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Transient Nature of Flight and Its Impact on Thermal Management for All Electric Aircraft

High power electronics are a key component in the electrification of aircraft. Large amounts of power need to be handled onboard to generate sufficient lift for flight. The transient nature of the aircraft's mission profile produces varied loading and environmental influences, making consistent cooling and device reliability difficult to maintain. Due to limitations in weight and performance metrics, the thermal management capability becomes a key inhibiting factor in preventing adoption of all electric aircraft. Many efforts are focused on the improvement of high-powered electronics such as the inverters, batteries, and motors, but there is a need for increased focus on the implications of each improved device on the total system with regard to thermal management. To address the many concerns for thermal management within aviation, this paper will review the prevalent factors of flight and couple them to their respective challenges to highlight the overarching effort needed to successfully integrate efficient electric propulsion devices with their protective thermal management systems. A review will be combined with a brief analytical study over inverter cooling to examine the effects of various transient parameters on the device temperature of an inverter in flight. The impact of failure in the cooling systems on the shutdown process will also be examined. Both studies are tied to the motivation for examining the impacts of new and transient challenges faced by electric power systems and help signify the importance of this focus as these systems become more present and capable within the aviation industry. [DOI: 10.1115/1.4055464]

1 Introduction

Electrification of vehicles has become a critical area of research due to the necessity to create more sustainable infrastructure for transportation. Environmental concerns, due to the pollution of combustion engines, are driving the need to develop motors and inverters optimized for high-power, low-weight situations. Until recently, this was not feasible due to the large discrepancy in energy density between combustion and electric power supplies. Energy density in batteries has increased enough to create the potential for electric propulsion to make its way into automotive and aircraft applications. The heightened focus on battery density research assures future increases in energy density that will continue to enhance the capability of these systems in aircrafts. These advancements are coupled with improvements in high power electronics to create systems capable of replacing combustion turbines for flight purposes. A major challenge for all electric aircraft is the significant weight to power increase in the system due to the introduction of large electrical systems. The batteries and thermal management system comprise the bulk of this increase in weight. As mentioned previously, a central research focus is currently the reduction of battery weight. Weight reduction in the battery is limited by energy requirements of flight and the energy density of the battery. The thermal management system in electric aircraft has historically had a lower research priority due to the complexities of high-power electronics and the newness of integration within aircraft.

Legacy aircraft systems benefit from needing less complex cooling solutions to protect the operating temperatures of multiple electronic devices. In combustion turbines, most of the thermal energy generated during the combustion process is easily rejected to the surrounding environment through the air brought onboard within the turbine (ram air) [1]. Since the thermal increase is generated in this ram air, the heat is easily removed from the system. Heat transfer mechanisms are not required to transition this energy out of a device and into the air. The higher operating temperature range of a combustion system and the ability to easily implement bleed valves along the turbine enable easy thermal management of this system and overall aircraft. By transitioning toward electrically driven aircraft, the thermal management systems become an integral part of the operation and the convenience of heat rejection within combustion engines is lost. Optimizing the electric propulsion system is a key component of reducing the total system weight and improving propulsion efficiency.

Temperature limits in electric components are much more difficult to manage than in the combustion turbines. Many components within the inverter and motor have ideal temperature ranges for operation that align with the best efficiency of the system. Maintaining this operating range is crucial for successfully bridging the energy density gap. The energy is generated within the devices themselves and must be removed through the means of additional thermal management systems. Thermal resistance networks of power electronics become integral design points. The increasing trend toward size reduction of electrical devices further increases the localization of energy dissipation, thus heightening the cooling

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challenges. Legacy aircraft also have the benefit of using the fuel reserve as a heat sink and storage device to direct heat away from critical locations [2]. This is not possible in all electric aircraft because the fuel reserve is replaced with a battery that generates its own thermal output. Due to the heat transfer application differences between combustion and electric propulsion systems, more advanced thermal management systems will be implemented in electric aircraft. Generally, this includes a global cooling system and local cooling systems for each device that are connected to the global cooling system. The devices have their own local systems because these can be optimized for heat transfer out of the specific devices with respect to ideal operating conditions. The global cooling system pulls all the energy from the local cooling systems and transfers it to the heat exchanger for rejection into the ram air. By combining the two systems, energy can be moved efficiently and the thermal management system can be designed as cost-effectively as possible.

At a local scale, each device has a specific thermal profile that will enable ideal operation. Inverters present good opportunity for a case study into the difficulties of transient loading because of the temperature gradients and resulting reliability concerns introduced throughout the device packaging. High-power modules generate significant temperature gradients, which lead to structural stresses, making them more susceptible to damage over time. As power electronics become more compact, cooling them becomes more critical to preventing device failures.

The push toward electric aircraft has fostered many studies into improving electric motor and inverter capabilities. Many present efforts to increase the capability of these systems focus on improving the performance of either the motor or inverter for higher power ratings. These studies are crucial to continued progress toward electrification of aircraft, but with most of the focus centered on the device enhancements, considerations for the implementation of these devices have been less scrutinized. Specifically, this includes the thermal performance of the full system and how it interacts with the transient nature of an aircraft's mission profile.

Figure 1 shows the transient nature of flight parameters and loading profile. During the initial takeoff and climb portions of flight, up to cruise altitude, the power load and ambient temperatures are at their highest values. This limits the potential energy rejection capability of the overall system as the combination of these two dictates the maximum capabilities of the thermal management systems. At cruise altitude, temperature is significantly lower, thus increasing the cooling potential. Device loads drop significantly because the power to maintain altitude is significantly less than that required to get there. This creates the possibility for overcooling of devices, which can also negatively affect the performance and reliability.

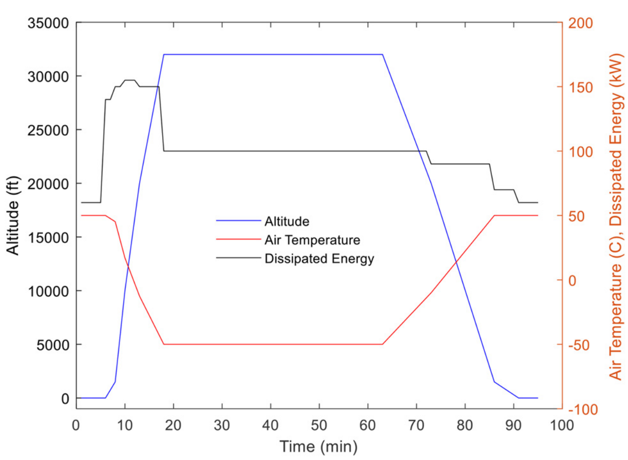

Fig. 1 Transient nature of environmental impact and loading structure of an aircraft

The aim of this work is to offer perspective for the impact of changing power loads and cooling parameters on the thermal profile for consideration into the discussion of full system integration and performance. Sections 2–7 will outline the many challenges associated with electrification of aircraft and highlight some attempted solutions. The presented solutions are not an exhaustive collection, but serve to emphasize the difficulty these transient challenges possess and demonstrate where technology needs to be focused to achieve successful integration.

2 Transient Conditions

The amount of rejectable energy from the thermal management system is limited by environmental factors and design parameters for the heat exchanger. To maintain ideal operating conditions for the power electronics, a strong understanding of the transient nature of these conditions is important for fine-tuning the thermal management system to handle a variable cooling output. This section will detail the impact of the environmental factors in regard to the heat exchanger and the power load variations. These will have direct influence on the ability of the heat exchanger to reject energy from the global cooling loop into the ram air through the fan or turbine.

