NASA's Quiet Electric ENgines (QUEEN): Thermal Analysis and Testing of the Electronic Speed Controller (ESC)

Firas G. Asfoor[1], Erik J. Stalcup[2], L. Danielle Koch[3], Sarah R. Freeman[4]
NASA Glenn Research Center, 21000 Brookpark Road, Cleveland, Ohio, United States

An electric ducted fan system was tested at the NASA Glenn Research Center. Main components of the system include a commercial-off-the-Shelf (COTS) fan and motor, electronic speed controller, and cooling system. Motor speed, voltage, current, and temperatures were measured in this static ground test of the propulsor. The thermal performance of the Electronic Speed Controller (ESC) was also measured using two different methods to cool the ESC: air cooling and cold plate cooling. This propulsor prototype is one of NASA's Quiet Electric ENgines (QUEENs) and is designated the 'QUEEN V1.' The Quiet Electric Engines are being developed for the 25% scale model of the Subsonic Single Aft Engine (SUSAN) Flight Research Vehicle and are intended to explore the potential of distributed electric propulsion for large regional single-aisle aircraft. Lessons learned will be used to guide development of future QUEEN prototypes and thermal management systems.

I. Introduction

The electrification of engines for large single-aisle aircraft (~180 passengers) and integration of these engines onto novel airframes, such as the Subsonic Single Aft Engine (SUSAN) concept aircraft is a formidable engineering challenge. To realize predicted performance benefits, these engines are more tightly integrated into the fuselages than in the past which implies more cooperation between engine and airframe manufacturers. New design and optimization tools are needed, as well as the data to validate these tools. New aircraft will need to prove flightworthiness, and certification requirements are not yet established for these new configurations, posing financial and technical risks to manufacturers.

The SUSAN concept aircraft is guiding this effort described in this report, notionally depicted in Figure 1. Quiet electric engines (QUEENs) are envisioned as wing-mounted propulsors for the SUSAN 25% Flight Research Vehicle (FRV).

A commercial-off-the-shelf (COTS) electric ducted fan system was tested at the NASA Glenn Research Center It is designated the Quiet Electric Engine (QUEEN V1). There were two objectives of this experiment. The first purpose of the experiment was to measure the noise and speed from the QUEEN V1 and the second was to characterize the performance of the electronic speed controller (ESC) using two different methods of cooling: air cooling and cold plate cooling. Results of these test of the QUEEN V1 pertaining to the ESC are presented and discussed in this report. Recommendations for future investigations are offered.

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[1] Engineer, Thermal Systems and Transport Processes Branch, AIAA Member, Firas.G.Asfoor@nasa.gov
[2] Engineer, Thermal Systems and Transport Processes Branch, AIAA Member, Erik.J.Stalcup@nasa.gov
[3] Aerospace Engineer, Acoustics Branch, AIAA Associate Fellow, L.Danielle.Koch@nasa.gov
[4] Student, Miami University, AIAA Student Member, srfreeman1173@gmail.com

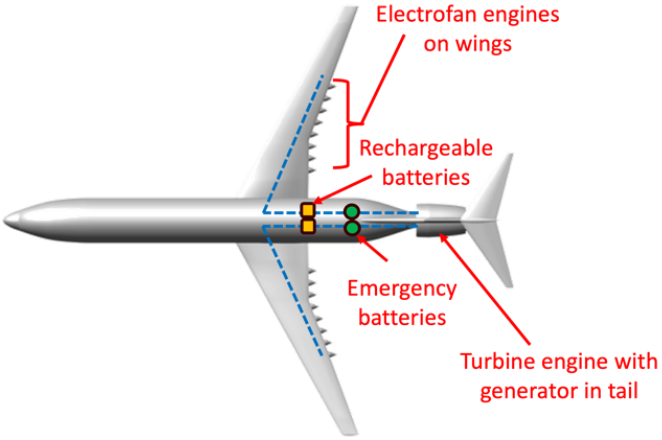

Figure 1: Illustration of one of NASA's Subsonic Single Aft ENgine (SUSAN) concepts with main components of the propulsion system indicated.

II. Description of the QUEEN Propulsor

The QUEEN V1 is an electric ducted fan that features a COTS Electric Ducted Fan (EDF), which is typically sold to remote-control airplane hobbyists. The COTS EDF features a rotor, stator, carbon fiber rotor shroud, and motor. Selected specifications are given in Table 1 and photographs of the COTS EDF are shown in Figures 2 and 3.

In the QUEEN V1, the containment shroud was 3D-printed at NASA GRC from a glass-filled photopolymer resin using a stereolithography additive manufacturing process (Figure 3). The NASA containment shroud provided additional protection since it fit over the carbon fiber shroud that was part of the COTS EDF. For the QUEEN V2, a heat exchanger around a motor that was integrated into the fan duct. The fan duct with the heat exchanger were additively manufactured from AlSi10Mg. More information can be found about the QUEEN V2 test in a separate paper [1].

The electronic speed controller regulated the speed of the QUEEN by controlling the power supply and sending timed electric signals to the motor. This action incurs power penalties and generates heat that must be considered, especially in high power operations. To remove heat from the ESC, two cooling methods were tested. For QUEEN V1, a cold plate with liquid coolant was used (Figure 5) while the QUEEN V2 has an air-cooled design (Figure 4). The 2-pass cold plate design uses water as the working fluid through copper pipes on an aluminum plate. The QUEEN V2, had a cooling fan installed on the fin side of the ESC housing to force air at speed through the fins and sides of the ESC housing.

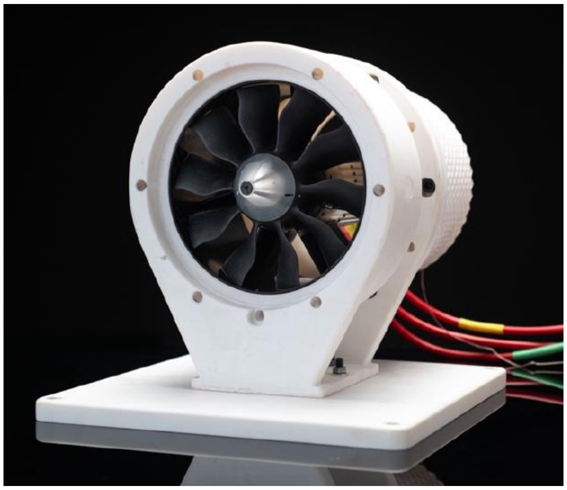

Figure 2: The COTS EDF was installed in the NASA custom-designed 3D printed containment shroud and the aft duct and pedestal mounting plate are visible. The bellmouth and inlet duct acoustic liner sections were not installed in this photograph.

