Challenges and Advances in Electric Propulsion
Motor Thermal Management for Aircraft

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I. INTRODUCTION

The global focus on reduction of CO$_2$ emissions and sustainable development is driving the transition to hybrid and electric propulsion. While greater attention has been captured by land vehicles, the aviation community, including the U.S. Air Force, NASA and Boeing, has been conducting research on more electric aircraft (MEA), more electric engine (MEE) and electric propulsion for years. Some low-power, low-range fully electric aircraft with limited loading capacity have been developed already, dedicated to the flight training market, electric short take-off and landing (eSTOL) or electric vertical take-off and landing (eVTOL) short range transportation, and also serving as early steps towards larger scale developments.

Compared to traditional combustion engines, a major advantage for electric propulsion is the significantly higher efficiency, which can easily surpass 90%, while combustion engines can only reach about 60%. Electric propulsion systems have lower emissions, diminished noise, and reduced fuel burn which can potentially reduce operating costs for aircraft operators. Thermal management, however, remains a major challenge. Transitional propulsion systems, although having much more heat loss, allow the waste heat to be easily removed through exhaust air and the power unit itself can tolerate as high as 1700°C. Fully electric propulsion systems do not produce waste heat as exhaust air, making it difficult to remove. In addition, the materials around the heat source, such as insulation paper and epoxy, severely limit the maximum temperature that the propulsion unit can survive to around 200 °C.

The heat generating components in an electric propulsion system include the electric motor, motor drive, and battery systems. Heat must be removed in order to keep them operational, and, if not removed properly, can damage the component and potentially lead to catastrophic failure. For small electric and hybrid aircraft, the ideal option for cooling and rejecting the heat from the motors and power electronics is to use the stream of air produced by the propulsion fans being powered by the motors. It is critical to maximize the efficiency of the motor and power electronic system to reduce the heat ejected from the system so as not to overwhelm the cooling power of this airstream.

In order to scale up the electrified drivetrain for commercial aircraft, power-dense multi-megawatt (MW) electric machines are necessary. The development of these aircraft class machines is an ongoing research topic due to the challenge of balancing the machine performance, power density, and cooling. Due to the low convective heat transfer coefficient and low dielectric strength of air, air cooling schemes are difficult to scale up to high-power-density, high-voltage motors. As such, the use of more efficient components, such as Litz wires, laminated magnetic steels, and SiC power switches, instead of silicon ones, are desired. However, it is also critical to develop ways to most efficiently remove waste heat from the motors and the integrated power electronics. To accommodate this requirement, liquid cooling is often desirable, which then requires that the heat in the liquid be shed to the airstream, redirected to warm the fuel, cabin and equipment bay, or harvested to run ancillary electronic equipment, such as personal entertainment systems.

II. HEAT LOSS IN ELECTRIC MOTOR

To achieve successful thermal management, the following two approaches are used in parallel: 1) reducing the heat loss through improvements in efficiency, and 2) increasing the cooling power, through improvements in cooling techniques. Heat losses can be divided into two major parts, core losses and winding losses. Core losses are generated by the magnetization of the steel and depend on numerous parameters, such as, excitation frequency, flux density and steel microstructure. Losses occur due to eddy currents and B-H hysteresis. Eddy currents are induced by an alternating magnetic field across the ferromagnetic material. The reduction of these eddy current losses is addressed by laminating steel with non-conductive sheets, constraining the eddy currents between the laminated sheets. The thinner the steel layers, the lower the motor core losses will be. The thickness of the lamination is limited by the manufacturability and the cost. The losses caused by manufacturing defects are much harder to quantify. Hysteresis losses are losses resulting from resistance to changes in the magnetic field. A magnetic field orients magnetic domains in the steel in the direction of the magnetic field; then, when the magnetic field is removed, most domains randomize. The energy loss required to reorient these domains to the new orientation under the new magnetic field are the hysteresis losses [1].
Winding (or copper) losses refer to losses caused by the resistance of the copper wire windings. As higher power density is desired, magneto-motive force (MMF), which is a good measurement of the strength of the magnetic fields, needs to be increased. The MMF generated in the motor stator has a direct correlation to the current and the number of turns. Thus, increasing the current and the number of turns can increase the power density. The limitation of this approach is that by increasing the current density we are also increasing the losses. The total copper losses can be summarized by the following equation:

$$P_{loss} = I^2(R_{DC} + R_{AC}) + P_{eddy}$$

Where $P_{loss}$ is the total loss in the windings, $I$ is the total current running in the copper, $P_{eddy}$ is the losses from the eddy current that are generated in the windings and $R$ is the resistance of the copper wires.

