

Bachelor's Programme in Engineering

Assessment of Altitude's Effect on the Cooling Capability of an Axial-Flux PMSM Coolant System

A Pipistrel Velis Electro Case Study

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Title of thesis Assessment of Altitude’s Effect on the Cooling Capability of an Axial-Flux PMSM Coolant System		
Programme Bachelor’s Programme in Engineering		
Major Energy and Mechanical Engineering		Code ENG4000.A
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Date 04.09.2026	Number of pages 32	Language English

Abstract

Electric aircraft require effective cooling systems to maintain motor temperatures at viable levels. High altitudes present a complication; outside-air-temperature (OAT) and air density decrease. These variables conversely influence the coolant system's ability to dissipate heat from the motor. Air density decrease reduces heat transfer, while OAT decrease augments heat transfer.

The purpose of this thesis is to evaluate the relative impacts of these variables on the air-side heat transfer of liquid cooling radiators, and the coolant outlet temperatures of axial flux permanent magnet synchronous motors (AFPMSM). The Pipistrel Velis Electro aircraft is used as a case study.

Reduced-order approximation methods for coolant inlet temperatures and radiator conductance are developed using a combination of convective heat-transfer equations, airspeed relationships and the Dittus-Boelter correlation. A MATLAB/Simulink model is developed to simulate the climb of a Velis Electro through International Standard Atmosphere conditions to its service ceiling of 3660m. The model incorporates both quasi-steady state and transient calculations methods, with the latter mainly serving as a consistency check.

The developed model suggests that the impact of OAT decrease substantially outweighs the impact of reduced air density. Reduced air density increases coolant outlet temperatures by 0.7904-3.1616K, depending on assumed sea level reference temperature. Meanwhile, reduced OAT decreases coolant outlet temperature by 23.7880K. The quasi-steady state and transient calculation methods are consistent with one another. The coolant's temperature decrease produces more favourable cooling conditions for the AFPMSM, but its influence is not quantified due to insufficient thermal motor data.

Keywords Outside-air-temperature, air density, convection, axial flux, coolant

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Symbols and abbreviations

Symbols

H	Altitude
T_0	Sea-level temperature
$T_{ambient}$	Outside-air-temperature
$T_{coolant,in}$	Coolant inlet temperature
$T_{coolant,out}$	Coolant outlet temperature
p_0	Sea-level pressure
ρ_0	Sea-level air density
R	Specific gas constant of air
σ	Air density ratio
h_{air}	Heat transfer coefficient of air
g	Gravitational acceleration
L	Lapse rate
$\rho(H)$	Air density at altitude H
$T(H)$	Temperature at altitude H
$p(H)$	Pressure at altitude H
$\dot{Q}_{dissipated}$	Power dissipated by radiator
P_{loss}	Power lost by motor as heat
$\dot{m}_{air}$	Radiator mass flow of air
$\dot{m}_{coolant}$	Coolant mass flow
c_p	Specific heat capacity of coolant
A	Radiator area
V_{IAS}	Indicated airspeed of aircraft
Nu	Nusselt number
Re	Reynolds number
T_{ref}	Assumed sea-level-to-ambient temperature difference

Operators

$\frac{dT_{coolant}}{dt}$	Temperature of coolant with respect to time
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Abbreviations

AFPMSM	Axial Flux Permanent Magnet Synchronous Motors
TAS	True Air Speed
IAS	Indicated Airspeed
ISA	International Standard Atmosphere
OAT	Outside-air-temperature
EASA	European Union Aviation Safety Agency

1 Introduction

Modern aviation plays a vital role in global transportation of goods and people. However, its continued reliance on kerosene powered propulsion systems contributes significantly to global energy-related CO₂ emissions, accounting for an estimated 2% in 2022 [1]. As the aviation industry attempts to reduce its environmental impact and explore fuel alternatives, electric aviation has emerged as a potential paradigm shift. Electric aviation provides economic advantages as it can make air travel more cost-effective by lowering maintenance costs; electric systems require fewer repairs and are more fuel efficient [2].

Despite the advantages associated with electric aviation, conventional aircraft remain the market standard. One of the main concerns in electric aviation has been the ability to provide sufficient power and energy density for flight. This stems from the low battery specific power and energy of lithium-ion batteries compared to kerosene [3], which constrains available onboard electrical power, and thus the mechanical power that can be produced. Despite this limitation, advancements in electric motors, especially axial flux permanent magnet synchronous motors (AFPMSM), have accelerated the electrification of aircraft. Axial flux motors can provide high torque and power density [4]. However, their high-torque design requires high current densities, meaning increased heat generation in the motor [5]. Consequently, this calls for good cooling systems and thermal management, because as altitude increases, air density and outside-air-temperature (OAT) decrease, affecting the air side convection capability of their heat exchanger systems. The decrease in density reduces the mass flow over the heat exchanger, reducing air side convection, while the decrease in OAT increases heat transfer due to the increased temperature difference [6].

This bachelor's thesis aims to weigh the relative impacts of these altitude-induced-variables, by assessing their effects on the Pipistrel Velis Electro's AFPMSM coolant system. The Velis Electro is the only full-electric manned aircraft certified by the European Union Aviation Safety Agency (EASA) [7]. Because of this title, it was chosen for this thesis as a real-world foundation for the analysis and modelling.

This thesis answers the following research question; how does altitude increase impact the cooling capability of the liquid-coolant system due to the heat exchanger performance change? Section 2 presents theoretical background. Section 3 presents the approximation methods and the developed MATLAB/Simulink model. Section 4 discusses the results and Section 5 summarizes the conclusions and limitations and presents opportunities for future research.

2 Literature review

2.1 International Standard Atmosphere

The atmosphere is a complex mixture of gases consisting of many layers. The lowest layer of the atmosphere is called troposphere, which generally refers to the region from sea level up to 11000 meters [8]. In this layer, variables such as temperature, pressure, and density are interlinked, and their values change constantly. The changes in these properties are unpredictable and difficult to monitor, making it difficult to apply them to avionics or meteorological models. As a result, the International Standard Atmosphere (ISA) has been created as a reference model of the actual atmosphere [9]. It provides a general estimate of the ambient conditions at certain altitudes [9], albeit with certain assumptions.

The ISA model equations use altitude as the only input; temperature and pressure change only with altitude, and no other variable factors are considered [8]. Temperature change rate relative to altitude is assumed as a constant. This is called the lapse rate, and is assumed to be 0.0065K/m [8]. It suggests that temperature decreases by 1 kelvin per every 153 meters of climb, or approximately 6.5K per km.

Although the real lapse rate varies based on atmospheric conditions, the model assumes the lapse rate to be linear throughout the troposphere. It's only at tropopause and stratospheric layers where lapse rate changes. Since this thesis focuses on the Pipistrel Velis Electro as a basis, whose service ceiling is 3660 meters [10], the lapse rate is considered to be constant.

The following ISA models equations are adopted from NASA Glenn Research Centre [8]:

$$T(H) = T_0 - LH \quad (1)$$

$$p(H) = p_0 \left(\frac{T(H)}{T_0} \right)^{\frac{g}{LR}} \quad (2)$$

$$\rho(H) = \frac{p(H)}{RT(H)} \quad (3)$$

As seen from Eqs. (1)-(3), all variables are functions of altitude. $T(H)$, $p(H)$, and $\rho(H)$ denote the air temperature, air pressure and air density relative to altitude, respectively. Since air density decreases with altitude, the ratio of the density relative to sea level can be calculated through the following:

$$\sigma = \frac{\rho(H)}{\rho_0} \quad (4)$$

The density ratio is vital to this thesis because it helps approximate radiator performance change due to altitude increase.