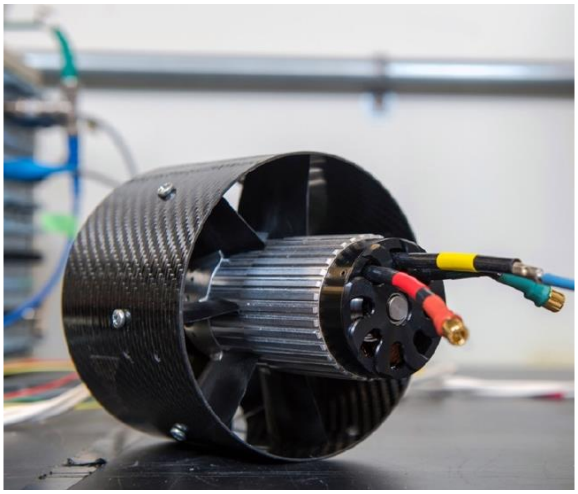

Figure 3: The COTS EDF with the carbon fiber shroud, outlet guide vanes, and motor visible, aft looking forward

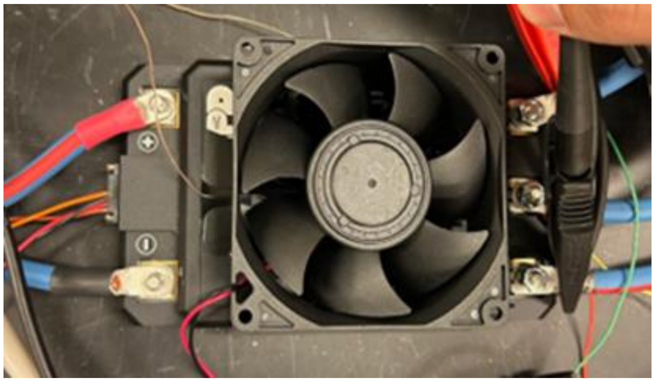

Figure 4: Electronic speed controller setup for QUEEN V2 testing. ESC was cooled using a fan and finned housing.

Figure 5: Electronic speed controller setup for QUEEN V1 testing. ESC was cooled using a cold plate mounted directly to the PCB.

Table 1: Selected specifications and Features of the QUEEN

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)
Maximum rotor speed tested	29,000 rpm
Maximum tested power	9.2 kW

III. Description of the Experiment

The QUEEN V1 propulsor was tested in the NASA Glenn Research Center (GRC) Acoustical Testing Laboratory ATL and Thermal Lab. The NASA GRC ATL is a reconfigurable anechoic/hemi-anechoic chamber. The test operators could control and monitor test equipment remotely from a separate control room located adjacent to the chamber

(Figure 6 & 7). The experimental apparatus, the instrumentation installed on the QUEEN, 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 6. Electrical power was supplied to the motor by a 10 kW DC power supply. Motor speed is controlled by an electronic speed controller (ESC) which processes throttle command inputs as well as converting DC to AC power. A stand-alone cooling cart allowed coolant, in this case deionized water, to be pumped and regulated through the ESC cold plate. A plexiglass enclosure covered the apparatus to protect people and laboratory equipment from harm, since high voltage connectors were exposed. A photograph of the laboratory and test equipment is shown in Figure 7.

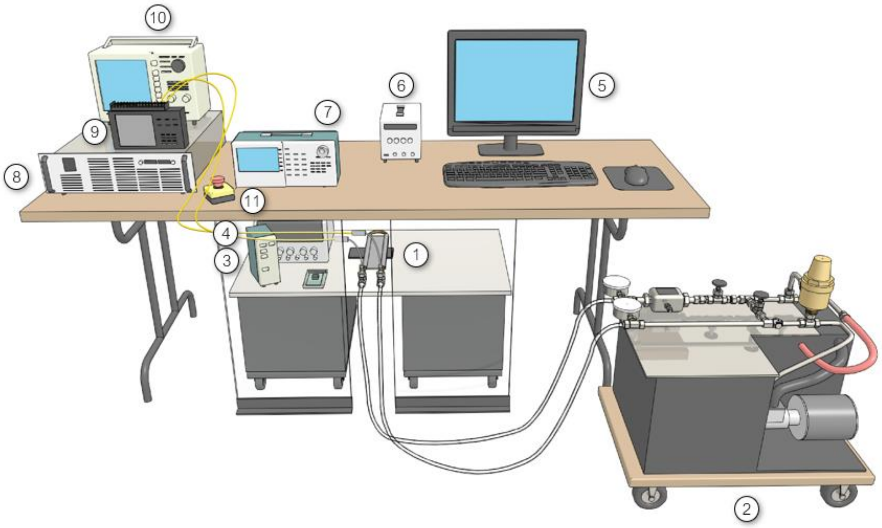

Figure 6: Illustration of the ESC test setup in the NASA GRC Acoustical Testing Laboratory: 1) ESC on cold plate, 2) Cooling cart, 3) Current probe, 4) Thermocouples, 5) Camera Display, 6) Tachometer, 7) Signal generator, 8) Power supply, 9) Data acquisition system (thermal), 10) Data acquisition system (electrics), 11) Emergency shutdown switch.

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	4
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
Data Acquisition Recorder	Endress+Hauser Picomag	1

B. QUEEN V1 instrumentation

An illustration of the QUEEN V1 with bellmouth and inlet liner spool piece is shown in Figure 8. Instrumentation included thermocouples, pressure transducers, accelerometers, current probes, voltmeters, oscilloscopes, a power analyzer, and a data acquisition system. Close up photos of the ESC in both cooling configurations with instrumentations including thermocouple, current probes, voltmeters, etc. are illustrated in figures 4 and 5. The QUEEN V1 electronic speed controller was water cooled and temperatures were measured separately using embedded probes from the supplier as well as additional probes in locations of interest on the ESC as well as in the coolant flow. The QUEEN V2 ESC was air cooled using a mounted fan that pushed air over the housing fins. 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 measurements needed to calculate the efficiencies across the ESC.

There are multiple strategies to cooling power electronics, in this case the electronic speed control. The efforts analyzed in this paper is to compare the air cooling and liquid cooling methods for the ESC to determine which strategy better cools the hardware. Air cooling was conducted with a fan mounted on top of the ESC to force air through the fins of the housing and facilitate convective cooling- (figure 4). Liquid cooling was conducted by stripping back the housing of the ESC and mounting a cold plate directly onto the PCB opposite of the MOSFETs (figure 5).