2.1 Environmental Factors. Ambient temperature is a major part of this the thermal management design problem. The ambient temperature is highly dependent on the altitude of the aircraft and the geographical location from which it begins its mission. Mission temperature profile studies aim to determine the worst-case temperature gradient and look at flight profiles taking off from hot locations, such as Arizona, where ground temperatures reach 40–55 °C on the tarmac [1,3]. Temperature decreases approximately linearly in the troposphere, the atmospheric layer closest to ground, which typically ranges from 0 ft to just above 32,000 ft (∼ 10 km) [4]. Above the troposphere is the tropopause, which has an approximately constant temperature of around −56 °C. Cruising altitudes for many planes are just above the 32,000 ft (∼10 km) mark to avoid weather in the troposphere and to improve fuel efficiency in less dense air. This means the temperature outside the plane can swing from 55 °C to −56 °C in a short time frame, 15 to 30 min for takeoff [1,4]. Such a drastic swing in temperature makes it difficult to manage the cooling rate required to maintain ideal device operating conditions. A study by Kabir et al. showed a dramatic decrease in the flow rate of air across the heat exchanger from high temperature conditions (near ground) to the cruise altitude [4]. To maintain a device temperature less than 45 °C, ∼7 kg/s of ram air was needed at ground level and ∼2 kg/s is needed at 32,000 ft (∼ 10 km), marking a 5 kg/s difference in necessary flow rate for this given setup [4]. This marks a large change in thermal management requirements that need to be addressed throughout flight. Temperature gradient is also dependent on the plane type. Many smaller planes and noncommercial aircraft have vastly different altitude profiles where the plane may not have an extended cruise at above 32,000 ft (∼ 10 km) [5]. Propeller planes often stay under around 20,000 ft (∼ 6 km) at peak altitude. Large and sharp variations in altitude, as seen in military aircraft, present even more challenges than those in general commercial applications as it removes the convenience of some predictability that exists in the commercial flight style [5]. Equation (1) demonstrates how the temperature at any altitude can be approximately found [4]

$$T_1 = T_s \left(\frac{P_1}{P_S} \right)^{\frac{a*R}{g}} \tag{1}$$

T_1 represents the desired temperature, P_S and T_s are the pressure and temperature at static sea level, a is the lapse rate defining the slope of temperature drop (for this study $a = 6.5$ K/km), R is the gas constant of air (287 J/K kg), and g is the acceleration of gravity (9.81 m/s^2). P_1 is the pressure at the desired altitude (z) and is given by Eq. (2) [4]. All variables are as previously designated. P_1 can be found for any altitude based on the sea level measurements. These two equations can be used to create a variable model of temperature and pressure inputs for a given altitude flight path

$$P_1 = P_s \left(1 - \frac{a*z}{T_S}\right)^{\frac{g}{a*R}} \tag{2}$$

Generally, the ambient temperature is considered for heat sink calculations due to the simplicity of determining it. This may not be accurate though due to viscous effects and compressibility of the air around aircraft features [6]. Ram air temperature, defined as "air brought to stop" in relation to the plane, and recovery temperature (adiabatic wall temperature), defined as the skin temperature of the aircraft, may differ and provide better insight into the cooling potential of the system [6]. Equations (3) and (4) give the ram, T_{ram}, and recovery, T_{rec}, temperatures, respectively, for low Mach number systems [6]. The Mach number is M, ambient temperature is T_∞, the specific heat ratio is γ, and r_f is the recovery factor which is shown in Eq. (5). The recovery factor is a function of the Prandtl number, Pr

$$T_{\text{ram}} = T_\infty \left(1 + \frac{\gamma - 1}{2} * M^2\right) \tag{3}$$

$$T_{\text{rec}} = T_\infty \left(1 + \frac{\gamma - 1}{2} * r * M^2\right) \tag{4}$$

$$r_f = \sqrt{\text{Pr}} \tag{5}$$

Pressure plays an important role in the heat exchanger. It has been shown that higher pressure differentials across the fan or turbine result in more effective heat transfer through the heat exchanger at the cost of drag increase.

Velocity also plays an important role in the achievable flow rate of air through the heat exchanger. Typically, a bleed valve system is used to pull a small percentage of air off the main fan intake to redirect for cooling purposes [7]. The velocity of the aircraft is therefore directly coupled to the flow rate for cooling [8]. At higher velocities, the increased air flow rate will increase the heat transfer out of the heat exchanger, improving the overall cooling capability. Unfortunately, the takeoff sequence consists of lower speeds during the time of highest load [7]. Highest velocity occurs during cruise when the cooling load is at its lowest point. This becomes an important factor when considering the relationship between effective heat transfer and device efficiency. Air speed is a highly variable parameter to consider in the design space because it is fixed to the capability of each plane, respectively. Changes in air density over time can affect the mass flow rate of air through the heat exchanger. Lower densities result in lower mass flow rate, which can hinder the potential heat transfer. Air density decreases with increasing altitude, while also being a function of temperature and pressure. It is important to understand all the characteristics of the air being used as a cooling fluid at each stage in the mission profile to have an accurate prediction of the cooling performance.

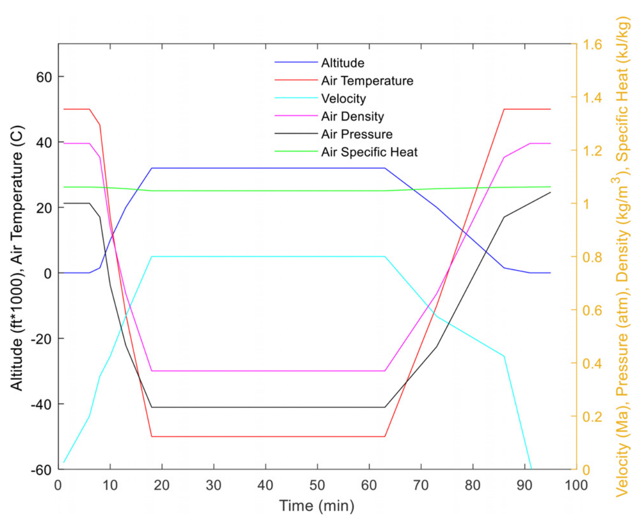

Fig. 2 Transient nature of environmental parameters over mission profile

The transient nature of environmental factors on the aircraft makes cooling a difficult task. These various factors, combined with the aircraft power requirements and spatial allocation, create a theoretical limitation on the max cooling output capable at any point in the mission profile. This is most prevalent during the takeoff and climb portions where the max load heightens the thermal management challenges. The peak load is often at least 2.5 times larger than the cruise phase load [9]. This is also the most inefficient operation point since most of the electric system is designed to be at peak efficiency during cruise, the longest section of flight [9]. Figure 2 gives a look into the changing environmental properties with respect to time and point in the mission profile. Critical mission points are shown as reference.

2.2 Power Loads. Energy density is a key driver of the electrification of aircraft. To achieve flight, motors must maintain high rotational motion, which requires high power devices. According to historical data regarding the capability of more electric aircraft, it is likely that by 2050 an aircraft could be equipped with 10 MW of power. This would be substantial enough for full all electric integration into many small and some medium range aircrafts [10]. Each engine for an ATR 72-600, one of the most fuel-efficient turboprop aircraft, needs over 2000 kW of power for each of its two engines [11]. For short-range applications on regional cruisers with approximately 100 passengers, peak power needs will reach 3–4 MW with ranges nearing 500 km [10,12]. Most of this power requirement is needed for propulsion, but around 300 kW are estimated for the auxiliary systems like the wing ice protection system [10]. To accommodate this, a 3 kV system would be needed to supply 617 A to reach desired power load. Higher voltage systems take advantage of lower current requirements to lessen the mass of the transmission lines and reduce current losses [10].

The change to electric propulsion for this scale of power requirements is notable due to the energy density difference in power source. Jet fuel has an energy density of almost 12,000 W h/kg while batteries peak in the 260–270 W h/kg range, 45 times less dense [13]. Even at high system efficiencies, there is a significant amount of dissipated thermal energy. Inverters can achieve efficiencies upward of 96%. Batteries and electric motors also see efficiencies greater than or equal to 90% [14]. Batteries are the major weight constraint for aircraft. Byahut et al. conducted a study showing the battery comprised 60% of the weight of the electric propulsion system where no other individual component contributed more than 15% [15]. For small aircraft (less than 15 passengers), rejected thermal loads of up to 200 kW are studied for feasibility [16]. Other small turbo-electric planes have been reported to require dissipation of 340 kW [17]. The STARC-ABL is projected to have 570 kW of dissipated losses in nonoptimized configurations [14]. As the size of the aircraft scales, the thermal losses become more significant and difficult to manage.

To help bridge this gap in the near future, NASA is working with engine producers such as Rolls-Royce to design hybrid electric propulsion systems [18]. The goal is to use supplemental electrical power for ground operations and for boosting the power output during takeoff, allowing smaller combustion motors to be used. It is also noteworthy to mention the implications of aircraft design in the impact on loading structure. Riboldi et al. conducted an analysis to show the implications of various aircraft configurations on the power needs [19]. Most present studies base the electric needs on the power requirements of existing aircraft. This study points out the potential of aircraft optimization that could more efficiently integrate the electric propulsion system and save on total aircraft weight, thus reducing power needs.

