



# Cooling of Electric Motors Used for Propulsion on SCEPTOR

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## Abstract

NASA is developing a suite of hybrid-electric propulsion technologies for aircraft. These technologies have the benefit of lower emissions, diminished noise, increased efficiency, and reduced fuel burn. These will provide lower operating costs for aircraft operators. Replacing internal combustion engines with distributed electric propulsion is a keystone of this technology suite, but presents many new problems to aircraft system designers. One of the problems is how to cool these electric motors without adding significant aerodynamic drag, cooling system weight or fan power. This paper discusses the options evaluated for cooling the motors on SCEPTOR: a project that will demonstrate Distributed Electric Propulsion technology in flight. Options for external and internal cooling, inlet and exhaust locations, ducting and adjustable cowling, and axial and centrifugal fans were evaluated. The final design was based on a trade between effectiveness, simplicity, robustness, mass and performance over a range of ground and flight operation environments.

## Introduction

NASA is developing a new generation of aircraft which incorporate batteries and electric motors for propulsion. The benefits of electric power include reduced energy consumption, lower emissions and less noise. NASA's flight testbed for demonstrating distributed electric propulsion is called Scalable Convergent Electric Propulsion Technology and Operations Research (SCEPTOR) (Ref. 1), which is shown in Figure 1. SCEPTOR will use permanent magnet motors to drive propellers and rechargeable batteries to power those motors. These motors have a high power density and the compact design limits the area available for cooling. Therefore a major task in this project was to design a motor cooling system that was compatible with the constraints associated with motor design, integration and operation.

SCEPTOR will have two electric-powered cruise motors one on each wing tip and a dozen smaller high-lift electric-powered motors distributed along the wings. This paper will discuss the development of the cruise motor, a.k.a. wing tip motor, which is shown in Figure 2. The motors for SCEPTOR are being developed by Joby Aviation and are permanent magnet synchronous motors which provide high torque at low speeds while retaining a high power density. The main components of the motor, Figure 3, are the electromagnetic core coils, which is stationary; and the permanent magnets, which are rotating. The rotating permanent magnets can either be located inside of the core coils or outside. These configurations, Figure 4, are respectively called 'in runners' or 'out runners'. The motors can also have both inside and outside rotating magnets, which would be called an 'in and out runner' or 'double runner'. Although the motor shown in Figure 3 is an example of an 'in runner' with cooling fins on the outside diameter, the motor for SCEPTOR will be an 'out runner' with cooling fins on the inside diameter.

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\*Retired.



Figure 1.—SCEPTOR.

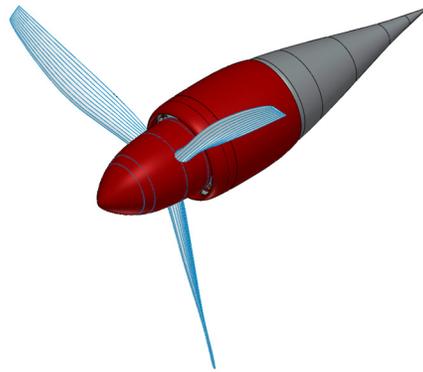


Figure 2.—Cruise motor.

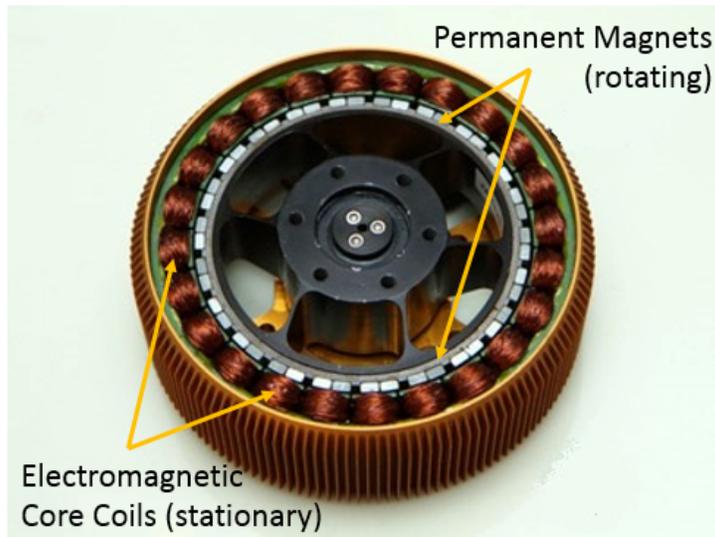


Figure 3.—Typical 'in runner' permanent Magnet synchronous motor.  
(*Photograph courtesy of Joby Aviation*)

