Development of Alternative Fuel Engines: Solution to Energy–Environment Crisis

Prof. L. M. Das
Centre for Energy Studies
Indian Institute of Technology Delhi

8th December, 2012
NEED FOR ALTERNATIVE FUELS

- Air quality degradation
- Stringent Emission Norms
- Reduced Fossil fuel Depletion
- Reduced Emission and Smog
- Lower Operating Cost
- Reduced Fuel Import Bill
- Increase in oil price
List of Alternate Fuels

- Hydrogen
- Compressed Natural Gas (CNG)
- Bio-Diesel
- Hydrogen Added Natural Gas
- Ethanol
- Methanol
- Liquefied Petroleum Gas (LPG)
- Biogas
- Producer Gas
- BtL
- GtL
Hydrogen: Not a Radically New Concept

Then

JULES VERNE
Mysterious Island (1876)

“...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”

Now


“With a new national commitment, our scientists and engineers will overcome obstacles to taking these cars from laboratory to showroom, so that the first car driven by a child born today could be powered by hydrogen and pollution-free”...
Building Hydrogen Energy

Source: T.Nejat Veziroglu, Hydrogen Energy Technologies, UNIDO
Strategies for Hydrogen Application

- Neat Hydrogen
- Hydrogen Supplementation (Petrol + Hydrogen)
- Hydrogen + CNG
- Dual Fuelling (Diesel + Hydrogen)
- FUEL CELL
Intrinsic Merits of Hydrogen Engine

- High Thermal Efficiency
- Energy Content
  - LHV: $\text{H}_2=120 \text{ MJ/kg};$
  - Gasoline=$43 \text{ MJ/kg}$
- Very tunable combustion
  LFL/UFL(Vol%):
  - $\text{H}_2=4/75$
  - Gasoline $=1/7.6$
- Near Zero Emissions

Smooth Engine operation
Minimum Ignition Energy as a Function of Equivalence Ratio for Hydrogen and Methane
STABLE ENGINE OPERATION RANGE

- Range of equivalence ratio for effective hydrogen engine operation in lean burn mode without showing any undesirable phenomena *
- Unstable engine operation above \( \phi > 0.8 \) reported #
- Combustion instability and reduction in thermal efficiency has been reported for \( \phi < 0.4 \)

*J.Breton Office of Natl. Combustion Liquids, 11 487 Theses Faculte Des Sciences
S.Wendlandt, Physik Chem. 110 637 (1924)

H.S.Yi, K.Min, E.S.Kim “the optimized mixture formation for hydrogen fuelled engines” Int.j. Hydrogen Energy 2000
## Hydrogen – Specific Properties for Engine Application

<table>
<thead>
<tr>
<th></th>
<th>Hydrogen $\text{H}_2$</th>
<th>Gasoline</th>
<th>Diesel Fuel</th>
<th>Methanol $\text{CH}_3\text{OH}$</th>
<th>Propane $\text{C}_3\text{H}_8$</th>
<th>Methane $\text{CH}_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ignition energy (mJ/kg)</td>
<td>20</td>
<td>250</td>
<td></td>
<td>200</td>
<td>250</td>
<td>300</td>
</tr>
<tr>
<td>Flame. limits (%)*</td>
<td>4-75</td>
<td>1-8</td>
<td>1-7</td>
<td>6-26</td>
<td>2-10</td>
<td>5-15</td>
</tr>
<tr>
<td>Auto-ignition temp.(°C)</td>
<td>580</td>
<td>400</td>
<td>220</td>
<td>380</td>
<td>490</td>
<td>650</td>
</tr>
<tr>
<td>Flame speed (m/s)</td>
<td>2.7</td>
<td>0.35</td>
<td>0.3</td>
<td>0.5</td>
<td>0.4</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Practical Mode of Operation

- Neat Hydrogen
- Hydrogen Supplementation (Petrol + Hydrogen)
- Dual Fuelling (Diesel + Hydrogen)
- Hydrogen + CNG
### Fuel Induction Techniques – IIT D

