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

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A liquid-cooled electric ducted fan system was designed, built, and tested at the NASA Glenn Research Center. Main components of the system include a Commercial-Off- the-Shelf (COTS) fan and motor, and a custom-designed heat exchanger integrated into the fan duct. Fan speed, thrust, and cooling system thermal performance was measured in this static ground test of the propulsor. This propulsor prototype is one of NASA's Quiet Electric ENgines (QUEENs) and is designated the 'QUEEN V2.' The Quiet Electric Engines are being developed for the 25% scale model of the Subsonic Aft Engine (SUSAN) Flight Research Vehicle and are intended to explore the potential of distributed electric propulsion for regional single-aisle aircraft. This test demonstrated the functionality of the QUEEN V2, quantified the thrust produced by the electrofan, and characterized the electrical and thermal performance of the system. Lessons learned will be used to guide development of future QUEEN prototypes.

I. Introduction

Since the 1960s, the number of vehicles on land, sea, and air in the United States has roughly tripled and transportation noise pollution remains a widespread health and environmental problem [1]. In response, the aviation research community is asking a challenging engineering question: How might we develop a commercial air transportation system, accessible to a growing world population, that is cleaner, safer, and quieter than the one we have today? NASA is working on flight vehicles of every size, shape, and speed and is using concept aircraft to guide our collective imagination, as we develop the systems and components for fuselages and propulsion systems for more sustainable flight. As technology matures by ground tests of components and systems, some of those concept aircraft advance to become experimental flight vehicles.

The Subsonic Single Aft eNgine (SUSAN) concept aircraft is guiding this effort described in this report [2, 3]. To provide proof-of-concept data and explore the potential of distributed electric propulsion for large single-aisle regional aircraft, teams are working towards a 25% scale model aircraft designated the SUSAN 25% Flight Research Vehicle (SUSAN 25% FRV). Quiet electric engines (QUEENs) are envisioned as wing-mounted propulsors for the SUSAN 25% FRV. Recently, an air- and liquid-cooled electric ducted fan system was designed, fabricated, instrumented, and tested at the NASA Glenn Research Center. It is designated the Quiet Electric Engine V2 (QUEEN V2). This report describes the fan design and static ground tests of the QUEEN V2 performed at NASA Glenn Research Center (NASA GRC). Lessons learned from this experiment will guide the design of future QUEEN prototypes.

II. Description of the QUEEN V2 Propulsor

The QUEEN V2 is a liquid-cooled electric ducted fan that features a Commercial-Off-the-Shelf (COTS) fan and motor. Illustrations of the fan assembly is shown in Figures 1 and 2. Selected dimensions and features of the fan are given in Table 1. The QUEEN V2 fan consisted of ten rotor blades and seven Outlet Guide Vanes (OGVs) downstream of the rotor. The maximum design speed of the QUEEN V2 motor was 45,000 rpm and maximum thrust was projected to be approximately 30 lbf. based on test of the QUEEN V1 that were performed at NASA Langley Research Center (LaRC) [4]. The rotor tip diameter is 5.113 inches at the rotor blade leading edge and the QUEEN V2 assembly weighs 2.59 kg (5.7 lbs.).

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To keep the motor cool, NASA GRC designed a motor housing that has integrated coolant flow channels into the fan duct. The coolant acts in two locations by moving in and around channels surrounding the motor and the housing surface. As the coolant flows around the motor, it pulls the heat generated and takes it away to the heat rejection channels to be transferred into the environment. Due to the complexity of the housing design, additive manufacturing was used to build a completed component with all necessary features. The material selected for the 3D printed housing is AlSi10Mg. Heat is transferred away from the motor via conduction through the aluminum duct walls and thermal grease and by convection to the flow of air through the duct and the flow of water through the cooling and heat rejection channels. Selected dimensions and features of the fan are given in Table 1.

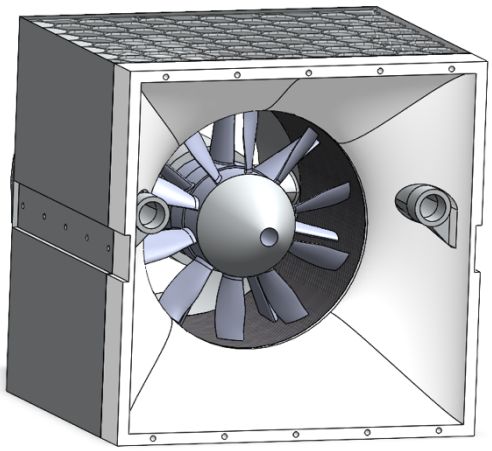


Figure 1: Illustration of QUEEN V2, forward looking aft. Inlet features supply and return ports for the liquid in the heat exchanger.

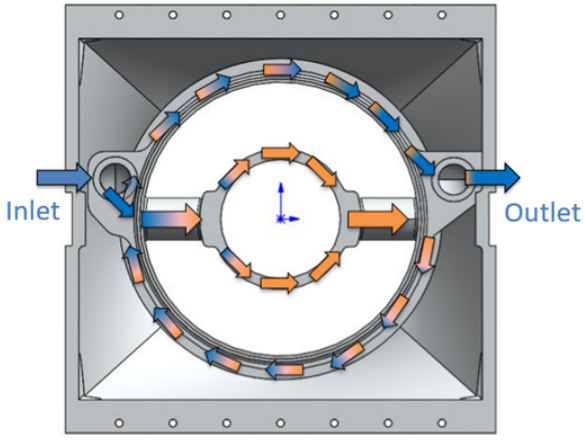


Figure 2: Illustration of QUEEN V2 cross-section showing with heat exchanger around the motor.