The main issue in cooling of an electric motor is the difficulty of extracting the heat from the copper to the coolant. The wires are covered with insulating material, bundled together with another layer of insulating material, then potted into the desired shape and wrapped with a slot liner. These multiple layers of insulation are to prevent partial discharge and electrical shorting, while also serving the structural function of holding the wires in place. However, by providing these features to the windings, the layers interfere with heat extraction as they are highly thermally as well as electrically insulating.

III. Air Cooling Technique

Air cooling has the advantage of being lightweight, low cost and can be easily integrated. Since air is obtainable from surroundings and can be released back, no coolant or radiator are needed to be carried with the motor. Air is also not damaging towards most of the components in the system, so air can get straight to the heat source. One of the more famous examples using air cooling is the NASA’s fully electric Maxwell X-57 aircraft, which resulted from the Scalable Convergent Electric Propulsion Technology Operations Research (SCePTOR) program [2] The propulsion power comes from two 60 kW cruise motors, and twelve 10.5 kW high-lift motor, distributed along the wings, all air-cooled [3]. The airstream flows around and into the motor, providing cooling to the motors and motor drives. For high power motors, despite the limited cooling power of air, it can still provide auxiliary cooling to critical locations where it’s too complicated or costly for liquid cooling to reach. Although seemingly straightforward, the interaction between different flow paths inside the motor could create different flow patterns at different rotating speeds, guiding the air away from the heat source and reducing the cooling power [4].

IV. Single Phase Liquid Cooling

Single phase liquid cooling utilizes the high specific heat of liquid to absorb the heat, allowing much more cooling capability compared to air cooling. However, liquid cooling generally requires auxiliary power and a cooling loop and reservoir for the liquid itself. Some common liquid cooling techniques includes finned plates or tubes, micro-/mini-channels, and jet impingement [5].

Depending on the location of the cooling surface, single phase liquid cooling can be divided into direct and indirect cooling, differentiated by whether the coolant is in contact with the heat source. Indirect liquid cooling, such as using a cooling jacket, has great advantages in an aerospace application. It can handle a much higher heat flux compared to air cooling. Compared to direct liquid cooling methods, such as spray cooling and jet impingement, the liquid is contained, allowing safer and more reliable operation. Indirect liquid cooling can also behave more consistently under acceleration in different directions and of different magnitudes, which is ideal for aviation applications. It also provides more choice of coolants, including liquids that are already accessible on the airplane. By utilizing existing liquid, pumps and pipelines, a minimum of additional weight will be added to the system [6].

Direct liquid cooling approaches include but are not limited to jet impingement on the end windings, and cooling channels in the back iron or in the slots. Direct contact reduces the thermal resistance between heat sources and the coolant significantly, with the price being the increased complexity of the system. Bennion et al studied the cooling capability of auto transmission fluid jets impinging on the winding [7]. Acquaviva et al built cooling channels in the in-slot potting materials between two adjacent stator teeth [8]. Lindh et al formed winding turns with Litz wires, wrapping them around cooling tubes [9], Yao et al discussed different geometries and arrangements of hollow conductors, where the coolant flows inside the windings [6].

A successful example of a direct liquid cooling method on an electric propulsion motor is the Siemens SP 260D electric motor, powering the Extra 330LE aerobatic plane [10]. This high power density 260 kW motor is directly cooled by flowing oil on the conductors.