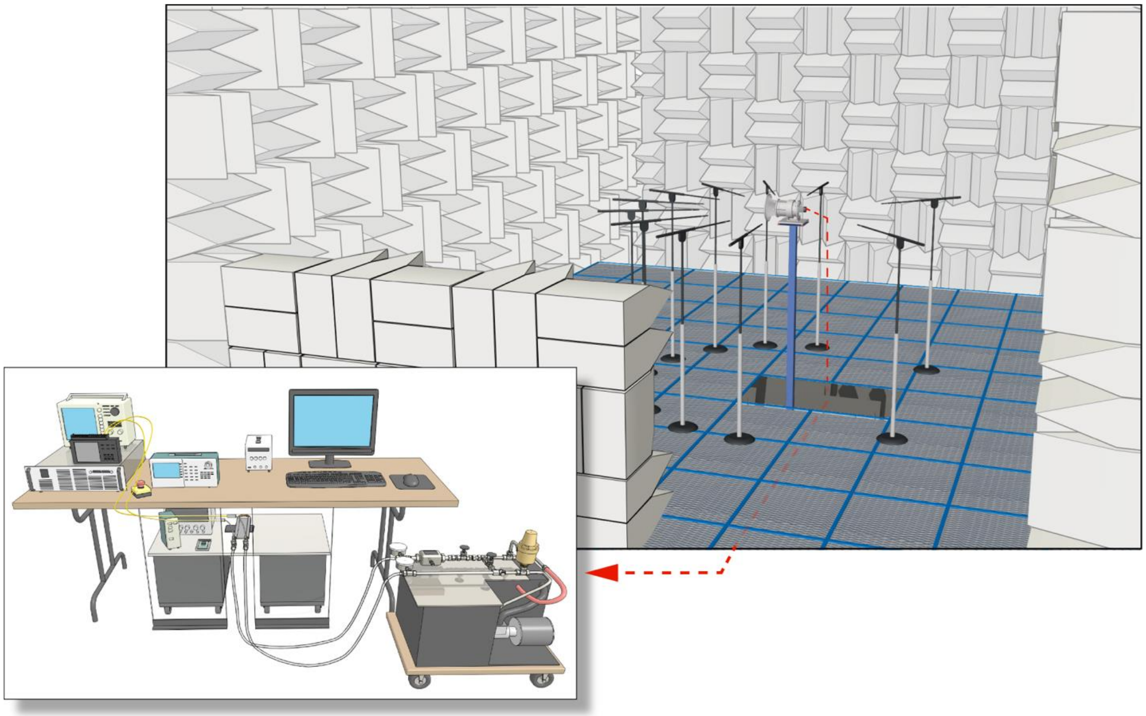

Figure 7: Illustration of the QUEEN V1 experimental apparatus installed in the NASA GRC Acoustical Testing Laboratory. The inset illustrates the equipment that was installed in the ATL control room.

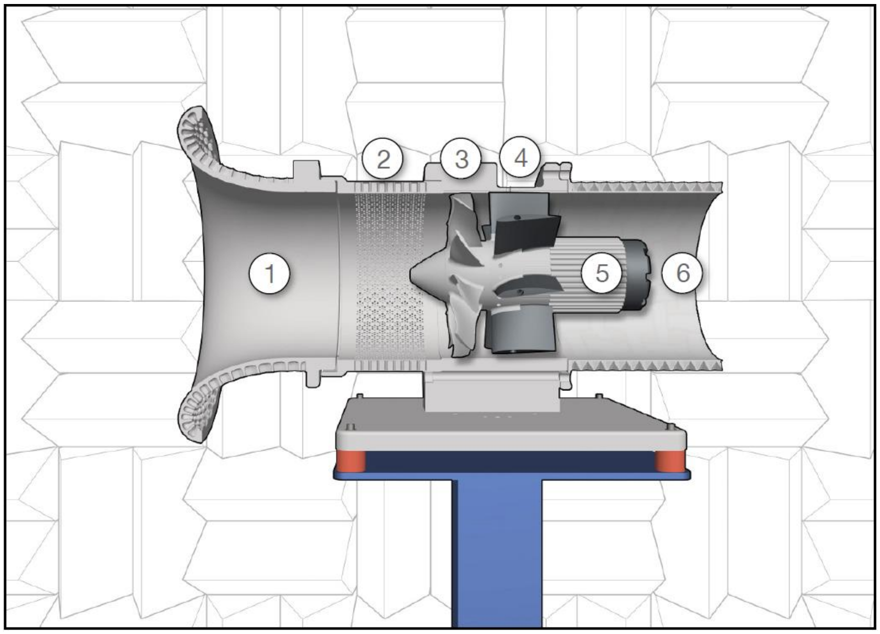

Figure 8: A cross-sectional illustration of the QUEEN V1 in the ATL. Main components of the system include: 1) bellmouth, 2) inlet duct acoustic liner, 3) rotor and shroud section, 4) outlet guide vane section, 5) motor, 6) aft duct.

C. Test objective and procedure

There were several objectives of the QUEEN V1 test program. Motor voltage was set first at 80V. Then the fan speed was increased from 0 to 25,400rpm in increments of 1,000rpm and measurements from the instrumentation was recorded at each speed as thermal and acoustic data was recorded. The first purpose of the experiment was to measure the noise and speed from the QUEEN V1 with four inlet duct acoustic liners. Quantities measured for the acoustic test for the QUEEN V1 included fan speed, housing vibrations, and sound that propagated from the fan upstream through the bellmouth and to the farfield. Eleven microphones placed on a 4 ft. radius from the fan centerline at the rotor leading edge were used to measure the noise. Details of the acoustic test are described in a separate paper [2]

The second objective was to characterize the performance of the electronic speed controller using two different methods of cooling: air cooling and cold plate cooling. Quantities measured for the thermal test of the ESC included fan speed, ESC temperatures, and coolant parameters. Thermocouples were used to directly measure temperatures of coolants, ESC surface, and motor winding. 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. Further testing at full throttle was conducted where the coolant flow rate was varied from (1-0.1 GPM). Once the testing was ended, the QUEEN V1 was removed from the stand and disassembled for inspection.

IV. Discussion of Thermal Results

The thermal results from the experiment are shown in Figures 9 through 14. The first objective of testing was to demonstrate functionality of the inlet liner technology, QUEEN motor/fan, and evaluate ESC cooling configurations. This paper is interested in the thermal results from the ESC and testing was able to show successful continuous operation from 0 rpm to 29,000 rpm.

First, a power analyzer is used, in conjunction with voltage and amperage data, to measure the efficiency across the ESC (figure 9 & 10). This efficiency will give the heat load at the ESC which will be the amount of energy needed to be managed with the cooling system (figure 12).