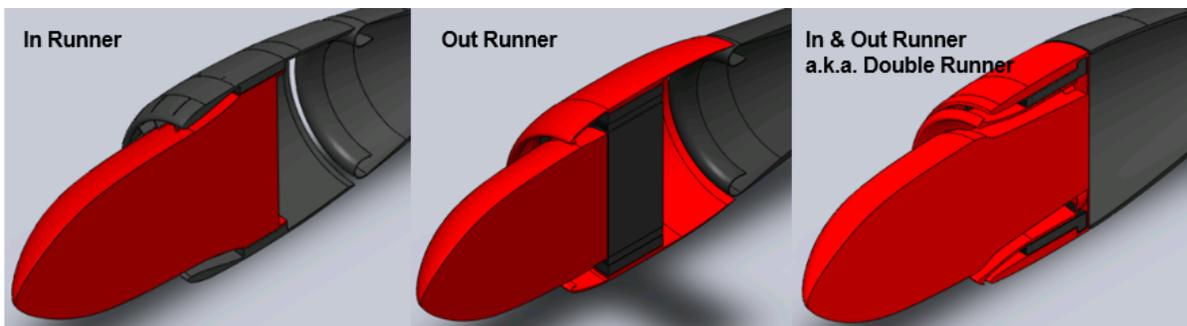


Figure 4.—Motor configurations.  
(Red components are rotating and grey components are stationary)

Many low-drag cooling concepts were explored by Joby Aviation to provide adequate cooling to the motor. A few of the flow paths examined are shown in Figure 5. The first concept provides simple axial flow through the motor. This is the least complicated design and generally provides adequate cooling in flight but there is very little airflow during ground operations. The second concept, referred to as ‘Updraft Exhaust,’ took advantage of the low static pressure associated with the accelerated flow over the outer lip of the inlet. This lower exhaust static-pressure led to increased flow rate which reduced the stator temperature approximately 10 °C. The benefit of this was outweighed by the increased flow duct complexity and the expected to increase nacelle drag. A version of this design also included a radial fan aft of the motor. The fan provides a minor increase in pressure but little benefit to cooling during cruise or climb. The third concept provides axial flow in combination with a radial fan. The main purpose of the fan is to generate adequate cooling during ground operations. Joby and NASA also considered non-annular inlets but quickly found that the annular inlet was very compatible with the permanent magnet motor. The annular inlet provides cooling air where it was needed without complicated ducting and performs well at high angles-of-attack. The annular inlet also requires a larger nacelle diameter for a fixed spinner size but that is a benefit to motor performance: Larger diameter motors can generate higher amounts of torque and provide improved efficiency.

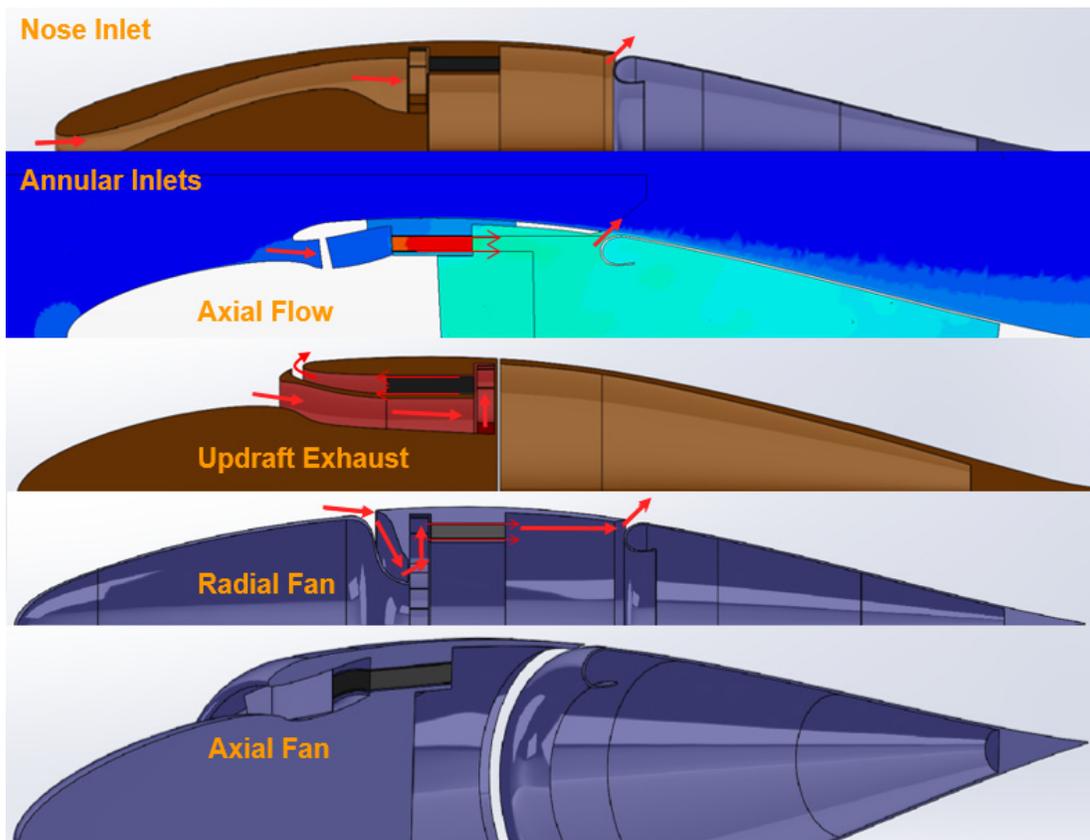


Figure 5.—Candidate cooling air flow paths.