Table 1: Selected Dimensions and Features of the QUEEN V2

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)

III. Description of the Experiment

The QUEEN V2 propulsor was tested in the NASA Glenn Research Center (GRC) Thermal Test Laboratory. This laboratory was selected since the primary objectives of the experiment were to begin to prototype the electrical power supply and speed control system, the thermal management system, and the data acquisition system needed to test the QUEEN thrusters. The Thermal Test Laboratory was also desirable since it provided a dedicated space to work, in preparation for future tests in one of the acoustical testing laboratories at NASA Glenn which are shared laboratories with more constrained schedules. The Thermal Test Laboratory can be used as a place to prepare for future tests in the NASA Glenn Acoustical Testing Laboratory [5]. The COTS electrofan that was integrated into the QUEEN V2 helped the team to quickly begin this iterative prototyping process. The experimental apparatus, the instrumentation installed on the QUEEN V2, the test objectives and procedure are discussed in more detail in the sections below.

A. Experimental apparatus

The main components of this experiment are indicated notionally in the schematic shown in Figure 3 and listed in Table 2. 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 people and laboratory equipment from harm if an unplanned failure of the rotor were to occur. A photograph of the laboratory and test equipment is shown in Figure 4.

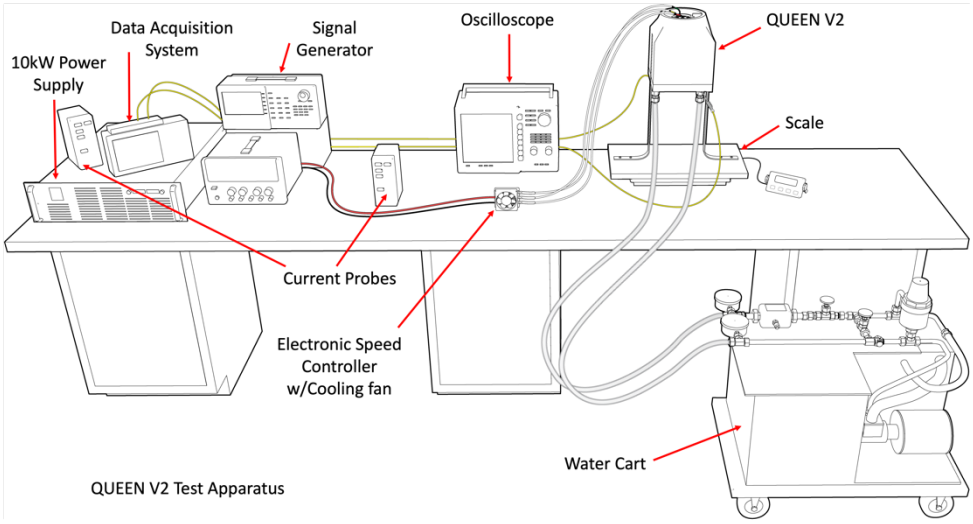


Figure 3: Schematic of QUEEN V2 Test Set-up

Table 2: Test Equipment and Instrumentation Used for the QUEEN V2 Test

Type	Description	Quantity
Power Supply	Genesys 80V/125A	1
Cooling Cart	Custom Built	1
Electronic Speed Controller	APD UHV	1
Dual Channel Arbitrary Function Generator	Tektronix AFG3022 250 MS/s, 25 MHz	1
Thermocouple	Type K	13
High Voltage Differential Probe	Tektronix THDP0200, 200 MHz	3
Current Probe	Tektronix TCP303, 150 ADC	3
Laboratory DC Power Supply	Tenma 72-7245, 10 kW	1
Data Acquisition System	Graphtec Midi Logger GL840	1
Amplifier AC/DC Current Probe	Tektronix TCPA300	3
Pressure Transducers	Omega DPG1001B-100G, 0-100 psig	2
Electromagnetic Flow Meter	Endress+Hauser Picomag	1
High Speed Oscilloscope and Data Acquisition Recorder	Yokogawa DL750 ScopeCorder	1
Digital Weight Scale	Galaxy Equipment Model 177RS110LP, 50 kg x 0.05kg capacity	1

