Cooling of Electric Motors Used for Propulsion on SCEPTOR

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Benefits of Electric Power

- Reduced energy consumption
- Lower emissions
- Less noise

SCEPTOR
Scalable Convergent Electric Propulsion Technology Operations Research
- Traction motors
  - Permanent magnet
  - Synchronous
  - High torque at low rotational speeds
  - High power density
    - High concentration of heat

SCEPTOR Cruise Motor
Typical permanent magnet synchronous motor

*In-Runner is shown but final design is an Out-Runner*
Motor Configurations

- Annular inlet
  - Very compatible with PM motors
    - Provides cooling where needed
    - No need for complicated ducting
    - Leads to a larger motor diameter which is beneficial for motor torque
Extreme high field temperature

Typical cold day at 15,000 ft ASL

Reduced for ProtoQual

Range for ESS
At surface use +45°C (113°F)

SCEPTOR Environment Temperature Operating Range at Altitude superimposed on measured temperatures at EAFB

Designing for 15,000 ft ASL per DO-160G Category A-1

Maximum operating altitude 8,000 ft ASL
Hardware Configurations for Full-Scale Test of NACA Cowlings
Lessons learned from NACA

- Shape #7 with spinner #10 was preferred
- Small diameter inlets, #3 & #9, were not acceptable
  - reduced turbulence on the front face of the engine
- Preferred nose shapes can be found in NACA report 662
- Because the flow velocity is so low inside of the cowling, the geometry of the internal flow path is not significant
  - True when motor has a high (3X) flow conductance relative to the inlet and outlet. This is not currently the case for SCEPTOR
- Fans/blowers provide little benefit for in flight cooling
- Propeller slip stream in only beneficial on the ground
- Variable geometry skirts proved to be inefficient
- Cooling drag is not just related to the geometry change: It includes the work done to pump the air through the motor, i.e. it’s a function of flow rate
Effect of prop wash on heat transfer coefficients

✓ Assumed propeller induced turbulence would increase heat transfer coefficients
✓ Holmes, Obara & Yip reported “propeller slipstream showed little if any apparent effect of the slip stream.”
✓ Derlaga @ LaRC also found little change in heat transfer in the wake of the propeller
Average: 185 W/m$^2$K
Empirical flat plate: 135 W/m$^2$K
Lumped Parameter Model

- Spreadsheet to perform quick parametric studies
- Empirical equations for heat transfer coefficients
- ‘Goal seek’ method to find solution to simultaneous equations
- Correlated with conjugated heat transfer & CFD model
- Parameters varied to see effect on core coil temperature, a.k.a. stator

Early ‘In and Out Runner’ Configuration
Lumped Parameter Model
‘In & Out Runner’ Configuration
Lumped Parameter Model

Results

✓ Increasing pressure head using fans or up-draft had little benefit

✓ Adding cooling area was most effective (*shown in plot*)

✓ Analysis of radial gap height showed 0.002m was desirable (*shown in plot*)

✓ Air flow gap between coils should be at least 0.001m wide

✓ Provided independent validation & verification and helped substantiate that the proper geometric dimensions, boundary conditions, and power levels were being used
Intra-Coil Core Cooling
Stator Cooling Fin Concepts
### Out Runner Motor Cooling

<table>
<thead>
<tr>
<th>Passage</th>
<th>% of Air Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor/Stator Gap</td>
<td>17%</td>
</tr>
<tr>
<td>Stator Fins</td>
<td>75%</td>
</tr>
<tr>
<td>Coil Gaps</td>
<td>3%</td>
</tr>
<tr>
<td>Fin Tip Gap</td>
<td>4%</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Passage</th>
<th>% of Cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor/Stator Gap</td>
<td>31%</td>
</tr>
<tr>
<td>Stator Fins</td>
<td>48%</td>
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<tr>
<td>Coil Gaps</td>
<td>8%</td>
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<tr>
<td>Fin Tip Gap</td>
<td>-</td>
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<tr>
<td>External</td>
<td>14%</td>
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</tbody>
</table>

- Exterior of Nacelle (rotating)
- Permanent Magnets (rotating)
- Electro-magnetic Coils (stationary)
- Stator Cooling Fins (stationary)
Lumped Parameter Model
‘Out Runner’ Configuration

- **Inlet**
- **Exhaust**
  - Weight average mass flow to obtain exhaust temperature

**Components:****
- **External Environment**
- **Outer Rotating Permanent Magnets**
- **Stationary Electromagnetic Core**
- **Cooling Fins**

**Notations:****
- Radial Gap Between Outer Rotor and Stator
- $h_cA$
- $0.3kW$
- $3kW$

**Diagram Details:**
- The diagram illustrates the flow through the components and connections between them.
Out-Runner Motor-Cooling

Observations:

✅ Adding fins to the ID of stator greatly increased the cooling area and air flow

✅ The fins provide 48% of the cooling

✅ The fins have an excess of air flow
  
  ➢ Causes lower exit temperatures, which allow the exit air to be used for inverter cooling
  
  ➢ Makes design robust, i.e. insensitive to moderate changes in airflow

➢ Pressure drop at inlet and outlet are of same magnitude as across the motor

Dual Inverters
Conclusions:

- Motor is adequately cooled for inflight operations
- A finned heat sink on the electromagnetic core is the most effective method to achieve adequate cooling
- The design is robust: Moderate changes in airflow will have minor effect on cooling
- Simple 1D models are very valuable
  - Provide insight into the what changes are most influential
  - Quickly do parametric studies
  - Perform independent verification
  - Discover errors or misunderstandings
- Details about the current design and a more in depth analysis will be presented by Arthur Dubois of Joby Aviation