## Definition of Thermal Environment

Defining the thermal environment for SCEPTOR was rather challenging. The motor developer stated that short duration motor temperatures had to be limited to +120 °C and long duration operation limited to +100 °C. These limits were quite constraining because of the high ambient temperatures at Edwards Air Force Base (EAFB) where air temperatures on the field can reach +45 °C. This limited the permissible temperature rise of the motor, relative to the environment to 55 °C. Using a maximum operating environment temperature of +45 °C and applying 10 °C as an analytical uncertainty margin, the high limit for the acceptance test thermal cycle test was set at +55 °C. Normally qualification thermal cycle testing is done at 11 °C above the acceptance test range, but since these motors are classified as protoqual units, MIL-STD-1540C allows this difference to be reduced to 5 °C (Ref. 3). The thermal requirements for SCEPTOR motors are summarized in Figure 6.

The lower temperature limit of -25 °C for the operating temperature was based on typical cold day temperatures at an altitude of 15,000 ft above sea level (ASL) (Ref. 4). This provides a lower limit of -35 °C for the acceptance test and a  $\Delta 90$  °C range for the thermal cycle which is acceptable for environmental stress screening; but numerous thermal cycles will be required in order to have a high probability of finding workmanship flaws (Ref. 5).

Although SCEPTOR will normally operate at 8,000 ft MSL, it was classified as Category A-1 per DO-160G which requires testing at pressure altitudes of 15,000 ft ASL (Ref. 6). A plot is shown in Figure 7 of the SCEPTOR operating temperature range superimposed on a plot of measured temperatures at EAFB. Because there is a rapid drop in temperature after climbing a few hundred feet, the extremely hot temperatures, above +35 °C, are only applicable near the surface. For surface operations the maximum operating temperature is +45 °C.



Figure 6.—SCEPTOR motor operating and environmental test temperatures.

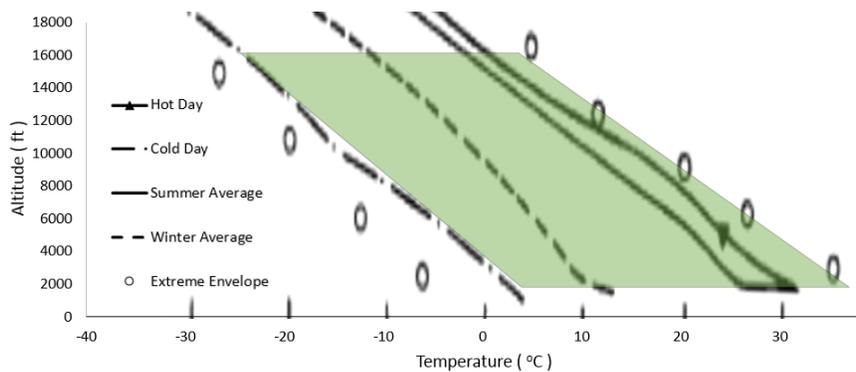


Figure 7.—SCEPTOR environment temperature operating range at altitude (underlay from NASA TM 64970 (Ref. 4)).

## NACA Literature Review

Electric traction motors have cooling problems similar to radial piston engines. They both need to be encased in a streamlined nacelle and allow for adequate cooling during normal climb and ground operations but not have excessive drag during cruise. A brief review of research performed on air cooled radial engines during the late 1930's yielded several interesting guidelines (Refs. 7 to 10). National Advisory Committee for Aeronautics (NACA) performed numerous full-scale tests of various cowling designs, including different style skirts which control the exhaust geometry. They also evaluated two different blowers and two spinners. Figure 8 shows the various hardware configuration that was tested.

Comparison of the cooling performance of the various nose shapes by NACA determined that shape #7 with spinner #10 was preferred and that small diameter inlets, #3 and #9, were not acceptable; probably because it reduced turbulence on the front face of the engine: This turbulence is a major source of cooling for radial engines. The dimensions for the profile of preferred nose shapes can be found in NACA report 662 (Ref. 8). Because the flow velocity is so low inside of the cowling, the geometry of the internal flow path is not significant.

The skirt tests showed that the exit flow should flow parallel to the mainstream; and when the flow conductance around the baffles is relatively low, the flow conductance at the exit should be three times the flow conductance through the baffles. The variable geometry skirts proved to be inefficient but could be used to reduce drag during cruise. The additional drag induced to accommodate cooling is not just caused by the geometry changes made but is also a function of the cooling air mass flow rate.