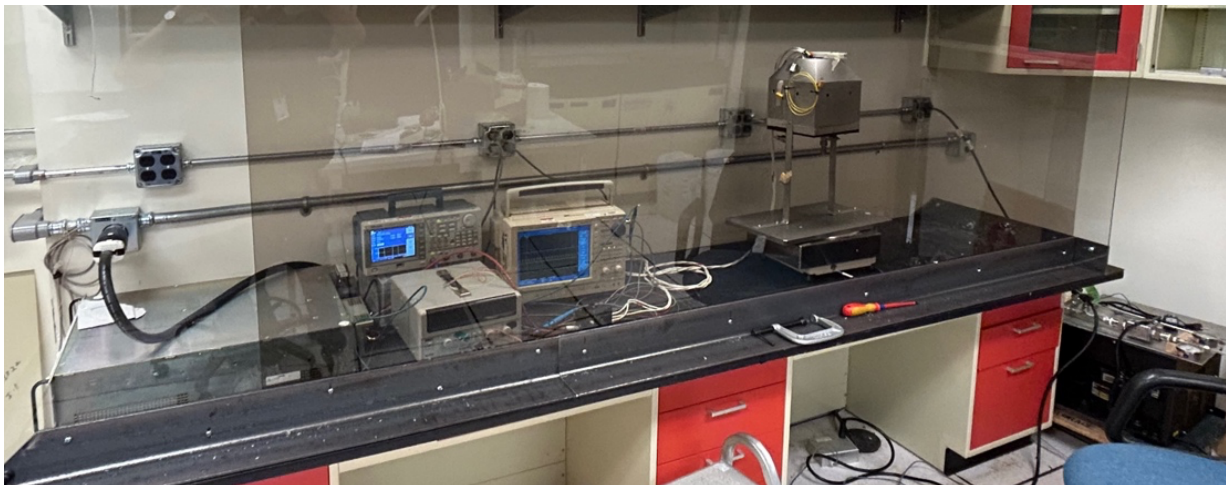


Figure 4: Photograph of the QUEEN V2 Test Set-up with Plexiglass Shields

B. QUEEN V2 instrumentation

A cut-away illustration of the QUEEN V2 with instrumentation marked is shown in Figure 5. Instrumentation is also listed in Table 2 and included a digital weight scale, thermocouples, pressure transducers, a flow meter, current probes, voltmeters, oscilloscopes, a power analyzer, and a data acquisition system. Water was used as the coolant and during the testing thermocouples were used to measure the temperatures of the coolant at the inlet, outlet, and at an intermediate location between the motor cooling and heat rejection loop. Surface temperatures were measured at the illustrated locations below for both the motor and housing as well as the motor windings. Pressure and flow rates were measured at the cooling cart's inlet and outlet. The Electronic Speed Controller (ESC) temperatures were measured separately using embedded probes from the supplier. For the electrical data, current probes and voltmeters were used to directly measure the current and voltage at the DC supply side as well as the AC motor side. A power analyzer was used to obtain efficiencies across the ESC.

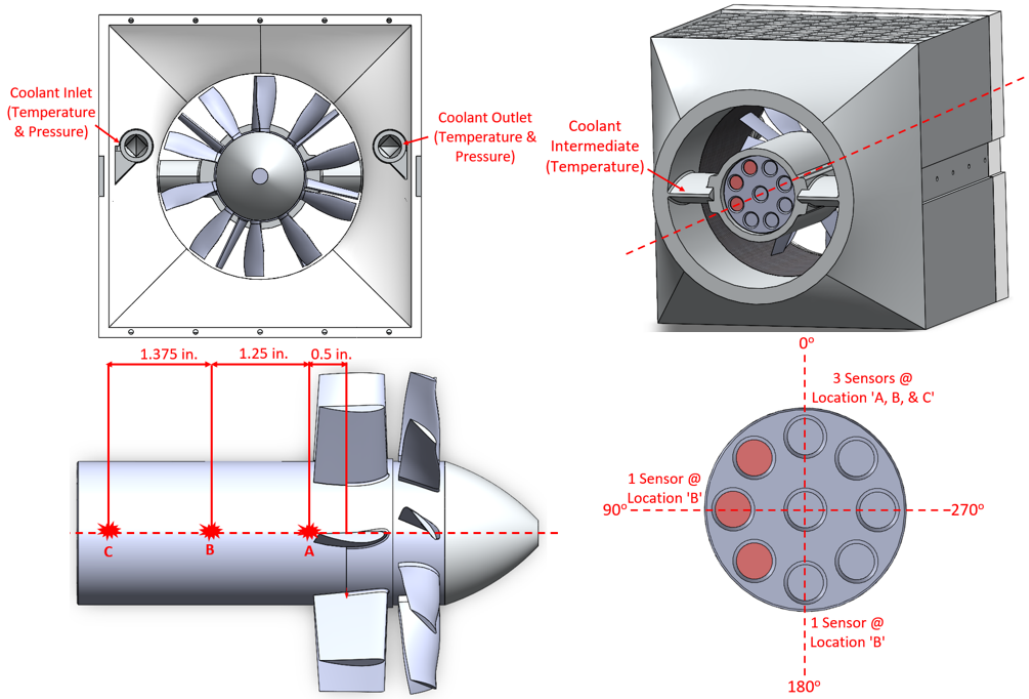


Figure 5: QUEEN V2 Instrumentation Illustration

C. Test objective and procedure

As mentioned earlier, the goal of this experiment was to design, build, and perform a static ground test of a small propulsor as the team develops wing mounted propulsors suitable for the SUSAN 25% FRV. There were three objectives to the QUEEN V2 experiment. The first objective was to demonstrate functionality of the electrical system by showing that the fan could be controlled through its full speed and power range. The second objective was to measure thrust produced by the QUEEN V2 prototype as a function of power and demonstrate that the thermal control system would keep the motor temperature within safe operating range. The third objective was to measure the efficiency and heat load of the QUEEN V2 and the ESC.