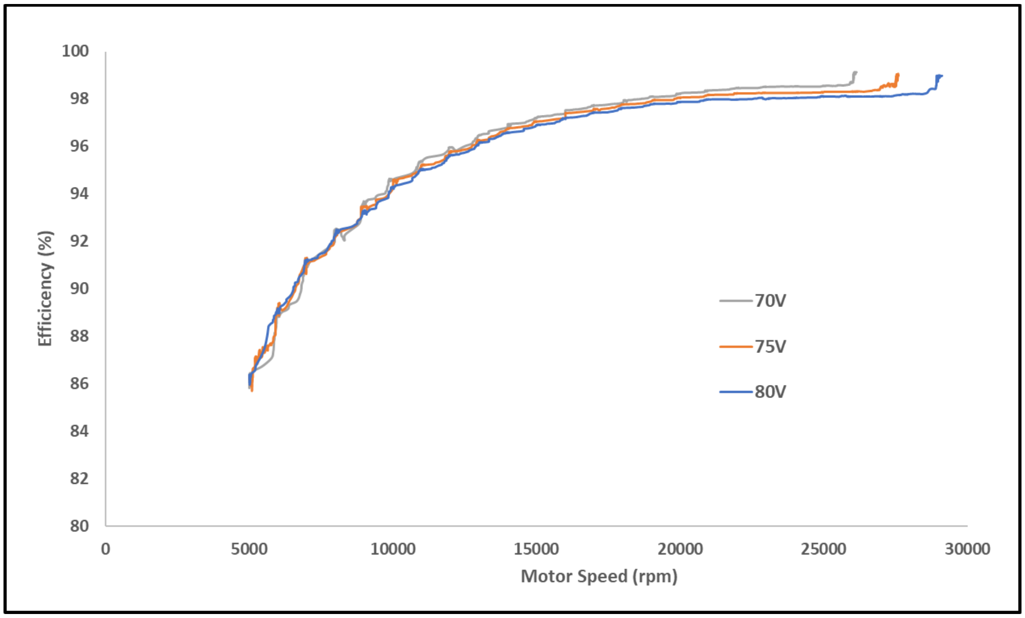

Figure 9: ESC Efficiency curves [1]

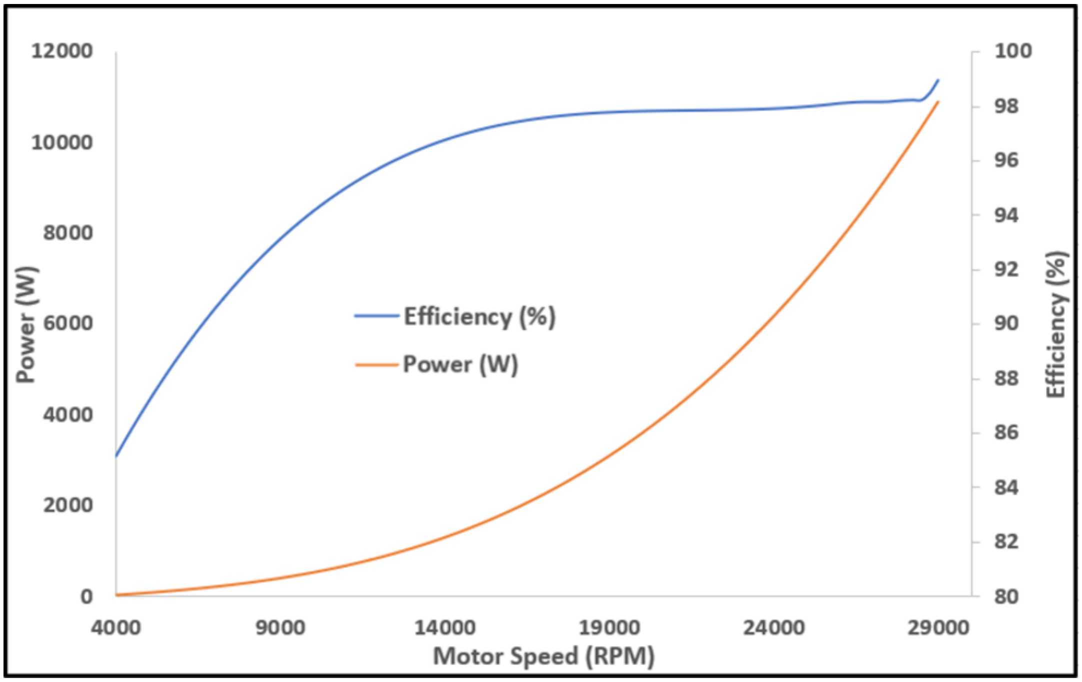

Figure 10: ESC performance and power curves

Having the efficiency and heat load will offer the ability to simulate the temperatures more accurately for the ESC. The temperatures were measured using direct installation of thermocouples at some centrally placed MOSFETs (figure 11) as well as on the housing, both on the fin side (top) and flat side (bottom). The ESC also has a surface mount NTC thermistor at a location on the board near the MOSFET that was measured and compared to the direct measurement (figure 13).

The data collected was compared to simulated results starting with the ESC V1 MOSFET temperatures (figure 13, 15, & 16). Modeling shows great agreement with test results on both speed curves and coolant flowrate curves. As the speed increases the heat load increases and the hotter the MOSFETs become. This is not a linear relationship and follows the squared power curve. This is in line with anticipated results and modeling data matches up within 1%. The coolant flow rate curves were conducted at 25,400 rpm and shows great agreement with modeling results. The ESC output temperature peaked at 70°C and 55°C for liquid cooling and air cooling, respectively. These temperatures are well below the rated limit of 105°C.

Comparisons between the air cooled and liquid cooled results shows that the air-cooled solution is more effective in cooling the ESC at higher speeds, and therefore, power levels (figure 13 & 18). At first the difference was thought to be due to a more effective heat conduction path from the MOSFETS to the bottom of the housing compared to the liquid cooled setup. In the air-cooled setup, the MOSFET are in more direct contact with the ESC housing bottom which allows for an easier path for heat to go through. In the liquid cooled setup, the housings were stripped, and a cold plate was bolted onto the PCB below the MOSFETs. However, the tops of the MOSFETs are no longer in contact with any surfaces and only have natural convection with the surrounding environment to transfer the heat away. This and the increased air temperature around the MOSFETS at higher power and the downwards orientation of the ESC, further inhibited natural convection on the MOSFETS surface and was thought to have contributed to reduced heat transfer and higher temperatures. The heat transfer coefficients for the two cooling methods are compared in figure 19 and further illustrates the air-cooling superiority, in the current setup. However, further analysis shows that the heat sinks in both setups serve as the dominant factors to the total heat transfer (figure 21) and that the top of the MOSFETs are contributing a negligible amount (2-3%). Liquid coolant flow was also throttled from 0-1gpm to see the effects on cooling performance (figure 20).

Therefore, it had been determined that the difference in performance is due to the effectiveness of the heat sink in the air-cooled setup compared to the cold plate in the liquid cooled setup. The fan mounting on the top of the housing, which pushes high speed air though the fins, as well as the large surface area for heat to transfer through, has allowed for better performance and therefore lower temperatures. The cold plate has not been optimized and has only two small tubes to transfer coolant through. The limitations of the cooling cart have allowed a maximum of 1gpm of water to be pushed through the cold plate which has also limited the performance of the liquid cooled setup. The sum of these effects on the equivalent total heat transfer coefficient is illustrated in figure 19.

