Toward the Development of a Thermodynamic Fuel Cell

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Hydrogen, Fuel Cells & Infrastructure Technologies Program
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Goal

Develop an ideal, thermodynamic cycle based electrical generator.

Otto cycle is fundamentally capable of high (>80%) conversion efficiency.
Modern 4 stroke Diesel is extreme case, pressure limitations control design.
Ideal, thermodynamic (Otto) cycle is constant-volume combustion

Possible approaches

- Spark-Ignition /Diesel
  - Piston stops and waits for combustion to finish.
  - Mechanically complex.
  - Greater heat loss.
  - Compression ratio limited by knock (SI).

- Homogeneous Charge Compression Ignition (HCCI)
  - Combustion is so fast that piston is stationary during burn.
  - Loss of timing control.

Details
Homogeneous Charge Compression Ignition

- Fuel / air premixed.
- Charge combusts due to compression heating.
  - No flame propagation / diffusion mixing required
  - Chemical kinetics dominate (VERY FAST!)
- Can achieve constant-volume combustion.
- Multi-fuel capable \(\rightarrow\) no flammability limits.
- NOx control by dilution.
  \(\rightarrow\) limits combustion temperatures
Device utilizing HCCI to its full potential will:

- Compress the fuel / air mixture rapidly to reach high compression ratio at ignition.
- Electronically control compression ratio.
- Be capable of surviving high peak, short duration pressure pulse.
- Have mechanical simplicity for high reliability / low cost potential.
Thermodynamic Fuel Cell

- Free piston → rapid compression
- HCCI combustion driven
- Direct electrical output
Characteristics of Thermodynamic Fuel Cell

- Optimizes thermodynamic cycle with free piston, rapid compression.

- Combustion experiments show high compression ratio and high efficiency, with near 0 NOx emissions.

- Utilizes linear alternator for compression ratio control and mechanical simplicity.

- Compression is developed inertially – no heavy support components required.

- Linear alternator is electromagnetic equivalent of brushless, direct-current permanent magnet generator, +96% efficient.
Approach to Development

- Demonstrate HCCI combustion potential.
- Develop linear alternator.
- Develop inlet / exhaust process.
  - Combine critical components into 30kW prototype research engine.
RCEM Combustion Experiment

Pressure – volume data using low BTU bio-gas
Linear Alternator

Parallel development plan

- **In-house (Sandia / Magsoft)**
  Electromagnetic modeling (FLUX2D)
  Describe velocity profile, anisotropic materials. Calculate $I^2R$ losses.
  Parametric variations to focus on optimal configuration.

- **Magnequench International**
  Design, fabricate and supply at no cost.

Experimental verification

Alternator Test Rig
**Intake / Exhaust System**

**Critical for efficiency / emissions goals**
- Charge preparation for HCCI combustion.
- Control of short-circuiting (fuel loss, HC emissions).
- Limit pumping power.

**CFD modeling and visualization**
- KIVA3V / Ensight.
- Parametric optimization.

**Turbocharging**

Increase in fuel-to-electricity conversion efficiency, and power density with increasing boost pressures

Scavenging performance for various charge delivery methods; desired operating region illustrated
Relevance

• Thermodynamic fuel cell provides electrochemical fuel cell like performance.
• Utilizes highly developed reciprocating engine technology.
• Near term cost will be low.
• Multi-fuel capability important.
• Provides an alternative, competitive path for hydrogen conversion.
• Meets FreedomCAR 2010 goals for internal combustion systems operating on hydrogen or hydrocarbons.

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<thead>
<tr>
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<th>GOAL</th>
<th>Thermodynamic fuel cell</th>
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<tbody>
<tr>
<td>Efficiency</td>
<td>45%</td>
<td>50%</td>
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<tr>
<td>Cost</td>
<td>$30 / kW</td>
<td>$20 / kW</td>
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<tr>
<td>Emissions</td>
<td>Meet Standards</td>
<td>$0</td>
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FY 2003 Progress

- Scott Goldsborough, PhD completed.
- Investigation of turbocharging / hybrid gas turbine systems performance.
- Preliminary 4kW gas compressor design.
- Hans Aichlmayr joins group, postdoc appointee.
- Magnequench linear alternator testing.
- 5 presentations.
- 2 publications.
Interactions / Partnerships

Caterpillar

- Inlet / exhaust process, free piston technology

Magnequench

- Permanent magnet / linear alternator

Magsoft

- Alternator modeling

Lotus Engineering

- Piston engine design

DOE

- Office of Distributed Energy and Electricity Reliability
  Distributed Energy Resources

- Office of FreedomCAR and Vehicle Technologies
  Engine and Emissions Control Technologies
Timeline

1995
- Initial concept developed

1996
- Sandia directed funding

1997
- Combustion Experiments (30kW)

1998
- SAE 982484 Horning Award

1999
- Alternator development

2000
- Nick Paradiso PhD

2001
- Lab Call ‘00 Funding 3YR

2002
- Scott Goldsborough PhD

2003
- SAE 2003-01-0001
- Hans Aichlmayr, PostDoc

Prototype Demonstration 2006