The propeller shaft driven NACA fan and the Wright blower provided little benefit to cooling during flight. The NACA fan, which is only used for in-nacelle cooling and not propulsion, was remarkably effective on the ground but had the lowest inflight efficiency. The propeller could provide some ground cooling if there was a carefully designed airfoil section near the hub of the propeller. At cruise ". . . the effect of propeller slipstream velocity being of little importance. At low air speed the situation is different . . . On the ground cooling depends . . . entirely on the propeller" (Ref. 9).

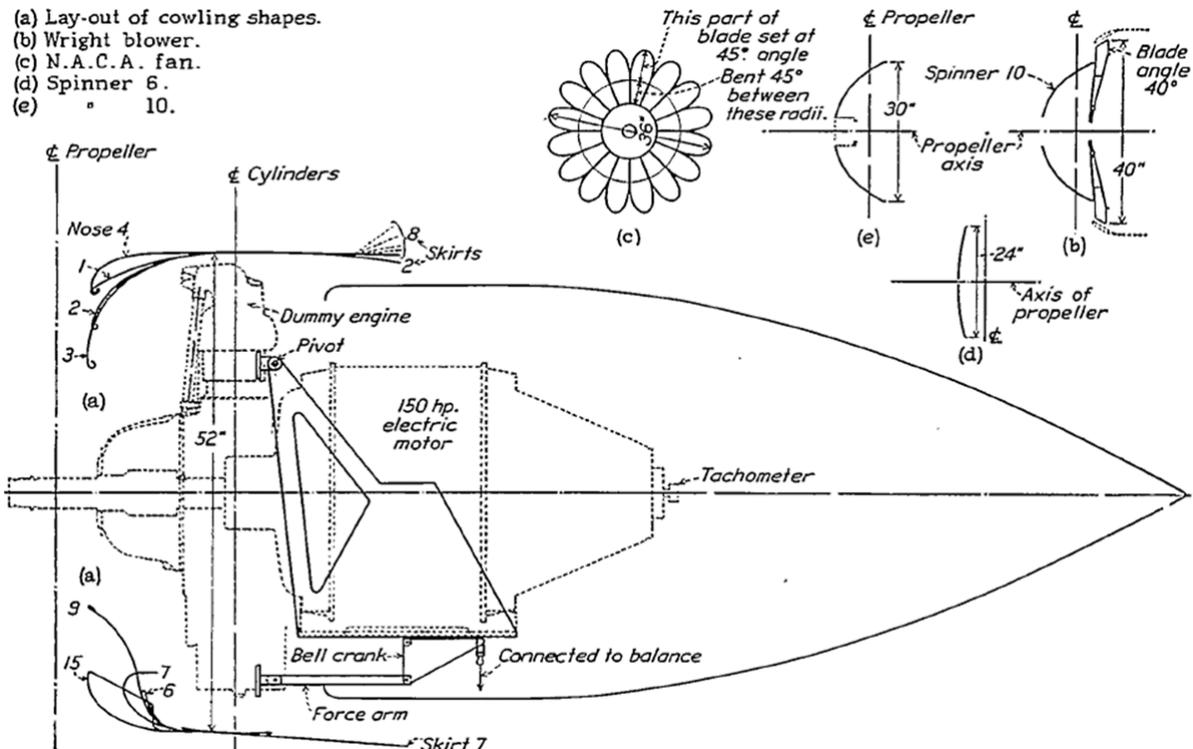


Figure 8.—Hardware configurations for full-scale test of NACA cowlings (Ref. 9).

## Effect of Propwash on Heat Transfer

At the start of the project it was thought that the motor, or at least the controller, could be cooled through the outer skin of the nacelle. It seemed logical that the turbulence created by the propwash would provide very high heat transfer coefficients on the outer diameter. On the other hand, the effect of propeller slipstream on laminar boundary laminar of airfoils was reported in a NASA TM by Holmes, Obara and Yip (Ref. 11). They reported that, in many cases, “the propeller slipstream showed little if any apparent effect of the slip stream.” This suggested that the cyclic nature of the propwash only has a momentary effect on the laminar boundary layer and when the boundary layer separates it quickly reattaches.

To confirm this a CFD analyses was performed at Langley Research Center using OVERFLOW (Ref. 12). The model is shown in Figure 9, where the red panel represents a region heated to 80 °C, and the heat flux occurring is shown in Figure 10. *The result shown is for the moment in time, i.e., it is **not** a time average.* It shows a very minor decrease during wake passage; confirming that propwash turbulence has little influence on heat transfer. The average transfer coefficient for the panel was found to be 185 W/m<sup>2</sup> °C which is very similar to the 136 W/m<sup>2</sup> °C that was calculated for a turbulent-flow flat-plate using empirical equations.