The ESC has an output that records the internal temperature of the ESC at a location on the PCB near the MOSFETS (figure 11). This temperature was compared between the two cooling setups and against simulated data (figures 13, 14, & 17). The simulated output temperatures agree with test results and further illustrate the correlation between the ESC output temperature and MOSFET temperature. This relation is important to understand for operating the ESC closer to the limits without risking damage to the hardware.

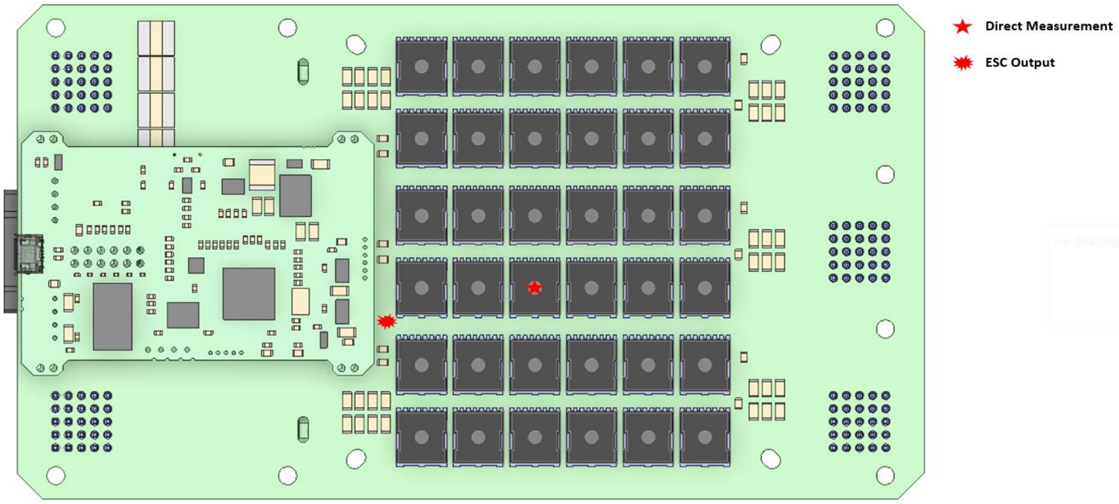

Figure 11: ESC temperature probe locations

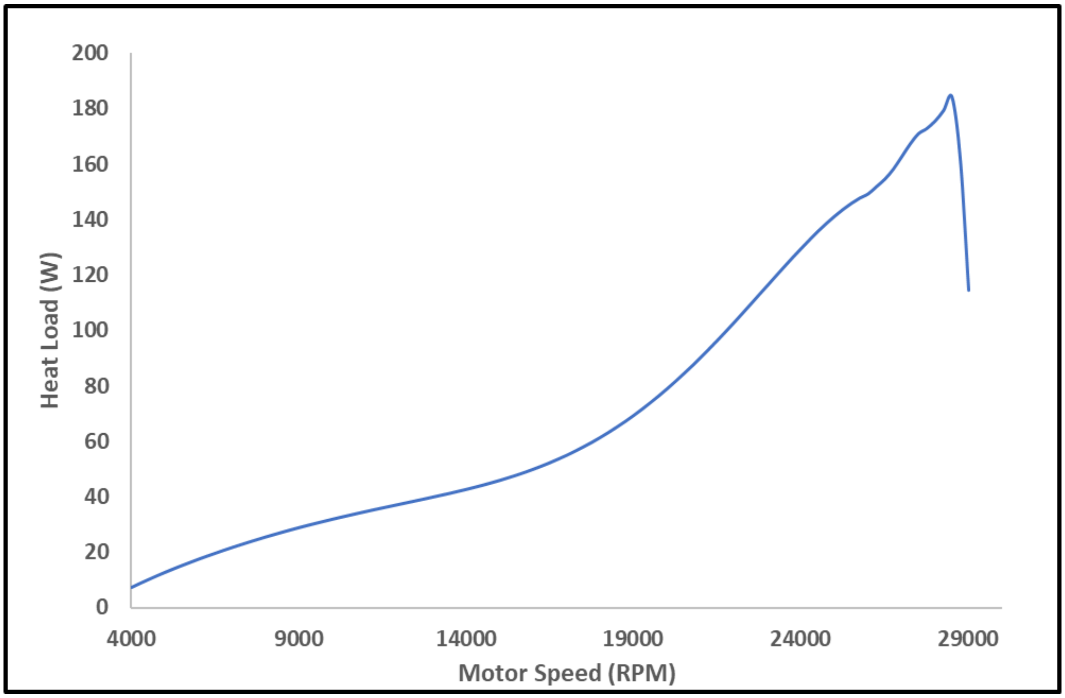

Figure 12: ESC Heat Load Curve

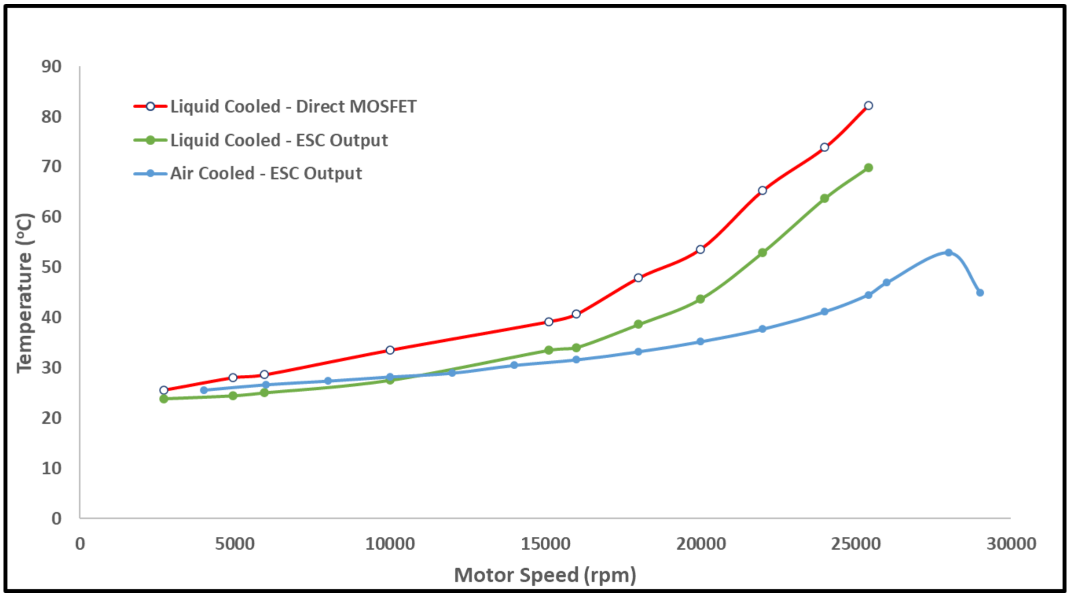

Figure 13: ESC Internal Temps.