<table>
<thead>
<tr>
<th>Mixture formation</th>
<th>Flow timings</th>
<th>Supply pressure</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous carburetion (CC)</td>
<td>Continuous flow</td>
<td>A little above atmospheric</td>
<td>Unsuitable for neat hydrogen but can be adopted for HANG</td>
</tr>
<tr>
<td>Continuous manifold injection (CMI)</td>
<td>Continuous flow</td>
<td>Slightly greater than atmospheric</td>
<td>Not essentially different from CC</td>
</tr>
<tr>
<td>Timed manifold injection (TMI)</td>
<td>Flow commences after the opening of the intake valve but completed prior to IVC</td>
<td>1.4 - 5.5 kgf/cm²</td>
<td>Most appropriate</td>
</tr>
<tr>
<td>Low pressure Direct cylinder injection (LPDI)</td>
<td>Flow commences after the intake valve closure and is completed before significant compression pressure rise</td>
<td>2.0 - 8.0 kgf/cm²</td>
<td>Requires tough thermal environment</td>
</tr>
<tr>
<td>High pressure Direct cylinder injection (HPDI)</td>
<td>Flow commences at the end of the compression stroke</td>
<td>Abnormally high pressure</td>
<td>Uncontrolled combustion</td>
</tr>
</tbody>
</table>
Combustion Characteristics of hydrogen

- High flame speed
- Low ignition energy
- Wider flammability

Hydrogen Combustion anomalies

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Air</th>
<th>H₂</th>
<th>CH₄</th>
<th>Gasoline</th>
</tr>
</thead>
<tbody>
<tr>
<td>NTP</td>
<td>4%</td>
<td>75%</td>
<td>5%</td>
<td>15%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7.6%</td>
</tr>
</tbody>
</table>
## Hydrogen Combustion anomalies

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SURFACE IGNITION</td>
<td>Uncontrolled ignition induced by a hot spot</td>
</tr>
<tr>
<td>PRE-IGNITION</td>
<td>Occurring during the compression stroke with the actual start of combustion prior to spark timing</td>
</tr>
<tr>
<td>Backfiring OR Back-flash</td>
<td>Hydrogen–air charge combusts in an intake runner or intake manifold</td>
</tr>
<tr>
<td>Engine “knock”</td>
<td>Autoignition of the remaining end-gas with high-pressure oscillations and the typical pinging noise</td>
</tr>
</tbody>
</table>
Measures to Avoid Pre-Ignition combustion

- Limiting the Equivalence Ratio
- Avoiding hot spots and protrusions & Using spark plugs with narrow gap settings
- Water Induction
- Design of the ignition system with low residual charge
- Specifically designed crankcase ventilation
- Sodium-filled exhaust valves
- Optimized design of the engine cooling passages
- Hydrogen direct injection into the combustion chamber
Bottlenecks in use for engines

- Reaching high power output.
- Reducing NOx at high loads.
- Avoiding backfire.
BACKFIRE-Hydrogen Engines

Back firing - Solid lines and Regular pressure trace with dotted lines
Prevention of Backfire

- Limit the end of injection in a fixed range based on engine operation.

- Pre-ignition heats up the combustion chamber, which ultimately leads to backfiring in a consecutive cycle.

- Variable valve timing for both intake and exhaust.

Injecting too early leads to a backflow of hydrogen.

Injecting too late results in leftover hydrogen in the manifold.
Knock characteristics of Hydrogen Engines

Autoignition of end gas with rapid rate of energy release at high amplitude pressure waves

Typical knock characteristics of a heavy knocking cycle- oscillations of almost 65 bar
Avoiding abnormal combustion

Injection system

- Direct Injection
  - Stratification is possible & high operation pressure 5–250 bar
- Timed Injection
  - External mixture formation: operated at lower injection pressures
- Carburetion

Risk of abnormal combustion
- Low
- High
Combustion characteristics of hydrogen

The causes of undesired combustion of hydrogen can be summarized as

- wider flamability-limit
- low ignition energy
- high flame speed
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
INJECTION SYSTEM INSTALLED ON A RESEARCH ENGINE – PARAMETER OPTIMIZATION

Hydraulically operated

- Diesel oil is used as the hydraulic fuel
- Jerk from the diesel injector forces open the hydrogen injector
- Diesel after passing through the nozzle is collected back
Cam Actuated

