NASA's Quiet Electric ENgines (QUEEN): Summary of the QUEEN V2 Test

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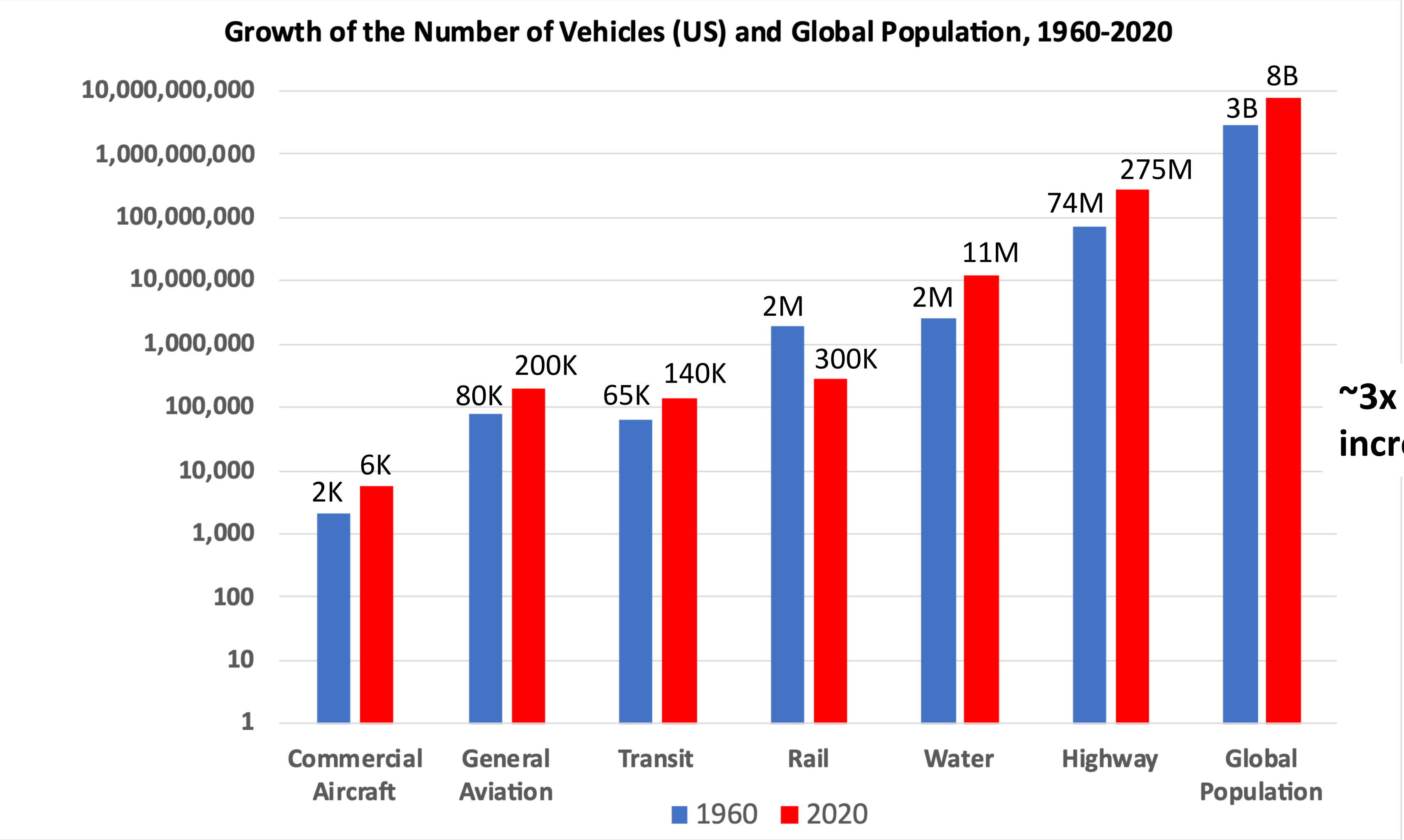
One of NASA's concept aircraft:
SUSAN, the Subsonic Single Aft Engine Aircraft

Introduction

World population and the number of vehicles on land, water, and air in the US have tripled since the 1960s.

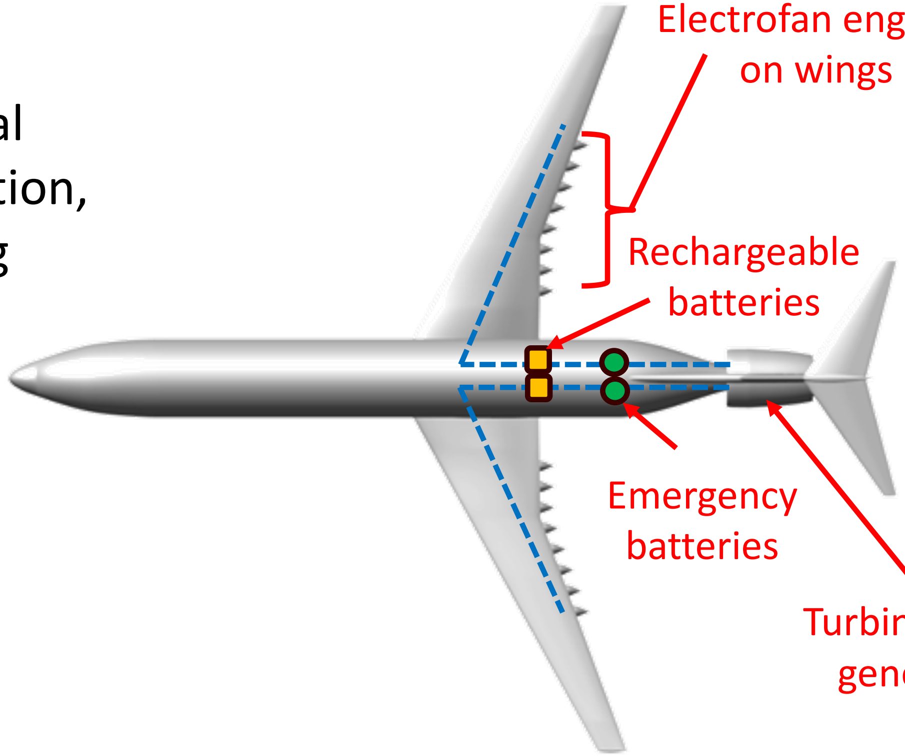
This prompts the question: How might we develop a commercial air transportation system accessible to a growing population that is safer, cleaner, and quieter than the one we have today?