V. Two Phase Liquid Cooling

Two phase cooling utilizes the high latent heat of either liquid or solid material. During phase change, the temperature of the coolant remains constant while a large amount of heat is absorbed. As such, this approach has higher coefficients of performance than single phase. Liquid evaporation is most common and some cooling techniques mentioned in single phase cooling such as micro-/mini-channels and spray can also be enhanced with two phase cooling [11]. Hollow conductors can also utilize evaporation to handle higher heat load. For example, Chen et al studied evaporative cooling on hollow conductors for stator windings [12]. However, the disadvantage is that flow boiling is a very complex process in which multiple flow regimes can exist, as shown in Figure 1. If the regimes are not properly managed, dry out can occur which drastically reduces the heat transfer coefficient. This is especially important in aerospace applications as the ambient pressure and temperature vary during flight, causing transitions between flow regimes.

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Heat pipes, which are thermally conductive pipes with liquid and vapor sealed inside, are another popular two phase cooling method. A heat pipe utilizes the latent heat of the liquid inside to transfer heat. A heat source is placed on the outer surface of the evaporator section, where heat is transmitted to the liquid through the wall. The working fluid is heated and evaporates. The vapor travels across the adiabatic section and condenses in the condenser section, transferring heat through the wall of the condenser section to a heat sink. The liquid then returns to the evaporator section, completing the cycle. Heat pipes can reach an effective thermal conductivity more than 100 times higher than copper, enhancing heat conduction significantly. This allows heat pipes to conduct the heat from inside the motor to where the coolant is more easily accessible. Sun used heat pipes to transfer heat from inside the potting material to the water-cooled casing [13]. Heat pipes can be categorized by the forces used to transmit the condensate from condenser back to the evaporator. Forces include gravity, capillary force, centripetal force, and magnetic forces, among others, which make it very versatile and capable of being applied to both stator and rotor. A table of heat pipe classification is shown in Table 1.

### Table 1 Types of heat pipe by driving force

<table>
<thead>
<tr>
<th>Driven Force</th>
<th>Type of Heat Pipe</th>
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<tbody>
<tr>
<td>Gravity</td>
<td>Thermosyphon</td>
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<tr>
<td>Capillary force</td>
<td>Conventional heat pipe</td>
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<tr>
<td></td>
<td>Vapor chamber</td>
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<td></td>
<td>Loop heat pipe</td>
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<tr>
<td>Centripetal force</td>
<td>Rotating heat pipe</td>
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<tr>
<td>Magnetic force</td>
<td>Magnetohydrodynamic heat pipe</td>
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<td></td>
<td>Magnetic fluid heat pipe</td>
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<tr>
<td>Osmotic force</td>
<td>Osmotic heat pipe</td>
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Heat pipe performance can be influenced by the thermal properties of the pipe wall and liquid, the geometry, the charge ratio and the operation mode. Charge ratio refers to the ratio of the working fluid volume to the total volume of the heat pipe. It can influence the response time, working temperature, effective thermal conductivity and the operational limits of the heat pipe. Similar to other two phase cooling techniques, heat pipes have a relatively small working range, limited by viscous limit, entrainment limit, boiling limit, etc.

Phase change materials (PCM) have high latent heat, which allows them to absorb and store heat during thermal transients by changing phase, and release that heat during subsequent cooler periods by returning to their original phase. Therefore they are ideal for energy storage. As a passive supporting cooling method, this can help flatten the temperature spike or store the heat for recycling. Wang et al. stuffed a motor casing with paraffin to dissipate heat and eliminate high temperature spots, resulting in a more uniform case temperature and a reduction of hot spot temperature [14]. Solid-liquid and solid-solid phase change materials are both used for energy storage. At present, solid-liquid phase change materials are most common due to their small volume change and easy availability. Concerns for the use of these materials in aeronautical applications include properly containing the liquid without leakage, especially during acceleration and when changing the plane’s attitude; along with minimizing the additional weight that is added by the presence of these materials. Properties of different types of solid-liquid and solid-solid PCMs are adopted from Fallahi et al. and shown in Figure 2 [15].

![Figure 1: Flow regimes along two phase boiling flow](image)

![Figure 2: Enthalpy and temperature ranges for SL-PCMs and SS-PCMs](image)

**REFERENCES**