3 Heat Exchanger Details

As aircraft move toward all electric propulsion, reliance on ram-air heat exchangers and other novel heat rejection methods will greatly increase. Legacy aircraft lacked large-scale heat generation within electric devices that will now drive the development of more advanced and involved systems. Most of the transient effects on the thermal management system are realized in the heat exchanger because it is the connection point between the global cooling loop inside the aircraft and the outside environment. It will be important to optimize this component, as an efficient heat exchanger can mitigate some impact of the transient loading structure. This will be difficult to achieve through all points in flight due to changing environmental conditions and the typically static nature of heat exchanger design. As discussed in Sec. 2.1, environmental parameters will be deciding factors for the type and design of the heat exchanger.

Heat transfer in a heat exchanger relies on the temperature difference between the inlet coolant fluid and the inlet rejection fluid, ram-air. The inlet fluid is often a 50% water–glycol mixture to help handle the low temperatures at high altitudes [20]. Larger temperature differences enhance heat transfer but are difficult to maintain because the coolant temperature will constantly be changing in response to variability in all affecting parameters. During high loading sequences, the ambient air temperature is at a maximum for that flight profile. Weight limitations for the coolant reservoir confirm the likelihood of significant coolant temperature rise during takeoff. This creates the minimum temperature difference during the max power output [4]. As a result, the heat exchanger must be sized so that its heat rejection capability during the takeoff phase is large enough to prevent device overheat. To improve heat transfer, the heat exchanger area needs to increase but there are practical limitations to the potential of this due to weight and pressure drop requirements of the aircraft. Large heat exchangers can also lead to overcooling during the cruise phase when increased temperature differences and reduced loads reduce the stress on the thermal management system. The size of the heat exchanger can be potentially reduced by adding secondary energy management devices as discussed later in Sec. 4.3. Microchannel technology also offers the ability to find optimal tradeoffs between increased surface area and pressure drop in both the coolant loop and bleed systems.

Diffuser pressure loss becomes a significant factor at low flight velocities [20]. In these cases, a puller fan may be necessary to help overcome loss in pressure. The puller fan is less efficient than the main propulsion fan. This reduces the overall effectiveness of the system and adds weight to the aircraft. The puller fan can be necessary for applications in more electric aircraft when the aircraft is stationary or at very low velocities in on-ground scenarios. The electrically powered puller fan is used to generate a flow rate to maintain heat transfer out of the heat exchanger [21]. Aircrafts vary in flight altitude and velocity as shown in Sec. 2.1. The heat exchanger area needs to account for the mass flow rate of air through it to assure the heat transfer area is adequate for the required energy rejection.

Different aircraft velocities can lead to a range of impacts resulting from differences in fluid flow. Heat exchangers in transonic conditions (Mach 0.8 to 1.2) are less studied in literature, but are now an important area of focus for understanding the heat rejection capabilities mid-flight. To observe this phenomenon, Sousa et al. designed a surface mounted heat exchanger with swirl angles of 40 deg to 50 deg [22]. This system is mounted outside the turbine casing and does not require a bleed piping system to direct air, though it still contributes to increased drag force in the same manner. Developing strong models and a more complete understanding of the flow interactions at this speed will help improve the efficiency of novel heat exchanger designs to reduce the overall drag addition and improve heat transfer out of the cooling loop.

Drag is a major disadvantage caused by a ram-air heat exchanger. Increased drag on the aircraft reduces overall performance. Larger heat exchangers will lead to increased drag on the aircraft, which will lead to increased power needs of the aircraft. The Meredith effect can be utilized to reduce the overall drag gained from the thermal management system. This effect uses system design to gain thrust from the rejected ram-air [6]. This does not eliminate the increased drag but helps mitigate the total net drag gained from a ram-air system.

Promising heat exchanger candidates for aircraft consideration are plate finned, printed circuit, and microchannel heat exchangers [20]. Plate-finned heat sinks are generally considered for ease of calculations and design [20]. Printed circuit specifies the broad category of additively manufactured heat sinks that take advantage of complex geometries to optimize heat transfer. Microchannel heat exchangers look to increase the heat transfer surface area by creating many small channels for air to pass through. Pressure drop is the main constraint limiting the implementation of these designs. Aircraft heat exchangers need to be lightweight and compact. The most effective heat exchangers will be a combination of these three categories with counterflow or cross flow configurations. Kellerman et al. performed a heat exchanger sensitivity analysis to determine the paramount parameters for improved heat transfer [20]. Abolmoali et al. provides a study over heat sink rejection using ram air and finds it to be an insufficient method to cool the electric propulsion system for a hybrid 5 MW structure [23]. This shows how important further optimization and more efficient cooling systems will be to progressing electric aircraft.

Heat exchangers, as detailed, represent the conventional method for rejecting thermal energy to the outside surroundings. A class called surface heat exchangers reintroduces a novel effort to direct heat to surface features of the plane for convection off the aircraft's body [24]. This concept has existed for some time but has not been widely implemented because legacy aircraft have not often demonstrated the need for advanced cooling measures. It has also been sidelined due to the likely increase of drag on the aircraft resulting from thermal disruptions in the boundary layer [24]. If the aircraft body was used as a heat sink, adding thermal energy to the laminar boundary layer will lead to earlier transition to turbulence, thus increasing drag. Implications for the drag and flight performance of the aircraft have been numerically studied, but understanding the full picture for managing the variable thermal outputs would need to be accounted for [24]. This version of heat rejection also needs added consideration for the movement of thermal energy to the aircraft face, which presents the more challenging component to this concept.

Overall, the design of optimal heat exchangers will require consideration of many parameters. Combinations of technologies such as passive cooling, puller fans, microchannels, additive manufacturing, and unique surface cooling techniques will be combined to increase thermal performance while limiting any negative performance reduction of the aircraft. Effective heat exchangers will be a crucial design point for providing the necessary technological improvements to allow electric aircraft to become a prominent mode of transportation.

4 Cooling Systems

4.1 Local Cooling Systems. The electric propulsion system is comprised of three main devices: battery, inverter, and motor.

Each of these devices requires its own unique cooling solution because of the vast differences in device size, configuration, and dissipated energy load. Designing a specified thermal management system for each device allows for distinct optimization and individual safeguards to be implemented in effort to improve performance. Energy transfer from the device to a working fluid is often the most difficult action due to reliability and packaging concerns associated with high density power electronics. Local cooling systems are somewhat shielded from the effects of various transient properties previously mentioned. The global cooling loop, discussed in Sec. 4.2, takes on the brunt of these issues as realized in the coolant inlet temperature, leaving the local systems to be responsible for ideal operation at variable loading profiles. Challenges and prospective solutions for local cooling are presented to demonstrate the challenges in each device.

4.1.1 Battery. Energy requirements for battery storage will reach thousands of kW h for large commercial aircraft [25]. Large systems introduce many safety and reliability concerns. Presently, lithium ion batteries are considered to be state-of-the-art and have high energy density potential. One major drawback is the safety concerns regarding lithium as it is a highly reactive material. Advances have mitigated this risk in electric vehicles, but increased aviation size demands present many packaging difficulties in structural support and thermal management [25]. Desire for high charging rates in commercial applications between flights leads to higher demand on the thermal management system for batteries in general. High thermal loads, coupled with increased structural and safety needs, contribute to the difficulty of designing an adequate cooling system that reaches the entirety of the battery to prevent overheat and thermal runaway. Thermal runaway is difficult to protect against once it has been initiated, so it is critical to prevent high temperatures that are conducive to this phenomenon [26]. Various techniques such as finned heat sinks, heat pipes, cooling plate, and immersion cooling have been used to remove the thermal energy from the battery cells [26,27]. Battery operating temperature is a crucial limiting operational factor as high battery temperatures can also lead to higher degradation levels within the battery [28]. In a resource limited environment, such as in aircraft, connected cooling architectures can prove difficult for maintaining optimal operating conditions at each device. Thermal profiles and structural considerations must be balanced to create a useable system [29].