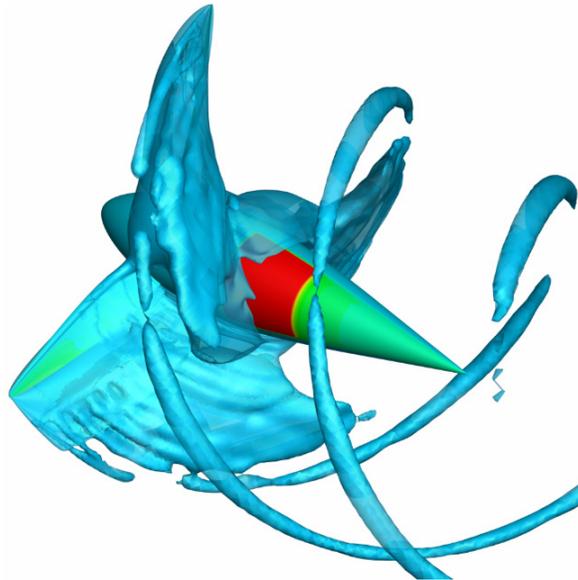


Figure 9.—CFD Analysis of prop wash.

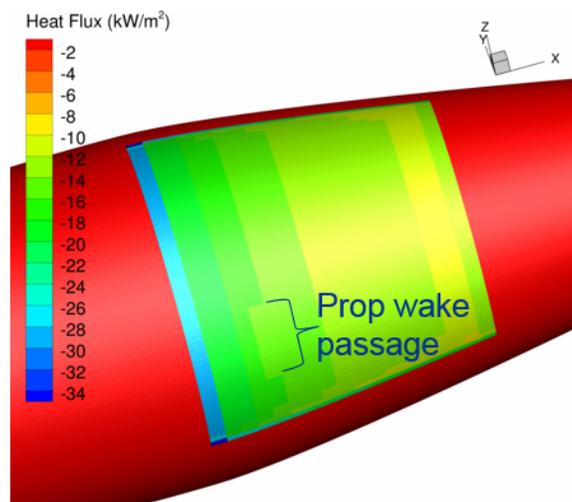


Figure 10.—Heat flux from nacelle surface.

## Lumped Parameter Thermal Model

Lumped-parameter thermal-models of the SCEPTOR motor were developed at Glenn Research Center. The initial purpose was to perform quick parametric studies, in-lieu-of doing conjugate heat transfer with the CFD model, which had a long turn-around time. The spreadsheet used empirical equations to calculate heat transfer coefficient and a ‘goal seek’ method to find the solution to the simultaneous equations. A schematic of one of the lumped parameter models is shown in Figure 11. Lumps are used to represent the stationary electromagnetic core and the inner and outer rotating permanent magnet rings. Other lumps represent inlet and exhaust airflows as well as the cooling flows around the three motor elements. The inverters are located aft of the motor, i.e., downstream, thus the inverter heat loads will not affect motor temperature and are not included in this analysis.

For simplicity, a constant motor efficiency of 95 percent applied to 60 kW of motor output power was used to estimate the heat loads in all cases. Variation of motor parameters such as gap heights will ultimately have some effect of motor efficiency; however, 95 percent was a reasonable lower bound on efficiency, given that the current models show greater than 96 percent for many of the design variations considered.

First the model was correlated to the CFD model; then the desired parameters, such as pressure head, were varied to see what the relative effect was on electromagnetic core coil temperature. The first model showed that increasing cooling area was the most effective way of increasing the temperature margin and that adding fans or doing geometry changes to increase pressure-head and flow-velocity offered little improvement.