2.2 Axial Flux Permanent Magnet Synchronous Electric Motors

With emerging technology, electric motors are becoming more common in aviation. They are extremely efficient, and possess only a few moving parts, meaning maintenance and repair is simple. The most common types of permanent magnet synchronous electric motors are the radial flux and axial flux. During the last century, radial flux has been the standard type of electric motor, mainly due to the complexity of axial flux motors [11].

Due to the increase in demand for power dense electric systems, AFPMSM technology has advanced and they have emerged as a geometrically compact, efficient and power dense variant of electric motors [4]. This makes them ideal for aviation purposes, because they maximize power while minimizing weight. They differ from radial flux motors by direction of flux lines. In axial flux motors, the flux lines are parallel to the rotational axis of the rotor [12]. Furthermore, instead of the conventional cylindrical shape of radial motors where the rotor spins in the hollow cylinder, axial motors are disc shaped. Consequently, this allows for a smaller total motor volume, meaning less mass and a smaller moment of inertia for the rotor [12].

There are various stator-rotor combinations in AFPMSMs, such as the single stator dual rotor (SSDR), single stator single rotor (SSSR), and double stator single rotor (DSSR) [4]. In the SSDR and the DSSR configurations, the disc shaped stator or rotor is interposed between the two rotors or stators, respectively. The rotors contain the permanent magnets, while the stators contain the windings that act as electromagnets. The three-phase alternating current supplied by the power controller [13] to the stator produces a rotating magnetic field, which rotates the rotor. According to [4], the SSDR configuration lowers axial forces, flux leakage and copper loss due to short end windings. Additionally, the short end windings permit good heat dissipation [4]. Despite its advantages, it is mechanically complex, and requires exceptional precision to align the discs to prevent eccentricity and magnetic losses [4]. The DSSR configuration presents its own advantages and disadvantages. It provides better rotor protection because of the embedded permanent magnets. However, due to the excessive amount of end windings, it generates more copper losses. [4].

The AFPMSM used by the Velis Electro is the E-811-268-MVLC. It is a highly efficient, lightweight and powerful motor [13]. It's stator-rotor configuration is classified under its type-certification by the EASA. Hence, the configurations influence is exempted from this thesis.

2.2.1 Power losses

Similar to other electric motors, AFPMSMs experience internal power losses mainly in the forms of copper losses, mechanical losses, and core losses [14].

Mechanical losses emerge in two main forms: bearing loss and aerodynamic loss. Bearing loss is composed of rolling friction, sliding friction, and viscous friction as a result of lubricant motion [15]. Aerodynamic loss refers to the loss of power due to friction generated by fluidal movement of air in the air gap between the stator and rotors [15].

Copper losses, also known as Joule losses, are induced by the current flowing through the stator winding, causing heat generation [14]. AFPMSM's design generates high amounts of copper losses, because the high power requires high current density in the end windings [5]. The amount losses depends on the amount of wire resistance in the windings [14].

Core losses consist of eddy-current losses and hysteresis losses. These losses are generated because of the rapidly changing magnetic fields [14]. The magnetic characteristics of the material in the stator and rotor cores determine the amount of hysteresis that it experiences. Meanwhile, the amount of eddy-current losses they experience depend on factors such as strength of the magnetic field, and lamination properties [14].

Power loss in the AFPMSMs can be represented by the following Eq. (5) and Eq. (6):

$$P_{loss} \approx P_{loss,cu} + P_{loss,core} + P_{loss,mechanical} \quad (5)$$

$$P_{loss} = P_{motor} \left(\frac{1}{\eta_{motor}} - 1 \right) \quad (6)$$

Equation (5) represents power loss through the summation of each loss component. Although the data on each of the individual loss components of the E-811-268-MVLC AFPMSM is unavailable, their combined magnitude is inferred through the available motor efficiency parameter in the Pilot's Operating Handbook [13]. Hence, the power loss is calculated via Equation (6), while using the documented motor efficiency.

2.3 Thermal management of AFPMSM

The thermal management of electric motors is a critical part of their function. It encompasses the cooling and heating systems as well as temperature monitoring systems. Inadequate thermal system setups can cause component overheating and permanent damage and pose serious operational risks.

In AFPMSMs, majority of the aforementioned losses are emitted as heat during operation. This emphasises the importance of heat removal methods from the core and windings. Heat removal methods comprise of air or liquid

cooling mechanisms. Air cooling is a method in which bypassing air passes through and absorbs heat from internal paths or surfaces in the axial flux motor, transferring heat from the components to the environment. Studies have modelled air cooling through rotor-integrated air channels, and it appears to be a provide viable results if inlet and outlet positions are optimised [11].

Liquid cooling generally offers greater cooling capacity and performance than air cooling. It is highly effective because the coolant can remove heat from geometrically complex parts. Liquid cooling mechanisms vary, from water jacket cooling to channel cooling [11]. In the water jacket cooling method, a hollow coating in which the coolant flows through is implemented on the outside surface of the stator. Although effective, its effectiveness largely depends on coolant flow rate [11]. In channel cooling, the coolant flows through inbuilt channels within the stator or windings. According to [11], channel cooling provides superior cooling performance, because it allows the coolant to remove heat directly from the windings and core components.

The Velis Electro's AFPMSM is liquid cooled. Although the liquid cooling mechanism used is unknown, this thesis discusses the cooling performance of the motors coolant system, rather than evaluating distinct cooling mechanisms.

3 Model

To assess the effect of altitude on the Pipistrel Velis Electro's AFPMSM coolant system, a MATLAB/Simulink model was created. It simulates the climb of the Velis Electro at its max climb rate of 3.3m/s and best climb speed of 75KIAS [10]. The model outputs the coolant outlet temperature from the motor relative to altitude. The inlet temperatures are approximated.

3.1 Cooling system

As mentioned earlier, cooling systems ensure the thermal management of AFPMSMs. Different cooling systems utilise different types of coolant depending on motor requirements. Coolants vary by specific heat capacity, density and thermal conductivity. The Velis Electro's motor coolant system utilises a solution comprised of 50% water and 50% automotive grade G12+ ethylene glycol [13]. Water has high specific heat capacity, ensuring effective heat absorption, while the ethylene glycol lowers the freezing point to -36.8°C [16], providing protection against low coolant temperatures and freezing.

