SYSTEM HARDWARE:

<table>
<thead>
<tr>
<th>Mixture formation</th>
<th>Supply pressure</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous carburetion (cc)</td>
<td>A little above atm.</td>
<td>Unsuitable</td>
</tr>
<tr>
<td>Continuous manifold injection (CMI)</td>
<td>Slightly greater than atmospheric</td>
<td>Not recommended</td>
</tr>
<tr>
<td>Timed manifold injection (TMI)</td>
<td>1.4-5.5 kgf/cm²</td>
<td>Most appropriate</td>
</tr>
</tbody>
</table>
Hydrogen for Auto Application

- As combustion fuel directly in IC engine
- In ad-mixture with CNG and LPG.
- As a fuel for fuel cell.
- In hybrid electric vehicles(H2 to run small generator for on-board charging of batteries).

OPTIMUM ENGINE PERFORMANCE DEPENDS ON

- Equivalence ratio-ultra lean to slightly rich mixture.
- Ignition timing
- Compression ratio
- Method of fuel introduction timed manifold injection.
PERFORMANCE OF HYDROGEN VEHICLES

- There is a tradeoff power and efficiency and Nox emissions: very lean operation increases efficiency and reduces Nox but also reduces the volumetric heating valve of the air/fuel mixture (because there is less fuel) and thus reduces power.
- Late direct injection of cryogenic hydrogen increases power output and efficiency, it eliminates pre ignition, backfiring and reduces Nox formation. For these reasons, many hydrogen researchers feel that it is the most desirable form of hydrogen injection.

Challenges facing HICEs:
- Backfiring common - premature ignition near the fuel intake valve
- To reduce Nox, the air/fuel ratio can be increased, reducing power output to half a gasoline engine’s
- To compensate for lost power, HICE engines are usually larger or have superchargers
- Ford claims that superchargers provide near-zero emissions and power equal to a gas engine
DISTINCTIVE FEATURES OF TMI

- A hydrogen operated engine adopting TMI system embraces the benefit of both the CI as well as SI engine.
- TMI designed so that the intake manifold does not contain any combustible mixtures thus eliminates the undesirable combustion phenomena.
- TMI provides a pre-cooling effect and thus renders the pre-ignition sources ineffective.
- In TMI system, hydrogen air mixing can be sufficiently rapid to ensure burning of hydrogen gas soon after it enters the cylinder.
- TMI is free from constraints such as injection pressure and charge mixing time.

TMI VS LPDI

- Both TMI and LPDI showed the possibility of eliminating backfire by the method of delaying fuel delivery.
- Compared to LPDI, the TMI required a less sophisticated design of the injection valve.
- There is a possibility of flow starvation for both hydrogen and air in case of LPDI whereas such a situation never arises in TMI.
- LPDI seemed to have problems of incomplete combustion due to very brief time allowed for the mixing of hydrogen and air after injection. Such a problem is intrinsically avoided in TMI system.
- Flow controllability seemed to be main stumbling obstacle in achieving higher speed in LPDI as compared to TMI operation.
LEAN BURN HYDROGEN ENGINE

- A way to reduce emissions from internal combustion engines is through lean burn combustion.
- Use excess combustion air to reduce flame temperature (consequently, reduce Nox).
- Carbon monoxide emissions from lean burn engines are also very low.
- Hydrocarbon fuels have lean limits less than an air/fuel ratio, \( l^* = 1.7 \)
- The lean limit for air breathing hydrogen engines is around \( l = 5 \)
- A pure hydrogen engine may be operated at ultra lean conditions without concern for unburned fuel emission (hydrogen is not toxic or an ozone producer).
- The maximum brake thermal efficiency ever measurement at HCCI with a lean burn hydrogen engine is 38%.

CONSTANT VOLUME FUEL INJECTION OF \( \text{H}_2 \)

- CVI is a robust mechanical/fluidic injection system that is controlled by electronics, much like a modern diesel injection system.
- Its fundamental operating principle is to maintain an approximately constant A/F ratio over a wide rage of engine operating conditions.
- No injection valves are big enough to serve the flow requirements of hydrogen engines and none can enhance the breathing capacity of an engine as CVI does (fuel- to air momentum transfer).
- CVI shares the advantage of sequential multi port fuel injected gasoline engines enhanced breathing, quick throttle response and good cylinder to cylinder distribution of air/fuel mixture.
PARALLEL INDUCTION: A SIMPLE FUEL CONTROL METHOD FOR HYDROGEN ENGINES

• Hydrogen and air enters the engine through separate, parallel paths
• The basic objective of parallel induction mixture control system are to separate and control the flow of fuel and air into the engine
• Each of the parallel system has its own throttle, its own manifold, and its own valve system.
• Parallel induction is conceptually similar to intake port injection in that fuel and air enter the cylinder during the intake stroke.
• A “sleeve valve” delays the induction of H₂

HYDROGEN ADDITION IN NATURAL GAS

• Hydrogen when burnt with other fuels makes emission reductions that are greater than the percentage of hydrogen energy in the fuel.
• The addition of hydrogen to natural gas amplifies the clean burning properties of both fuels in a way that produces a large leverage factor.
• Hythan bus fuel is a blend of 7% hydrogen by energy content in natural gas (20% H₂ by volume).
• Hytane is a registered trademarke of hydrogen components, Inc.
• The most effective way to get started with hydrogen energy is in highly lever aged applications with other fuels.
LEAN BURN HYTHANE ENGINES

- Adding hydrogen to natural gas allow leaner operation with less spark advance.
- Both of these tuning variable reduce Nox emissions.
- Non-methane hydrocarbon (NMHC) emission increase with leaner mixtures in natural gas engines.
- NMHC emission are reduced by adding hydrogen.