For each test, motor voltage (70 V, 75 V, and 80 V) and coolant flowrate (1 GPM) were set first. Then the fan speed was increased from 0 to 29,000 in increments of 1,000 rpm and measurements from the instrumentation was recorded at each speed. Measured quantities included fan speed, thrust produced by the fan, and temperatures and pressures throughout the motor heat exchanger system. Thermocouples were used to directly measure temperatures at multiple angles along the axial length of the motor, adjacent housing surface, motor winding, coolant inlet, coolant outlet, and coolant intermediate temperatures, as shown in Figure 5. Thrust was measured by the digital scale placed underneath the QUEEN V2 which was oriented vertically, as shown in Figure 6. Voltages and currents on both the AC and DC side of the ESC were measured and a power analyzer was used to directly calculate the electrical efficiency as well as the heat load produced by the ESC. Once the testing was concluded, the QUEEN V2 was removed from the stand and disassembled for inspection. Again, basic parameters of the QUEEN V2 are given in Table 1.

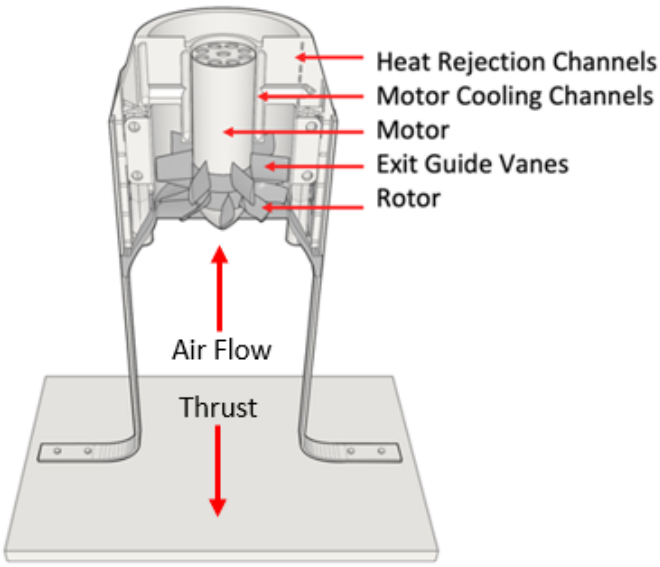


Figure 6: QUEEN V2 and bracket for thrust measurements.

IV. Discussion of Results

The results from the experiment are shown in Figures 7 through 12. The first objective of testing was to demonstrate functionality of the electrofan and the electrical control system. The test was able to show successful operation from 0 rpm to 29,000 rpm for up to 30 minutes. Higher speeds were not achieved due to power limitations from the DC supply. The thrust values shown in Figure 7 were obtained by supplying 80 V to the motor and allowing the current to vary to increase the power. The data shown for the QUEEN V2 in Figure 7 at 80 V was typical of the speed sweeps at the lower voltages (75 V and 70 V). Thrust-to-weight ratio (TWR) has also been plotted against speed as shown in Figure 8.

Thrust values for the QUEEN V2 were lower than the thrust measured by the QUEEN V1, as shown in Figure 7. Repeatability of the QUEEN V2 thrust measurements was studied by performing several speed sweeps. The difference in measured thrust between the QUEEN V1 and the QUEEN V2 was attributed to the performance of the inlets and installation effects unique to the test setup in the GRC Thermal Testing Lab.

The inlets on the QUEEN V1 and the QUEEN V2 were different. The QUEEN V1 test used a short round inlet that was provided with the COTS ducted electrofan and the QUEEN V1 was installed in the NASA LaRC 12-Ft Wind Tunnel. A heat exchanger was not included in the QUEEN V1 prototype. The QUEEN V2 test used a custom square-to-round inlet with ports and tube fittings needed to accommodate the coolant to the heat exchanger around the motor, as shown in Figure 1. The QUEEN V2 inlet was designed to resemble one of the SUSAN 25% FRV configurations with the wing mounted engines positioned downstream of the wing.

The installations of the QUEEN V1 and the QUEEN V2 were also different. The QUEEN V1 was oriented horizontally inside the NASA LaRC 12-Ft Wind Tunnel and was attached to a sting that was used to measure thrust loads. The QUEEN V2 was oriented vertically in the GRC Thermal Testing Laboratory so that thrust could be measured by a digital scale. The inlet of the QUEEN V2 was approximately 12 inches from the scale. Air was drawn into the QUEEN V2 inlet from below and it was exhausted upwards. It is likely that the proximity of the QUEEN V2 to the laboratory wall, ceiling, and plexiglass shield affected the flow through the fan and the thrust measurements shown in Figure 7. Since this experiment was to mostly to explore functionality of the electrical and thermal systems, these compromises were acceptable at this early phase of the project.

Power curves were also recorded on the DC and AC side during the speed sweep and Figure 9 shows the rise is power demand with increasing speed. The weight used for this curve does not include the ESC, instrumentation, or coolant mass, it is solely the weight of the QUEEN housing and electrofan. Therefore, the true TWR is expected to be lower, especially as the plane weight is considered. Electrical efficiencies across the ESC were very high at about 98% which suggests that the thermal management system is adequate and the heat loads could be managed well using air or liquid cooling, as shown in Figure 10. 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.

The test was also able to show successful operation of the thermal control system for the speed range. The overall temperatures of the electrofan components and the ESC shown in Figure 11 and Figure 12 were well within rated limits, 120 °C and 115 °C respectively, and do not pose a critical threat to the operability of the machine. Motor temperatures were measured at multiple locations, as illustrated earlier in this paper. The surface temperature of the motor was uniform at the various angles and axial depths. The housing surface temperature directly adjacent to the motor surface is also uniform with the motor surface temperature, within error. While a temperature differential from the surface of the motor to the housing exists, it is small enough to be within the uncertainty of the sensors as well as additional error from installation of the thermocouples and grease to fill the gaps. As motor speed is ramped up, the winding temperature diverges from the surface and increases at a higher rate with increasing rpm. This is due to the coolant's effect on the surface and the internal resistance of the motor that shields the windings from cooling.