4.1.2 Inverter. Inverters are crucial for converting the DC battery input into a usable AC output for the motors. For required motor power ratings, this requires a large signal through the inverter resulting in significant energy dissipation. Large thermal gradients in the device can lead to cracking or fracture within the device layers [27]. It is important to maintain consistent operating temperatures in the device to prevent thermal expansion and contraction that will ultimately lead to coefficient of thermal expansion failures. SiC power converters offer high potential because their increased thermal stability at high temperatures reduces strain on potential thermal management systems. Cross talk or other parasitic mechanisms occurring due to electromagnetic interference represent a major challenge within SiC device design [28]. This becomes problematic at desired high switching frequencies. Switching losses are a significant contributing factor in high power inverters [30]. Inverters have many reliability issues related to protecting the device against structural and electrical failure. High voltage systems upward of 3 kV are being examined in experimental works. Inverters can also be combined in parallel to reach higher power classes. This has been done to form an operable 1 MW inverter [12]. Inverters being cooled through many novel techniques. In order to facilitate the large power increases, conventional inverter structures are being changed to reduced stack sizes and thermal resistances. This brings the cooling mechanism closer to the energy generation point. Many devices utilize double-sided cooling and internal cooling architectures that are built into the package rather than attached as a separate unit [31]. These devices are more complicated and expensive to manufacture but can yield twice as much cooling potential under double sided cooling. This concept can be undertaken with liquid, air cooling mechanisms, or a combination of the two to enhance the overall energy removal [31]. Advancements in packaging and additive manufacturing have enabled the use of more complicated cooling designs as high-power electronics require substantial enhancements to the cooling system to continue progressing inverter capabilities.

4.1.3 Motor. There are two components to energy generation in the motor. Dissipation occurs in the motor windings and in the rotor or core. Core losses are generated by the magnetization of the structure. Eddy currents and changing magnetic domains within the steel core contribute to losses in efficiency of the system manifesting as thermal energy [32]. Losses in the windings occur as a function of the copper resistive losses which increase in high power motors that require large magnetic field strength to drive the rotation [33]. High current can lead to large thermal energy generation. Due to the need to insulate the wires against partial discharge and shorting, this becomes very difficult to cool.

Motors take advantage of heat sinks in the core to cool the rotor section through convection generated by rotation of the motor. In most low power cases, this approach is adequate, but at higher loads more efficient heat transfer is needed. Additive manufacturing has become an integral part of heat sink design for motor cooling in many experimental studies [33]. The flexibility in design shape offered by this process allows for the complex geometry of the motor to be more optimally adhered to. Various fin ratios and shapes can now be easily manufactured and have been shown to improve efficiency of cooling architectures for higher load motors [33]. Additive manufacturing of ceramic and nonmetallic materials has added new avenues for cooling designs within the stator. Ceramic and other nonconductive materials can be used as separators for the winding coils. These separators are hollow and allow the flow of fluid through to minimize insulation separating the windings from the cooling jacket [34]. Various other techniques have attempted to limit the insulation barrier typically dealt with in winding cooling by implementing the cooling jacket within the winding coils by means of nonconductive fluid flow channels [35].

Thermal management systems for motors depend on the motor size. Typically, smaller motors will utilize air-based cooling mechanisms because of their lower weight and smaller size requirement versus liquid cooling systems. This is especially important for aircraft applications. The abundance of air-cooling potential in aircraft makes this the logical choice in many applications [36]. In high torque or high RPM applications, liquid cooling may be used.

4.2 Global Cooling System. The global cooling system is typically comprised of a cooling loop that moves coolant through the local cooling systems to remove the dissipated energy from each device. The energy gained in the global cooling system is then rejected to the surrounding environment through a heat exchanger, taking advantage of the ram air brought onboard by the propulsion mechanism. Figure 3 gives a general depiction of the overall system, where the coolant moves through a local cooling system at each device. Each device typically has its own local cooling system to optimize the heat removal depending on the device temperature requirements and structure. This is done to best protect each device and ensure improved efficiency. The local cooling system can easily be connected into the global loop by connecting the coolant inlet and outlet for liquid cooling systems.

The global cooling loop is greatly impacted by the rejection limit of the heat exchanger. Ideally, the coolant reservoir volume is minimized to reduce weight and required power. During the takeoff phase, this can be problematic as the reservoir temperature will increase because the heat exchanger cannot remove all the

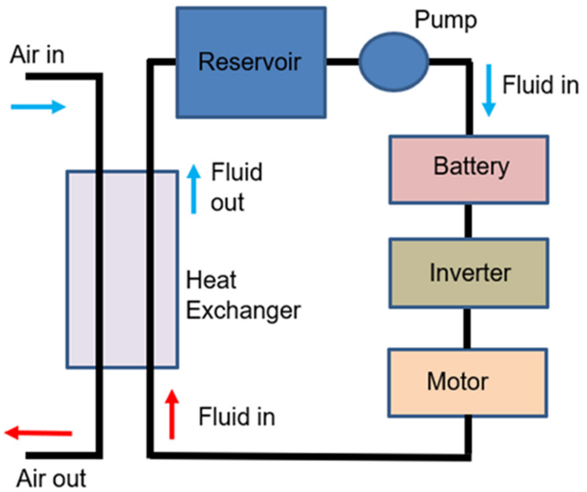

Fig. 3 General schematic for global cooling system that is connecting the electric devices

heat generated by the propulsion system. A balance must be struck between increasing coolant temperature and device level temperature during the takeoff phase to maintain safe operating conditions until the cruise altitude is reached and the max dissipated energy subsides.

4.3 Advanced Cooling Solutions. Increased power density will drive the need for more innovative solutions for cooling electric propulsion. Many of the problems associated with the transition to electric have been highlighted so far, including the various environmental and design parameters contributing to the difficulty of thermal management during takeoff. This section will detail a few current efforts to mitigate the issues faced during takeoff to demonstrate various technological combinations that can improve efficiency.

Passive cooling systems represent a significant opportunity to reduce the load on the cooling loop and thus increase the propulsion to thermal management power ratio. Thermosyphons and heat pipes present two-phase cooling solutions where a working fluid is evaporated and condensed repeatedly to move thermal energy away from the generation point [37]. This offers good cooling potential as a secondary or support system for the main cooling loop. One of the main issues with implementation of this technology is the high potential for condenser flooding [38]. The large variance in temperature in these devices makes it difficult to choose a working fluid that will avoid freezing and overheating throughout the mission profile. Either scenario removes the heat pipe from contributing cooling and puts the devices in danger of overheating.

Phase change materials (PCMs) offer another passive option that has been studied. PCMs undergo an isothermal energy absorption process at their melting temperature and can be utilized to help mitigate sharp energy spikes. This can be beneficial for takeoff load management. PCMs are widely known for their use as energy storage systems. This concept is applied to aircraft cooling by using the PCMs to store some of the large amounts of energy generated during takeoff [17]. This energy can then be slowly released during the cruise phase where thermal loads are significantly reduced. Due to large latent heat values, the PCMs can store significant energy per unit mass. Sanders et al. demonstrated this to be a viable concept by comparing a PCM-integrated cooling system to a cooling loop with dual reservoirs. To maintain consistent coolant temperature, hot fluid that cannot be cooled by ram-air rejection is directed into a separate reservoir to prevent raising the coolant temperature [17]. This adds significant weight to the system and has been shown to be less effective than PCMs, though PCMs are not without their challenges. PCMs only work if the system rises above their melting temperature and effective implementation uses PCMs that are near the upper range of the operating temperature to support the main cooling loop as overheat prevention. Many promising PCM candidates have low thermal conductivity. This means the methods for transferring heat into the PCM must be well designed to overcome the poor conduction ability of the material itself to achieve full melt propagation. If the temperature of the primary cooling device reaches the PCM's melting temperature, the PCM will melt and absorb the excess energy. This keeps the system temperature constant during an isothermal process and helps set a max temperature safety point on the system. When the inverter is operating at low power later in the mission profile, the energy can be dissipated back into the cold plate. Due to many challenges with material properties and implementation techniques, PCMs have not yet developed into widely used energy management systems, but offer upside in many experimental studies.