- Uses a lift rod moved by a cam and the motion being transmitted through a specially designed linkage
- Engine control depends on the response, controllability, durability and the fuel – feeding capacity of the injector
The system provided adequate flexibility to control the injection timings and injection duration to provide an appropriate and desired fuel quantity at the appropriate point in the engine cycle operation.
PRESSURE CRANK ANGLE DIAGRAM-$H_2$
TOTAL HYDROGEN S.I. ENGINE GENSET
HYDROGEN UTILISATION IN DIESEL ENGINE

- Auto ignition temperature of Hydrogen is 576°C - ignition by compression alone –not possible even at a CR of 29 (Study at Cornell Univ)

- Prof Ikegami’s work at Kyoto University

- Dual fuel operation - most practical mode of diesel engine operation using hydrogen

- Small horse power diesel engine –converted to hydrogen-diesel operation in IITD

- Multicylinder Diesel engine --- 45% Energy substitution
Compact portable Hydrogen diesel genset unit has been tested for long running hours.

Upto 38% full load energy substitution without any abnormal combustion.
MULTICYLINDER HYDROGEN – DIESEL DUAL ENGINE GENSET

Multicylinder high horse power diesel engine modified to hydrogen diesel dual fuel mode of operation.

Hydrogen substituted upto 45% on energy basis
HYDRAULICALLY OPERATED INJECTION SYSTEM

CAM-ACTUATED INJECTION SYSTEM

Neat Hydrogen-fuelled S.I. Engine Genset

TOTAL HYDROGEN S.I. ENGINE GENSET USING ELECTRONIC FUEL INJECTION SYSTEM

SIX CYLINDER HYDROGEN – DIESEL DUAL ENGINE GENSET

HYDROGEN FUELLED DIESEL ENGINE
NOx vs Equivalence Ratio

Ultra lean operation -- close to zero emissions
BTE vs BMEP

Maximum Thermal efficiency close to 44% at lean engine operation
Effect of charge Diluents (CI engines)

- No Diluent
- Water: 2640 ppm
- Helium: 10%
- Nitrogen: 30%
Development and Demonstration of H₂-Fuelled Three-Wheelers in New Delhi
Hydrogen operated Three Wheeler - Passenger Version

Demonstrated in Auto Expo 2010

His Excellency Mr Binali Yildirim, Minister of Transport Republic of Turkey, is discussing with Prof. L.M. Das about the newly designed passenger version.
Inaugural Ceremony of DELHY -3W

9th January 2012, Pragati Maidan
Hydrogen operated auto displayed during auto expo
Official inauguration was held on 9th January 2012 in Pragati Maidan, New Delhi

From left to right - Dr M. Hatipoglu, Mr. Nigel Gibson, Prof. L.M. Das, H.E. Burak Akcapar, Ms. Kiran Mehra-Kerpelman, Ms. Ayumi Fujino, Ms. Rita Menon, Dr. Pawan Goenka
Dr. K. Yumkella, Director General of UNIDO having joy Ride in DELHY 3W
FUELLING STATION IN PRAGATI MAIDAN
Use of Vegetable oils

“The use of vegetable oils for engine fuels may seem insignificant today, but such oils may become in course of time as important as petroleum and the coal tar products of the present time”

Rudolf Diesel (1912),
- Inventor of Diesel engine - Address to the Engineering Society of St Louis, Missouri in 1912
Biodiesel Developed in lab from typical non-edible Indian Feedstock

- Castor (C)
- Cottonseed (CS)
- Jatropha (J)
- Karanja (K)
- Linseed (L)
- Mahua (M)
- Neem (N)
- Polanga (P)
- Rubber (R)
- Simarouba (S)
PROBLEMS ENCOUNTERED WITH NEAT VEGETABLE OIL

Clogging of Fuel Lines

Carbonization of injector tips

Deposit on Cylinder Walls

Poor Ignition and combustion due to improper atomization

Lube oil Contamination
CARBON DEPOSIT ON INJECTOR TIP USING NEAT VEGETABLE OIL
TRANSESTERIFICATION (IN LAB)