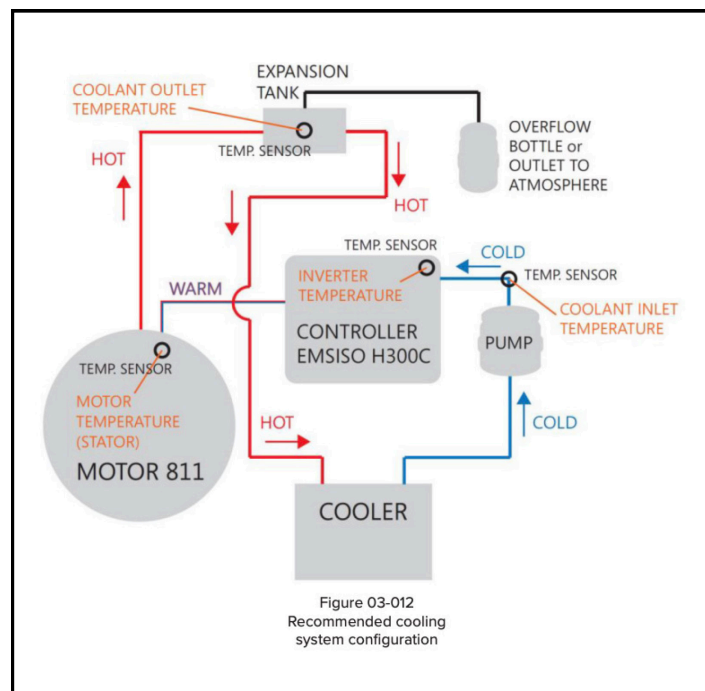


Figure 1 – Coolant circuit of Pipistrel Velis Electro's motor [17]

Figure 1 demonstrates the Velis Electro's motor cooling architecture. The coolant flows through the power controller and the motor before flowing into the cooler component. Based on Pipistrel's documentation, the Velis Electro has inlet and outlets for the radiator, suggesting that its cooler component is

likely a ram-airflow radiator [10]. In this thesis, only the heat load from the motor is considered, meaning the power controller is exempted due to insufficient data.

The motors inlet coolant temperature is heavily dependent on the radiator, because it's the component that dissipates heat from the coolant into the environment after it gains heat from the motor. The environment acts as the heat sink for the generated heat. The heat transfer that occurs in radiators is dependent on variables such as mass flowrate, and temperature difference [6]. A NACA study conducted by W. S. James and S. R. Parsons suggested that decrease in density and air temperature both have distinct impacts the radiator's performance [6]. A lower temperature tends to increase heat transfer due to increase in mean temperature difference between coolant and the environment. Meanwhile, a lower density tends to decrease heat transfer because of the reduced mass flow through the radiator [6]. Due to the unavailable radiator heat transfer data and coolant temperatures, these principles are used as a basis in subsequent sections. These sections approximate the radiator performance change and coolant inlet temperatures relative to altitude.

3.1.1 Radiator performance approximation

The radiators performance is approximated in this section via indicated airspeed (IAS) and true airspeed (TAS) correlations, and Dittus-Boelter correlations. The total heat absorbed by the coolant passing through the AFPMSM can be represented through the heat transfer equation:

$$\dot{Q} = \dot{m}_{coolant} c_p (T_{coolant,out} - T_{coolant,in}) \quad (7)$$

Where $\dot{Q}$ is the heat load transferred to the coolant from the motor, and $\dot{m}_{coolant}$ and c_p are the mass flow rate and specific heat of the coolant, respectively.

At the radiator, air flows through its heat-transfer area, cooling the coolant and dissipating heat to the environment. The heat dissipation by convection that occurs at the radiator, and the mass flow rate of air over the radiator area is given by:

$$\dot{Q}_{dissipated} = h_{air} A (T_{surface} - T_{air}) \quad (8)$$

$$\dot{m}_{air} = \rho A V_{IAS} \quad (9)$$

Where $\dot{Q}_{dissipated}$ and h_{air} are the heat dissipated by the radiator and the convective heat transfer coefficient of the bypassing air, respectively.

In Eq. (9), the radiator heat-transfer area (A) and IAS (V) are assumed constant, suggesting that the decrease in air density, ρ , decreases the mass flow

rate. According to the NACA study, this hints that radiator performance undergoes reduction of some magnitude with altitude increase.

The assumption that IAS is constant throughout the climb suggests that TAS is not constant. This is because the IAS is measured via the pressure applied by air particles during flight. With decreasing air density, for the IAS to remain constant, the aircrafts speed must increase, because less particles apply pressure on the aircraft. This indicates that the actual speed of the aircraft grows, meaning its TAS is higher than its IAS. The conversion from IAS to TAS relative to altitude can be represented by Eq. (10), as obtained from Firgelli Automations [18]:

$$TAS = \frac{IAS}{\sqrt{\sigma}} \quad (10)$$

Where σ is the density ratio is calculated in Eq. (4). This equation illustrates that the aircrafts true airspeed increases with altitude when IAS is assumed constant.

As a result, the mass flow rate change relative to altitude through the radiator can be represented as:

$$\dot{m}_{air}(H) = \rho A \frac{V_{IAS}}{\sqrt{\sigma}} \rightarrow \rho_0 A V_{IAS} \sqrt{\sigma} \rightarrow \dot{m}_{air,0} \sqrt{\sigma} \quad (11)$$

Thus:

$$\frac{\dot{m}_{air}(H)}{\dot{m}_{air,0}} = \sqrt{\sigma} \quad (12)$$

Where Eq. (12) demonstrates the sea-level to altitude relationship of mass flow rate at constant speed due to air density change. However, the radiators heat transfer conductance change cannot be calculated using the $\sqrt{\sigma}$ variable alone, because the relationship between mass flow rate and heat transfer is not directly proportional. Therefore, using the $\sqrt{\sigma}$ variable alone would provide an incomprehensive approximation of the effect of reduced air density on the radiator.

The relationship between heat transfer and mass flow exists through the Dittus-Boelter correlation. The Dittus-Boelter correlation is a heat-transfer correlation utilised to calculate convective heat transfer in ducts [19]. It relates the Nusselt number to the Reynolds and Prandtl number for turbulent flow. Ram-airflow radiators rely on ducts, as it is where air passes through the coolant coil. The Dittus-Boelter correlation, obtained from [20], is represented as:

$$Nu = 0.023 Re^{0.8} Pr^n \quad (13)$$

As seen in Eq. (13), the Nusselt number and Reynolds number are correlated through relationship:

$$Nu \propto Re^{0.8} \quad (14)$$

When assumed for constant geometry and Prandtl number, Nusselt and Reynolds numbers are directly proportional to the heat transfer coefficient of the fluid, and mass flow rate, respectively [20].

$$Re \propto \dot{m}_{air} \quad (15)$$

$$Nu \propto h_{air} \quad (16)$$

These relationships can be combined to form:

$$h_{air} \propto \dot{m}_{air}^{0.8} \quad (17)$$

Therefore, using Eq. (12), the relative heat transfer change with altitude, can be weighted and modelled using the variable:

$$(\sqrt{\sigma})^{0.8} = \sigma^{0.4} \quad (18)$$

Using the derived variable, the radiator's air-side conductance change due to altitude can be scaled despite the unknown heat-transfer (hA) variables. Traditionally, the Dittus-Boelter correlation depicts heat transfer in smooth ducts [19], while ram-airflow radiators contain fins and complex pathways. Thus, the correlation is not applied as a complete radiator performance change indicator, but a reduced-order approximation method due to insufficient data. Therefore, for this thesis, the coolant inlet temperature can be weighted using this variable.