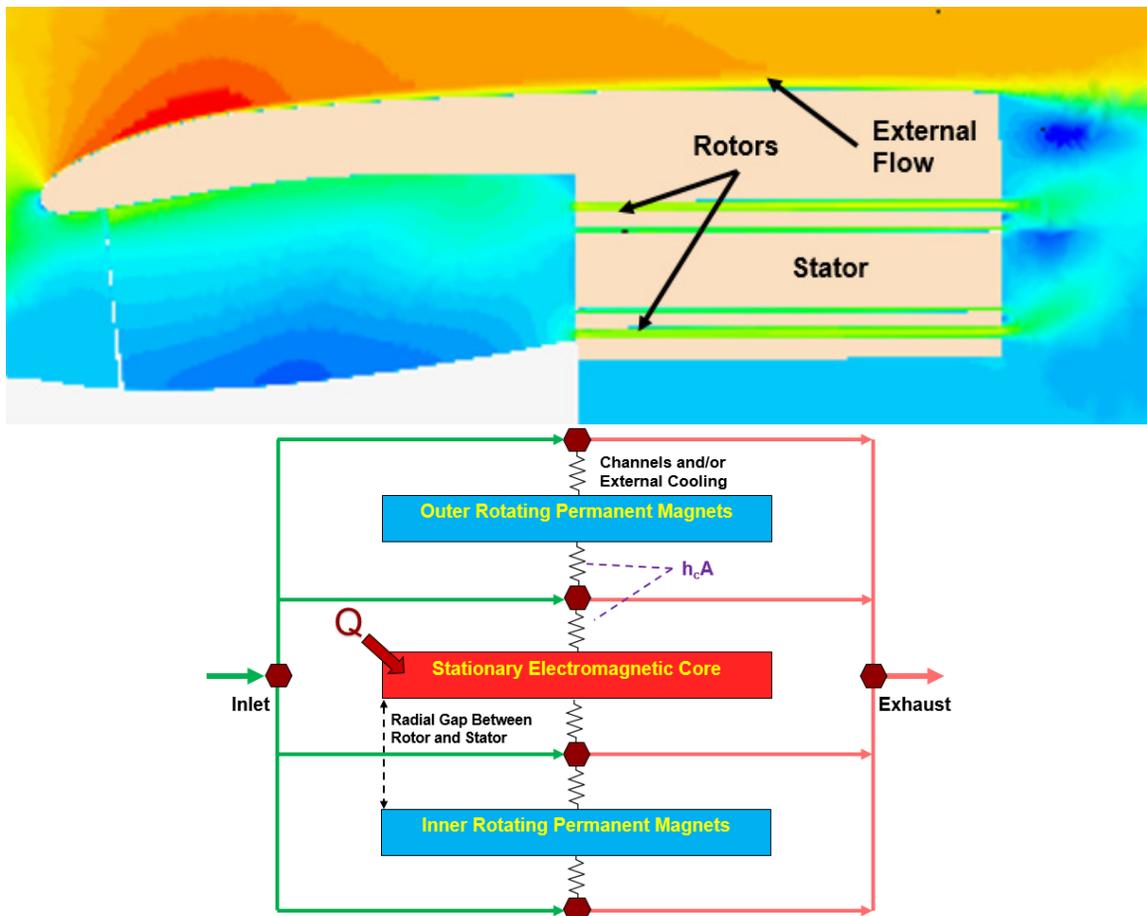


Figure 11.—Lumped parameter thermal model “in and out runner configuration”.

Another study was performed to determine the optimal radial gap height between the stator and rotors. The gap height was varied from 1 to 3 mm and the effect on coil temperature is shown in Figure 12. From these results it was concluded that the radial gap should be increased to 2 mm and little benefit is gained when using a larger gap.

During these studies, while comparing the one-dimensional model with the designer’s model, it was discovered that the wrong diameter propeller hub was being incorporated. Thus the process of developing this simple model revealed something it was not even looking for. This started a fortunate chain of events that lead to a larger diameter out-runner motor.

A similar study was performed on the tangential gap between the electromagnetic core coils. These gaps, shown in Figure 13, allow cooling air to pass between the coils and more than double the cooling area available to the coils. Analyses were performed to determine how narrow the gaps can be without reducing the thermal margin excessively. The study concluded that the gap needs to be at least 1mm wide. For the early motor designs, this proved to be a very effective cooling path but the width of this gap is not typically controlled during manufacturing. Thus the study also asserted that this dimension needs to be controlled and verified during the assembly process. *In the current design the intra-coil cooling is not significant, thus controlling this dimension is no longer critical.*

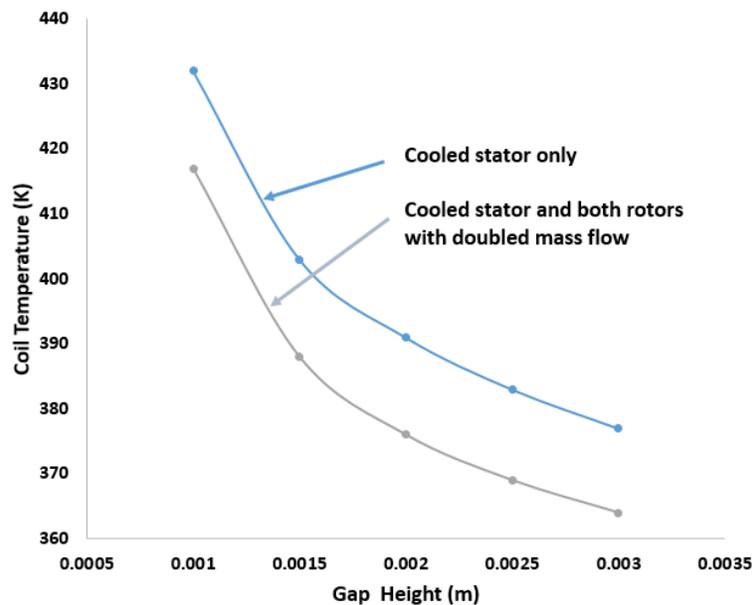


Figure 12.—Effect of stator-rotor radial gap height on electromagnetic core coil temperature.

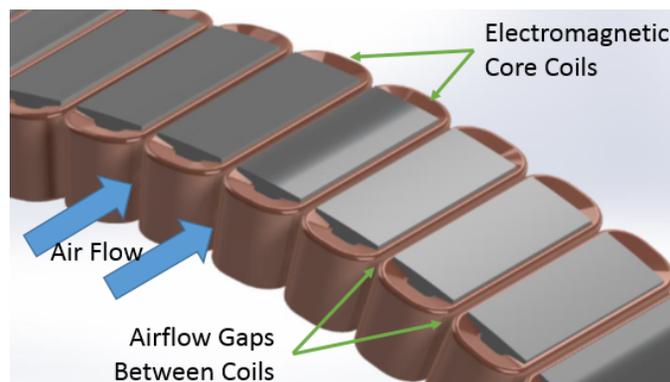


Figure 13.—Intra-coil core cooling.