Karanja Oil → KOH (Catalyst) → Biodiesel (unrefined) → Alcohol free Biodiesel

Alcohol (Methanol/Ethanol) → Glycerine (unrefined) → Biodiesel (with moisture) → Moisture removal by Anhydrous Sodium Sulphate or by heating

Byproduct: separated from biodiesel by settling

Waste water → Neat Biodiesel (B100)

Neat or blended with diesel → CI Engine
Biodiesel production: lab and Pilot plant

Biodiesel plant for process optimization (one Liter capacity)

Fifty liter Batch capacity-Biodiesel Pilot Plant at IIT Delhi
50 Litres/Batch Capacity - Biodiesel Pilot Plant In IITD
Glycerol separation and Washing Biodiesel with water
Biodiesel produced in IIT Delhi
Biodiesel PILOT plant installed at IITD
General Motors (USA) team’s visit
Tavera vehicle in Bhubaneswar during ORISSA Tour after covering 1500km one way (fueled with KOME 20%)
Performance Test of Tavera on Chassis Dynamometer at IOC (R&D) Centre, Faridabad
Biodiesel-fuelled vehicle at different places of India
MNRE sponsored TATA Indica car fueled with KOME (B20)
Covered >30,000 km
ESCORT Tractor powered by Karanja biodiesel (B20)
BSEC Vs BMEP

(MOME)

- BMEP (N/m$^2$)
- BSEC (KJ/hr/KW)
- Diesel
- 10% MOME
- 20% MOME
- 30% MOME

Graph showing the relationship between BSEC and BMEP for different fuel mixtures.
Thermal Efficiency Vs BMEP (LOME)
BMEP Vs BTE

KOME

BMEP (MPa)

BTE (%)

Diesel

B20

B100

B10

BMEP vs BTE

BTE (%)

BMEP (MPa)

Diesel

B20

B100

B10
Evaluation of performance & Emission Characteristics done on Stationary Engine

Brake Thermal Efficiency vs Engine Power Output

Brake Thermal Efficiency

Engine Power Output in kW

Diesel
B 20
B 50
B 100
Brake Specific Fuel Consumption vs Engine Power Output

Brake Specific Fuel Consumption vs Engine Power Output

Brake Specific Fuel Consumption in kg/kWh

Engine Power Output in kW

- Diesel
- B 20
- B 50
- B 100
B 50 Karanja oil
Methyl Ester

B 100 Karanja oil
Methyl Ester
Smoke Opacity Vs BMEP (LOME)
NOx Vs BMEP

IIT Delhi
Carbondioxide Emission in g/kWh

Carbondioxide Emission vs Engine Power Output

Engine Power Output in kW

Carbondioxide Emission in g/kWh

- **Diesel**
- **B 20**
- **B 50**
- **B 100**
Carbonmonoxide Emission vs Engine Power Output

- **Diesel**
- **B 20**
- **B 50**
- **B 100**
UBHC Emission in g/kWh

Unburnt Hydrocarbon Emission vs Engine Power Output

Unburnt Hydrocarbon Emission in g/kWh

Engine Power Output in kW
Nitrogen oxides Emission in g/kWh

Oxides of Nitrogen vs Engine Power Output

- Diesel
- B 20
- B 50
- B 100

Oxides of Nitrogen in g/kWh vs Engine Power Output in kW
Smoke Opacity (%)

Smoke Opacity vs Engine Power Output

Smoke Opacity in (%) vs Engine Power Output in kW

- Diesel
- B 20
- B50
- B 100
Emission of Carbon-dioxide

Engine Power Output (kW)
Emissions in g/kWh
Diesel
B20
B50
B100
Carbon monoxide emissions increase with load because fuel burning gets hindered at high loads due to which more fuel goes and doesn’t get time to get completely burned. B 20 has minimum CO emissions
Hydrocarbon emissions are due to incomplete combustion and poor atomization. Therefore, B 20 is having minimum HC emissions as compared to other blends and diesel.
NOx is temperature dependent and biodiesel blends have after combustion temperature due to presence of oxygen molecules. Hence more NOx with increasing % of biodiesel.
Smoke minimum with B 20 blend due to appropriate mixing of diesel and biodiesel.
Thank You

Indian Institute of Technology, Delhi