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. These heat transfer paths to the environment were lumped together for simplification and the fraction of heat rejected through the coolant and through the internal air paths into the environment was quantified in Figure 13. The heat rejection ratios show that at low motor 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. The heat rejection channels are also predicted to transfer around 35 W of energy into the air based on the thermal modeling of the flow around the housing downstream of the motor cooling channels.

The ESC internal temperatures shown in Figure 11 peak at around 55 °C, well below the rated limit of 105 °C. A small fan was mounted to the ESC to blow air against fins incorporated onto the electronics housing. In future tests, a liquid cooled cold plate or immersion cooled design that can be integrated into the QUEEN coolant loop to reduce packing volume and total weight of the aircraft thermal management system are being considered.

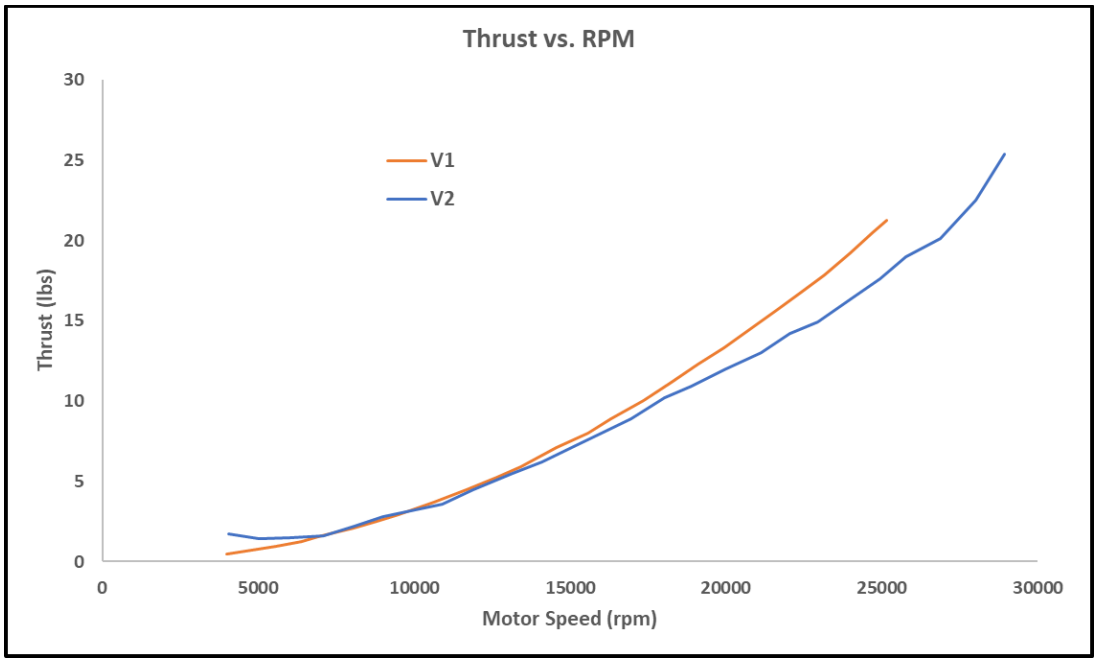


Figure 7: QUEEN V1 and QUEEN V2 Variation of Thrust with Fan Speed

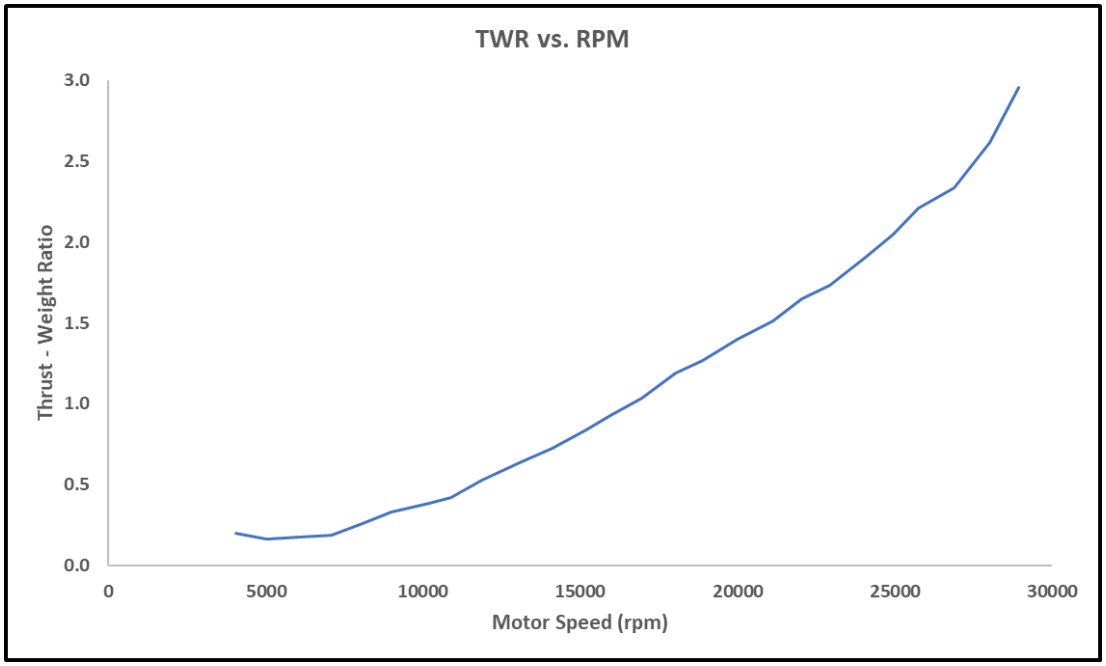


Figure 8: QUEEN V2 Variation of Thrust to Weight (TWR) Ratio with Fan Speed

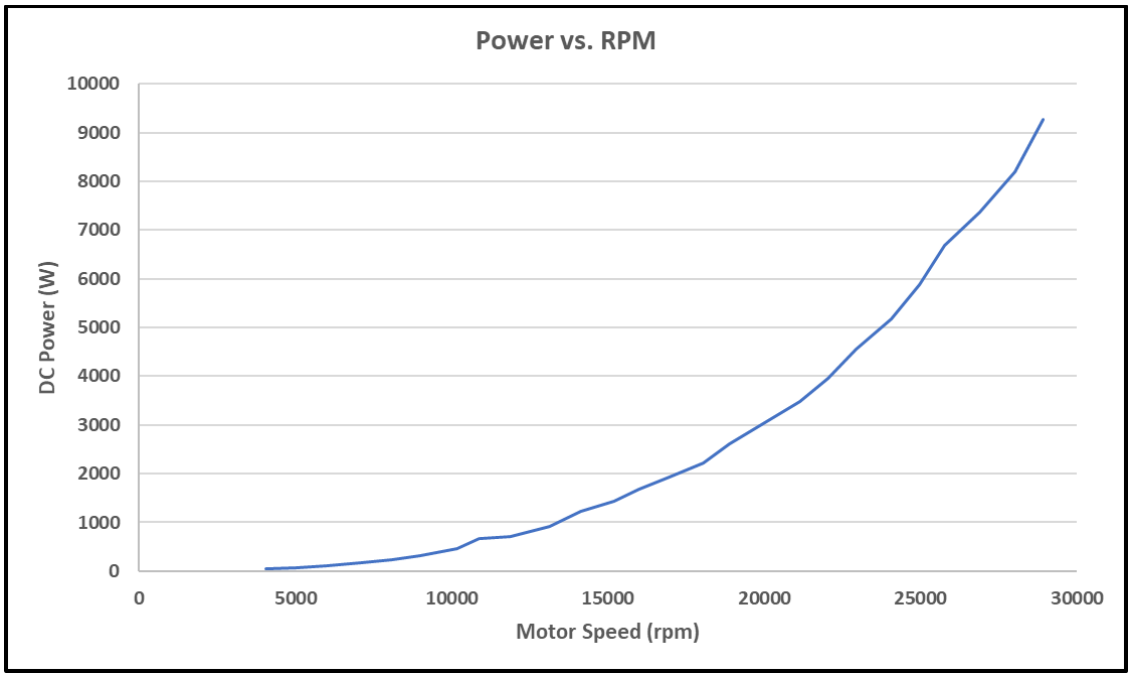


Figure 9: QUEEN V2 Variation of Power with Fan Speed

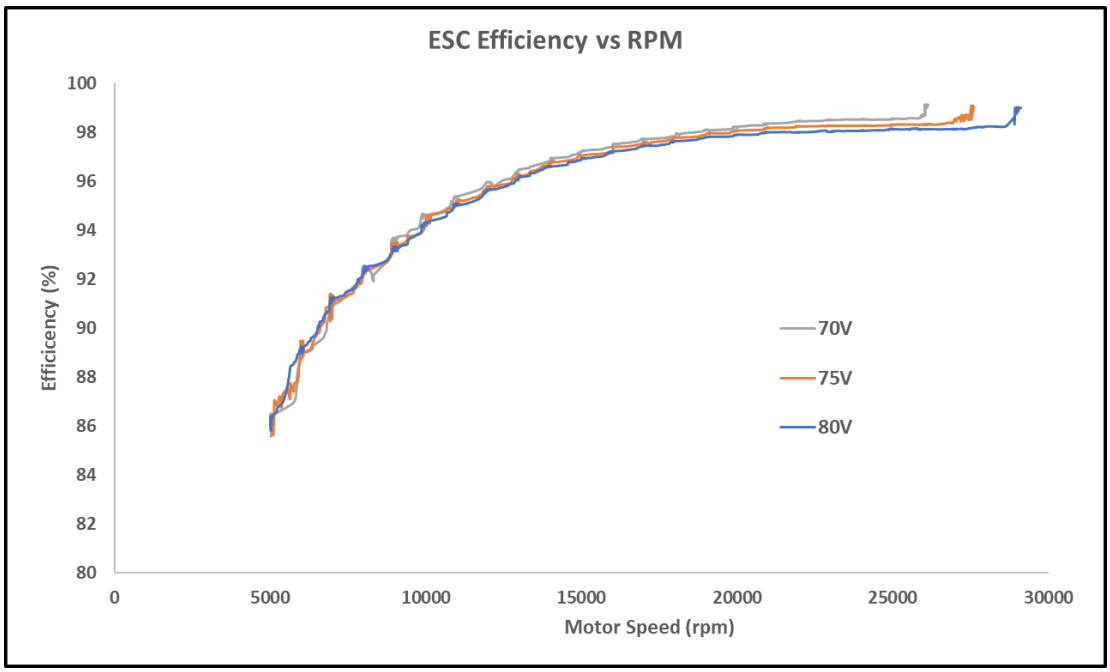


Figure 10: Variation of Electronic Speed Controller Efficiency with Fan Speed for Three Motor Voltage Settings