There is a strong demand for secondary passive cooling techniques to help mitigate the thermal spike during takeoff. Large cooling systems severely limit aircraft capability and therefore must be reduced in size and weight to improve overall efficiency. Lowering the necessary cooling demand that must be taken by the global cooling loop will help reduce thermal stresses throughout the system. Passive cooling can also be beneficial by reducing the reliance on the heat exchanger for energy removal, which as discussed has many efficiency impacting challenges. Energy storage and other passive techniques present a strong opportunity for leveling out the thermal profile. Other advanced techniques will also be needed to help direct heat away from the devices through the aircraft to safe rejection areas.

5 Semiconductor Technology

Semiconductor materials play an important role in the operating conditions of the inverter used for turning the DC battery input into an AC signal for driving the motors. Silicon is the current industry standard and has been extensively researched. Si MOSFETs are ideal up to 600 V and Si insulated-gate bipolar transistors (IGBTs) operate from 600 V to 6.5 kV, before maxing out their material limits [38]. Silicon-based devices must maintain an operating temperature below 175 °C to prevent material damage. Silicon also has limitations in switching speed. These are the main disadvantages to silicon, which has led to research into gallium nitride (GaN) and silicon carbide (SiC) as wide bandgap semiconductors.

SiC presents many benefits as a wide bandgap semiconductor. SiC has a higher temperature capability than Si [39]. It can reach higher power densities while reducing the parasitic capacitances and drift layer thickness due to smaller device sizes [37]. Higher thermal conductivity and higher critical field strength help contribute to size reduction in comparison to Si devices. A major benefit is the increased switching frequencies that SiC is capable off. SiC also offers higher blocking voltage with many experimental investigations reaching 15 kV and significant performance enhancement of SiC 6.5 kV MOSFETS over Si IGBTs [10]. Recent advancements have begun implementing the "trench-gate" structure in SiC to improve performance, which further reduces chip size [10]. A major drawback to SiC is the lack of commercial advancement with the technology. Typically, 1.7 kV is the highest rated chip commercially produced and wafer production sizes are much smaller than that of Si, causing SiC to be very costly. Once manufacturing capabilities of SiC come closer to the levels of Si, this can be a promising option for increasing power electronics capability.

GaN is another potential material for the future of power electronics. It has promising features with low capacitance output and high frequency capability. The small achievable size of these devices is optimal for reductions in weight and dissipated thermal energy, reducing cooling demands [10]. Commercially, GaN devices up to blocking voltage of 650 V can be found [10]. This technology needs to see growth to become an ideal candidate for aviation-based electronics, but the properties displayed in lower voltage devices show promise for future improvements in power electronics. Improvements in the thermal stability and maximum junction temperature for semiconductor technology will help reduce the stress on the thermal management systems. By developing more robust and efficient electronic components, structural and thermal management weight can be reduced leading to overall improvements in aircraft performance.

6 Transient Loading Predictions

To better understand the impact of various transient parameters on the thermal management system, a MATLAB program was developed to analytically model interactions between the many factors previously described in this paper. Using the diagram from Fig. 3, preliminary analysis was done to show the impact of various transient variables on the response of the thermal management system, specifically the global cooling loop here. This is shown as progression of key coolant temperatures over time.

This is a general prediction example for impact of transient variables on the thermal management performance metrics. A global cooling loop connects the local cooling systems for a battery, inverter, and motor that dissipate a total energy profile shown in cyan in Fig. 4. Using 50% water ethylene glycol as the coolant, due to its low temperature capability, the global cooling solution moves energy from the local devices to the shell and tube heat exchanger. This was calculated using the NTU effectiveness method with the air inlet properties derived from the altitude and velocity of the aircraft at each position, as demonstrated in Sec. 2.1. The dissipated energy into the cooling loop from the devices is given as a single changeable parameter for this model to remove the complexity of determining the heat transfer characteristics for each local cooling system. Equation (6) shows the fluid temperature ($T_{c,2}$) after receiving the dissipated energy (Q_{diss}) and before entering the heat exchanger. This is a function of the inlet temperature ($T_{c,1}$), specific heat capacity (Cp), and mass flow rate (mdot) of the coolant

$$T_{c,2} = T_{c,1} - \frac{Q_{\text{diss}}}{\text{Cp} * \text{mdot}} \tag{6}$$

The NTU effectiveness method for a shell and tube heat exchanger can be used to determine the outlet fluid temperatures based on the effectiveness of the heat exchanger and the inlet fluid properties. Equation (7) shows the effectiveness (ε) correlation used for this shell and tube heat exchanger. This is for a simple one shell pass where Cr is the ratio of the minimum to maximum of the heat capacities multiplied by the mass flowrate and NTU is the number of transfer units

$$\varepsilon = \frac{2}{1 + \text{Cr} + \sqrt{1+\text{Cr}^2} * \left(\dfrac{1 + e^{-\text{NTU} * \sqrt{1+\text{Cr}^2}}}{1 - e^{-\text{NTU} * \sqrt{1+\text{Cr}^2}}}\right)} \tag{7}$$

The effectiveness of the heat exchanger can then be used to determine the outlet fluid temperatures. Equation (8) gives the calculation for the coolant outlet temperature ($T_{c,3}$). This is a function of the coolant inlet temperature ($T_{c,2}$), air inlet temperature ($T_{a,1}$), and the ratio of $C_{\min}$ to C_c, the minimum heat capacity multiplied by the mass flowrate for the minimum fluid and coolant, respectively. The coolant temperature leaving the heat exchanger can be used in an energy balance using the coolant reservoir as a control volume to determine the temperature change within the reservoir

$$T_{c,3} = T_{c,2} - \varepsilon * \frac{C_{\min}}{C_c} * (T_{c,2} - T_{a,1}) \tag{8}$$

Finally, the reservoir temperature can be calculated using an energy balance on the flow into the reservoir from the heat exchanger and the flow out of the reservoir to the local cooling systems. The energy difference between the inlet and outlet yields a temperature change in the reservoir that will be used as the key metric for thermal performance in this demonstration as it shows the system response to increased or decreased cooling capacity of the heat exchanger based on the transient system parameters.

Figure 4 shows the resulting coolant temperatures into and out of the heat exchanger for the given load profile. The results are graphed against time and changes in load reflect ten prominent flight mission points that give areas of reference for parameter changes over a total flight. The properties of air are changed according to the altitude of the aircraft. The blue coolant line represents the working fluid temperature after passing through the local cooling systems. The red line represents the ambient air temperature entering the heat exchanger. Both dotted lines represent the temperature of the respective fluids leaving the heat exchanger. The black line gives the reservoir temperature, which is the coolant temperature entering the local cooling solutions. Due to the limited thermal rejection of the heat exchanger, the reservoir temperature will rise as a function of the excess energy not rejected. This can cause problems in the local cooling systems if

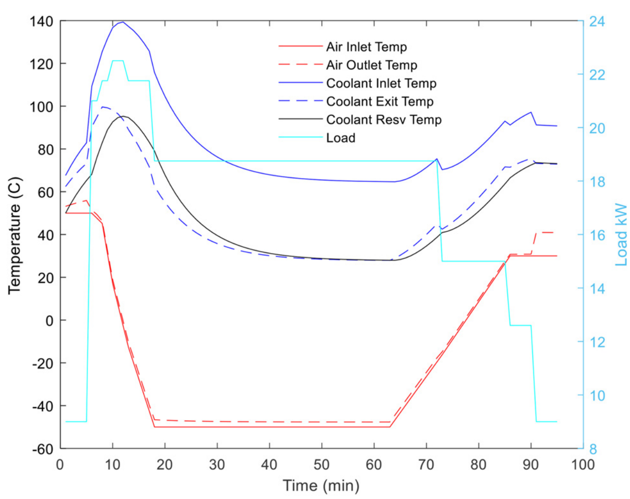

Fig. 4 Coolant temperatures and load profile for thermal performance of global cooling loop

