Optimizing Thermal Management Systems in Electric Aircraft

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Cleveland, OH

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NASA has executed a plethora of EAP activities over the last 10 years and is in the process of advancing the future of sustainable flight. Work spans from fundamental research to flight demonstrations.

**X-57, 100kW class flight demo of all electric distributed propulsion.**

**Revolutionary Vertical Lift Technology Studies of Electric, Hybrid, Turboelectric Concepts and Technology.**

**Electrified Powertrain Flight Demo – ground & flight demonstration of integrated MW-class powertrain.**

**Advanced Air Transport Technology/Propulsion & Power Subproject - powertrain technology.**

**Transformational Tools & Technology – EAP materials & modeling.**

**Hybrid Thermally Efficient Core (HyTEC) Advanced turbine engine technologies in a high-power-density core.**

**SUSAN – A 20 MW hybrid-electric aircraft concept study featuring a single aft engine with distributed wing-mounted propulsors.**
Why Electric Aero-Propulsion?

- Why electric?
  - Fewer emissions
  - Quieter flight
  - Fuel savings
  - New mobility options
  - Better utilization of infrastructure
NASA is advancing Electrified Aircraft Propulsion (EAP) technology across a variety of markets, ranges, aircraft sizes, VTOL/CTOL configurations and electrical power levels. Fully electric, hybrid, and turboelectric are potential EAP system configurations. Electrified aircraft propulsion impacts vary on aircraft design, depending on the key requirements of the market the vehicle is intended to serve.

<table>
<thead>
<tr>
<th>MARKET</th>
<th>AIRCRAFT</th>
<th>PASSENGERS</th>
<th>SPEED</th>
<th>RANGE</th>
<th>POWER</th>
<th>WASTE HEAT</th>
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<tr>
<td>On demand mobility</td>
<td>VTOL</td>
<td>1-19</td>
<td>~50-200 mph</td>
<td>~25-200 miles</td>
<td>~1 MW</td>
<td>~200 kw heat</td>
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<td>Regional</td>
<td>General Aviation / Small</td>
<td>1-19</td>
<td>~150-200 mph</td>
<td>~100-500 miles</td>
<td>~1 MW</td>
<td>~200 kw heat</td>
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<td>Turboprop</td>
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<tr>
<td>Regional</td>
<td>Regional Turboprops &amp;</td>
<td>20-150</td>
<td>~300-400 mph</td>
<td>~500-1500 miles</td>
<td>1-5 MW</td>
<td>~200 kw-1MW heat</td>
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<td>Turbofans</td>
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<td>National/International</td>
<td>Single Aisle</td>
<td>150+</td>
<td>~500-650 mph</td>
<td>~1500-7000 miles</td>
<td>3-30 MW</td>
<td>~600 kw-6MW heat</td>
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# EAP Ecosystem

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• **Challenge is to highly integrate all systems:**
  - improve fuel efficiency
  - reduce emissions
  - reduce low grade waste heat
  - reduce vehicle mass
  - manage distributed heat sources

All components must integrate
Current proposed solutions 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

**Energy Transfer Medium**

<table>
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<tr>
<th>Energy Transfer Medium</th>
<th>Limits</th>
<th>Scale</th>
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<tbody>
<tr>
<td>Electrical</td>
<td>Voltage, Copper Mass and Heat</td>
<td>$I^2R$</td>
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<tr>
<td>Mechanical</td>
<td>Lubrication, Vibration, Heat, Mass</td>
<td>$0.5 \tau \omega^2$</td>
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<tr>
<td>Fluid</td>
<td>Freezing, Pump, Impurities, Heat, Mass</td>
<td>$m C_p T$</td>
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<tr>
<td>Phase Change/Vapor</td>
<td>Gravity, Orientation, Distance, Freezing</td>
<td>&lt;1 m</td>
</tr>
<tr>
<td>Acoustic</td>
<td>Design Challenge, Some Heat</td>
<td>$0.5 * p v^2$</td>
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50kW to >600kW of low-grade thermal heat trapped within composite aircraft body
Thermal Management System Integration Benefits

Can increase specific power of the powertrain components while also increasing system efficiency.
Conventional Aircraft Thermal Rejection Limits

Dumping heat into:
- Fuel (currently limited to 50 kW),
- Outer mold line (limited 300 kW),
- Ram air (see below for losses),
- By-pass air (see below for losses),

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<tr>
<th></th>
<th>1% Hot Day Total Penalty</th>
<th>1% Hot Day Total Penalty</th>
<th>Standard Day Total Penalty</th>
<th>Standard Day Total Penalty</th>
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<tr>
<td></td>
<td>(zero exit velocity)</td>
<td>(non-zero exit velocity)</td>
<td>(zero exit velocity)</td>
<td>(non-zero exit velocity)</td>
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<tr>
<td>900NM</td>
<td>4.98%</td>
<td>3.31%</td>
<td>2.76%</td>
<td>2.36%</td>
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<tr>
<td>3500NM</td>
<td>5.00%</td>
<td>3.62%</td>
<td>3.01%</td>
<td>2.57%</td>
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Powertrain Technology Requirements

- MW-Scale Transport Class Powertrain Requirements:

ARPA-E ASCEND Powertrain

- Specific power ≥ 12 kW/kg
- Efficiency ≥ 93%
- Heat Rejection
- Thermal Management System (TMS)
- Electric Motor
- Electronic Drive & Protection
- Mechanical Output, Power & Speed
- Electrical Input, Voltage & Current