~3x increase

Introduction

In response to the pervasive health and environmental problems associated with aviation noise and air pollution, NASA's Quiet Electric Engine (QUEEN) team is working to increase the peace and quiet in the world by researching ways to make engines for large single-aisle aircraft safer, cleaner, and quieter.



One of NASA's concept aircraft:
SUSAN, the Subsonic Single Aft Engine Aircraft

Introduction

Our mission is to live in a quieter world
by designing, building, testing, and analyzing
electrofans for the 25% SUSAN Flight Research Vehicle,
exploring distributed electric propulsion
for conceptual large single-aisle aircraft and
including acoustics early in this
iterative prototyping process.

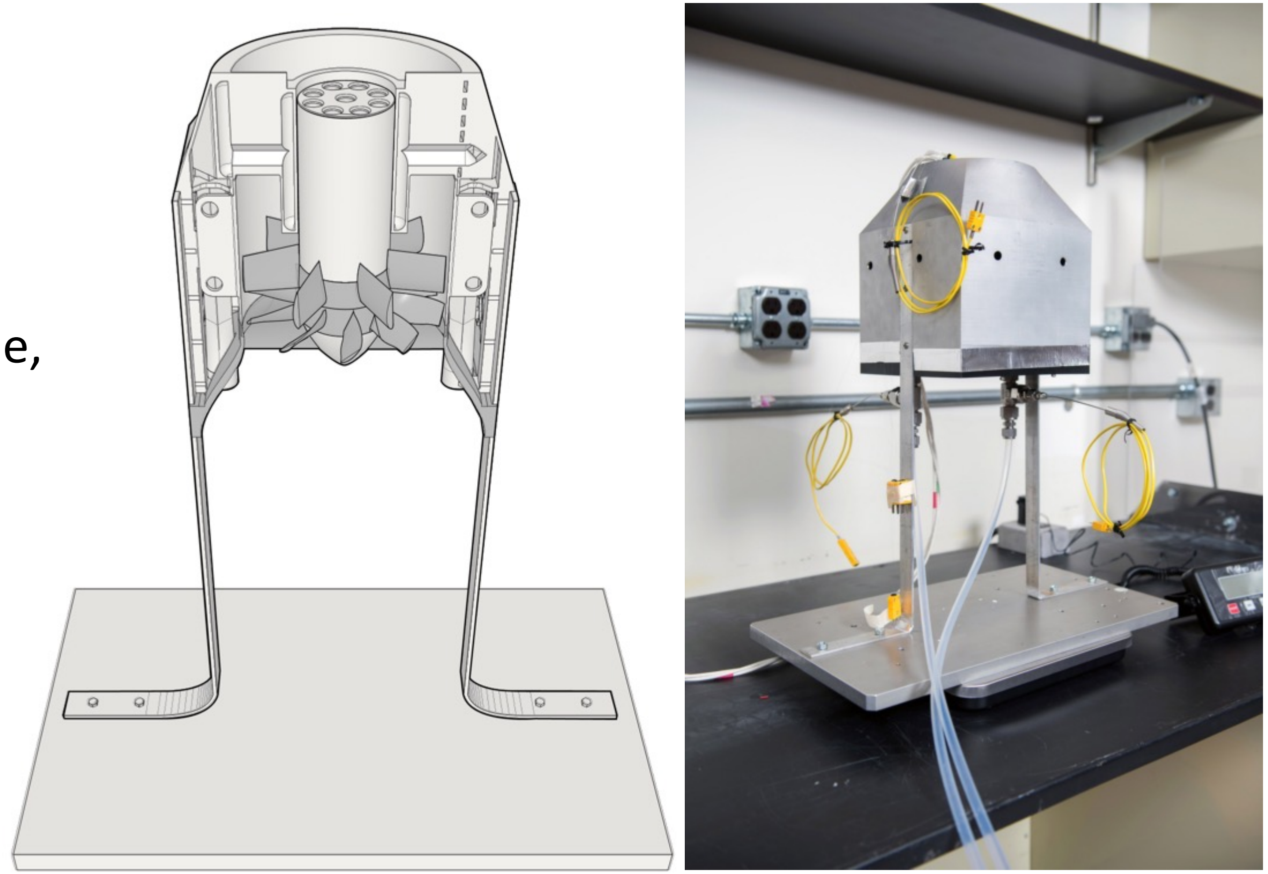


Illustration and photograph of the Quiet Electric Engine Prototype, QUEEN V2

Description of QUEEN V2 Propulsor

Rotor tip diameter	13.0 cm (5.11 in)
Duct diameter	13.3 cm (5.23 in)
Number of rotor blades	10
Number of outlet guide vanes	7
Maximum motor rotational speed	45,000 rpm
Tip clearance	1.5 mm (0.060 in)
Overall axial length	11.8 cm (4.65 in)
Weight (including the inlet and heat exchanger)	2.59 kg (5.70 lbs)