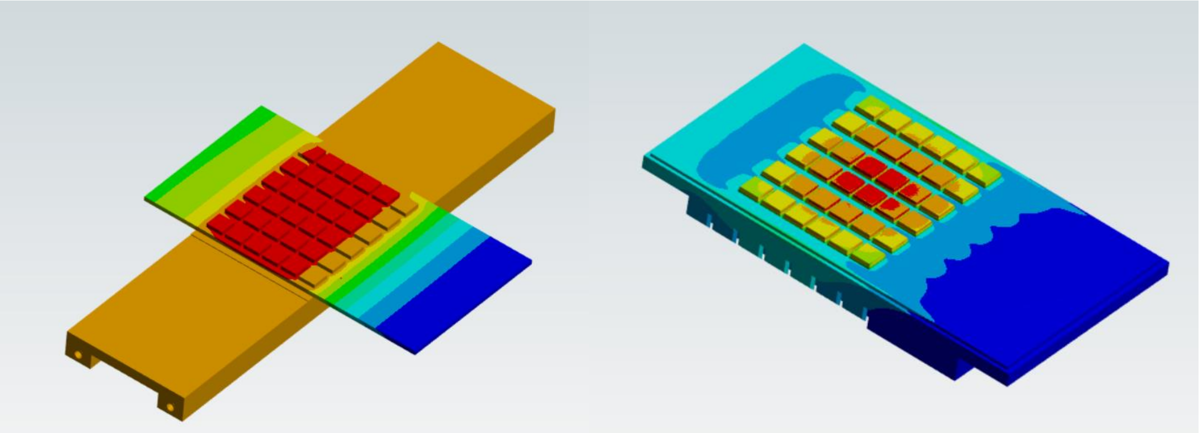

Figure 14: Modeling of Liquid cooled (left) and air cooled (right) ESC configurations.