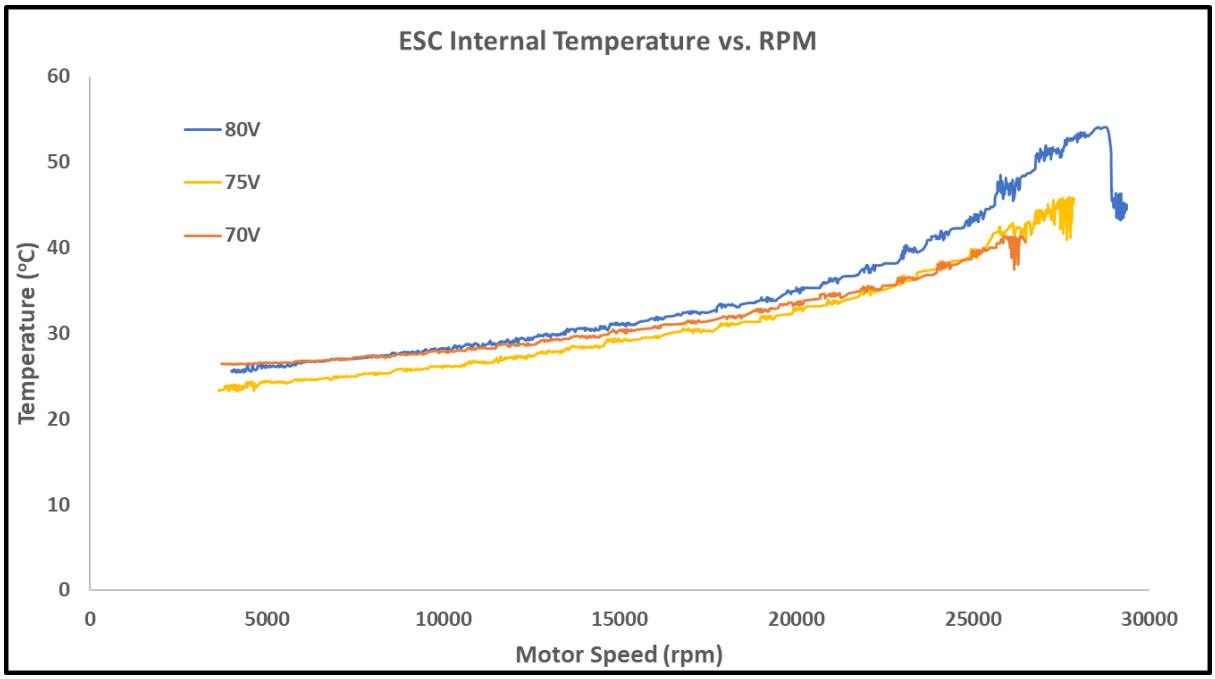


Figure 11: QUEEN V2 Variation of Electronic Speed Controller Internal Temperature with Fan Speed for Three Motor Voltage Settings