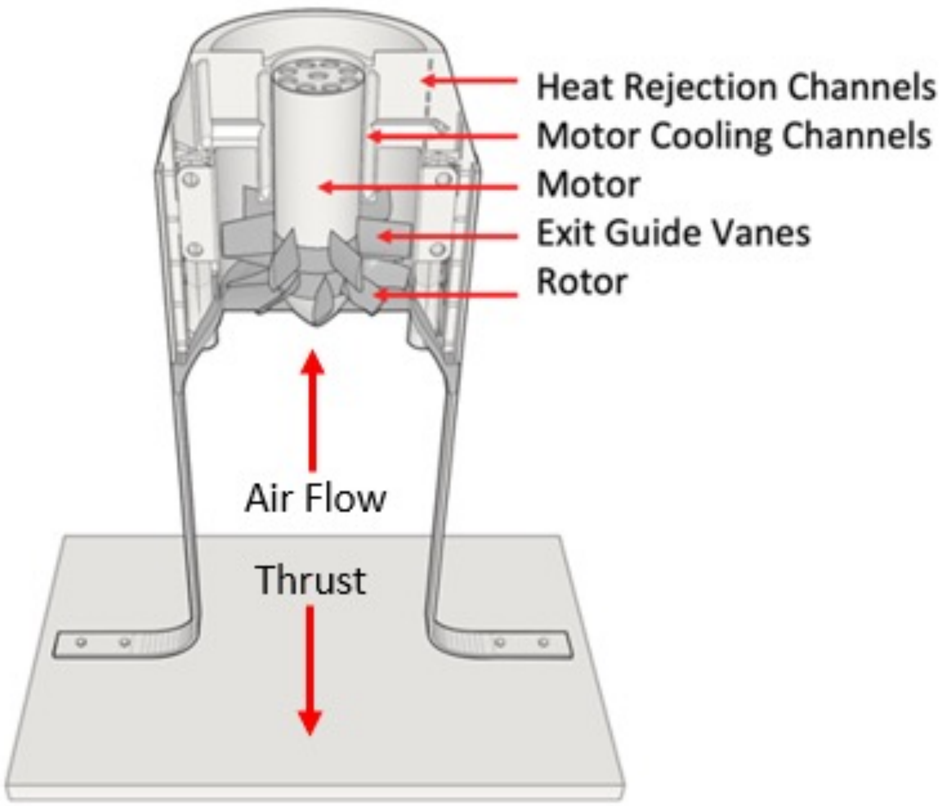
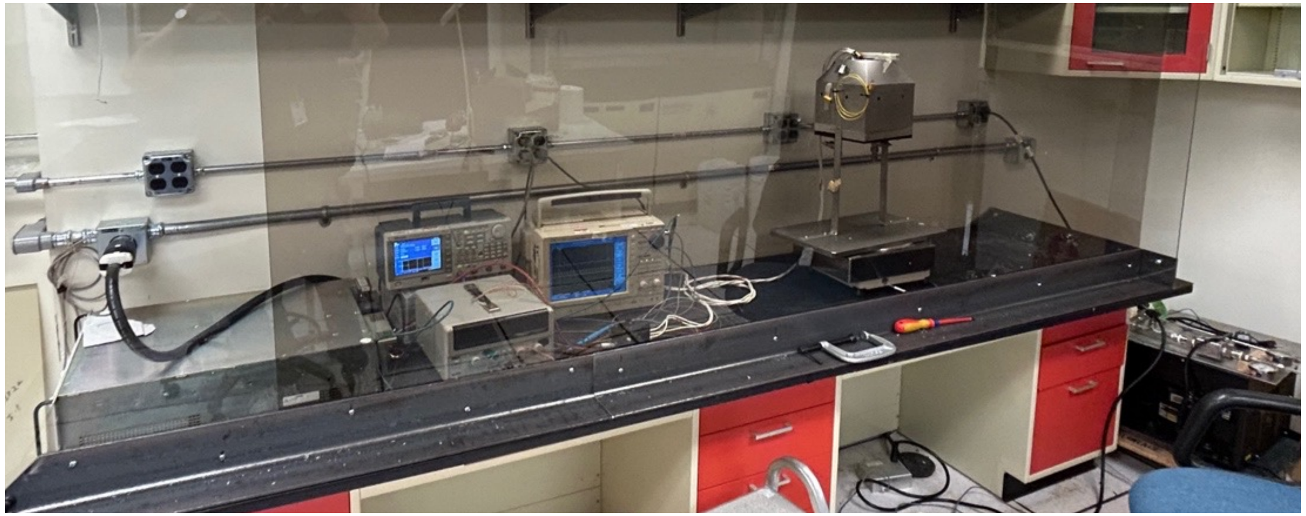
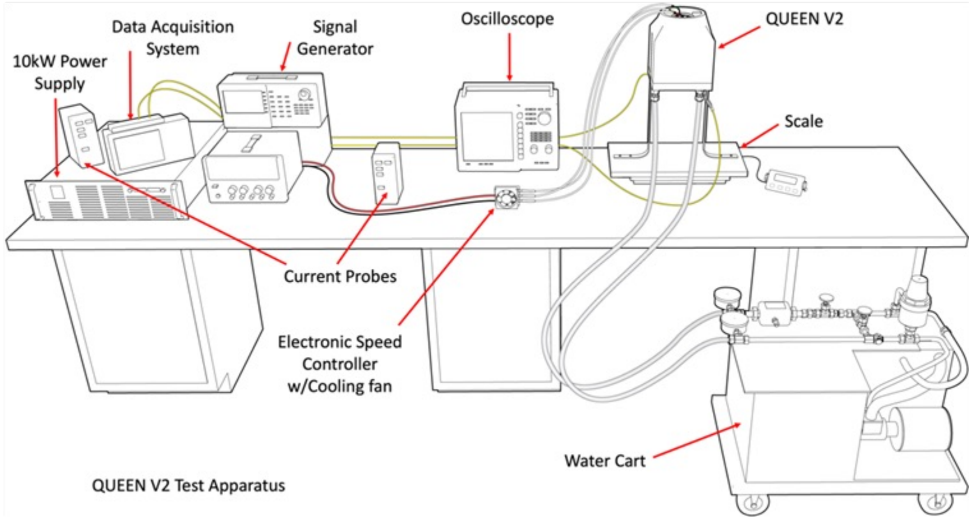