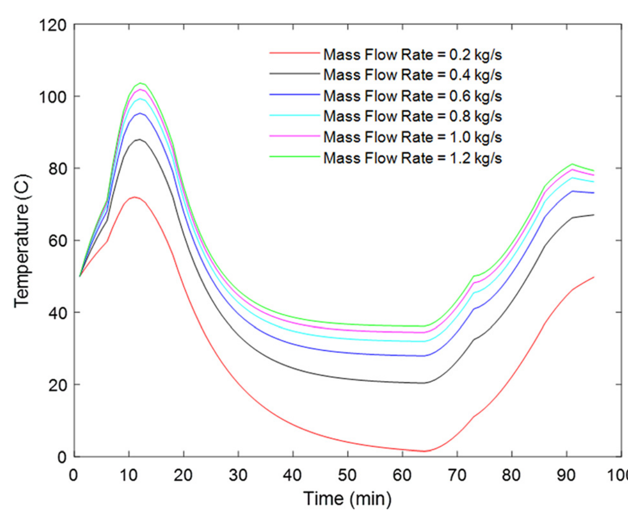

Fig. 5 Impact of changing mass flow rate in coolant loop

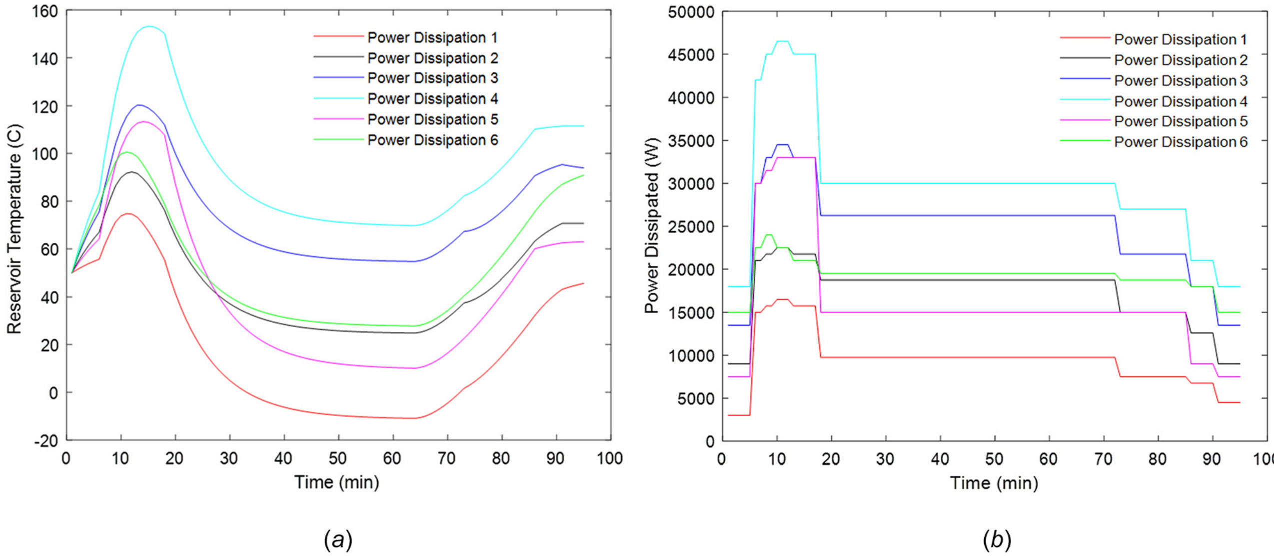

Fig. 6 Power load variation (*b*) for impact on reservoir temperature (*a*)

the temperature difference between the coolant and the device is not large enough to remove sufficient energy. As demonstrated in Fig. 4, the temperature difference between the coolant and the air entering the heat exchanger plays a massive role in the thermal performance. The reservoir temperature rises drastically during the takeoff phase due to high ambient air temperature and high dissipated loads. In the cruise phase, the reservoir temperature drops significantly because of the large increase in temperature difference and the reduced loads.

Using this MATLAB program, various parameters can be changed to examine the impact of each factor, or factor set, on the thermal performance of the system. For these examples, the reservoir temperature throughout the mission profile is given as the evaluated result. It reflects the inlet coolant temperature to the devices' local cooling systems and functions as a short evaluation of the temperature swings that would be seen in said devices. Figure 5 shows how changing the coolant mass flow rate impacts the reservoir temperature. This is based on increasing the flow velocity through the cooling system and the heat exchanger, which reduces the time the hot coolant is transferring heat to the air in the heat exchanger, thus increasing coolant reservoir temperature. Higher flow rates through the heat exchanger lead to higher reservoir temperatures as a result, if all other parameters are kept consistent. This gives a balancing act for the flow rate as higher flow rates will be considered more advantageous for reducing the temperature in the local cooling devices, but too high of a flow rate will increase the reservoir temperature significantly and reduce overall performance. The impact becomes most prominent during the cruise stages after approximately 30 min because of the longer duration and high temperature difference in the heat exchanger at this phase. This analysis can be used to build operation regions for specific parameters, based on their influence on the thermal performance of the cooling loop.

Applied power load is another metric that can drastically impact the thermal state of the cooling system. Figure 6(*b*) gives six various loading profiles that are applied to the cooling loop analysis to provide the reservoir temperatures in Fig. 6(*a*). The load profile variation demonstrates how much larger the temperature range can be during the cruise phase with lower power loads. The fifth and sixth power profiles rise in temperature at a quicker rate during climbing sequence due to higher initial power requirements but drop to much lower temperatures during the cruise phase due to more efficient cruise operation. This happens with a relatively small change in power load during the cruise phase.

The reservoir mass is a large part of the variability in the system. Ideally for aviation applications, the reservoir mass is kept to a minimum but thermal stability is more achievable at higher masses. Figure 7 demonstrates this by showing the reservoir temperature as a function of changing coolant mass over the mission profile. Smaller masses lead to higher temperatures during the climb phase and lower temperatures during the cruise phase. The small coolant mass is more susceptible to changes in either the dissipated load or the environmental parameters, mainly ambient air temperature. Large temperature swings are not advantageous for reliability of electrical components and present a design tradeoff between aircraft functionality and thermal management potential. This highlights the need for many of the passive cooling innovations discussed in earlier sections. As the system architecture changes, parameter sensitivity varies as well, making the ideal operating range difficult to determine.

Heat exchangers using ram air can have varied cooling performance based on the velocity of incoming air. The impact of different velocities will change the performance by altering the mass flow rate of air through the heat exchanger. Depending on the heat exchanger, this can have repercussions on the efficiency of the energy transport between the two working fluids. To model this, Fig. 8(*b*) shows varied velocity profiles for possible aircraft missions and Fig. 8(*a*) shows the resulting reservoir temperature. For this simple heat exchanger, the velocity does not play a