A similar approximation method was used in a 1989 MIT study that analysed the impact of altitude on the amount of natural convection for aircraft avionics [21]. They made use of a similar σ variable that weighted the heat transfer coefficient. This variable was derived through Nusselt and Rayleigh correlations for natural convection [21]. However, this thesis adopts a different approach; the thesis assesses air side convection at the radiator as the heat rejection mechanism, rather than natural convection that occurs throughout the aircraft. As a result, the derived $\sigma^{0.4}$ variable depicts the impact of air density changes on the radiators heat transfer performance. Natural convection occurring outside the radiator's heat-transfer interface is exempted from this thesis.

3.1.2 Coolant inlet temperature approximation

The radiators conductance determines the inflow temperature of the coolant. As mentioned earlier, in this thesis it is assumed that the radiators heat transfer capability scales predominantly with derived variable $\sigma^{0.4}$. Under these

assumptions, the heat transfer of the radiator relative to altitude can then be represented as:

$$(h_{air}A)(H) = (h_0A)\sigma^{0.4} \quad (19)$$

Meaning Eq. (8) can be rearranged as:

$$(T_{surface} - T_{ambient})(H) = \frac{\dot{Q}_{dissipated}}{h_0A\sigma^{0.4}} \quad (20)$$

Where $T_{surface}$ denotes the surface temperature of the radiator coil. $T_{surface}$ is approximated to be equal to the inlet coolant temperature, $T_{coolant,in}$, due to insufficient data. In actuality, the temperature of the coolant generally decreases along the coil as heat is dissipated into to the air from the coolant. Therefore, this approximation may overestimate the real $T_{surface}$ variable. As a result, it is only used as a reduced-order approximation method. If the data were available, the assumption could be avoided, and instead methods such as logarithmic mean temperature difference could be implemented. These would provide more comprehensive assessment of the coolant's temperature variation along the coil and thus more accurate estimate of the coolant's real inlet temperature.

At sea level, if assumed thermal steady-state balance is achieved, the heat dissipated by the radiator is equal to the heat generated by the motor, the latter of which is calculated in Eq. (6). Because the radiators conductance is finite, at thermal steady-state balance, there is a temperature difference between the coolant and OAT. If it had infinite thermal conductance, the difference between the coolant and OAT would approach 0 K because the radiator would dissipate all heat absorbed by the coolant. This induced temperature difference can be estimated as a variable T_{ref} . Therefore:

$$T_{ref} = T_{coolant,in} - T_{ambient} = \frac{P_{loss}}{h_0A} \quad (21)$$

Thus, by combining Eqs. (20) and (21), the coolant temperature change due to estimated radiator heat transfer change can be represented as:

$$\Delta T(H) = \frac{T_{ref}}{\sigma^{0.4}} \quad (22)$$

T_{ref} is not fixed. Rather, it is analysed as a parameter variable, and a sensitivity analysis is conducted. A larger T_{ref} indicates a weaker radiator conductance, while a smaller T_{ref} indicates the opposite. Pipistrel declares the maximum inlet temperature of the coolant for the motor as 60°C, and the maximum OAT the motor can withstand is 40°C [17]. Under these conditions, the upper bound T_{ref} is established to be the difference: 20K. The parameter is iteratively tested in increments of 5K from 5K-20K.

3.2 Quasi-steady state

Equation (7) can be modified to calculate the temperature of the quasi-steady state outlet coolant temperature at every altitude increment by:

$$T_{coolant,out} = \frac{\dot{Q}}{\dot{m}c_p} + T_{coolant,in} \quad (23)$$

$$T_{coolant,in} = T_{ambient} + \frac{T_{ref}}{\sigma^{0.4}} \quad (24)$$

This calculation method assumes that the coolant reaches its relative altitude-temperature equilibrium at every step. This entails that there is no thermal lag. Equations (23) and (24) present the outlet temperature as a function of altitude with OAT decrease and density decrease variables.

3.3 Transient

The transient calculation method approximates the inlet temperature of the coolant by averaging the temperature of the coolant's total mass. Unlike in the quasi-steady state, thermal inertia is considered, meaning it takes time for the coolant to reach thermal equilibrium as it absorbs heat. The average temperature of the total coolant mass can be represented through heat transfer balance Eq. (25), as obtained from [22]:

$$mc_p \frac{dT_{coolant}}{dt} = \dot{Q}_{heat} - \dot{Q}_{dissipated} \quad (25)$$

Where dissipated heat is defined, by combination of Eqs. (8), (19) and (21), as:

$$\dot{Q}_{dissipated} = \frac{P_{loss}}{T_{ref}} \sigma^{0.4} (T_{coolant} - T_{ambient}), T_{ref} > 0 \quad (26)$$

Quasi-steady and transient calculations methods are used in this thesis to evaluate the effects of altitude, as well as the examine whether thermal inertia plays a key role. The quasi-steady state method is used as the main derived calculation method. The transient calculation method was incorporated as a consistency check approach. Because the transient method incorporates thermal inertia and is time dependent, it is used to determine whether the results are consistent. Both methods are initialised at the same sea-level-to-ambient reference value (T_{ref}).

3.4 Assumptions

This thesis relies on the following assumptions that simplify and facilitate the calculations and prevent too many invariable factors. Some of the following have been introduced previously.

- Aircraft climbs from sea level to 3660m with constant shaft power of 49.2kW and a constant climb rate of 3.3m/s
- The efficiency of the E-811-268 MVLC AFPMSM is assumed constant, and all power lost by the motor is transferred to coolant as heat.
- Density and temperature vary according to the ISA model
- Aircraft flies at constant speed of 75KIAS, while true air speed varies with the density ratio
- The radiator is treated as a ram-airflow radiator with constant geometry and its inlet airspeed is assumed to be the aircraft's true airspeed
- Only heat load from motor is considered, and power controller heat is exempted
- Thermophysical properties of air such as viscosity, thermal conductivity and specific heat are assumed constant.
- The surface of radiator coil is considered equal to coolant's inlet temperature
- Coolant flow rate constant and density are constant.
- The unavailable sea level radiator conductance is represented through variable T_{ref} .

3.5 Simulink Model

Figure 2 demonstrates the implemented Simulink model, which outputs the coolant temperatures relative to altitude. It was assembled utilising the ISA model equations, and the derived coolant equations. The model also comprises of a MATLAB script, located in the Appendix. The script is used to define the parameters, run the simulation, and present numerical results.