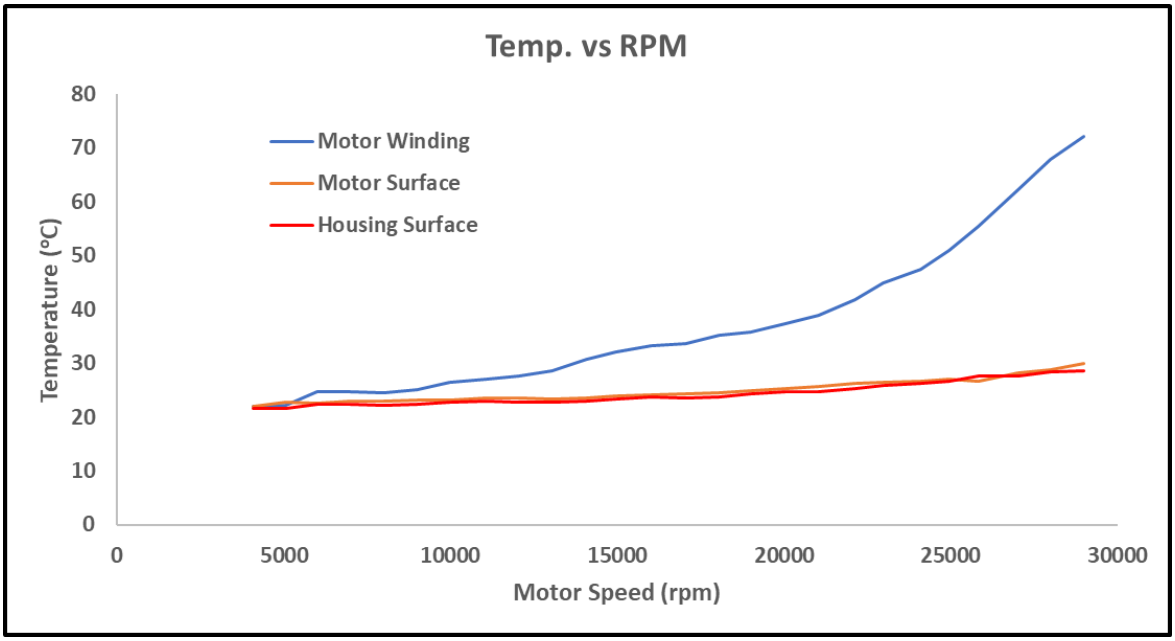


Figure 12: QUEEN V2 Variation of Motor Temperatures with Fan Speed

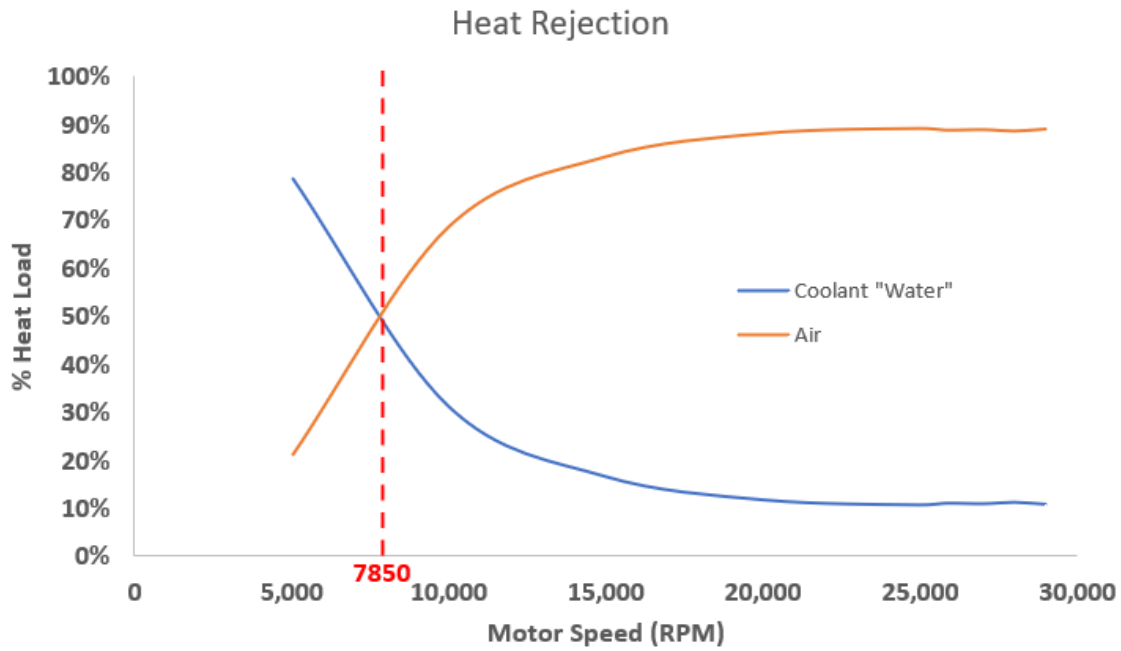


Figure 13: QUEEN V2 Fraction of Heat Transfer from the Motor

Recommendations

Experiments of the QUEEN V1 and QUEEN V2 propulsors helped a multi-center team at NASA to perform propulsion system experiments supporting the SUSAN 25% FRV, while simultaneously overcoming the many disruptions of the pandemic. However, while the QUEEN V1 and QUEEN V2 propulsors were useful for facility check-out purposes, they do not produce the estimated 36 lbf of thrust required for the SUSAN 25% FRV. This could be due to many factors outside of the scope of this paper. NASA GRC is currently designing ducted electric fans specifically for the SUSAN 25% FRV design point. 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 at speeds above 20,000 rpm. 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 [5].

V. 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.

Acknowledgments

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References

1. Bureau of Transportation Statistics, U.S. Department of Transportation, "*Table 1-11: Number of U.S. Aircraft, Vehicles, Vessels, and Other Conveyances"* [online database], URL : https://www.bts.gov/content/number-us-aircraft-vehicles-vessels-and-other-conveyances [retrieved 9 November 2023].
2. Jansen, R., Kiris, C. C., Chau, T., Machado, L. M., Duensing, J. C., Mirhashemi, A., Chapman, J., French, B. D., Miller, L., Litt, J. S., "Subsonic single aft engine (SUSAN) transport aircraft concept and trade space exploration," AIAA-2022-2179, 2022, https://arc.aiaa.org/doi/abs/10.2514/6.2022-2179
3. Lee, B. J.,Liou, M.-F. "Conceptual Design of Propulsors for the SUSAN Electro-fan Aircraft," AIAA-2022-2305, 2022, https://arc.aiaa.org/doi/abs/10.2514/6.2022-2305
4. R. Weinstein, B.M. Simmons, "Experimental Characterization of an Electric Ducted Fan for the SUSAN 25% Scale Research Vehicle" AIAA-2024-(To be published), 2024
5. Cooper, B. A., "NASA Glenn Research Center Acoustical Testing Laboratory," *The Journal of the Acoustical Society of America*, Vol. 109, No. 5, pp. 2328-2328. 2001, https://asa.scitation.org/doi/pdf/10.1121/1.4744168