* Only protections between motor and electronic drive subsystems are included

Goal is to reduce TMS specific mass from 2 kg/kW(th) to <1 kg/kW(th)
Solid-State Dynamic Thermal Management System

- **Solid-State Exergy Amplification**
  - No moving parts
  - No pumped fluids
  - No increased drag
  - Maximize specific power
  - Improve powertrain efficiency

- **Areas of Development**
  - Turbofan WHR HX
  - Acoustic Heat Pump
  - OHP Heat Collection
  - Thermal Transport
  - Thermal Recycling
  - Dynamic Thermal Redirection
  - Gradient-based System Optimization
Thermal Recovery Benefits

- **Solid-state Energy Recycle Benefits**
  - localized skin heating
    - for active lift/drag management,
  - de-icing/anti-icing,
  - powertrain cooling,
  - cabin thermal management,
  - engine recuperation,
  - thrust enhancement with by-pass air
  - military cloaking

Potential Range of up to 16% Fuel Burn Savings with Waste Heat Recovery
Turbomachinery WHR Challenges

Material, Surface Area, and Engine Cycle Performance Impacts Available Waste Heat Recovery
Available Waste Heat Recovery from Turbofan

Typical Gas Turbine Casing Liner Materials
- Nickel Alloy Honeycomb (usually united)
- Thermal Spayed metal matrix and ceramic coatings
- Thermal Spayed Nickel Chromium Aluminum Silicides
- Thermal Spayed Aluminum Silicon Boron Nitride

Liner extraction > 500 kW

Nozzle extraction > 1 MW

Credit: Shyam

Turbo-electric Potential Energy Extraction > 10 MW
Nozzle Waste Heat Energy Extraction Example

- **Key Point:** Most thrust (>80%) produced in by-pass air of commercial aircraft
  - Turbofans have bypass ratio from 6 to 12
  - Turboprop have bypass ratio from 50 to 100
  - Hybrid electric distributed propulsion up to 100
  - Small core further increases by-pass ratio

- **Idea:** Extract waste energy from core
  - Minimal impact on overall thrust
  - Reduce jet noise that scales as $V^8$
  - ~30 MW waste heat available on B737
  - Extract only 10%, 3 MW -> **1MW acoustic energy available**
Acoustic Heat Pump

Acoustic Energy Amplification and Refrigeration with Same Traveling Wave
• $P_1$ phasors everywhere nearly constant
• $U_1$ phasors progressively lag due to volume (compliance)
• Ideally, $P_1$ and $U_1$ in phase in regenerators
• Gas inertia (inertance) can be used to counter $U_1$ lag
• E.g. Swift inter-stage inertance tube
• Modeling tools like Sage automatically account for distributed compliance and inertance
Acoustic Heat Pump COP

Reject at Higher Temperature

Heat Lifted Vs. Duct Length

Cold reservoir

Accept at Lower Temperature

Ratio of input acoustic energy required for heat pumping

<table>
<thead>
<tr>
<th>Th (k)</th>
<th>Tc (k)</th>
<th>Ratio (W/Qc)</th>
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<tbody>
<tr>
<td>400</td>
<td>300</td>
<td>1:3</td>
</tr>
<tr>
<td>600</td>
<td>300</td>
<td>1:1</td>
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<td>900</td>
<td>300</td>
<td>2:1</td>
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<td>1200</td>
<td>300</td>
<td>3:1</td>
</tr>
<tr>
<td>300</td>
<td>50</td>
<td>40:1</td>
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Solid-State Energy Delivery and Control

Acoustic Energy Control Method
- Small Input/No Input
- 300K
- 800K
- Acoustic Wave On
- 900K
- Acoustic Wave Off
- 330K
- Heat

Vapor Energy Control Method
- Heat Transport On
- Heat Transport Off
- Working Fluid
- Noncondensable Gas
- Evaporator
- Active Condenser
- Inactive Condenser
- Gas Reservoir
- No Heat
- Low Heat

Dynamic Refrigeration and Thermal Transport with No Pumps or Moving Parts
Successful 10-meter Acoustic Heat Pump Test

Refrigerated Section Highlighted with Optical Sensors
10-meter Acoustic Heat Pump Prototype Test Results

Thermal energy heat pump at single location along 10-meter tube with no detected acoustic waveguide tube heating
Next Step – 6 Stage Amplification!

Stage 1 | Stage 2 | Stage 3 | Stage 4 | Stage 5 | Stage 6
---|---|---|---|---|---
Waste Heat In | Waste Heat In | Waste Heat In | Waste Heat In | Waste Heat In | Waste Heat In

Acoustic Tube Waveguide

High Power Heat Pump Refrigeration

(Thot/Tcold)^6
Acoustic Energy In

5000W refrigeration

MW DC Breaker Refrigerated

5000W refrigeration

Acoustic Tube Waveguide
Conclusion

NASA is broadly investing in Electrified Aircraft Propulsion (EAP)

NASA investments are guided by a combination of potential market impacts and technical key performance parameters.

The impact of EAP varies by market and NASA is considering three markets: on-demand mobility, regional and national/international air transportation.

Technical advances in key areas have been made that indicate EAP is a viable technology.

Flight research is underway to demonstrate integrated solutions and inform standards and certification processes.

Additional work is needed to transition the technology to a commercial product and further improve the technology to realize the benefits across the world.

Feasible Vehicle Class Driven by Powertrain Specific Power and Efficiency and Integrated Vehicle Design Optimization

Power, Propulsion, Thermal, and Airframe Integration Key