Ammonia Based Fuels For Environmentally Friendly Power Generation

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Why Electricity Generation?
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Transportation vs Electricity Generation

Due to its high hydrogen density, ammonia has been studied as transportation system fuel extensively.

“The following are quoted as the main reasons
– Safety – toxicity
– Ammonia cracking issues: start up, efficiency, conversion rate
– Storage: Lack of light, compact and robust storage tanks

<table>
<thead>
<tr>
<th></th>
<th>Transportation</th>
<th>Electricity Generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety</td>
<td>Very critical</td>
<td>Not as critical</td>
</tr>
<tr>
<td>Cracking</td>
<td>Cracking reactors heavy/expensive</td>
<td>Easily done</td>
</tr>
<tr>
<td>Storage tank weight</td>
<td>Critical</td>
<td>Not an issue</td>
</tr>
<tr>
<td>Storage tank robustness</td>
<td>Need to be “Indestructible”</td>
<td>Existing storage tanks are suitable</td>
</tr>
<tr>
<td>Distribution</td>
<td>Complicated</td>
<td>Relatively simple</td>
</tr>
<tr>
<td>Start up</td>
<td>Problematic</td>
<td>Not many start ups</td>
</tr>
<tr>
<td>Operational</td>
<td>Pumps operated by unprofessionals</td>
<td>Delivered/handled by trained pers.</td>
</tr>
</tbody>
</table>

Major shortcomings of ammonia for transportation systems are NOT relevant to electricity generation.

“DOE does not plan to fund R&D to improve ammonia fuel processing technologies for on-board use on light weight vehicles at the present time”
Why Gas Turbines?
Older plants are rapidly being displaced by gas turbine power generators

- Gas turbines supplied 15% of US power generation in 1998.
- Portion will be 39% by 2020.
- Of new demand 81% is for gas turbine power.
- Market is ~ $10 billion. About 700 to 800 new units sold per year.

Engine Types in Use

- Heavy duty gas turbines - centralized power production, 30 to 500 MW.
- Lightweight gas turbines - derived from aircraft engines, generally less than 60 MW.
- Micro gas turbines - distributed power, less than 5 MW

Why Gas Turbines?

- High efficiency - Up to 60% with steam co-generation.
- Low emissions - NOx < 10 ppm.
- Low installed cost - 25,000 hr maintenance interval.
- Multi-fuel capability - Natural gas (methane) is fuel of choice when available. Fuel transition while running.
One of the Applications
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Applications – Small Scale

NH3 Production

- Small scale NH3 production units based on electrolysis are currently available
- These can be converted to mobile systems
- If SSAS technology is developed successfully, efficient, cost effective and compact units can be manufactured
- NH3 can also be produced from HC feed stocks

NH3 Fuel

- NH3 can be easily and safely stored
- Gas turbines can be used to generate electricity
  - Microturbines: 30 kW-200 kW
  - Aerobased: 10 MW
- Exhaust gas can be used for heating
- Eventually NH3 can be used in mobile applications
Background
Ammonia Fired Turbines
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Gas Turbine Power Generation – Fuels Comparison

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Fuel/air ratio*</th>
<th>Tcombuster* K at 20atm</th>
<th>Texhaust K at 1 atm</th>
<th>Enthalpy change (work) kJ/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>0.058</td>
<td>2277</td>
<td>1260</td>
<td>1551</td>
</tr>
<tr>
<td>JP-4</td>
<td>0.068</td>
<td>2342</td>
<td>1313</td>
<td>1539</td>
</tr>
<tr>
<td>Ethanol</td>
<td>0.111</td>
<td>2295</td>
<td>1289</td>
<td>1546</td>
</tr>
<tr>
<td>NH3</td>
<td>0.164</td>
<td>2092</td>
<td>1114</td>
<td>1549</td>
</tr>
</tbody>
</table>

* Stoichiometric fuel/air combustion at a pressure ratio of 20:1

- NH3 requires higher fuel mass flow rate
- NH3 generates the same work output at lower temperature
- Or NH3 generates more power at the same temperature
Past Experience with Ammonia Fueled Gas Turbines

**History**
- Ammonia as a turbojet engine fuel has been tested in 1960’s
- At least two DoD programs (reports available)
- Some recent research activity in University of Florida
- No active programs as far as we know

**Lessons Learned**
- Ammonia is a satisfactory substitute for hydrocarbon fuels in a gas turbine engine
- Complexity and cost of engines using ammonia vapor combustors will NOT be significantly greater than existing hydrocarbon engines
- Use of ammonia would also lead to reduction of NOx emissions?