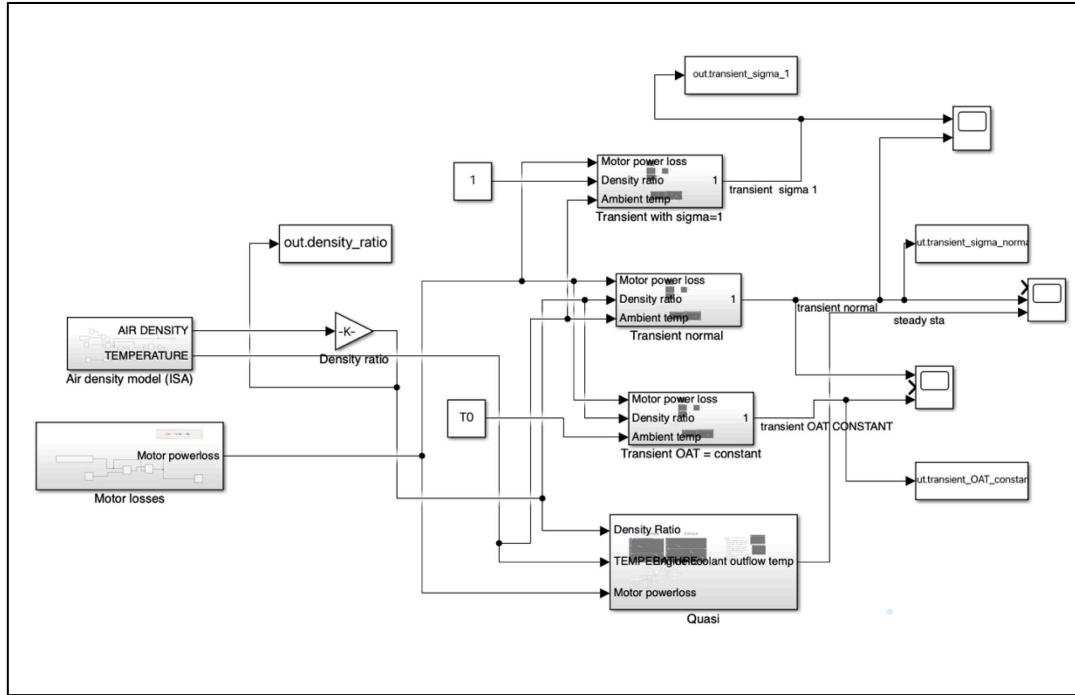


Figure 2 – Image of the created Simulink model

3.5.1 ISA component of the model

Figure 3 illustrates the ISA model equations which were implemented in Simulink to calculate the changing OAT, pressure and air density. The climb of the aircraft is simulated across 1109 seconds.

The ISA model uses the standard sea-level temperature of 15°C (288.15K), which decreased to -8.8°C (264.35K) across the climb. The air density drops to 0.85kg/m³ from the original 1.225kg/m³ at sea level. During the climb to 3660m, the density ratio reaches a lowest of 0.69, meaning a 31% decrease in air density relative to sea level. This suggests that air density is approximately two-thirds of what it is at sea level. The input parameters used for the equations are given by the table 1 and were obtained from NASA Glenn Research Centre [8].

Table 1 – Input parameters for ISA model

CONSTANT PARAMETER	VALUE
T_0	288.15K
ρ_0	1.225kg/m ³
G	9.81m/s ²
L	0.0065K/m
R	287J/kgK
P_0	101325Pa
H_{MAX}	3660m
H_0	0m

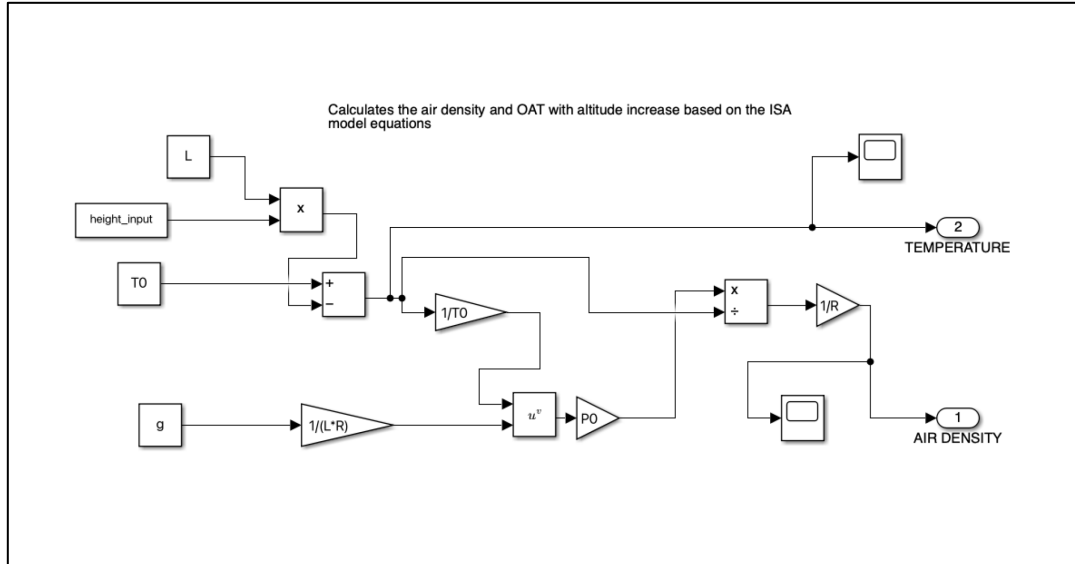


Figure 3 – Implementation of ISA

3.5.2 Coolant outlet calculations

The quasi-steady state and transient methods use the outputs from the ISA model as inputs. This includes the OAT, and the calculated density ratio. Furthermore, they make use of the T_{ref} variable and the calculated power loss of the AFPMSM as inputs. Using Eq. (6), the power loss generated by the AFPMSM is calculated as:

$$P_{loss} = P_{motor} \left(\frac{1}{\eta_{motor}} - 1 \right) \quad (6)$$

$$P_{loss} = 49200 \left(\frac{1}{0.89} - 1 \right) = 6080.9W$$

The calculated power loss of the AFPMSM is 6080.9W. Under the assumption of constant efficiency, this value remains constant throughout the climb, and it is the heat load transferred to the coolant from the motor every second. This is the heat that must be dissipated by the radiator.

Figures 4-5 below illustrate how the equations were implemented in Simulink. The Velis Electro parameters used for both transient and quasi-steady state model calculations are shown in table 2. The values were obtained from the Pilots Operating Handbook [13], and Engineering Toolbox [16]. Furthermore, as seen in Figure 4 and 5, both calculation methods incorporate a look-up table used for the specific heat capacity of the coolant. The coolant's specific heat capacity is treated as temperature dependent, and the look-up table updates its value throughout the climb. This is implemented because a temperature-dependent value allows a more realistic prediction of results than utilising a constant value. The look up table interpolates the specific heat of the coolant using a list of specific heat values and their corresponding temperatures, which were obtained from [16]. The coolant temperatures used for the interpolation ranged from 263.15-323.15K, and specific heat capacities ranged from 3381-3565J/kgK.

Table 2 – Input parameters for coolant calculations

COMPONENT	PARAMETER	VALUE
MOTOR	Efficiency	0.89
MOTOR	Max continuous power	49.2kW
MOTOR	Coolant volume	0.9L
MOTOR	Power loss	6.081kW
COOLANT	Density	1090kg/m ³
COOLANT	Specific heat	3381-3565J/kgK
COOLANT	Fluid flow	5.5L/min
COOLANT	Mass flow	0.1kg/s