Illustration and photograph of the Quiet Electric Engine Prototype, QUEEN V2

Description of Experiment

- The main components of this experiment are indicated notionally in the schematic.
- Electrical power was supplied to the motor by a 10 kW DC power supply.
- Motor speed is controlled by an electronic speed controller (ESC) kept cool by a small fan.
- A stand-alone portable cooling cart allows water to be pumped, regulated, and measured through the QUEEN V2 heat exchanger.
- A plexiglass enclosure covered the apparatus to protect operators and laboratory equipment from harm if failure of the rotor were to occur.

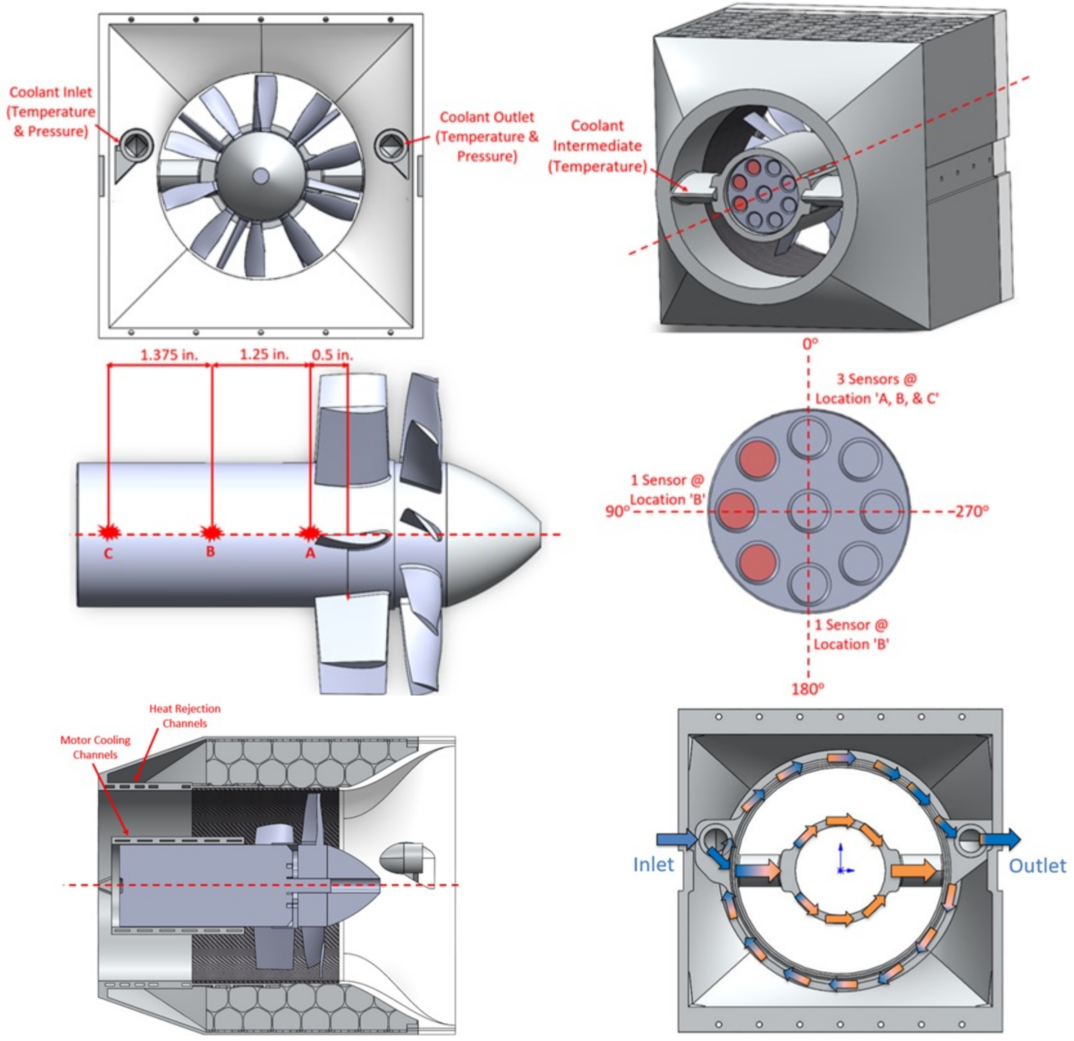




Photograph of the Quiet Electric Engine Test Set-up, QUEEN V2

Instrumentation

- Thermocouples were installed on the surface of the motor, surface of the housing, motor windings, coolant inlet, coolant outlet, and coolant intermediate.
- The electrofan was cooled by the air being accelerated around it as well as by internal coolant passages around the motor and housing.
- Temperature data was taken by a combination of hand recording and data acquisition (DAQ) systems.