**Technical Challenges**
- Low flame temperatures and slow kinetics results in challenges with pure ammonia in a turbojet combustor
- Stable efficient combustion with liquid NH3 is problematic. Additives would help with this issue
- The DoD programs concluded that ammonia in the vapor phase can be burned in a turbojet combustor. This requires a heat exchanger to vaporize the ammonia
- Cracking helps flame stability

Oxidation chemistry of ammonia is well established

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Past Experience with Ammonia Fueled Gas Turbines

- Investigations have been conducted by Solar Company and UC Berkeley in the 60’s
- Solar used its 250 HP model T-350 single can burner engine.
- UC Berkeley studies were limited to subscale combustors
- Performance of the T-350 engine with ammonia is compared to the performance with JP-4
- Tests were limited to ammonia in vapor phase

Some Observations

- Both vapor and catalyst combustors have been tested.
- Using ammonia at 2.35 times the HC fuels resulted in cooler turbine inlet temperatures at a given power.
- When the turbine inlet temperatures are matched, the ammonia engine resulted in a power increase of 10-20%.
- Efficiencies were high with the ammonia combustors.
Development Path
SPG/MADA’s Core Competence

SPG/MADA personnel have broad experience in:
- Combustion, thermochemistry of fuels, design and analysis of gas turbines
- Testing of gas turbine engines and rocket motor systems
- SPG is an experienced DoD contractor (DCAA approved accounting system etc…)

SPG/MADA’s capabilities include:
- Laboratory testing of fuel properties
- Testing of turbojet engines (AEROTEC test facility in Butte Montana)

We have access to several J79 and J85 engines and all test equipment from the RASCAL program.
Development - Program Elements

Phase I – Feasibility (Funded by SPG IR&D Funds and Montana Board of Research and Commercialization Technology)
- Objective: Evaluate the feasibility and economical/technical viability of the concept
- Conduct feasibility studies: Modeling of ammonia combustion, testing in combustors and design of fuel nozzle for microturbines and J79 engine

Phase II – Technology Development
- Objective: Develop the necessary technologies to implement the concept
- Work includes: Fuel formulation and laboratory testing, engine cycle analysis, extensive engine testing (using engines C200 and J79 – two exist in the AEROTEC facility), development of fuel conditioning systems, coordinate with NH3 plant manufacturers

Phase III – Pilot Plant
- Objective: Implement the concept on a small gas turbine power generation plant
- Work includes: Conversion of the existing facility to an ammonia fired gas turbine, evaluation of the economical viability of the concept
- Partner with DoD

Phase IV – Implementation
- Objective: Convert existing gas turbine power generation facilities to burn ammonia and develop new ammonia-fired gas turbines if necessary
- Partner with a gas turbine producer
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Phase I Progress – Developed of Test Set up

- Test rig designed to simulate gas turbine combustor conditions
- Bleed air from a J-79 turbofan engine supplies high pressure, hot air for combustion
  - Air flow rates of >8.0 kg/s can be achieved
- At full thrust, an NH3 mass flow rate of 0.690 kg/s required for stoichiometric mixture
- NH3 vapor is pulled from the run tank and mixed with N2/H2 to simulate cracking
- Extent of simulated cracking is precisely controlled
Phase I Progress – NH3 Test Setup

• Primary Measurements
  – Flow rates
  – Pressures
  – Temperatures
  – NOx

• 3 kHz sampling rate
Achievements to Date

- Developed a facility to test ammonia combustors
- Achieved self sustained combustion with ammonia in a simulated gas turbine combustor
- Developed a combustor configuration suitable for burning ammonia
- Successfully simulated cracking
- Developed expertise in the safety of ammonia
- Developed operational experience with ammonia
- Designed a facility to burn ammonia using existing C200 microturbines
- Developed a technology to crack ammonia in a cost effective and efficient way
Cracking Technologies
Why Crack?

• Uncracked NH3: Slow flame speed, large ignition energy, large quenching distance, poor flame stability
• Cracking is needed for 1) stability, 2) efficiency, 3) Low NOx emissions and 4) good power loading

Ref: Vercamp, Hardin and Williams 11th Symposium on Combustion 1967

- Uncracked NH3
- Methane
- 6% 14% 28%
Fuel Conditioning: Partial Cracking of Ammonia

**Autothermal Reformation of Ammonia**
- These are designed for fuel cell applications
- Not suitable to gas turbines requiring high flow rate and small conversion rates

**Off-the Shelf Crackers**
- Thermal cracking method
- High temperature catalysts (800-900 °C)
  - Expensive
  - Short life
- Large quantities of electric energy
- Heat losses
- Slow start up

**Improved crackers:**
Combustion with air over a catalyst bed

Ammonia cracker devised by Apollo Energy Systems

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Fuel Conditioning: Research

Pre-burner with O2

- Pursued by SPG
- Have small liquid rocket engine operating fuel rich
- Generate O2 if not available on site
- Pre-burn with NH3
- Energy efficient process
- Not funded

Development of Low Temperature-Cost Effective Crackers

- Pursued by KOC University
- Working with a catalyst expert
- Well equipped University lab. available for development
- Possible funding: Turkish government
Thank You!