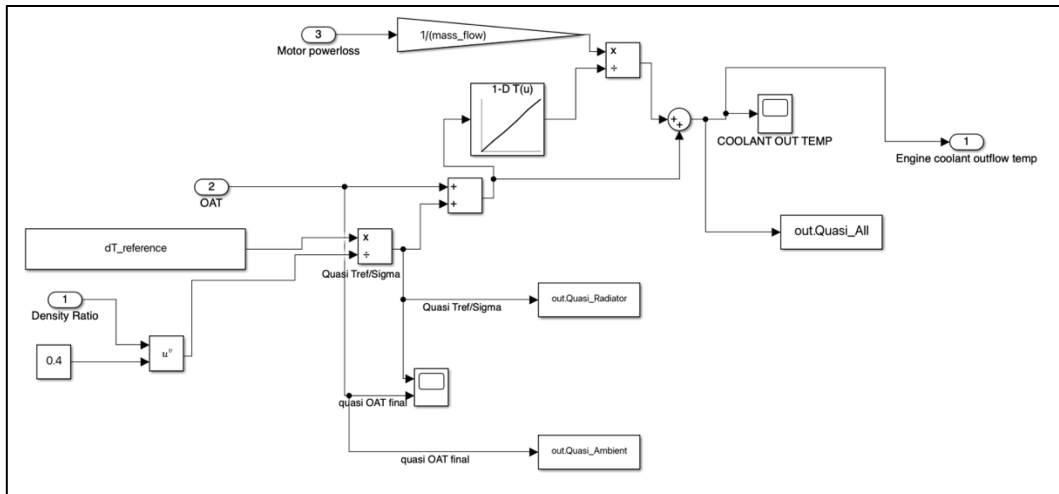


Figure 4 – Implementation of Quasi-steady-state calculation

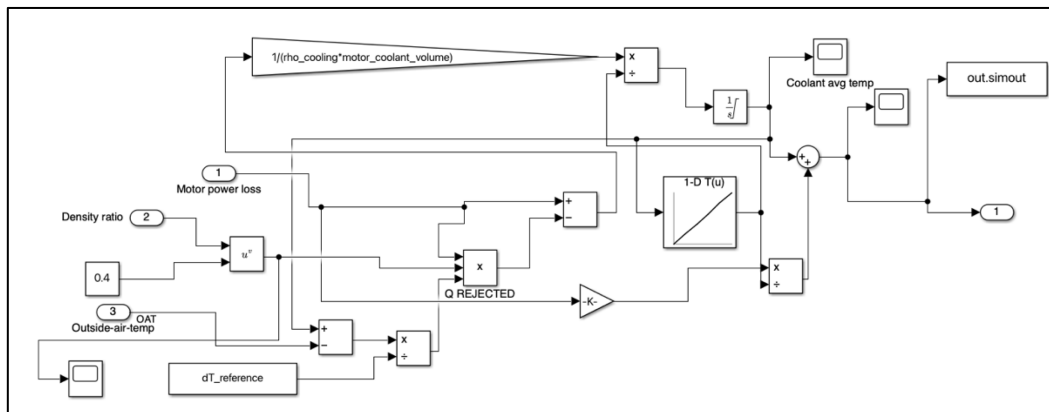


Figure 5 – Implementation of Transient calculation

4 Results

This section discusses the coolant outlet temperatures predicted by the developed model.

Compared to a constant specific heat case, the implementation of a look-up table caused a predicted average increase of coolant outlet temperature of 1K. Although the difference induced is relatively small, it provides a more realistic representation of the coolant relative to altitude and minimizes assumptions. This increase occurred consistently for all T_{ref} values.

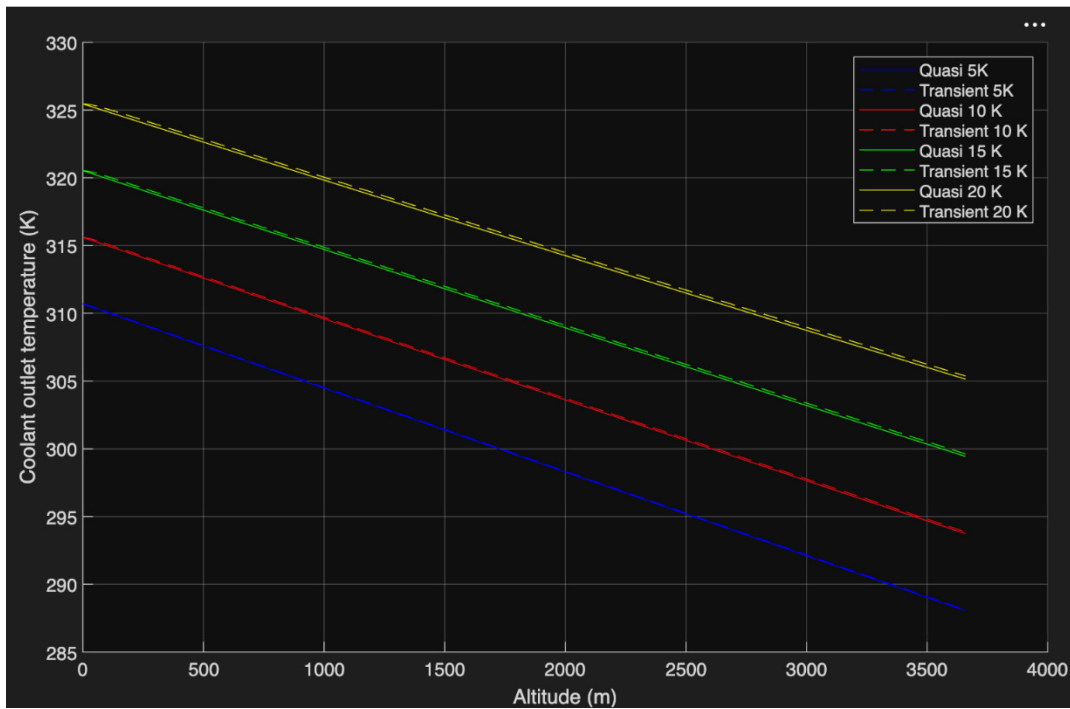


Figure 6 – Coolant outlet temperature for quasi-steady state and transient methods at each reference temperature

Figure 6 presents the coolants outlet temperature predicted by both transient and quasi-steady state methods at each reference temperature interval. In the figure, the dashed transient line appears to be slightly above the solid line. This demonstrates the lag due to thermal inertia, as the temperature of the transient method does not change instantaneously, like the quasi-steady state. However, the lag induced by the transient is relatively small. This can be attributed to the relatively slow climb rate, which gives the coolant enough time to approach temperature equilibrium at the specific altitude. It is a relatively natural and an expected outcome; the faster the climb, the less time the coolant possesses to achieve temperature equilibrium at each altitude. Although the maximum climb rate of the Velis Electro was utilised in the model, the climb rate was not fast enough to provide large differences

between methods. The effects of other climb rates were not evaluated in this study.

The T_{ref} value was originally introduced because of the lack of data on the radiator's sea-level conductance. Each T_{ref} value increased the outlet temperature of the coolant by the interval differences: 5K. This is an expected outcome, given the assumption of constant AFPMSM heat load, and the density ratio being equal to 1 at sea level, meaning all initiation points differed only due to the T_{ref} parameter. A T_{ref} of 5K provided the lowest mean outlet temperature, indicating that it is seemingly the optimal value for AFPMSM cooling. The lower mean coolant temperature could provide more favourable motor-to-coolant convection, due to the increased temperature difference.