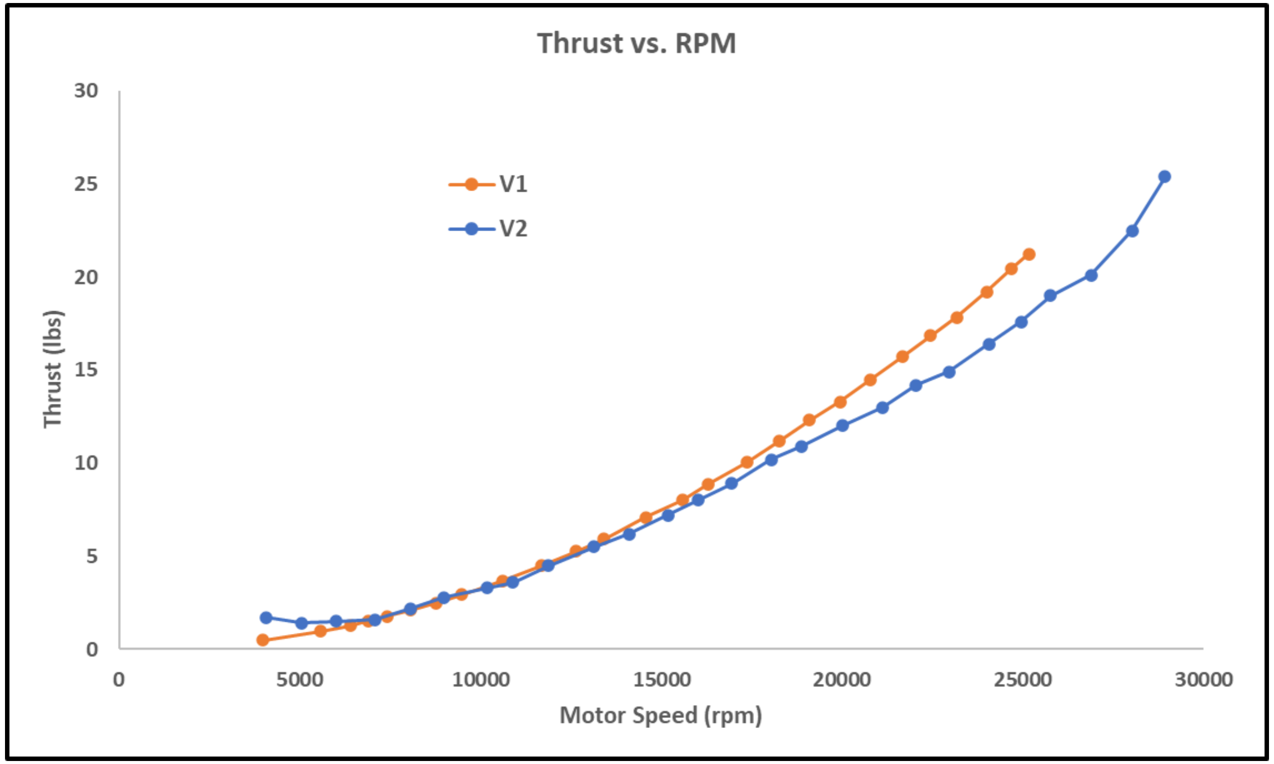
Photograph of the Quiet Electric Engine Test Set-up, QUEEN V2

Discussion of Results

Discussion of Results (Thrust):

- Thrust was measured by orienting the motor in the vertical direction and pointing the thrust vector downwards.
- Using a scale, the thrust can be directly measured as different operating conditions are cycled through.
- Thrust values were hand recorded at each testing point.
- Speed sweeps between 4000-29000rpm were recorded.
- V1 testing done with the motor and fan independent of a housing and custom inlet.

Max speed = 29,000rpm
Max Thrust = 25.4 lbs
Max Power = 9.6 kW



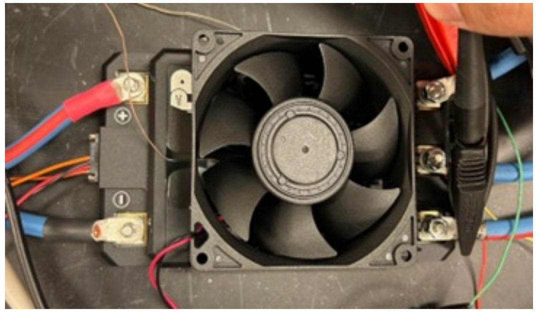
QUEEN V1 and QUEEN V2 Variation of Thrust with Fan Speed

Discussion of Results

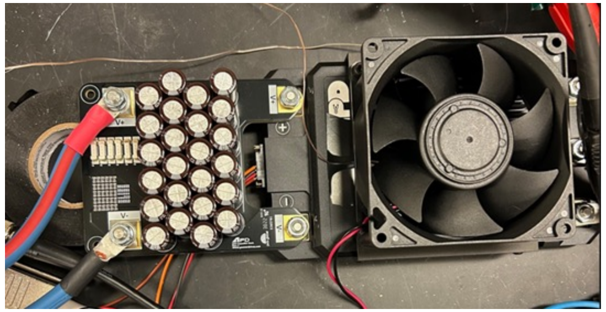
Discussion of Results (Electrical):

- Electrical efficiency and characterization of the ESC was conducted by using a power analyzer to measure the voltage and current on both sides of the ESC.
- Testing was done with the cap. bank to understand the effects on total efficiency.
- Efficiency is measured as the motor is sped up and down through the rpm range (4000rpm-29000rpm)
- Voltage is held constant while current is ramped up depending on power needs.
- Power sweeps were conducted at three voltages (70,75,80V) to characterize the efficiency at varying voltages.
- The sudden jump in efficiency past 28,000 rpm is due to the ESC having minimal electrical switching at full throttle which limits power losses.