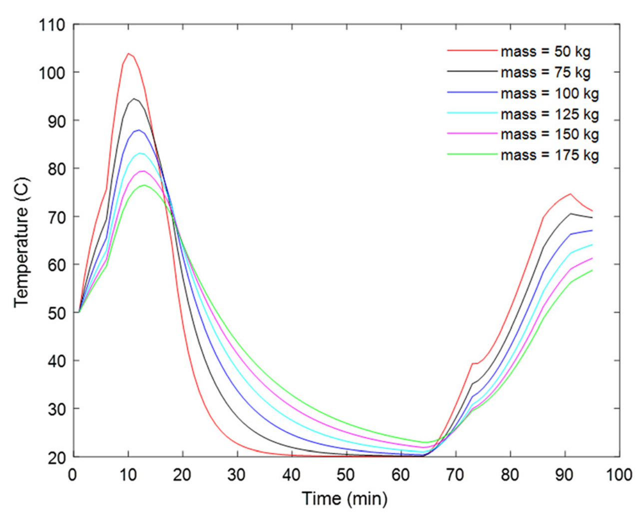

Fig. 7 Varied reservoir mass implications on reservoir temperature

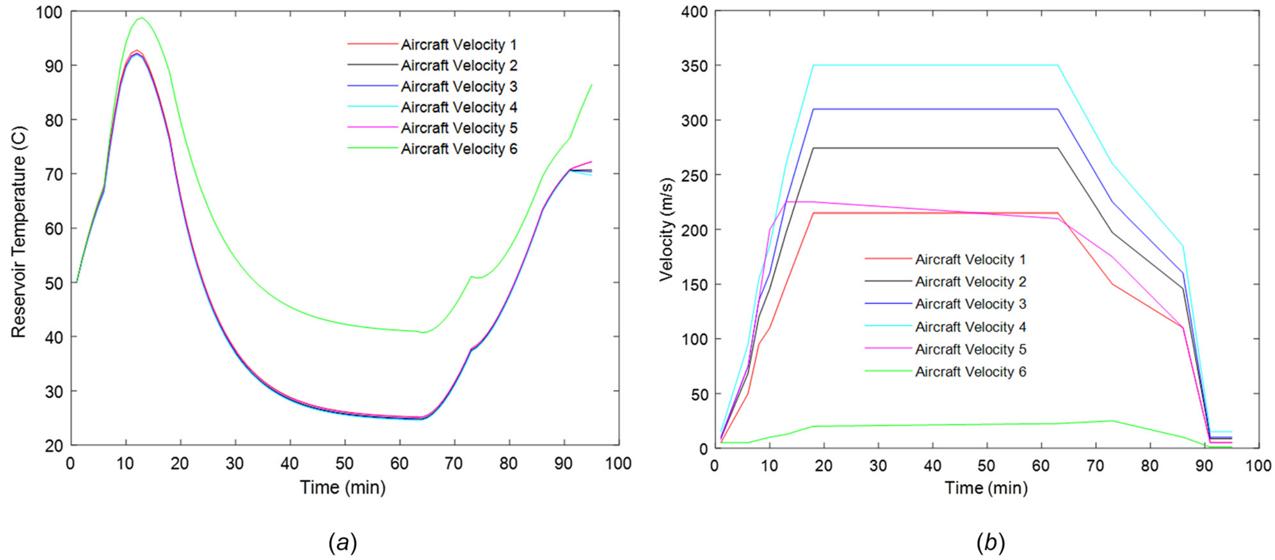

Fig. 8 Varied aircraft velocity (*b*) for changing air mass flow rate through the heat exchanger impact on reservoir temperature (*a*)

critical role unless it is significantly different from the initial case as demonstrated by the green line. The other cases do not generate a substantial change in the heat exchanger performance because their velocities provide a high enough air mass flow rate to maintain energy rejection. This may not be the case in other heat exchanger styles or configurations like surface mounted heat exchangers or heat exchangers that require high pressure at the inlet. The highly variable nature of flight parameters across the wide variety aircraft types makes this an important metric to consider, even if it does not always produce a sizeable performance change.

One of the most prominent driving factors in thermal performance is the temperature difference across the working fluids in the heat exchanger. This is largely affected by the ambient temperature of the air entering the heat exchanger, which drastically changes over the mission profile due to large swings in altitude of the aircraft. Air temperature, density, and specific heat are functions of altitude and change based on aircraft height and starting conditions, as outlined in Sec. 2.1. All these parameters are altered accordingly in this analysis, but only air temperature is shown for conciseness as it is the main contributing factor. Figure 9(*a*) shows analysis for changing the temperature profile. The temperature profiles are shown in Fig. 9(*b*). As shown, the reservoir temperature is highly correlated to the ambient temperature. Profiles with larger exterior temperature swings pose more danger to internal electronics as the thermal management system will struggle to maintain consistent temperatures as configured. Different aircraft will experience significantly different sets of environmental parameters in each flight. The proposed cooling solution must work to offer variable control of the thermal management systems to ensure large temperature gradients to not occur and damage the internal components.

This section is intended to highlight the impact of various transient variables on the thermal management systems. It gives a preliminary look at the problem and defines challenges that will be faced with electric propulsion. The results show that many parameters impact thermal performance, and efficient thermal management architecture will require novel structures

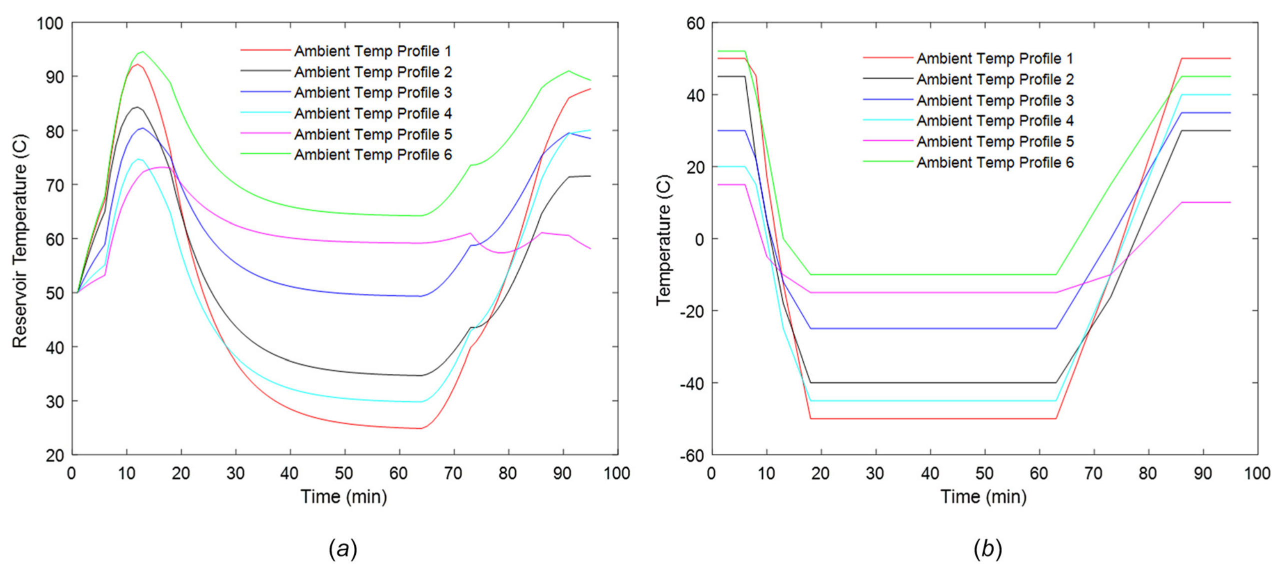

Fig. 9 Varied air temperature (*b*) for thermal performance of coolant temperature (*a*)

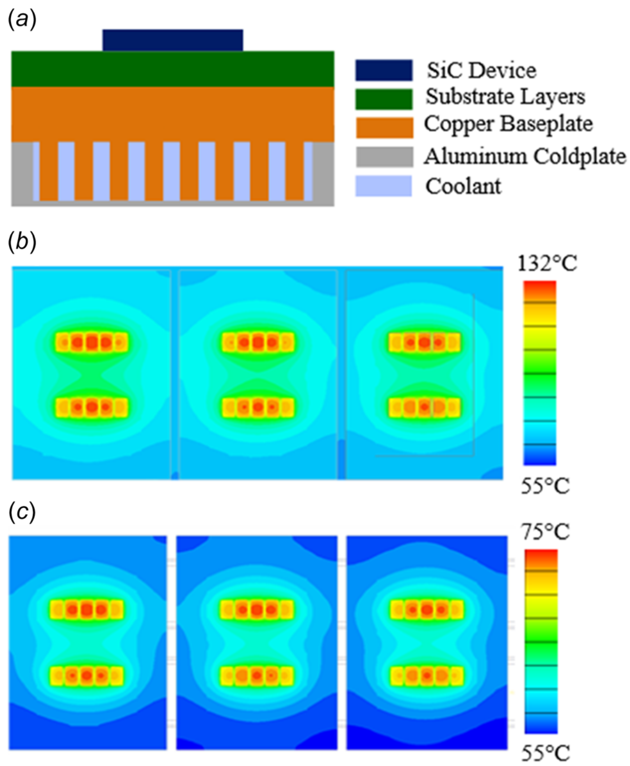

Fig. 10 Stack layer schematic of (*a*) direct cooled finned module, module stack-up is approximated to consist of base plate, power substrate layer comprising of copper, solder, and ceramic layers. (*b*) Simulated thermal profile of three XM3 modules integrated on a cold plate with 8 LPM flowrate during (*b*) takeoff (100% power) and (*c*) cruise operation (25% power).

and operational procedures. Future efforts will focus on creating a thermal reliability model to understand the consequences of system configuration and operating limits on coupled parameters for the feasibility of implementation within an aircraft environment.

7 Emergency Shutdown

The reliability of aircraft electronic devices is dependent on the ability of the thermal management system to maintain ideal operating temperatures to prevent degradation of the device structure. Sec. 6 outlined scenarios where varying power loads and power times could contribute to pushing the device above or below ideal operating temperatures. Another major concern for these devices during in-flight operation would be the temporary or complete failure of the cooling system. Under these circumstances, it becomes important to understand how the inverter temperature profile reacts and how long the device has until reaching limiting temperatures and eventual failure. To demonstrate the reaction of cooling loss, the following case study is presented.