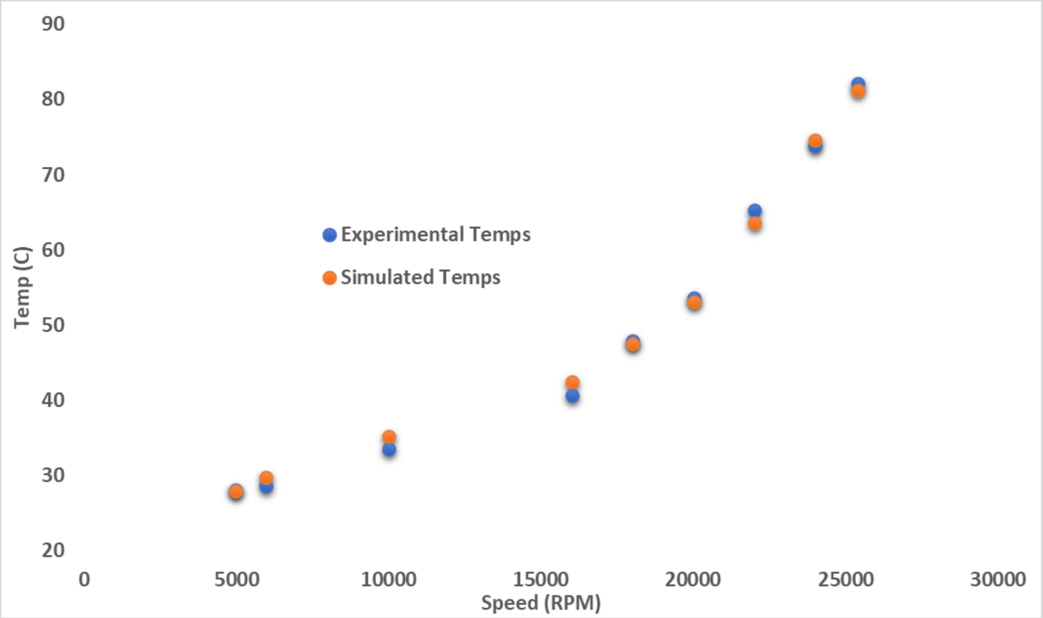

Figure 15: QUEEN V1 ESC MOSFET temperature with cold plate cooling @ 1 GPM

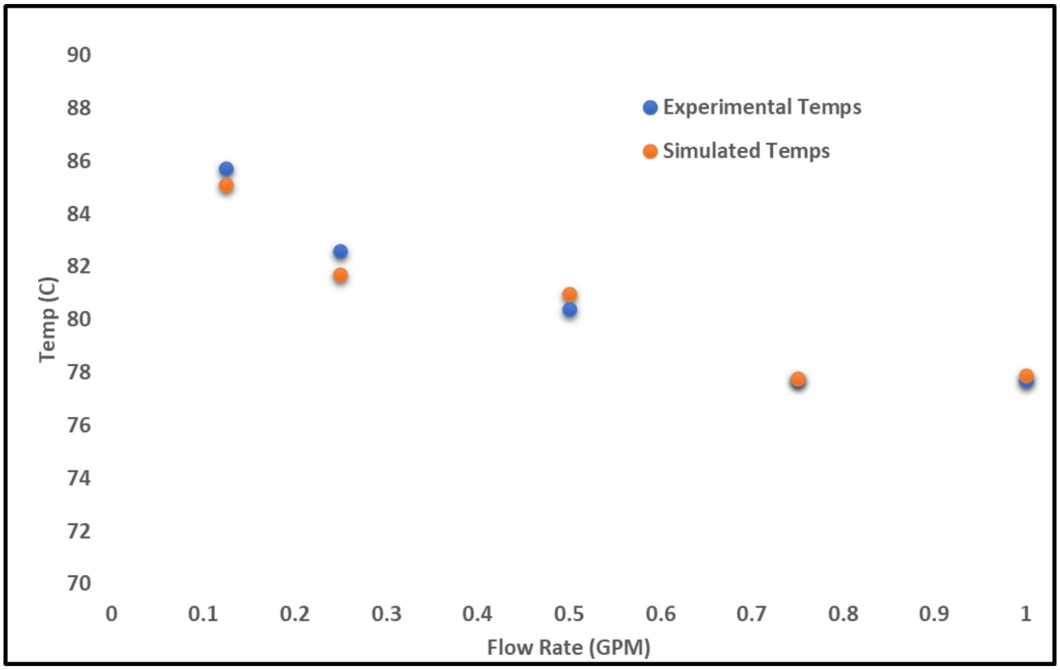

Figure 16: QUEEN V1 ESC MOSFET temperature @ 25,400 rpm

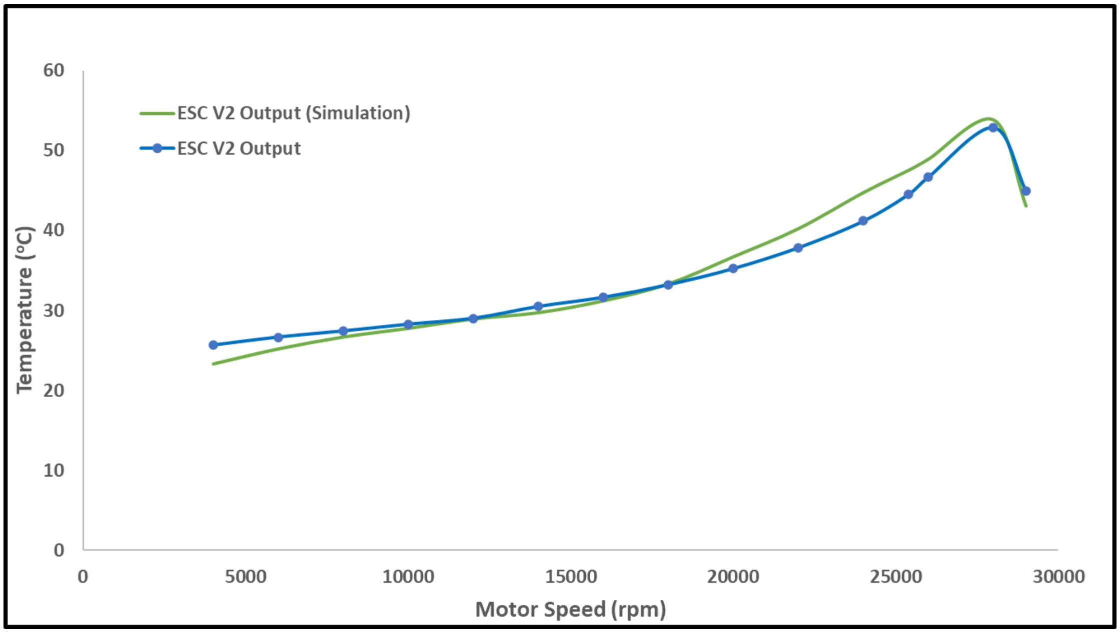

Figure 17: QUEEN V2 ESC output temperature with air cooling

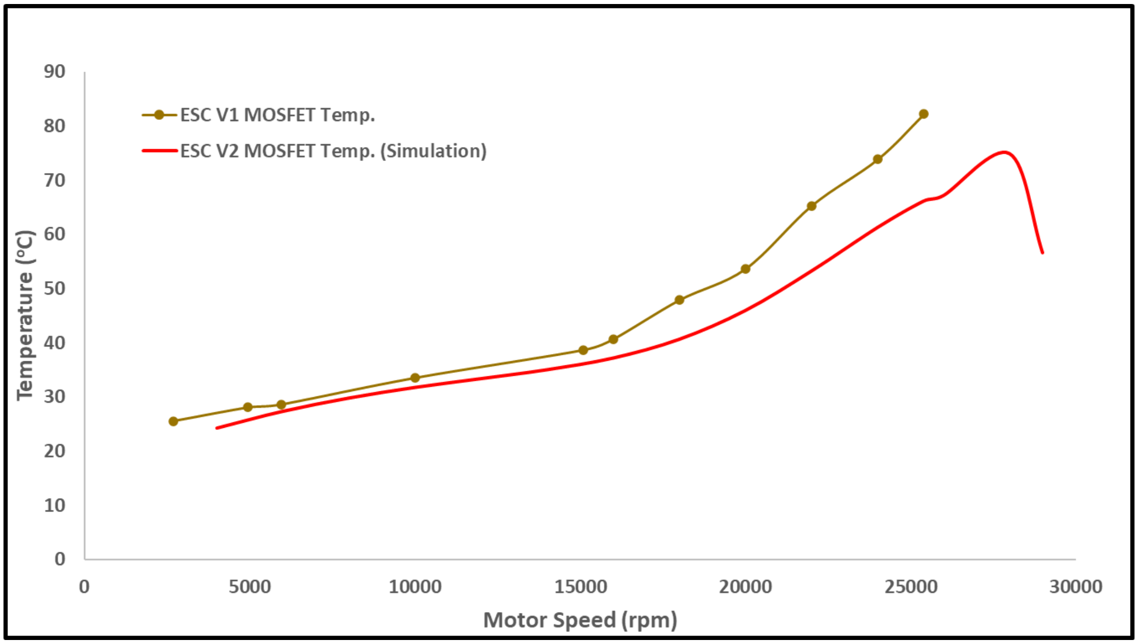

Figure 18: QUEEN ESC MOSFET temperature comparison between liquid cooling and air cooling

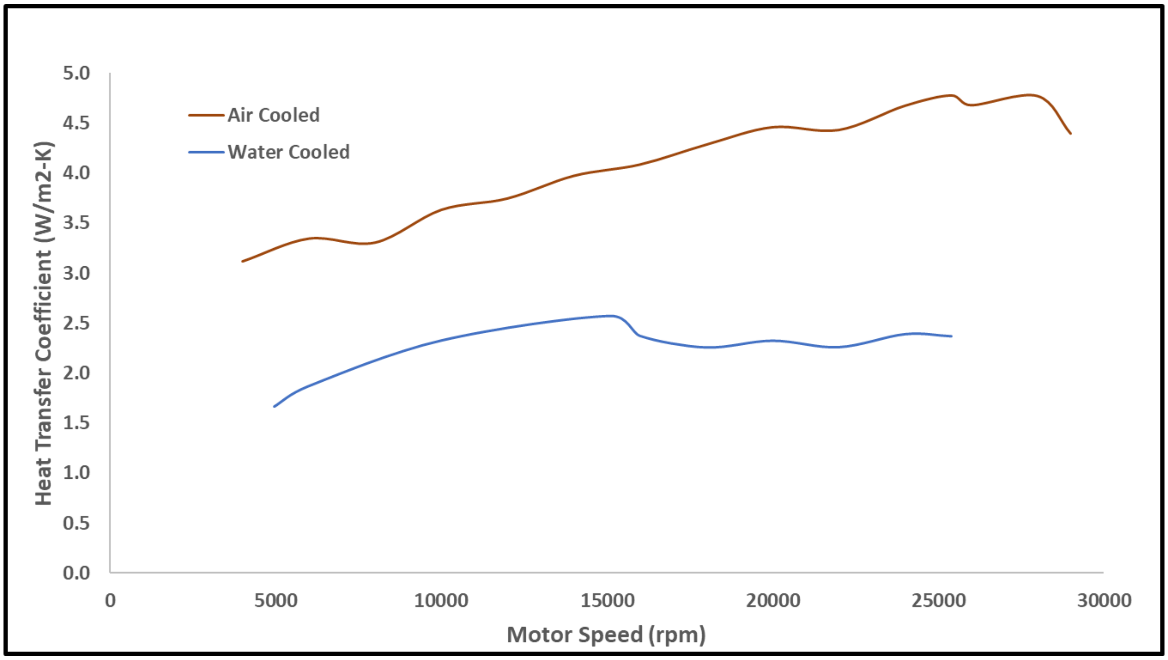

Figure 19: Comparison of total heat transfer coefficient for the two cooling methods.