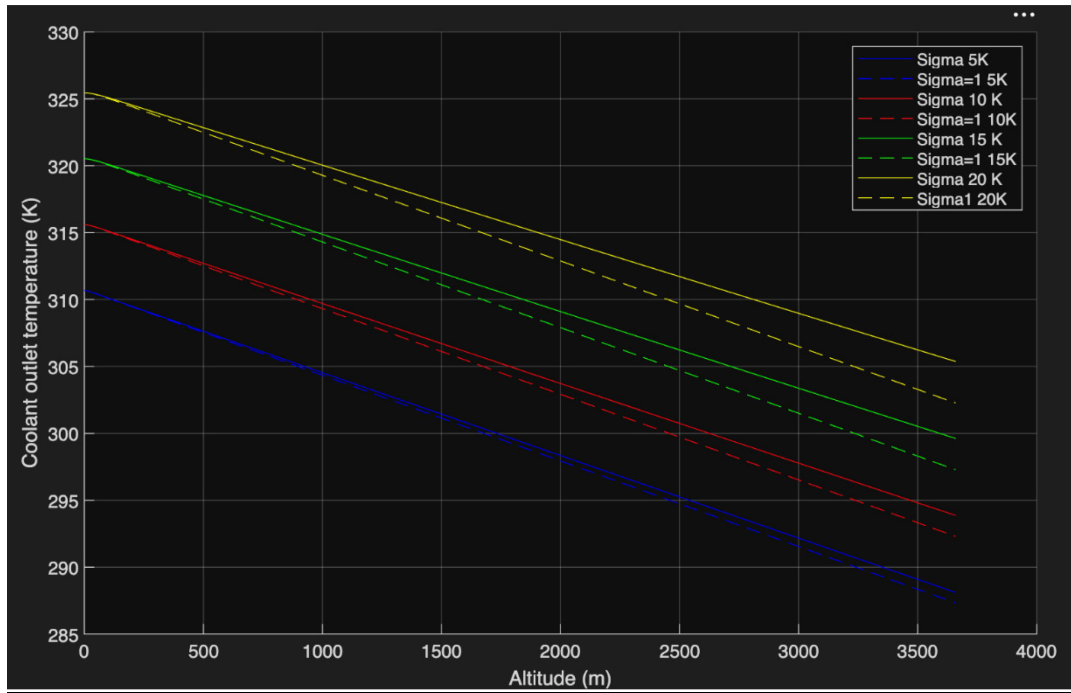


Figure 7 – Transient outlet temperatures cases with and without the effect of reduced air density

Figure 7 presents the impact of the derived air density correlation using the transient methods. The dashed lines indicate the coolant's outlet temperature in the case where only the change in OAT is considered and the density ratio remains at its sea level value ($\sigma = 1$) throughout the climb. The solid lines represent the normal case, where both OAT and air density decrease are incorporated. As seen in the figure, there is separation between pairs of transient cases. The separation is caused by the impact of density on air-side convection at the radiator. It suggests that when the reduction in air density is considered, the coolant outlet temperatures are higher than when it is excluded. This can be attributed to decrease in mass flow rate, which decreases

air side convection at the radiator, increasing the coolants temperature. The separation increases with altitude and reaches its maximum at the service ceiling of the Velis Electro.

Table 3 – Numerical results at each T_{ref} interval

T_{ref}	Coolant outlet temperature	Value (Kelvin)	
		Quasi-steady state	Transient
5K	Temperature change due to decreased air-density	+0.7904	+0.7840
	Temperature change due to OAT	-23.7880	-23.3475
	ΔT_{net}	-22.9976	-22.5635
10K	Temperature change due to decreased air-density	+1.5808	+1.5634
	Temperature change due to OAT	-23.7880	-23.2834
	ΔT_{net}	-22.2072	-21.72
15K	Temperature increase due to decreased air-density	+2.3712	+2.3380
	Temperature change due to OAT	-23.7880	-23.2185
	ΔT_{net}	-21.4168	-20.8805
20K	Temperature increase due to decreased air-density	+3.1616	+3.1077
	Temperature change due to OAT	-23.7880	-23.1527
	ΔT_{net}	-20.6264	-20.045

Table 3 presents the values of the distinct impacts of air density and OAT on the coolant temperature via the radiator. The quasi-steady-state method predicts that reduced density increased the temperature by 0.7904-3.1616K, depending on the T_{ref} value, while OAT decreased the temperature by 23.7880K. The transient method suggests that density increased the coolants temperature by 0.7840-3.1077K, while OAT decreased it by 23.1527-23.3475K.

The density values presented for the transient method are the difference between the ($\sigma = 1$) case and regular cases for each reference temperature at the max altitude. Another similar case was conducted, with temperature assumed a constant sea level value of 288.15K (15°C), and the total difference at service ceiling is provided in the transient column for temperature change

due to OAT. Despite the transient method considering thermal inertia, the transient method is consistent with the quasi-steady state and the difference between the two methods is minimal.

The ΔT_{net} variables establish that the OAT change had a significantly higher impact on the temperature of the coolant through the radiator. The increase in temperature difference drives heat transfer at the radiator more than the reduction in air density and hence mass flow rate decreases it. Despite the air density at 3660m being 31% less than at sea level, its impact on the heat transfer of the radiator is limited. This is likely because of the derived Eq. (19). At a density ratio of 0.69, the reduction in density only impacts the heat transfer variables by a factor of:

$$\sigma^{0.4} = 0.69^{0.4} \approx 0.86$$

indicating a 14% decrease in air side heat transfer. The relatively small effect of density decrease can be attributed to this.

Equation (21) presents that the coolant-to-air temperature difference required to dissipate a constant heat load is inversely proportional to radiator conductance hA . If density decreases heat transfer by 14%, then the temperature difference must be greater by a factor of:

$$\frac{1}{0.69^{0.4}} \approx 1.16$$

This indicates a required 16% increase in temperature difference. This relationship can be seen in the outputs predicted by the varying T_{ref} values, as a 16% increase corresponds to 0.8K and 3.2K when T_{ref} is 5K and 20K respectively.

Overall, the results suggest that the temperature drop produced conditions more favourable for cooling, and likely the thermal margin of the AFPMSM increased. Because of the lack of actual Velis Electro axial flux temperature data, the coolants direct impact on the temperature of the motor remains inconclusive. However, due to the temperature decrease of the coolant, the range of the motor's temperature range increases. The motor's temperature could increase while maintaining a similar to-coolant heat transfer.

A 1989 MIT study concluded that convective resistance increases with decreased air density and thus forced convective cooling capability decreases with altitude [21]. This coincides with the developed model, as the heat transfer is assumed to decrease by factor $\sigma^{0.4}$ relative to altitude. However, the model also predicted the heat transfer caused by decreased OAT outweighs the penalty caused by the decrease in density. This entails that convection at the radiator is dictated by OAT decrease, rather than mass flow decrease.

5 Summary and conclusion

5.1 Summary

The objective of this thesis was to analyse the impact of altitude on the liquid coolant system of axial flux motors in electric aviation. The thesis studied the impact of variables induced by altitude change; outside-air-temperature (OAT) and air density decrease. It aimed to weigh their relative impacts on the coolant outlet temperature from the axial flux permanent magnet synchronous motor (AFPMSM). The thesis utilised the Velis Electro's AFPMSM as a case study, because of its applicability. Being the only manned electric aircraft certified by the EASA, it served as a valid and relevant real-world foundation.

A MATLAB/Simulink model was built using equations derived via a combination of Dittus-Boelter correlations, airspeed relationships and convective heat transfer equations. Both quasi-steady-state and transient calculation methods were used.

The results were evaluated by comparing the relative numerical impacts of OAT and density decrease on the absolute coolant outlet temperature, the sensitivity to assumed sea-level temperature delta T_{ref} , and the thermal lag induced by the transient calculations.