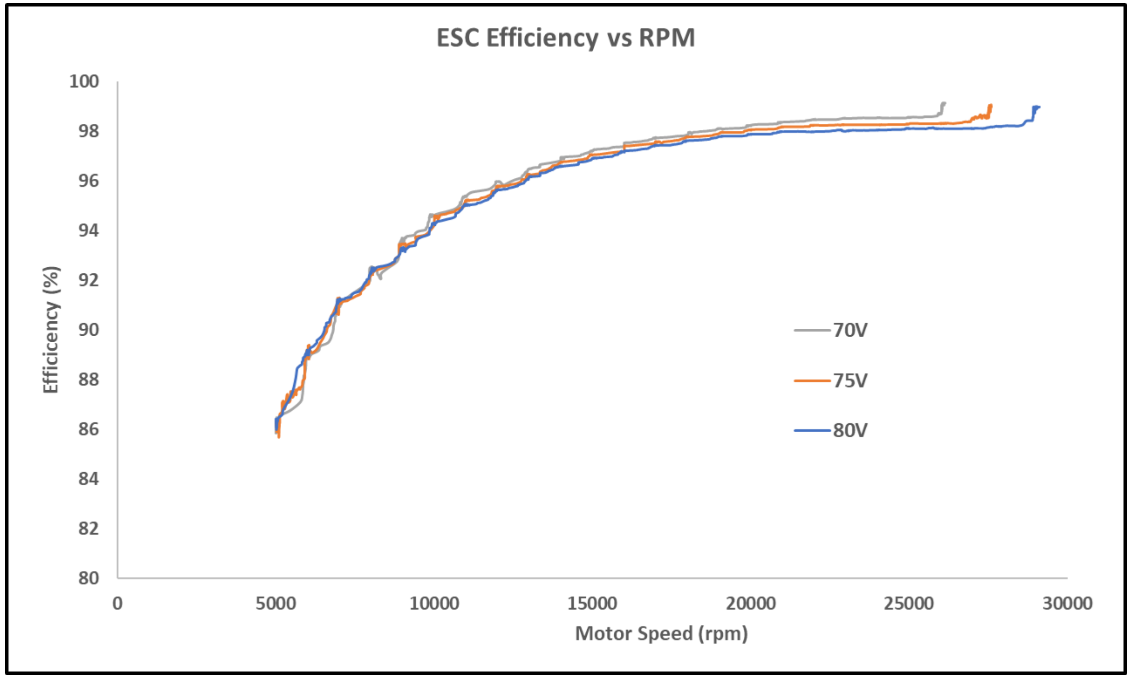
Peak Efficiency = 99.2%



ESC without Cap Bank



ESC w/Cap Bank

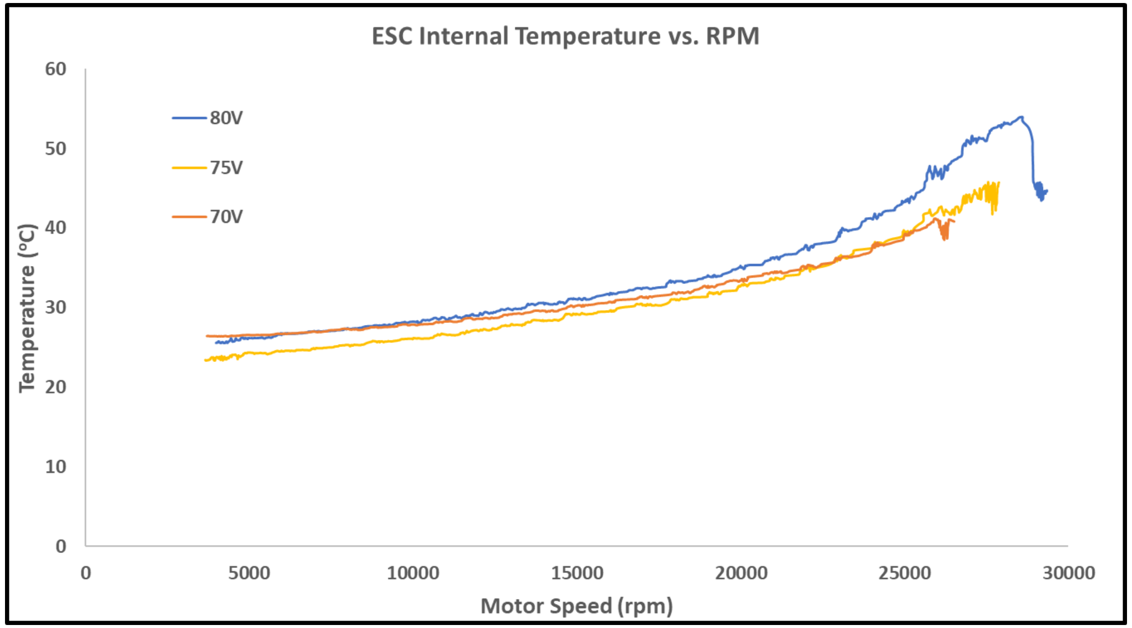


Variation of Electronic Speed Controller Efficiency with Fan Speed for Three Motor Voltage Settings

Discussion of Results

Electronic Speed Controller (ESC)

