Demonstration of Ammonia-Gasoline Dual Fuel System in a Spark Ignition Internal Combustion Engine

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The Ideal Transportation fuel

- Can be produced from any raw energy source (i.e. wind, solar, biomass, coal, nuclear, hydro etc.)
- Is cost effective
- Has significant storage and delivery systems already in place
- Environmentally friendly
- Can be used in any prime mover (i.e. diesel engines, fuel cells, SI engines, gas turbines, etc.)
- Has a proven, acceptable safety record
• Ammonia (NH3) can be produced from any raw energy source, including all fossil, renewable and nuclear sources.
• Ammonia is cost competitive with gasoline as a transportation fuel
• Ammonia has extensive, worldwide transportation and storage infrastructure already in place
• Ammonia is very environmentally friendly when used as a transportation fuel and produces only N₂ and H₂O at the tailpipe with low-cost emissions controls.
• Ammonia has been successfully demonstrated in SI engines, CI engines, and fuel cells.
Energy density (LHV) for fuels in liquid state

- Cetane (diesel): 20 MJ/liter
- Octane (gasoline): 18
- Heptane: 18
- Hexane: 17
- Pentane: 16
- Butane: 15
- Ethane: 12
- Propane: 12
- Ethanol: 9
- Methane: 8
- Methanol: 4
- Ammonia: 11
- Liquid hydrogen: 13
- Hydride: 13
- Water: 13

Hydrogen density range

From George Thomas, BES workshop 5/13/03
End Use Applications

• Spark-Ignition Internal-Combustion Engines (w/hydrogen or ethanol)
• Diesel Engines (w/biodiesel and/or DME)
• Direct Ammonia Fuel Cells
• Gas Turbines
• Gas Burners (including residential furnaces)
Progress accomplished

- **Flex fuel (gasoline/ammonia) vehicle** successfully driven from Michigan to California (nh3 Car)
- Over **50% efficiency** demonstrated in a SI engine (HEC)
- **Irrigation pump** demonstration with SI engine (HEC)
- **Direct ammonia fuel cell** bench-scale demonstration (Howard U.)
- 1.5 Mw **wind to ammonia demonstration** funded, construction underway (U. Minn. Morris)
- 95% ammonia, 5% diesel, 110% rated power in a John Deere **diesel engine** (IEC/ISU)
Combustion Equation

• \((0.790 \: N_2 + 0.210 \: O_2) + 0.024 \times b \: C_6H_{11} + 0.280 \times (1-b) \: NH_3 \Rightarrow (0.930 - 0.140 \times b) \: N_2 + (0.420 - 0.288 \times b) \: H_2O + 0.144 \times b \: CO_2\)

• □ Gasoline is the combustion promoter.

• □ \(b = \) Chemical Equivalence basis gasoline fraction.  
  \(0 \leq b \leq 1.\)

40% replacement of gasoline into NH3 gives  
**Reduction of CO₂ more than 200 Mton yearly**
- Ammonia internal combustion engine
- A vehicle prototype

- Performance development with ammonia fuel
  - Substitution of gasoline upto 70%
  - Gasoline equivalent power output

- Ammonia + Gasoline dual fuel vehicle prototype
  - Fuel consumption : above 10 km/l (10 L/100 km)
Installation of the test engine

- HMC Kappa 1.0 LPG-gasoline bi-fuel engine
- Baseline test – LPG only
- RP-ECU – Wiring, Matching for Sensors/Actuators, Start problems

**Specification of the test engine**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Number of cylinders</td>
<td>3</td>
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<tr>
<td>Bore x Stroke (mm)</td>
<td>71.0 x 84.0</td>
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<tr>
<td>Displacement (cc)</td>
<td>998</td>
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<tr>
<td>Compression ratio</td>
<td>10.5 : 1</td>
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<tr>
<td>Firing order</td>
<td>1-2-3</td>
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<tr>
<td>Intake valve</td>
<td></td>
</tr>
<tr>
<td>Opening</td>
<td>BTDC 22.5° ~ ATDC 27.5°</td>
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<tr>
<td>Closing</td>
<td>ABDC 3.7° ~ ABDC 53.7°</td>
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<tr>
<td>Exhaust valve</td>
<td></td>
</tr>
<tr>
<td>Opening</td>
<td>BBDC 40.6° ~ BBDC 0.6°</td>
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<tr>
<td>Closing</td>
<td>BTDC 12.6° ~ ATDC 27.4°</td>
</tr>
</tbody>
</table>

- Separated LPG-Gasoline bi-fuel
- Full variable valve timing (VVT)
- Variable intake system (VIS)
Baseline performance (LPG)

- Flat torque output with RPM
- Maximum torque = 101 Nm at 3600 rpm
- High level of NOx and moderate CO, HC emissions
- Target assessment for ammonia engine
Immersion test method

- Immersion of the relevant parts into ammonia liquid
- Reinforced glass window
- Corrosive material analyses
Immersion test for injectors and fuel line

- Corrosion checkup for the LPG parts (injectors, pump etc.)
- Some sealant was prone to be corrosive (1)
- HNMR, Kalrez elastomer are the substitutes

<0 min>  <30 min>  <75 min>

HNBR  Kalrez

(1)
Immersion test for the fuel tank assembly

- Corrosion check for the parts inside fuel tank including LPG pump
- All the sealants and the level floater should be replaced.
- In-line type delivery pump is recommended for monitor and service.

*Different sealants* *Electrodes*
*Metal parts in the tank* *Fuel delivery lines* *Level floater*

Feed pump Before immersion After 12 hrs
Fuel injection effect

Fig. 7. Engine performance results of LPI and mixer fuel supply systems

Fig. 8. Engine output and volumetric efficiency with LPG fuel supply systems

Source: LPG gas engine TFT in KIMM
Fuel injection strategy

Source: Co-work with LPG gas engine TFT, KIMM
In a two stroke engine

1. Stable stoke attainment
2. Effective piston work
3. Minimizing port–valve overlap
4. Minimizing unburned fuel going out
5. Fuel stratification – rich mixture near the spark plug
6. Utilizing internal EGR – to suppress NOx formation
Injector icing

1min 2min 3min 4min 5min 6min 7min 8min 9min 10min
(LPG P/B=6/4, fuel supply pressure: 12bar, air flow rate: 9.2L/min)

Fig. 4 Formation of the icing with time (air temperature of 20°C, 80% of humidity)
NOx, NH3 slip problem

• Increase in NOx emission with fuel load

• NO emission is far from fuel mix ratio (relative gasoline quantity)
  - Small increase in NO2 with ammonia combustion up to 10~40 ppm
  - Steep increase in the fuel lean conditions

• Unburned NH3 (NH3 slip) increases with NH3
  - Not a big deal in fuel lean condition

• **AOC** (Ammonia Oxidation Catalyst) to deal with NH3 slip

• **SCR** (Selective Catalytic Reduction) to reduce both NOx and NH3
Summary 1

• LPG-gasoline dual fuel system conversion is completed

• NH$_3$ corrosion test was conducted to prepare the fuel supply system

• Considerations to lead better performance with respect to the fuel supply strategy
Future work

- LPG-gasoline dual fuel system
- Ammonia-gasoline dual fuel system
- Vehicle installation of the ammonia fuel system
- Vehicle evaluation (Fuel consumption)
Thank you for your attention!