5.2 Conclusion

As altitude increases, the coolant system of Velis Electro's AFPMSM undergoes significant temperature changes. As per the quasi-steady state calculations, the reduced air density increases the coolants outlet temperature by 0.7904-3.1616K depending on the T_{ref} value. The reduced OAT conversely decreases the coolants outlet temperature by 23.7880K, because of the greater temperature difference between coolant and OAT. This temperature difference increases heat transfer at the radiator. When compared, the reduced OAT substantially outweighs the impact of air density decrease. The transient method remains highly consistent with quasi-steady state results, despite the coolant temperature being time dependent.

This conclusion remains within the limitations of the Velis Electro and the assumptions incorporated into the developed model. These include parameter approximations, the derivation assumptions, and the ISA model assumptions.

5.2.1 Evaluation and future research

This topic could be further explored with additional data. If provided enough data, the scope could be enlarged to include the effect of altitude on the AFPMSM's actual temperature. The lack of data made this unviable for this thesis. Investigating this would require physical data for radiator heat transfer, AFPMSM geometry as well as cooling channel geometry and its thermophysical properties. By including this, the effect of altitude on the AFPMSM's temperature could be modelled.

Additionally, one crucial aspect of heat transfer that could be investigated is the role of radiative heat transfer. This thesis did not explore its role in the AFPMSM's coolant system because of missing radiative parameters. Previous studies have suggested that radiative heat transfer helps deter unwanted temperature growth of the motor [21]. Incorporating this would provide a more comprehensive assessment of the effects of altitude on the thermal behaviour of electric motors and their coolant systems.

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Appendix

MATLAB Script

```
clear
clc
load_system('SimulinkElectroModel.slx');

% ISA MODEL VARIABLES
h_max = 3660; % Velis Electro service ceiling / max altitude (m)
T0 = 288.15; % Standard sea level temperature (K)
P0 = 101325; % Air pressure at sea level (Pa)
R = 287; % Specific gas constant of air
g = 9.81; % Gravitational acceleration (ms^-2)
L = 0.0065; % Lapse rate as per ISA model (K/m)
rho_air_sealevel = 1.225; % Sea level air density (kg/m^3)
h = (0:3.3:h_max)'; % Climb vector used for simulation, with 3.3 max climb
rate m/s
t = (0:length(h)-1)'; % Clock for climb (s)
height_input = [t,h]; % Height time vector

% AFPMSM VARIABLES
eff = 0.89; %electric motor efficiency
P_max_cont_shaft = 48000; %Max continuous providable mechanical power (W)
motor_coolant_volume = 0.9*10^-3; %Volume of motor's coolant system (m^3)

%COOLANT VARIABLES
rho_cooling = 1090; %Density of coolant (kg/m^3)
Cp = 3473; %Specific heat capacity of coolant (J/kgC)
Cp_temps = [-10:10:50] + 273.15; %Range of temperatures used for specific
heat look up (K)
Spec_heat = [3381:30.5:3565]; %Specific heat of coolant at each tempera-
ture (J/kgC)
fluid_flow = 5.5; %Fluid flow throughout coolant system
(L/min)
mass_flow = fluid_flow/1000 * 1090/60; %Calculated mass flow of coolant in coolant
system (kg/s)

figure(1)
hold on
figure(2)
hold on
figure(3)
hold on
for dT_reference = [5, 10, 15, 20]
    out = sim('SimulinkElectroModel.slx');
    quasi = squeeze(out.Quasi_All.Data); %Data from simulink for quasi-steady fig-
ure
    transient = squeeze(out.transient_sigma_normal.Data); %Data from simulink for
transient figure
    transient_1 = squeeze(out.transient_sigma_1.Data); %Data from simulink for
transient (sigma=1 case) figure
    transient_OAT_constant = squeeze(out.transient_OAT_constant.Data); %Data from
simulink for transient (OAT=15C case) figure

    if dT_reference == 5
        colour = 'b';
    elseif dT_reference == 10
        colour = 'r';
    elseif dT_reference == 15
        colour = 'g';
    else
        colour = 'y';
    end

    figure(1)
```

```

    plot(out.Quasi_All.Time *3.3, quasi, colour) %Plotting quasi-steady coolant
outlet temperature vs alt
    plot(out.transient_sigma_normal.Time*3.3, transient, [colour '--']) %Plotting
transient coolant outlet temperature vs alt
    figure(2)
    plot(out.transient_sigma_normal.Time*3.3, transient,colour)
    plot(out.transient_sigma_1.Time*3.3, transient_1, [colour '--']) %Plotting
transient normal case vs sigma=1 case
    figure(3)
    plot(out.transient_sigma_normal.Time*3.3, transient,colour)
    plot(out.transient_OAT_constant.Time*3.3, transient_OAT_constant, [colour '--
']) %Plotting transient normal case vs OAT=15C case

    quasi_radiator_final = out.Quasi_Radiator.Data(end); %How much Sigma variable
increases coolant temperature
    quasi_ambient_final = out.Quasi_Ambient.Data(end); %How much ambient decrease
coolant temperature
    quasi_radiator_start = out.Quasi_Radiator.Data(1); %This is dependent on
dT_reference
    quasi_ambient_start = out.Quasi_Ambient.Data(1); %This is always 15C or 288.15K
    delta_radiator_quasi = quasi_radiator_final - quasi_radiator_start;
    delta_ambient_quasi = quasi_ambient_final - quasi_ambient_start;

    transient_sigma_1_final = out.transient_sigma_1.Data(end); %Constant density
case
    transient_normal_final = out.transient_sigma_normal.Data(end); %Normal
    delta_transient_sigma1 = transient_normal_final-transient_sigma_1_final; %Dif-
ference caused by air density

    transient_OAT_constant_final = out.transient_OAT_constant.Data(end); %Constant
OAT case
    delta_transient_OAT_constant = transient_normal_final-transient_OAT_con-
stant_final; %Difference caused by OAT

    %Print the numerical values
    fprintf('\nT_ref = %d K\n', dT_reference);
    fprintf('Quasi radiator delta = %.4f K\n', delta_radiator_quasi);
    fprintf('Quasi ambient delta = %.4f K\n', delta_ambient_quasi);
    fprintf('Transient density delta = %.4f K\n', delta_transient_sigma1);
    fprintf('Transient OAT delta = %.4f K\n', delta_transient_OAT_constant);
end

figure(1)
xlabel('Altitude (m)')
ylabel('Coolant outlet temperature (K)')
legend('Quasi 5K', 'Transient 5K', 'Quasi 10 K','Transient 10 K', 'Quasi 15
K','Transient 15 K','Quasi 20 K','Transient 20 K')
grid on
hold off

figure(2)
xlabel('Altitude (m)')
ylabel('Coolant outlet temperature (K)')
legend('Sigma 5K', 'Sigma=1 5K', 'Sigma 10 K','Sigma=1 10K', 'Sigma 15 K','Sigma=1
15K','Sigma 20 K','Sigma1 20K')
grid on
hold off

figure(3)
xlabel('Altitude (m)')
ylabel('Coolant outlet temperature (K)')
legend('OAT 5K', 'OAT=15C 5K', 'OAT 10 K','OAT=15C 10K', 'OAT 15 K','OAT=15C
15K','OAT 20 K','OAT=15C 20K')
grid on
hold off

```