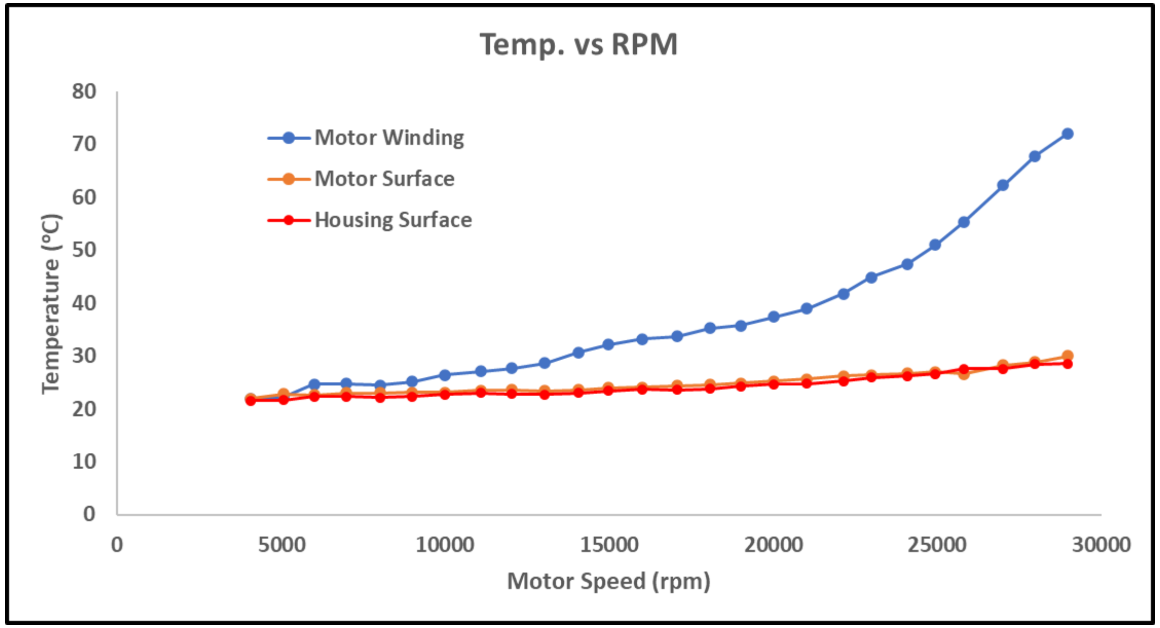
- The overall temperatures of the electrofan components and the ESC were well within rated limits, 120 ^oC and 115 ^oC respectively.
- The temperature results show no critical threat to the operability of the machine.
- Higher temperatures at higher voltages are due to lower efficiency.



Variation of Electronic Speed Controller Internal Temperature with Fan Speed for Three Motor Voltage Settings

Electrofan

- The electrofan was cooled by the air being accelerated around it as well as by internal coolant passages around the motor and housing.
- As motor speed increases, the motor winding temperature increases faster than the motor and housing surface temperatures.
- This is due to the coolant's effect on the surface and the internal resistance of the motor that shields the windings from cooling.



Variation of Motor Temperatures with Fan Speed

Discussion of Results

Thermal Modeling

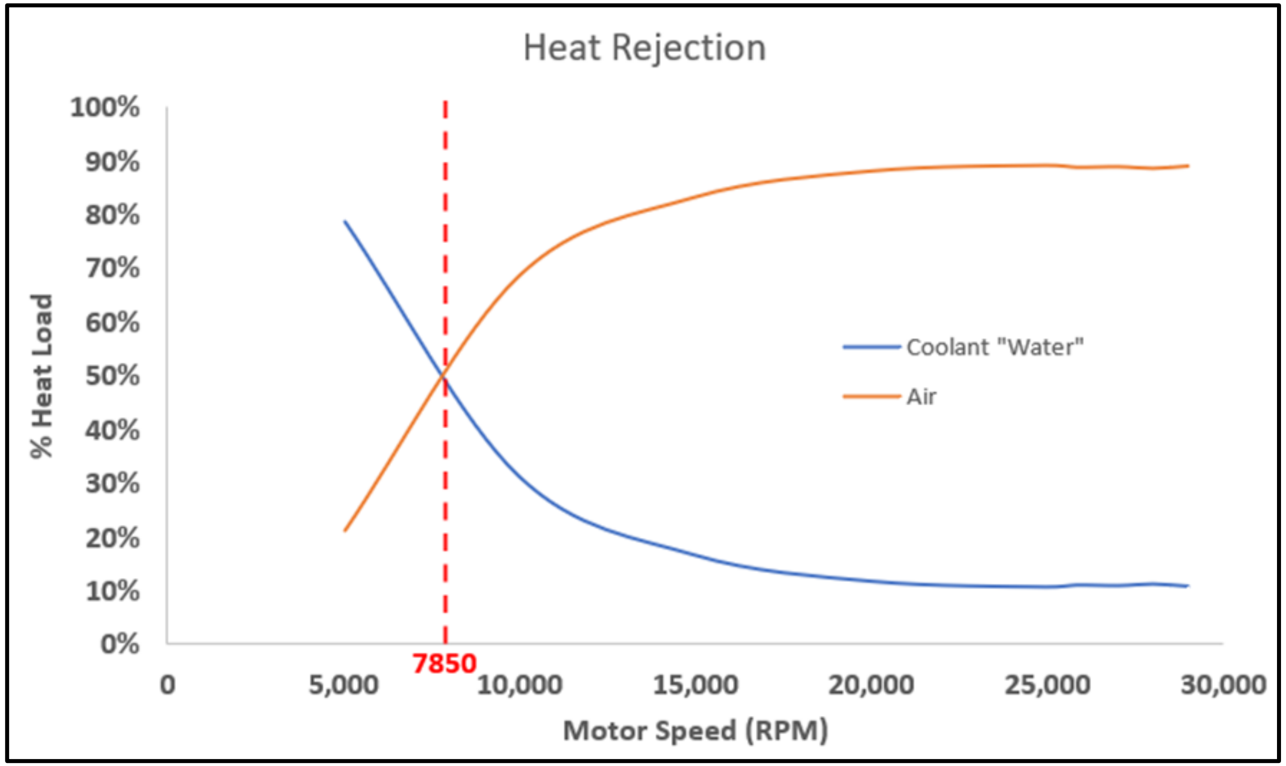
- Preliminary results from thermal modeling overpredict the motor surface and winding temperatures. This is likely due to non-negligible air cooling occurring within the motor which is difficult to characterize for a COTS product.