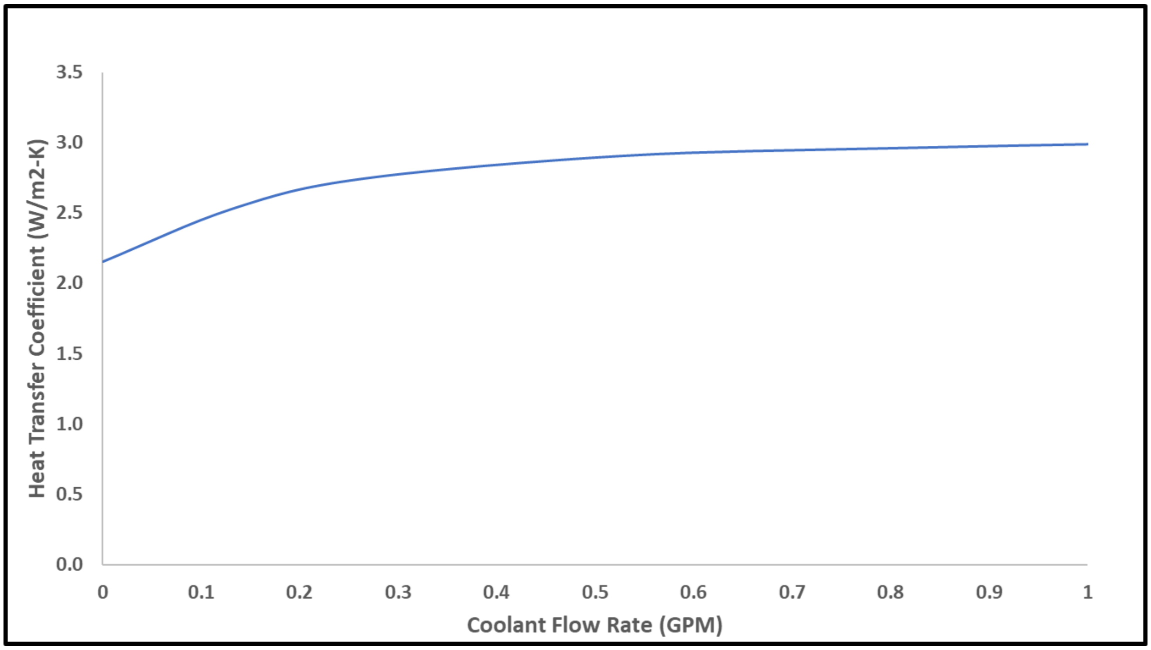

Figure 20: Water cooled heat transfer coefficient as a function of coolant flow rate.

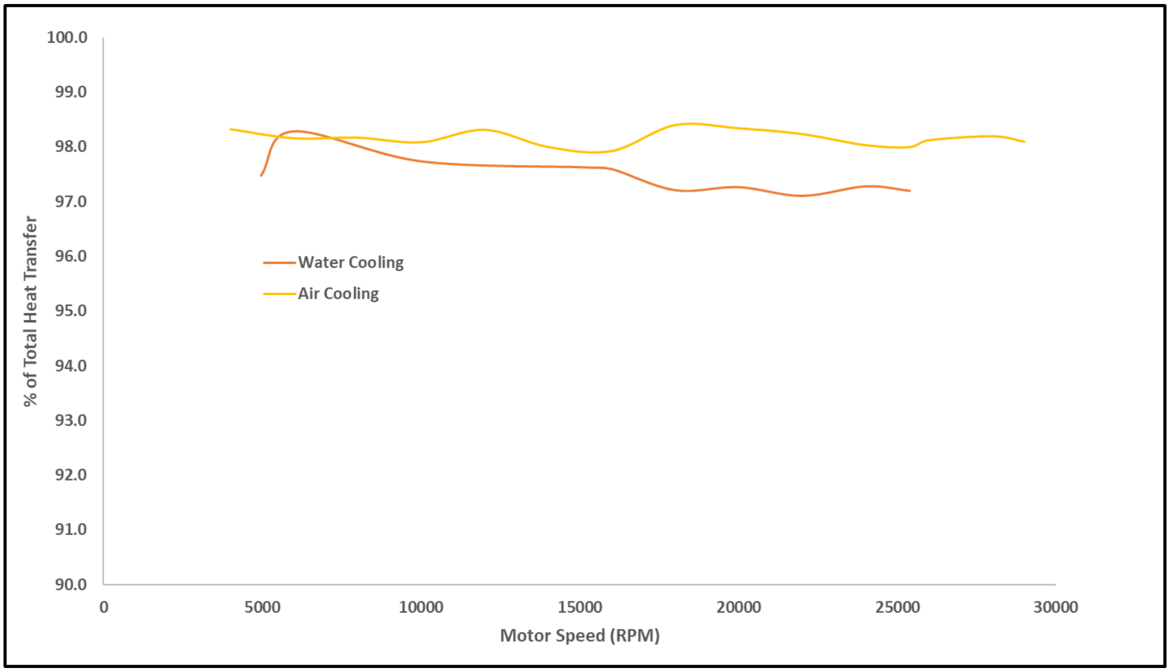

Figure 21: Electronic speed controller heat sink percentage of heat transfer comparison between water cooling and air cooling.

Recommendations

Cooling prediction and results show that both air cooling and water cooling are feasible methods to maintain operating temperatures of the ESC during high power operations. While the air cooling setup did perform better, the liquid cooled setup has a lot of room for improvement. The current use of a two-pass cold plate can be optimized with a 4 pass or flat cold plate that allows for the coolant interaction to increase and happen at a closer distance. The configuration of the ESC to have the MOSFETS sitting face up will facilitate easier natural convection. Similarly, inducing some air flow over the MOSFETs to encourage forced convection can increase heat transfer and better cool the hardware.

Finally, a third cooling method, immersion cooling, should be considered and tested. Immersion cooling will have the hardware placed in a bath of dielectric fluid to facilitate heat transfer through direct contact with the coolant. This should improve the cooling efficiency greatly and simplify the setup of the ESC.

V. Conclusion

The QUEEN electric ducted fan was designed, built, instrumented, and tested at NASA GRC Acoustical Testing Laboratory and thermal lab. Measurements of the ESC temperatures were recorded for two different cooling methods: air cooling and cold plate liquid cooling. Results from this experiment will be used to make informed decisions about the next design iteration of the QUEEN ESC thermal management. This effort demonstrates that NASA GRC can measure the performance of electronic speed controller and successful thermal testing of power electronics which can be used to explore distributed electric propulsion envisioned for hybrid-electric large single-aisle regional aircraft concepts.

Acknowledgments

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