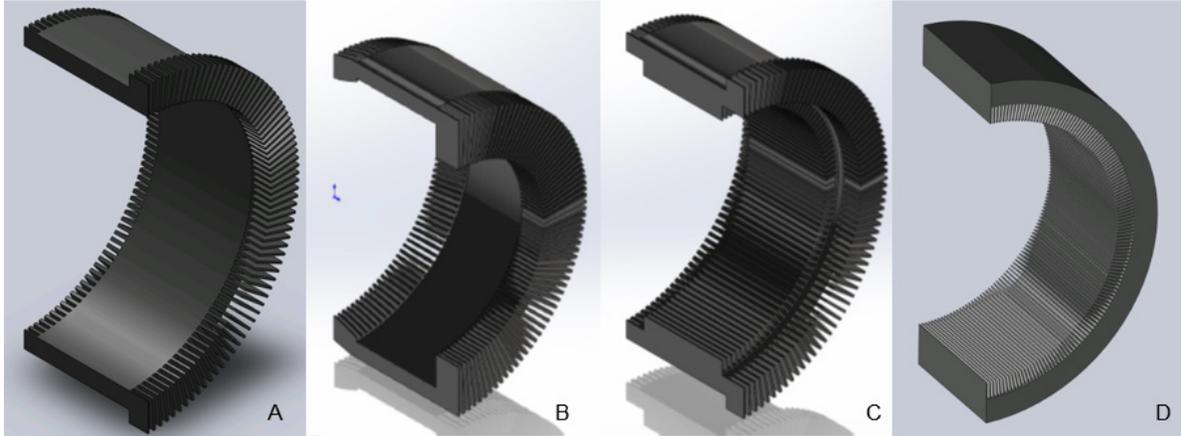


Figure 14.—Stator cooling fin concepts.

Other studies looked at the effect of adding fins to the forward and aft end of the stator and enhanced cooling of the rotor. These studies showed that the most effective way to improve cooling is to add convective cooling area to the stator, i.e., to the electromagnetic coil core. Adding cooling area was accomplished by adding fins to the stator, as shown in Figure 14. The rotating magnets have relatively little heat generation and cooling them is not a major issue. The lumped parameter model was also useful as a form of independent verification and validation and helped substantiate that the proper geometric dimensions, boundary conditions, and power levels were being used.

Figure 15 shows the cooling paths for the current design. The major change is the addition of the finned heat sink to the inner diameter of the stator. This heat sink significantly increases the convective area and enables this application. Other cooled surfaces include the annular gap between the rotor and stator, the gaps between the core coils and the external surface of the nacelle. The airflow also significantly increased and the majority of it flows through the fins, see Table 1.

The lumped parameter model for this configuration is shown in Figure 16. The model includes thermal and fluid circuits for the flow paths listed above and heat sources are applied to the stator and magnets. In this case 3,000 W of heat are applied to the stator and 300 W to the magnets. As discussed earlier, this is a limiting case—the motor efficiency models to date predict lower losses.

The results were consistent with the conjugate CFD and heat transfer model: Dubois (Ref. 13) reported an electromagnetic-core peak-temperature of 89 °C using a 35 °C environment, whereas the lumped parameter model shows an average-temperature of 91 °C using a 45 °C environment. The relative distribution of cooling is listed in Table 2. The temperature of each flow was weighted according to its mass flow rate and an average was found. The average temperature of the air exiting the motor is 56 °C. This air is cool enough that it can be reused to cool the inverters which are located behind the motor, see Figure 17. *The mass flow through the annular gap at the tip of the fins was not included in the cooling analysis but the mass flow was included in the temperature averaging, i.e., added to the fin flow.*

During the design process three lumped parameter model were generated and each produced results consistent with the analysis results reported by the manufacturer. This served as an independent verification that the correct boundary conditions and geometry were being used. More details about the current design and a more in depth analysis is presented by Dubois, et al. (Ref. 13). Their studies and this analysis show that the motor design is adequately cooled during inflight operations.