EMISSIONS

- No HC, CO, Sox and particulates etc.
- Nox is the only pollutant of concern
- Ultra lean operation achievable with hydrogen engine drastically reduces Nox.
Is Hydrogen Fuel Safer?

Former Lockheed Manager: maintains air crashes involving kerosene fuel would have resulted in fewer deaths if H2 were the fuel:

- Radiated fire heat is less with H2
- No smoke from H2 fires
- LH2 safer upon impact than kerosene
- H2 volatile/ burns quickly
- H2 vaporizes/ disperses quickly
- Less fire area

Are HICEs unsafe at any speed?

- H2 is volatile and is 10x more explosive than gasoline
- H leaks and static present risks
- Special sensors and ducts that pull in fresh air may be necessary whenever HICEs are parked indoors
- Stringent, universal safety regulations are needed for storage, handling, and disposal of H2
BMW Tests indicate HICEs are Safe

- '94 BMW: safety valves of double-walled LH2 tanks were blocked, cooked, shaken, rammed with pole; slow LH2 leak, no explosion
- H2 escaped after 10 minutes in open fire; burned with no effect on tank
- OTHER TESTS: some tanks burst under extreme pressure buildup

Ford’s 2000 H2, LH2 vehicles

- Model U concept car: 3 millimeter aluminum barrier tank, carbon-fiber structural casing, rated to a pressure of 10,000 psi
- P2000 FUEL system - redundancy for safety:
  - fueling system under trunk
  - Triple redundant system based on natural gas, designed to use H2 natural dispersion
  - H2 ventilators
  - Sensors in engine, passenger and trunk compartments
  - Alarms triggered at concentrations below flammability
  - H2 detected = fuel system/engine starter disable, roof opens, ventilation fans activate
### HICEs & POLLUTION

**ADVANTAGES:**
- Emissions are a fraction of convention ICE emissions
- Ford HICEs emit almost no pollutants and are 25% more fuel efficient than gas ICEs
- H2/CH4 mixed fuel emits extremely low NOx

**DISADVANTAGES:**
- High temperature H2 combustion makes NOx that of gas, can be lessened with additional control equipment
- Even without after-treatment, NOx emissions are low
- Fossil fuel electrolysis lessens pollution gains

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### Barriers to Commercial Availability

- H2/LH2 infrastructure needed
- Low cost H2 production needed
- Economics of H2 cars are ill-defined

- ICE-HICE conversion availability
- Like current vehicles, H2/LH2 vehicle design will likely vary
- Lack of uniform regulations of H2
Commercial HICE Availability

• Shell: "marathon, not a sprint, and the race has just begun," H2 fuel network by 2030-2050. Others estimate 10-50 years to the H2 economy
• BMW’s HICE cars are available today
• John C. Anderson, Pres. & CEO of AFS says:
  (1) the existing ICE infrastructure
  (2) the demand for clean emissions; &
  (3) H2’s flammability characteristics make H2 the "ultimate low cost fuel" which, when widely available, can be adapted to conventional autos and diesel engine vehicles

PIioneerIng Hydrogen ENGINE RESEARCHERS

• Rev.w.cecil (1820) "hydrogen gas as a moving power in machinery" paper presented before Cambridge Philosophical Society
• "Hydrogen engine prototype " by Benini in 1856 (Refereed in I.C. engine text book by Lichy )
• R.O king et al in Candada Exhaustive combustion studies
INDIA’S ADVANTAGES FROM HYDROGEN

• Potential to build a “National Hydrogen Industry” at aggressive pace using exiting oil & natural gas infrastructure produce at refineries or locally supply through existing distribution & retail network.

ENERGY SECURITY
• Hydrogen vehicles & gensets can replace diesel, gasoline & kerosene, fueled polluted power units.

ENVIRONMENT PROTECTION
• Allow India to “leap frog” in technological advancement.

ECONOMIC ADVANCEMENT
• Will enable smooth transition to use of more efficient energy conversion fuel cells.

STATUS OF HYDROGEN DEVELOPMENT IN INDIA

• METAL HYDRIDE STORAGE
BHU has developed metal hydride storage system for storage and release of hydrogen which can be used in gensets and two wheelers- technology at demonstration stage.

USE OF HYDROGEN IN IC ENGINES
IIT, Delhi has developed hydrogen gas induction system for IC engine which can be used from small genset to large capacity spark ignition engines.

Development of fuel cells. Agencies working are
BHEL-Hyderabad
SPIC Science Foundation- Chennai
Glass & Ceramic Research Institute-Kolkata.
IICT-Hyderabad
DRDO-Naval Material research Lab.
TERI-Delhi are working on.