- Modeling suggests that at higher power levels, up to 80% of the motor heat is removed via internal air convection, with the remainder being removed via the liquid cooling loop and external air convection.

- The fraction of heat rejected through the coolant and through the internal air paths into the environment was quantified.

- Heat rejection ratios show that at low speeds, the coolant dominates as there is not enough airflow in and around the motor. However, as the motor speed ramps up, heat rejection becomes dominated by the air flow.

- The point of equal heat transfer is around 7,850 rpm.



Fraction of Heat Transfer from the Motor

Recommendations

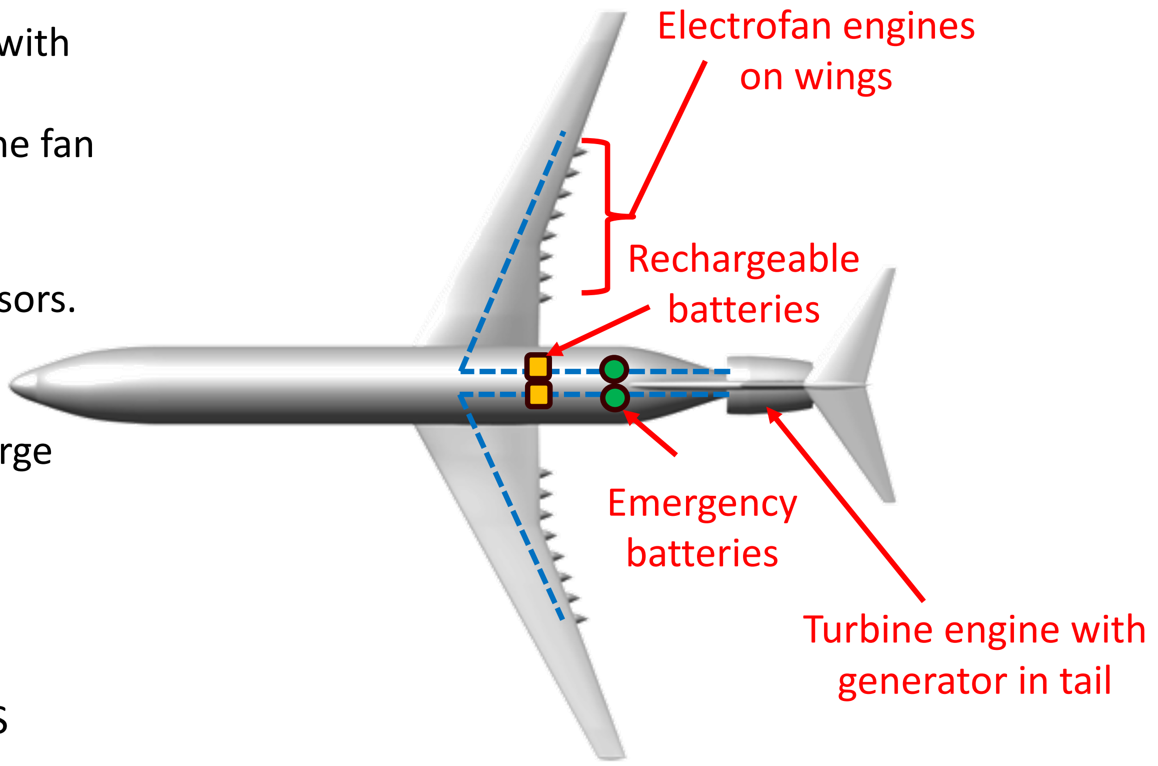
- The QUEEN V1 and QUEEN V2 propulsors were useful for facility check-out purposes and produce within the ballpark of thrust required for the SUSAN 25% FRV. The requirements are being refined and updated as the project matures.
- At lower power levels and fan speeds, liquid cooling is expected to provide the majority of the heat rejection and as motor speed ramps up, heat rejection becomes dominated by the air flow. This can become a valuable feature during hot day taxing and take-off conditions to maintain comfortable component temperature limits.
- Noise was significant during the test of the QUEEN V2, and double hearing protection was required for the operators.
- Since aircraft noise is regulated, including acoustics measurements in future tests will be helpful.
- Tests of future QUEEN prototype in the NASA GRC Acoustical Testing Laboratory is recommended.

Photograph of some of the Quiet Electric Engine Team with the SUSAN 25% Flight Research Vehicle,
NASA GRC AeroDayz 2023

Conclusion and Future Work

Conclusion

- The QUEEN V2 electric ducted fan was designed, built, instrumented, and tested at NASA GRC.
- The QUEEN V2 features a single Commercial-Off-the-Shelf fan with an Outlet Guide Vane.
- The motor was cooled with a heat exchanger integrated into the fan duct that was custom-designed by NASA GRC.
- Results from this experiment will be used to make informed decisions about the next design iteration of the QUEEN propulsors.
- This effort demonstrates that NASA GRC can measure the performance of small propulsors which can be used to explore distributed electric propulsion envisioned for hybrid-electric large single-aisle regional aircraft concepts.



Future Work

Conceptual design of the QUEEN V3 propulsor is nearing completion and features two counter-rotating blisks and two COTS motors. ESC thermal management architecture to move from air cooling to liquid cooling.

Acknowledgements

NASA Glenn QUEEN Team

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