A high-fidelity thermal performance simulation using ANSYS Icepack simulation environment was conducted. These simulations are designed to depict the steady-state thermal performance of an inverter system using three Direct Liquid Cooling IGBT Modules for Automotive Applications [40,41]. Commercial cold plates from Wieland Microcool (CP4012) were considered for state-of-the-art cooling solutions [42]. To improve the thermal efficiency of the cooling system a more novel technique was used where the modules utilized finned base plates that were interfaced directly with the cold plate tub and sealed using O-rings. This was done to improve the thermal performance when compared to a conventional connection where a thermal interface material (TIM) layer would be used to connect the cold plates and modules. Eliminating the TIM reduced the thermal resistance between the device junction and coolant inlet. This led to a 15 °C difference in max temperature in the takeoff simulations. Figure 10(*a*) shows the schematic for the approximate power module and the cooling system stack-up used in the simulation.

Steady-state simulations were performed to observe the thermal profile due to heat losses during takeoff and cruise portions of flight. This represents the max load, 800 W per module, and roughly 25% of the max load, 200 W per module, respectively. In each case, the module heat loss is evenly distributed among the SiC devices. Water–ethylene glycol mixture (50% by volume) was used as the coolant for this simulation. The coolant inlet temperature was set at 55 °C and the flow rate was 8 LPM. Figures 10(*b*) and 10(*c*) show the simulated temperature profiles for takeoff and cruise conditions, respectively. The difference in max temperature is approximately 47 °C.

Flow shutdown signifies failure in the thermal management system for this inverter simulation. The change in thermal profile due to flow shutdown can be seen in Fig. 11(*a*) for takeoff and Fig. 11(*b*) for cruise conditions. The simulation reaches steady-state temperature after running coolant described previously at 8 LPM. At this point, the coolant was reduced to near 0 LPM to simulate flow shutdown before transient thermal analysis was performance. During takeoff, the max operating junction temperature of 175 °C was exceeded 12 s after flow loss for the XM3 modules with direct cooled cold plate. Under the cruise conditions, the max junction temperature was exceeded after 190 s (around 3 min) due to the lower thermal load. These results represent the time allowed to reduce the power load to the devices to prevent incurring damage. Figures 11(*c*) and 11(*d*) show the expected cooldown performance of the system from a high temperature back to the steady operating conditions under takeoff and cruise loss conditions, respectively. In this case, the system is allowed to cool from a high temperature of 300 °C and the time taken to reach steady operating condition from the limiting device temperature is recorded. Under a takeoff cooling loss condition, the cooldown time for the system is 80 s. The cooldown time required at the cruise condition is 30 s. This result highlights that the system needs different times to respond to shutdown failures under different loading conditions. The preventive guidelines in place to stop system failure are influenced by the results of this study. These guidelines can help protect the inverter and improve reliability of the whole system.

8 Conclusion

Thermal management of electric propulsion systems onboard aircraft presents many challenges that are not present in the operation of these devices in other applications. Individual testing of each device can be done to simulate the impact of transient conditions, but the overarching impact of transient conditions on the collective cooling network is not seen from this. It is important to understand the combined effects of the global and local cooling systems to determine the feasibility of certain designs. Creating high power electronics capable of producing large amounts of lift is one aspect of the problem. The design of thermal management systems design is equally important. To successfully integrate electric propulsion, the thermal management system needs to be optimized across the entire aircraft to reduce weight and power imprint. Environmental and system design considerations can significantly vary the thermal performance of any cooling solution across the entire mission profile. This outlines the coupled nature of many parameters critical to design on overall thermal performance. The impact of air properties, coolant loop parameters, and dissipated load were shown with respect to the change in thermal performance as a function of coolant reservoir temperature. To supplement this, a study was done to analyze the time to critical temperature of the inverter after cooling system failure and the

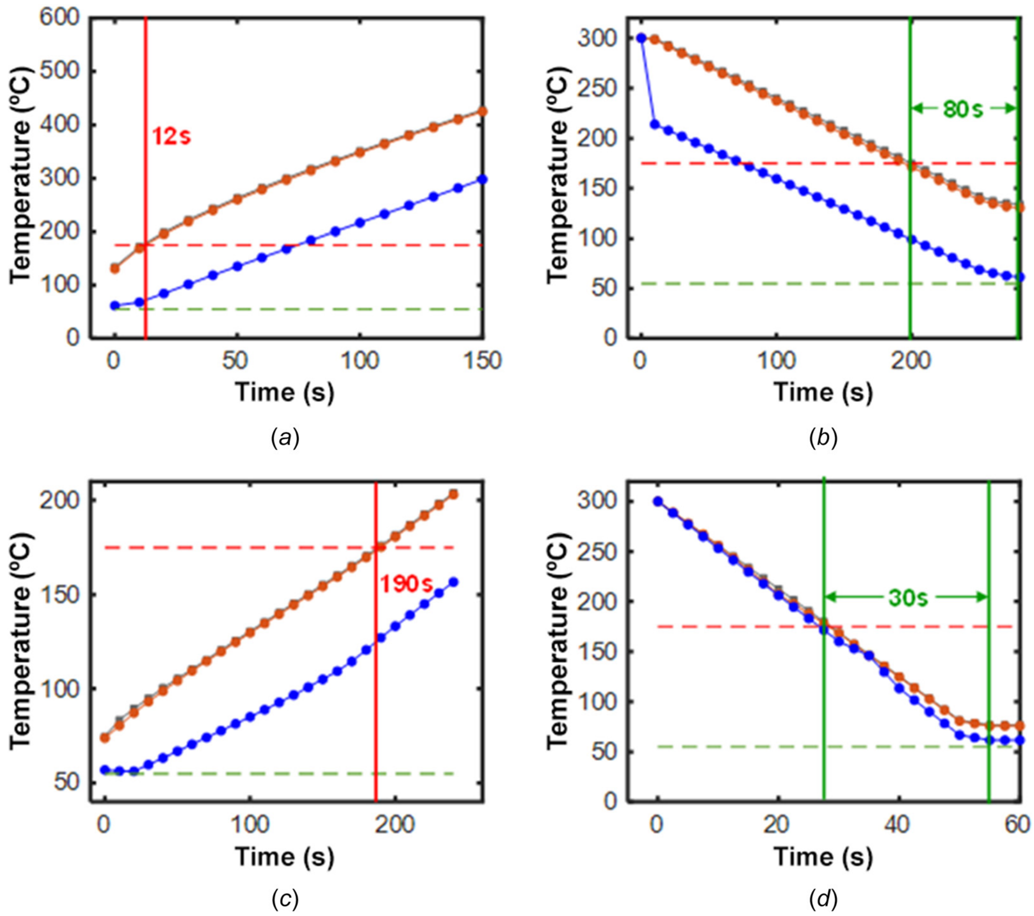

Fig. 11 Transient thermal response of direct cooled system during (*a*) takeoff and (*b*) cruise considering flow shutdown. Cool down response for inverter during (*c*) takeoff and (*d*) cruise considering reinitiating of flow.

time necessary to recover proper operating temperatures with the recovery of the thermal management system.

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Nomenclature

a = lapse rate defining slope of temperature drop
$C_{\min}$ = minimum specific heat capacity multiplied by mass flow rate
Cp = specific heat
Cr = ratio of min to max specific heat capacity multiplied by mass flow rate
g = acceleration of gravity
GaN = gallium nitride
IGBT = insulated-gate bipolar transistor
M = Mach number
mdot = mass flow rate
NTU = number of transfer units
P_s = static sea level pressure
P_1 = atmospheric pressure
Pr = Prandtl number
PCM = phase change material
Q_{diss} = dissipated energy rate
R = gas constant
r_f = recovery factor
SiC = silicon carbide
$T_{a,1}$ = air inlet temperature to heat exchanger
$T_{c,1}$ = coolant inlet temperature into local devices
$T_{c,2}$ = coolant inlet temperature to heat exchanger
$T_{c,2}$ = coolant outlet temperature from local devices
$T_{c,3}$ = coolant outlet temperature from heat exchanger
T_{ram} = ram air temperature
T_{rec} = recovery temperature
T_s = static sea level temperature
T_∞ = ambient temperature
T_1 = atmospheric temperature
TIM = thermal interface material
γ = specific heat ratio
ε = effectiveness

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