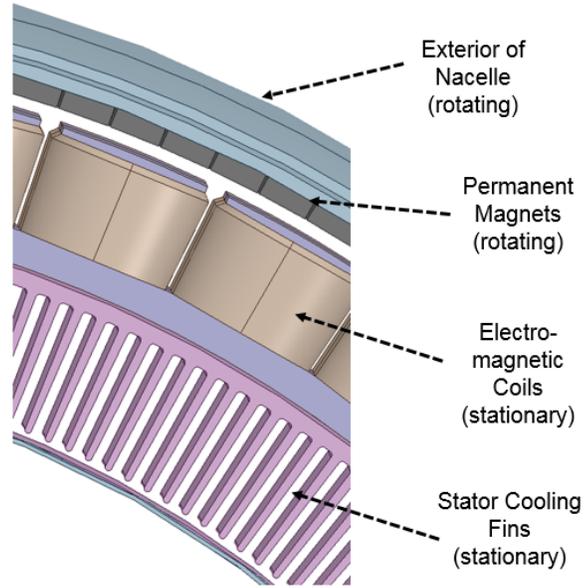


Figure 15.—Out-runner motor.

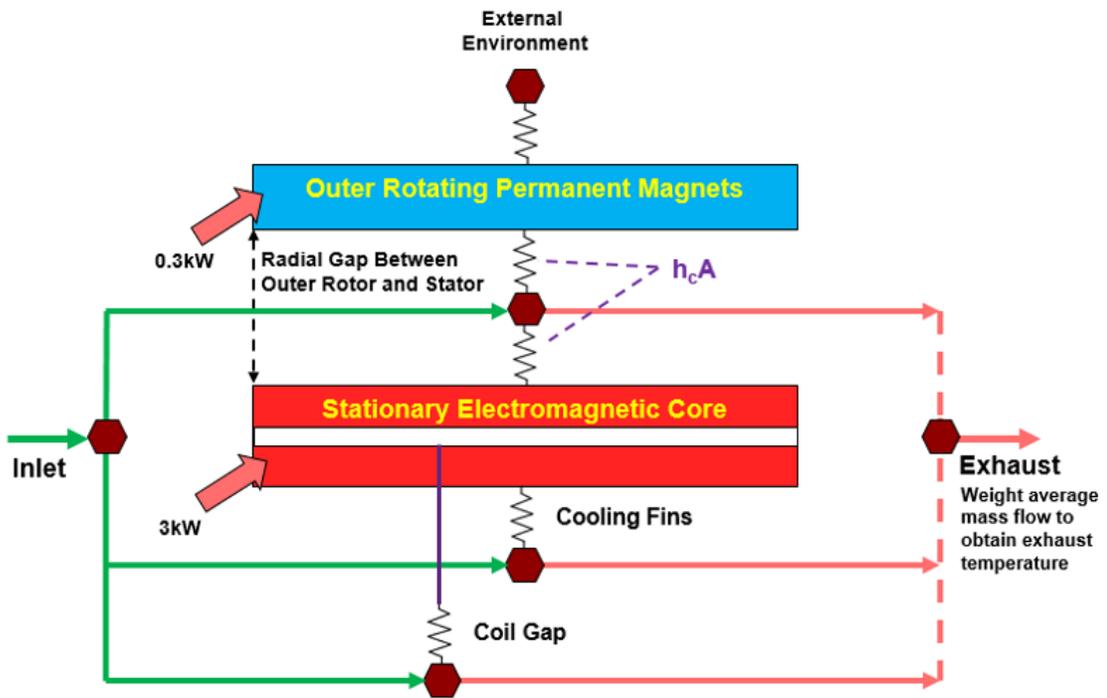


Figure 16.—Lumped parameter model for out-runner motor.

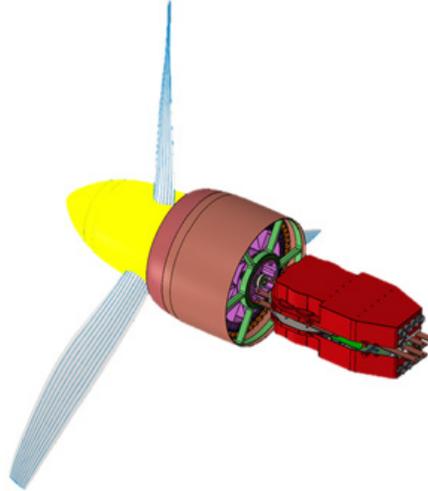


Figure 17.—Out-runner motor with dual inverters.

TABLE 1.—RELATIVE AIR FLOW THROUGH MOTOR PASSAGES DURING CLIMB

Passage	Percent of air flow
Annular gap	17
Stator fins	75
Coil gaps	3
Fin tip gap	4

TABLE 2.—RELATIVE COOLING DURING CLIMB WITH 3000 W OF HEAT APPLIED TO STATOR AND 300 W APPLIED TO ROTOR

Passage	Percent of cooling
Annular gap	29
Stator fins	53
Coil gaps	8
Fin tip gap	---
External	9

## Conclusion

The main lesson learned during this analysis is: increasing convective area is the most effective way to increase motor cooling. Increasing pressure in order to increase flow velocity and mass flow rate was not as effective. The analysis proved that simple one-dimensional models can quickly be created and are very valuable to:

1. Provide insight into the what changes are most influential
2. Quickly conduct parametric studies
3. Perform independent verification
4. Discover errors or misunderstandings

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