Novel Thermal Energy Conversion Technologies for Advanced Electric Air Vehicles

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Basic Building Block for Electric Aircraft: Thermo-Acoustic Engine and Heat Pumping

**KEY PROPERTIES**
Can be used for thermal energy conversion:
- From heat to mechanical power
- From mechanical power to cooling
- From heat to heat pump when used in double configuration shown
Power Options

- FC/Turbine Hybrid
- PEM/SOFC
- Micro/Gas turbines
- Diesel
- ICE
- DELTA
- Strayton

<table>
<thead>
<tr>
<th>Technology</th>
<th>Net System AC Power (kW)</th>
<th>Net Fuel LHV to AC Electric Power Conversion Efficiency</th>
<th>Full Production Equipment Manufacturing Cost $ per W</th>
<th>System Maintenance Cost $/kwh</th>
<th>System Availability Percent</th>
<th>System Life (yrs)</th>
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</thead>
<tbody>
<tr>
<td>Ideal</td>
<td>&gt;100</td>
<td>&gt;70</td>
<td>&lt;0.9</td>
<td>0.02</td>
<td>&gt;95</td>
<td>&gt;20</td>
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<td>SOFC-GT</td>
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<td>&gt;70</td>
<td>&lt;4</td>
<td>&lt;1</td>
<td>&gt;95</td>
<td>&gt;5</td>
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<tr>
<td>Strayton</td>
<td>&gt;100</td>
<td>&gt;50</td>
<td>&lt;0.05</td>
<td>&lt;0.02</td>
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<tr>
<td>Fuel Cell</td>
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<td>&gt;50</td>
<td>&lt;5</td>
<td>&lt;1</td>
<td>&gt;95</td>
<td>&gt;5</td>
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<tr>
<td>µ-Turbine</td>
<td>&lt;300</td>
<td>&lt;20</td>
<td>&lt;1</td>
<td>&lt;0.1</td>
<td>&gt;95</td>
<td>&lt;5</td>
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<tr>
<td>ICE OTTO</td>
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<td>&lt;0.5</td>
<td>&lt;0.1</td>
<td>&gt;95</td>
<td>&lt;5</td>
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</table>

Comparison of Efficiencies

Region of Interest
**Key Features**

- Combines Stirling and Brayton cycles synergistically for <2MW high efficiency and specific power
- Provides both topping and bottoming cycles using a Brayton and Stirling cycle (both are top and bottom!)
- Achieves recuperation without a recuperator
- Naturally cools the turbine blades
- Power is extracted via rotating and oscillation
- Fuel Flexible with high turn-down ratio

**Key Features**

- High-speed Brayton cycle and internal Stirling cycle use no-maintenance air and flexure bearings
- Power balancing between cycles via direct control
- No contact rotating bearings and power transfer
- High speed rotation enable short conductive blades
- No hot moving Stirling cycle parts
- Leverages recent HEMM work for flexure stiffness
- Pedigree from previous DOE/Reliance Electric 2008
Thermodynamic Efficiency Step-by-Step

Baseline Performance

Stirling adds 17% efficiency

Stirling Recuperation adds 10% efficiency

Scales to 125kW

Note T4 blade is conductively cooled to 1500K, waste heat recuperated drops fuel required by 121kW

Note T4 blade is conductively cooled to 1500K, waste heat recuperated drops fuel required by 368kW
Double-Acting Extremely Light-Weight Thermo-Acoustic Generator (DELTA)

**Key Features**

- Utilizes multistage high frequency thermo-acoustics
- Uses a double-acting piston and engine reactive power to minimize required spring
- Fuel flexible including cryogenic
- Shape flexible for embedding in unusual locations
- Silent operation
- Higher efficiency and comparable specific power with ICE

Provides silent power for APU and UAV applications
Propulsion Options

- Fully Superconducting
- Partially Superconducting
- PM Synchronous
- Induction
- Double-fed
HEMM w/Embedded Cryocooler

HEMM is designed to operate as:
- a 1.4 MW motor
- with direct drive
- High torque/low speed
- >98% efficient
- >16 kw/kg (active E-M parts)

Cryocooler Key Features:
- Cool superconducting rotor
- Fit inside rotating motor
- Integrates cooler and linear machine
- Operate rotating or stationary
- No cold moving parts

Superconducting inside the motor and provides Strayton risk reduction
Linear Machine and Pulse-Tube Cooler

No cold moving parts

Flexure Stiffness Increases Under Rotation

Long Linear Magnet has Distributed Forces
Current proposed solutions (and limits) include:

- Ram air HX
  - adds weight and aircraft drag
- Convective skin cooling HX
  - adds weight, drag, and inefficient
- Dumping heat into fuel
  - limited thermal capacity
- Dumping heat into lubricating oil
  - limited thermal capacity
- Active cooling
  - adds weight and consumes engine power
- Phase change cooling
  - adds weight and limited thermal capacity
- Heat pipe, pumped multiphase, vapor compression
  - adds weight and consumes engine power
Thermal Limits
Into Fuel
Recirculate Fuel
Ram Air
Into Engine
Vapor-Compression

<table>
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<tr>
<th></th>
<th>1% Hot Day</th>
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<tbody>
<tr>
<td></td>
<td>Total Penalty (zero exit velocity)</td>
<td>Total Penalty (non-zero exit velocity)</td>
</tr>
<tr>
<td>900NM</td>
<td>4.98%</td>
<td>3.31%</td>
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<tr>
<td>3500NM</td>
<td>5.00%</td>
<td>3.62%</td>
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Variable Conductance Heat Pipe

Solid-state Heat Transfer Switching

Acoustic and Heat Pipe Tubes Embedded in Airframe
TREES – Thermal Recovery Energy Efficient System Complete Cycle

Solid-state (no moving part) energy recycle and control
• Localized skin heating for active lift/drag management, de-icing, powertrain cooling, cabin management, and military cloaking
Integrated Benefit

**Strayton Engine**
- High efficiency/specific power
- Integrated thermal conversion

**TREES**
- Distributes waste heat with waste heat
- Saves fuel
- Improves aerodynamics
- Naturally de-ices

**HEMM Motor**
- High efficiency/specific power
- Integrated thermal conversion

**DELTA**
- High efficiency/specific power
- Quiet

Advanced Integration is Required at Component and System Level
Conclusion

• Maximum benefit with electric aircraft is achieved by integrating at both the component level and system level.

• Thermal Energy Conversion technologies provide the fundamental building block for this integration.

• HEMM motor provides flight-weight high efficiency at high power

• Strayton engine provides flight-weight high efficiency at medium power

• DELTA engine provides flight-weight high efficiency at low power

• TREES enables the tight integration of all these technologies at the vehicle level.